Impact Cratering in the Solar System

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LUNAR AND PLANETARY INSTITUTE

USRA

Outline

- What is an impact crater?
- Why should we care about impact craters?
- Inner Solar System
- Outer Solar System
- Conclusions
- Open Questions

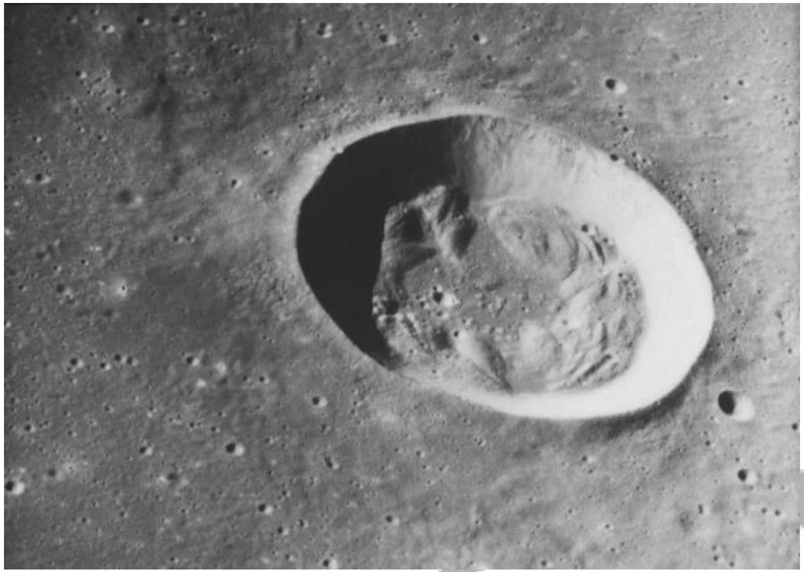
What is an impact crater?

Basically a hole in the ground…

Barringer Meteor Crater (Earth)

Diameter = 1.2 km

Depth = 200 m



Bessel Crater (Moon)

Diameter = 16 km

Depth = 2 km

What creates an “impact” crater?

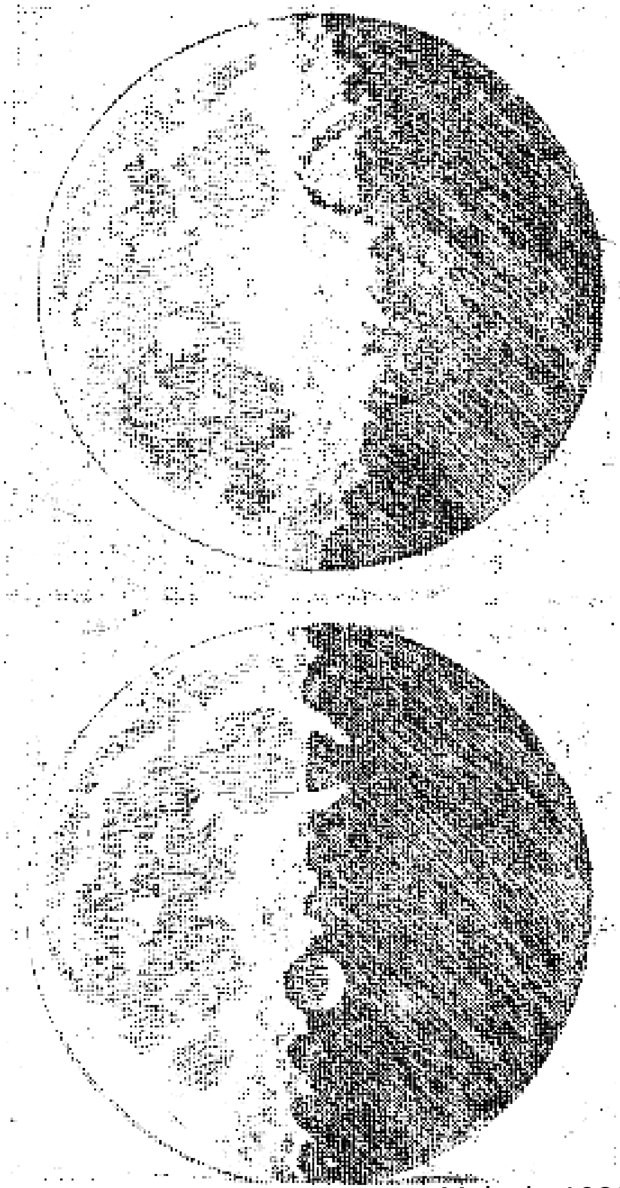
•Galileo sees circular features on Moon & realizes they are depressions (1610)

•In 1600-1800’s many think they are volcanic features: look similar to extinct volcanoes on Earth; some even claim to see volcanic eruptions; space is empty (meteorites not verified until 1819 by Chladni)

•G.K. Gilbert (1893) first serious support for lunar craters from impacts (geology and experiments)

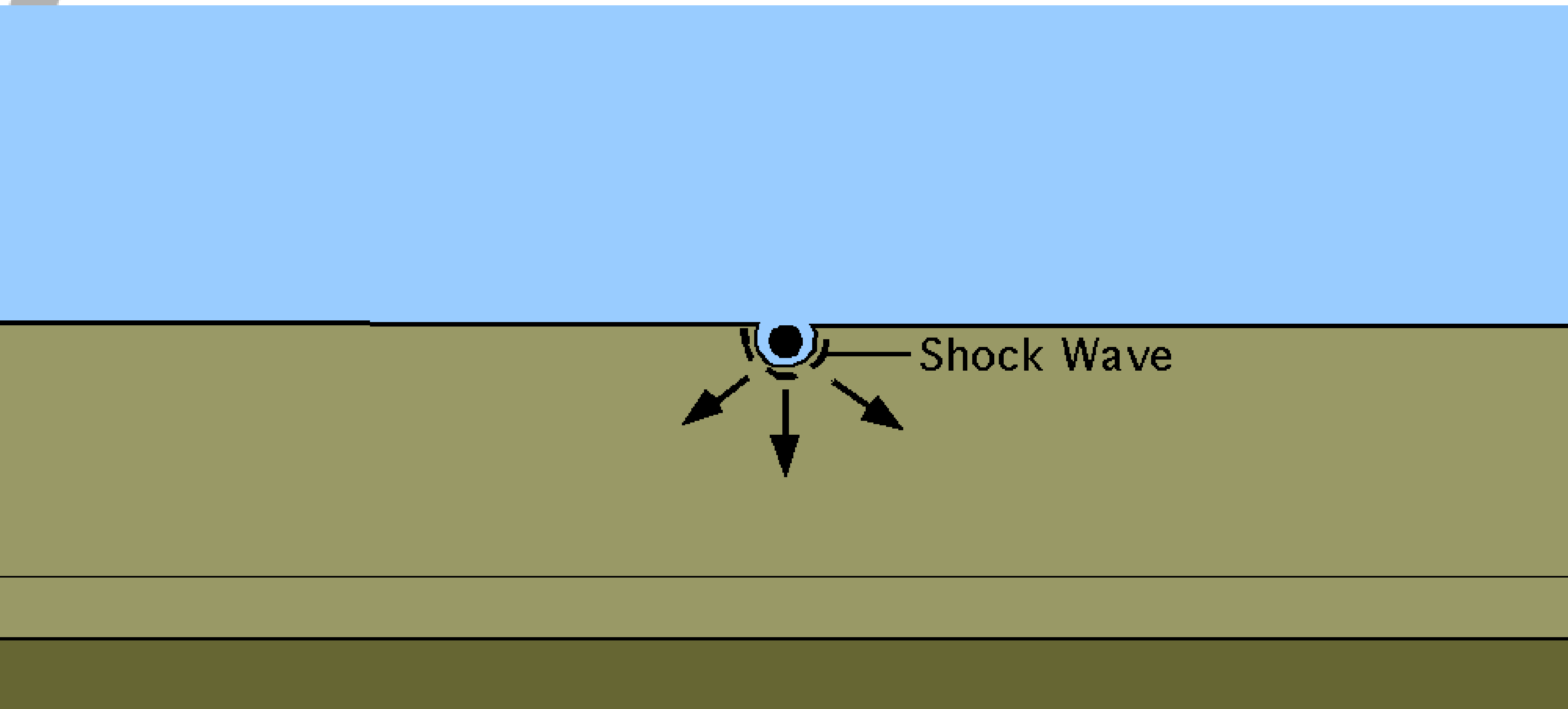
•On Earth Barringer (Meteor) crater recognized as created by impact by Barringer (1906)

•Opik (1916) - impacts are high velocity, thus create circular craters at most impact angles



Melosh, 1989

…High-Velocity Impacts!

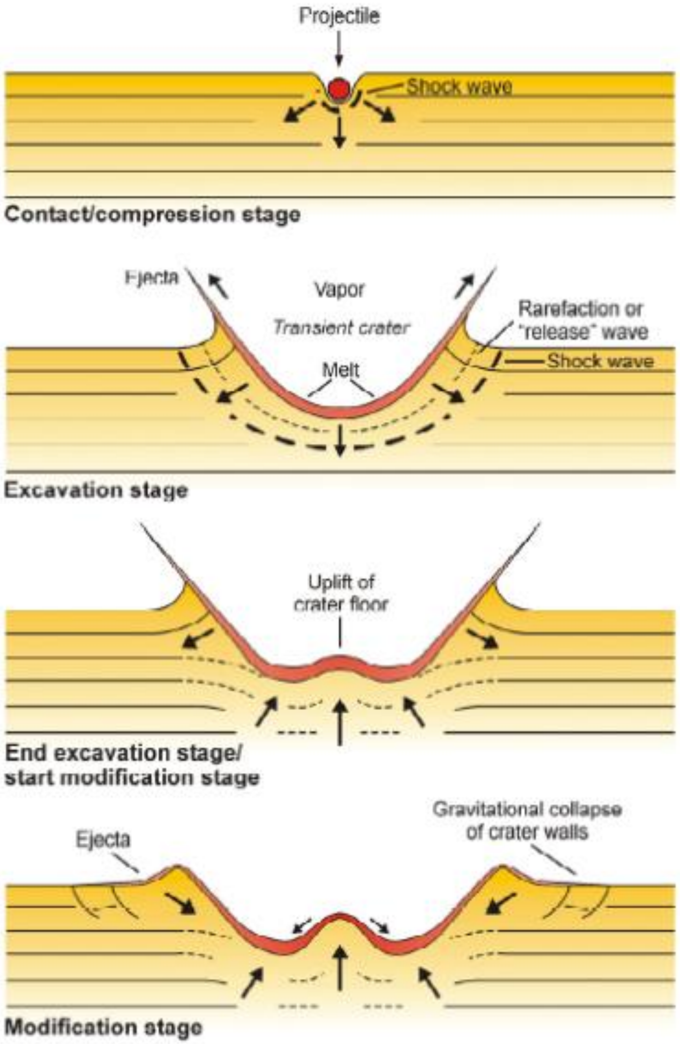


www.lpl.arizona.edu/SIC/impact_cratering/Chicxulub/Animation.gif

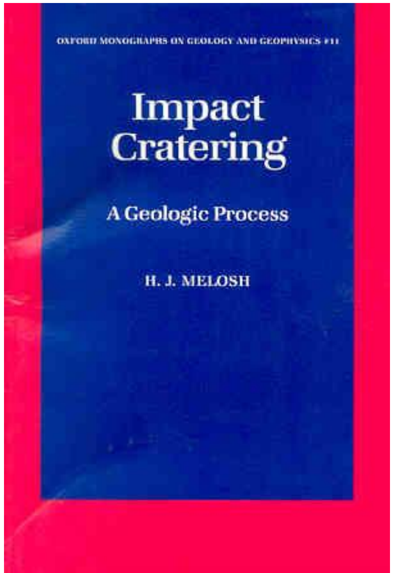
Physics of Impact Cratering

Understand how stress (or shock) waves propagate through material in 3 stages:

1. Contact and Compression
2. Excavation
3. Modification



www.psi.edu/explorecraters/background.htm



Hugoniot Equations

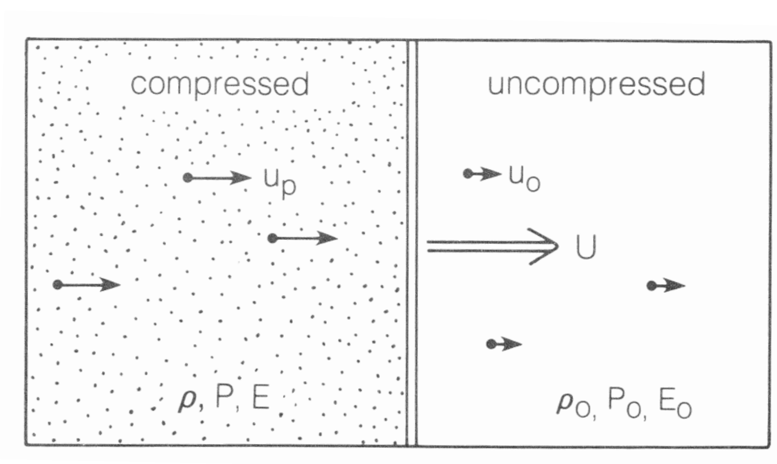
Derived by P.H. Hugoniot (1887) to describe shock fronts using conservation of mass, momentum and energy across the discontinuity.

+ equation of state

$\rho(U-u_p) = \rho_o U$

$P-P_o = \rho_o u_p U$

$E-E_o = (P+P_o)(V_o-V)/2$



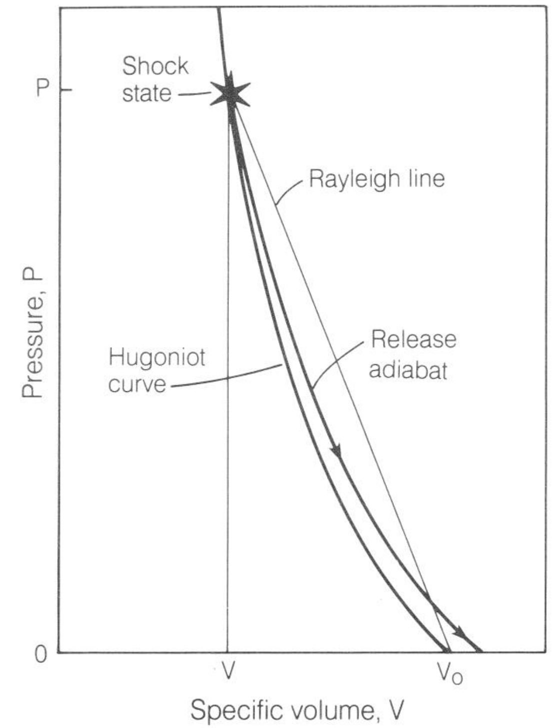
P - pressure

U - shock velocity

u_p - particle velocity

E - specific internal energy

V = 1/ρ (specific volume)

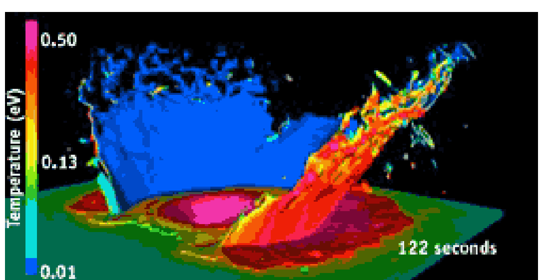


Understanding Crater Formation

large explosives (1940's)

laboratory simulations (1950's)

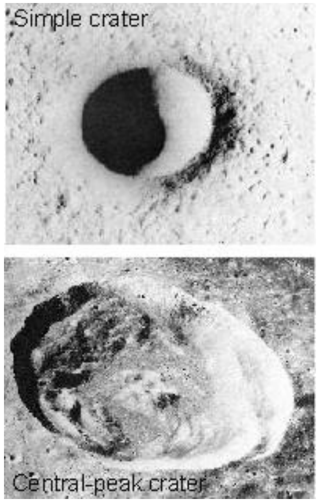
numerical simulations (1960's)



www.lanl.gov/

Crater Morphology

- Simple
- Complex
  - Central peak/pit
  - Peak ring
- Multiringed Basins
- Secondaries



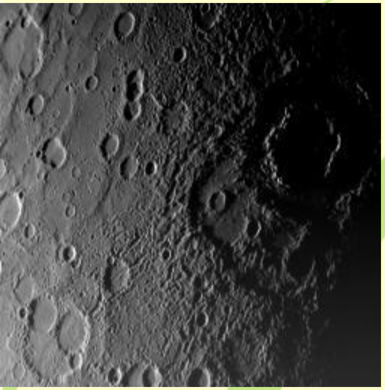
www3.imperial.ac.

www.uwgb.edu

www.geologyrocks.co.uk/

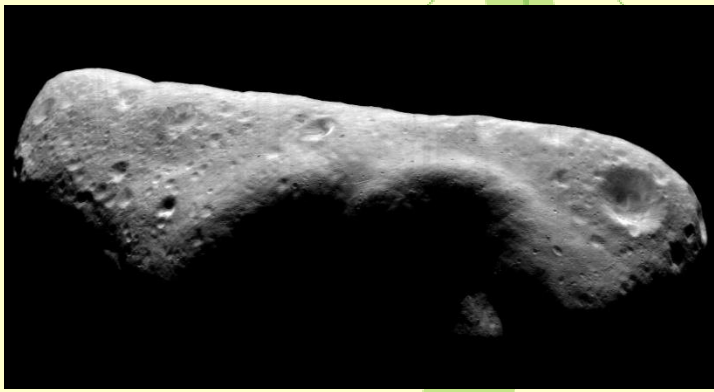
Why should we care about impact craters?

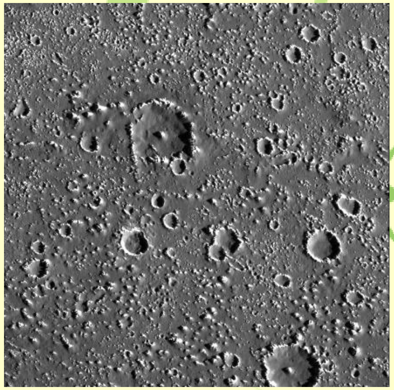
Found on every solid planetary surface except Jupiter's moon Io!

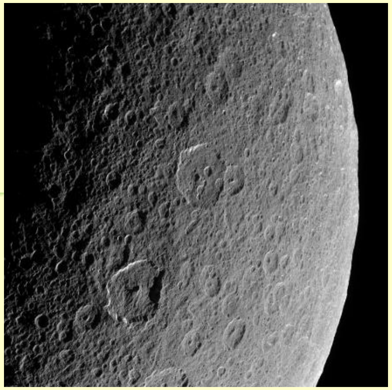

Mercury


Venus

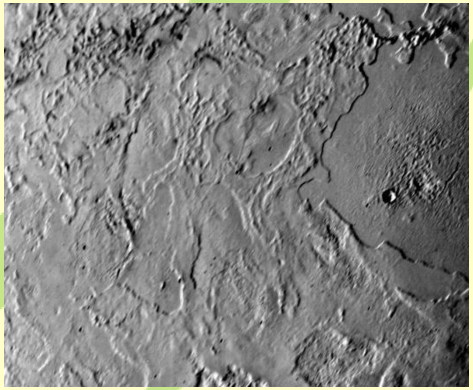

Mars


Eros


Callisto (J)


Rhea (S)

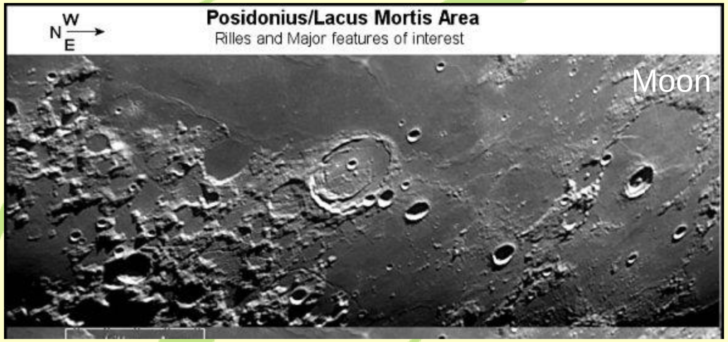

Titania (U)


Triton (N)

photojournal.jpl.nasa.gov

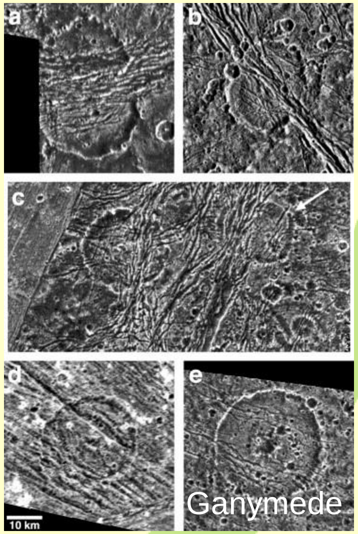
Surface Processes

Volcanism



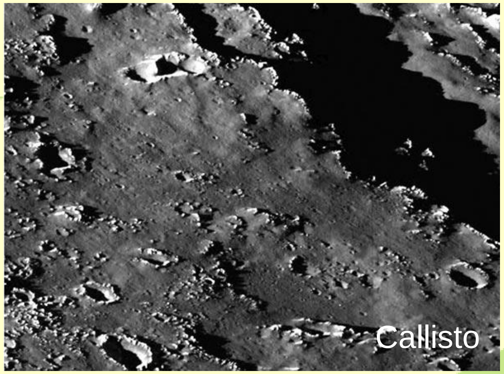
www.cityastronomy.com/

Tectonics



Pappalardo & Collins, 2005

Erosion

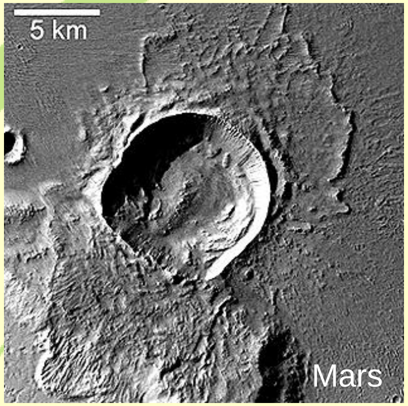


www2.jpl.nasa.gov/

Interiors

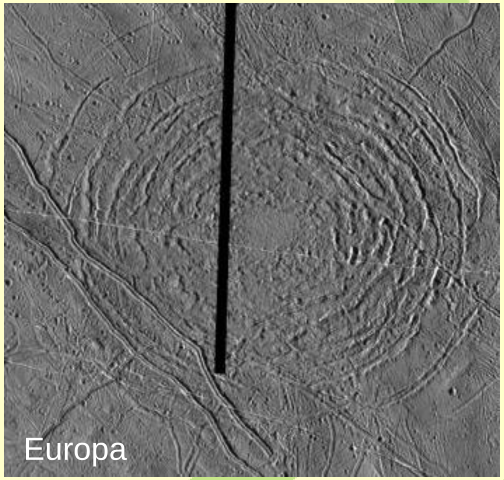
Holes Into Crust w/ Ejecta

http://marswatch.astro.cornell.edu



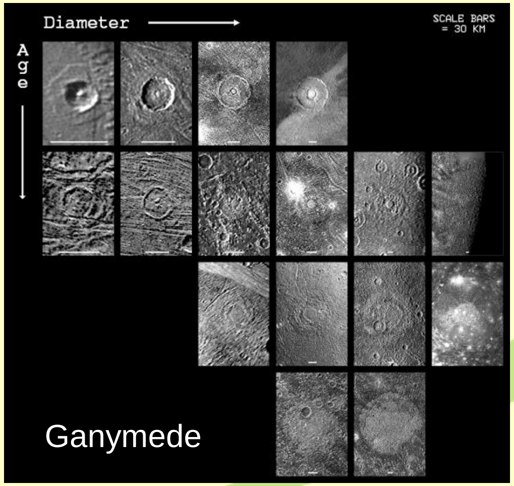
rst.gsfc.nasa.gov

Deeper Layers



www.lpi.usra.edu/

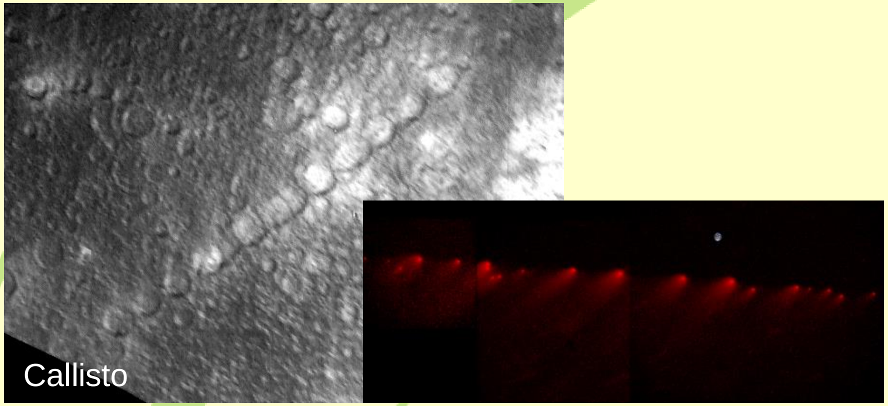
Heat Flow



www.lpi.usra.edu

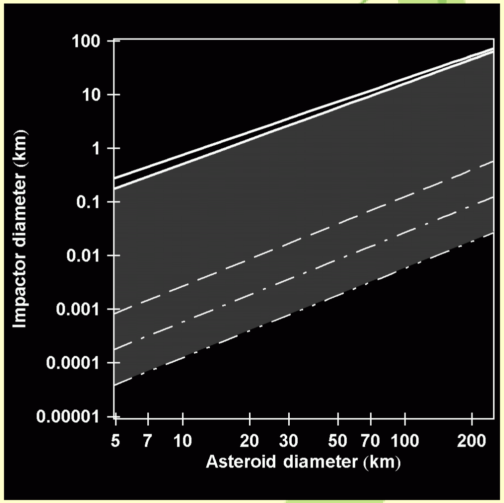
Solar System Dynamics

Breakups



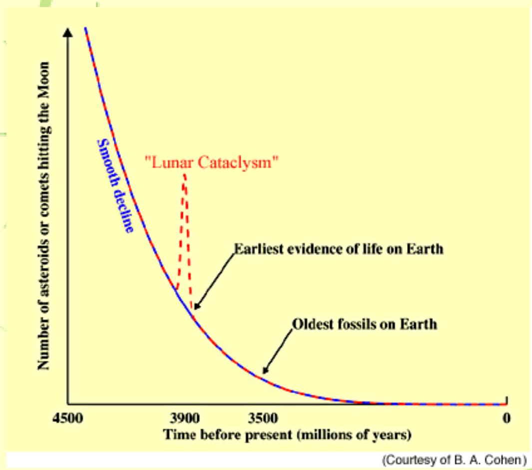
Schenk et al., 1996

Populations & Rates

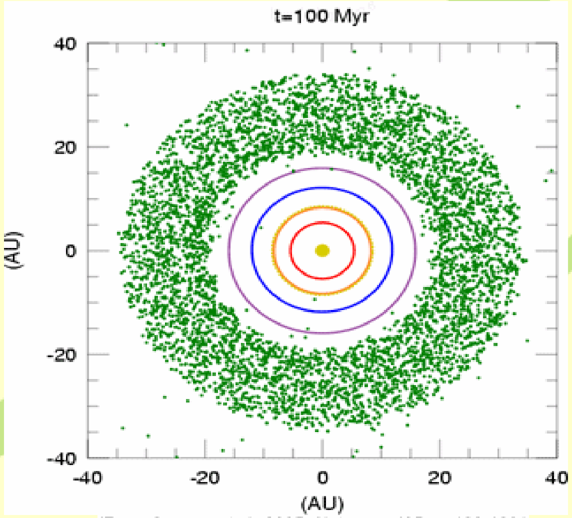


www.astro.cornell.edu

Orbital Dynamics



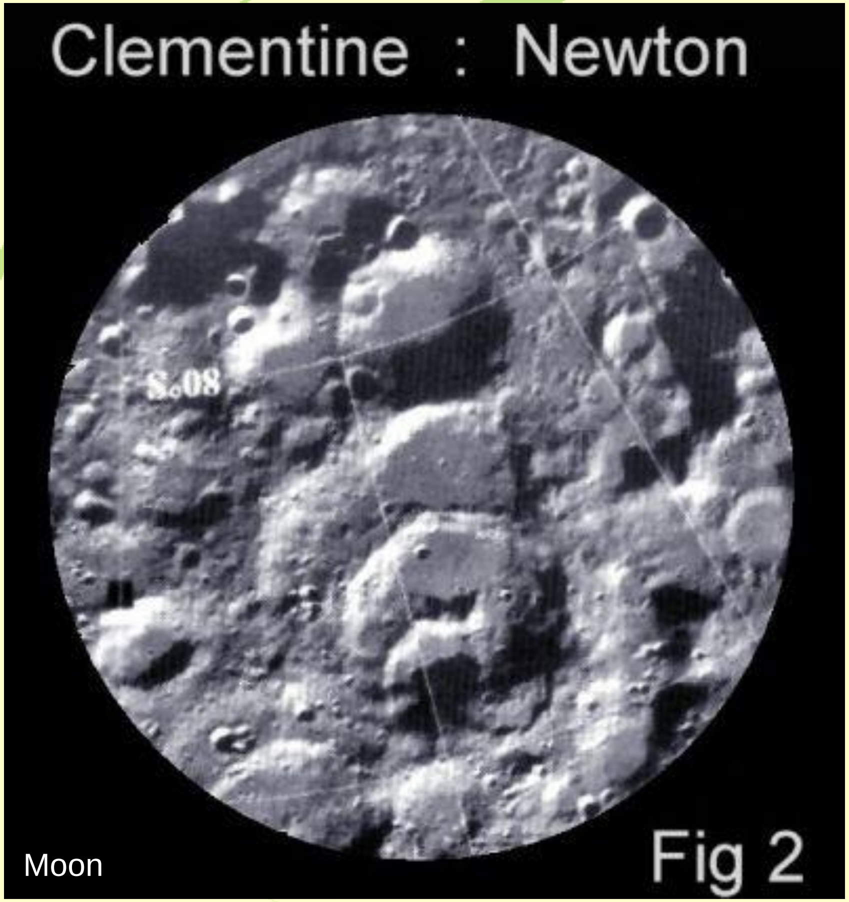
www.psrd.hawaii.edu



(From Gomes, *et al.*, 2005, *Nature*, v. 435, p. 466-469.)

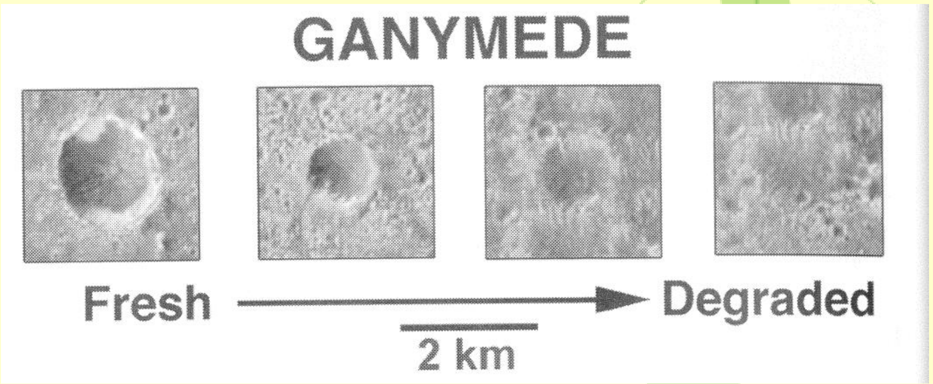
Historical Geology & Ages

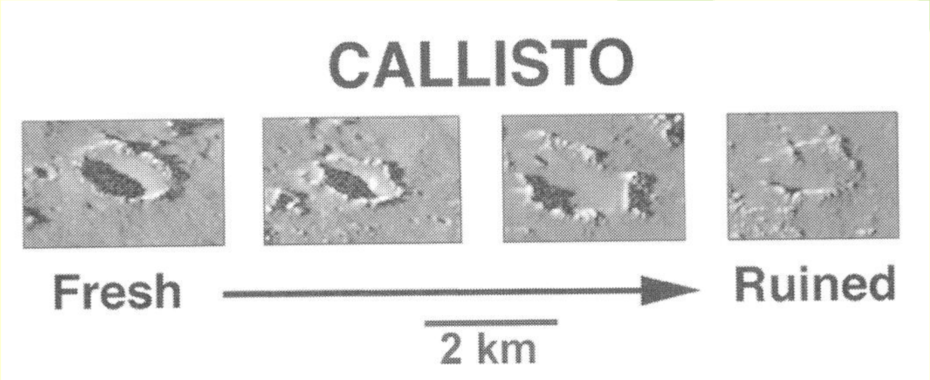
Stratigraphy



www.sydneyobservatory.com.au/

Morphology

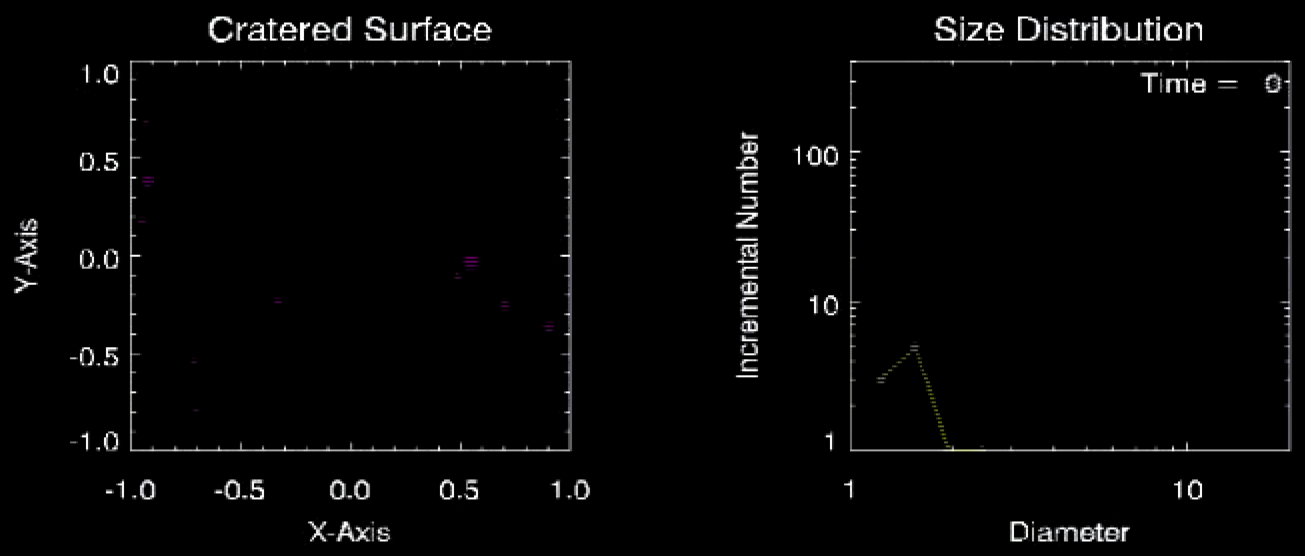


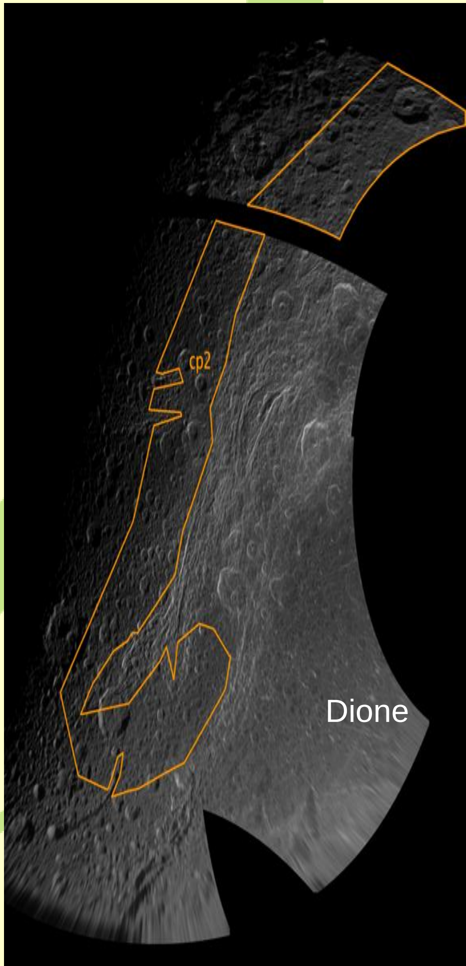


Schenk et al., *Jupiter*, 2004

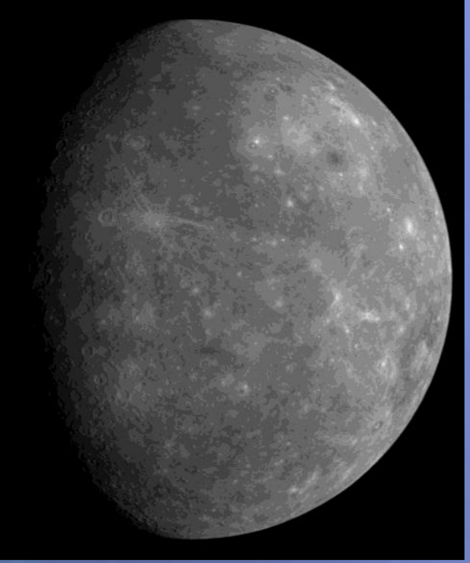
Historical Geology & Ages

Crater Counting



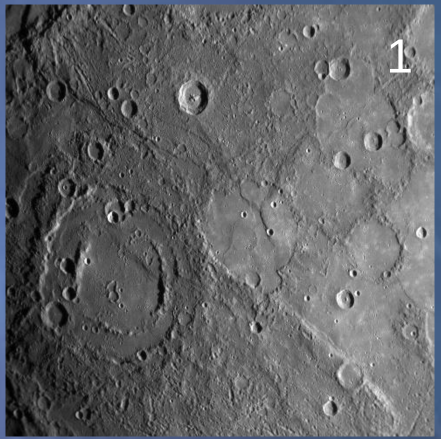


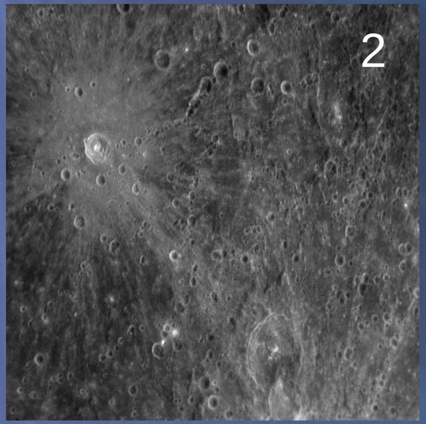
Crater Studies in the Inner Solar System



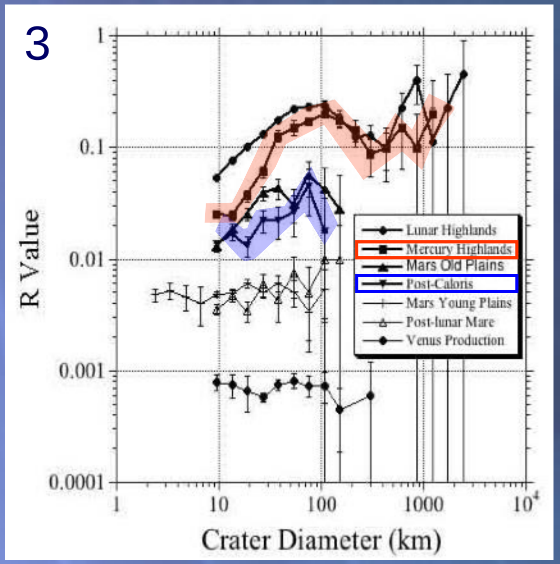
Mercury

- Heavily cratered
- Mariner 10: 1974-75
- Messenger: now





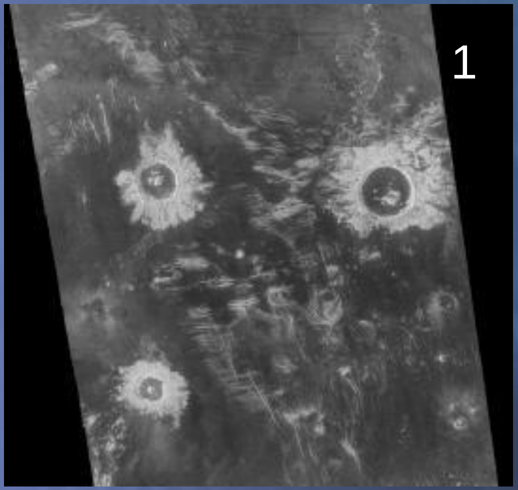
- Material embays/fills some craters (1)
- Scarp disrupts craters (1)
- Younger craters have bright ejecta & floors (2)
- Old surface, but areas exist with differing crater densities (3)
- Degradation occurs faster
- Transition diameter for simple to complex craters same on different terrains



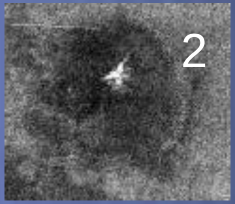
Resources: Ch. 8-10, *Mercury*; Ch. 7, *New Solar System*; photojournal.jpl.nasa.govv

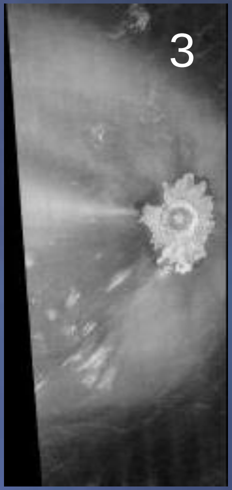
Venus

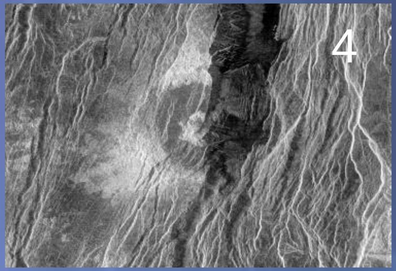
- Lightly Cratered
- Magellan: 1992-94
- Venera Lander: 1982
- Venus Express: now



- Material embays/fills some craters (1)
- Little erosion affecting craters (1)
- Craters scattered randomly across surface; surface only ~500 Myr (using Lunar chronology)
- No small craters - atmosphere
- Dark splotches - disruption of meteorites in atmosphere (2)
- Ejecta tails - indicate wind patterns (3)
- Tectonics disrupt crater (4)
- Crustal thickness ~10-20 km derived from study of non-viscously relaxed craters





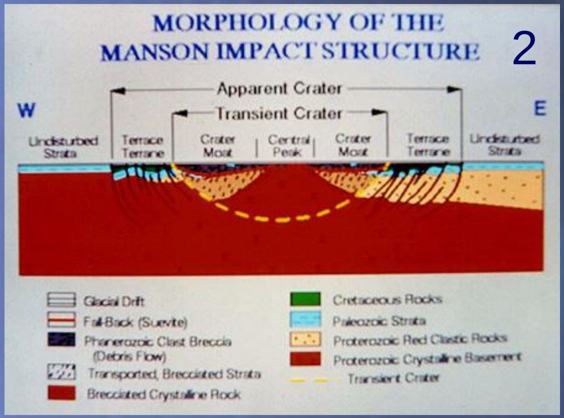


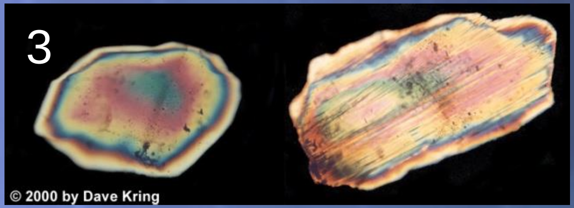
Resources: Ch. 8, *New Solar System*; Grimm & Solomon, 1988; photojournal.jpl.nasa.gov

Earth

- Very Lightly Cratered

- ~ 150 known craters
- Activity on Earth very efficient at erasing craters
- Like Venus, Earth's atmosphere affects impactors (Tunguska airburst 1908)
- Impacts and global damage (Chicxulub & K/T boundary extinction) (1)
- Bring up deeper rocks (2)
- Explore compositions of impactors
- Study effect of the large stresses - e.g., shocked quartz (3)

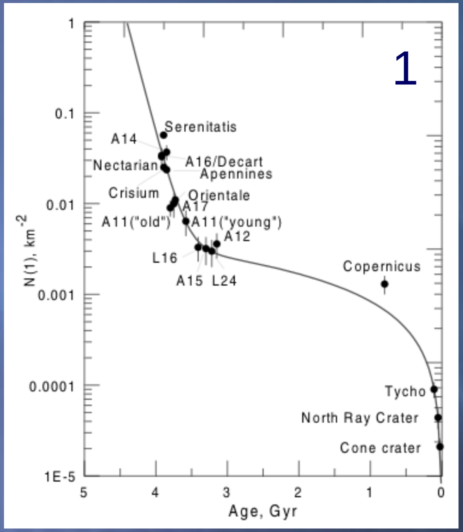


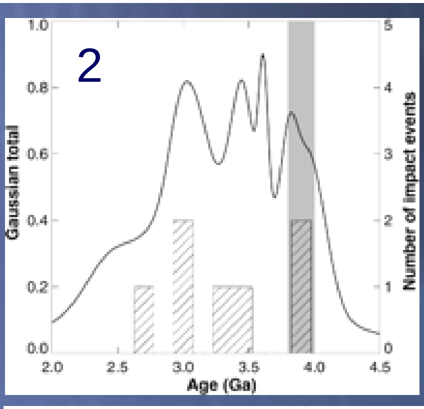


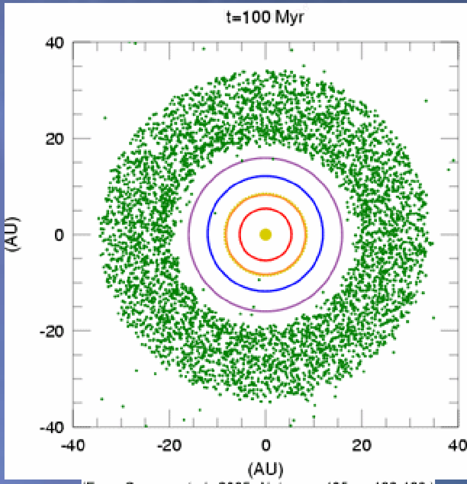
Resources: Ch. 15, *Hazards due to Comets & Asteroids*, 1994; science.nationalgeographic.com; www.fas.org; www.lpi.usra.edu;

Moon

- Heavily Cratered
- Apollo: 1969-72
- Clementine: 1994
- Men going back



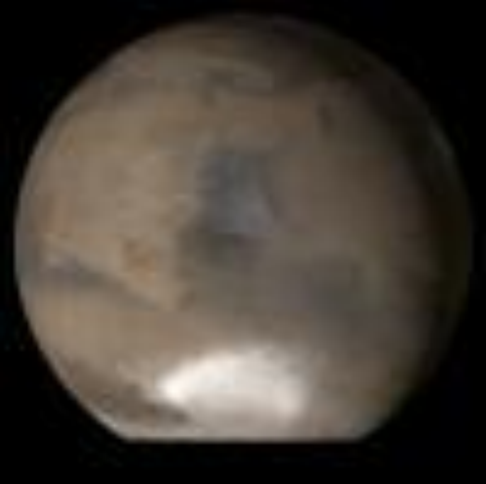




(From Gomes, *et al.*, 2005, *Nature*, v. 435, p. 466-469.)

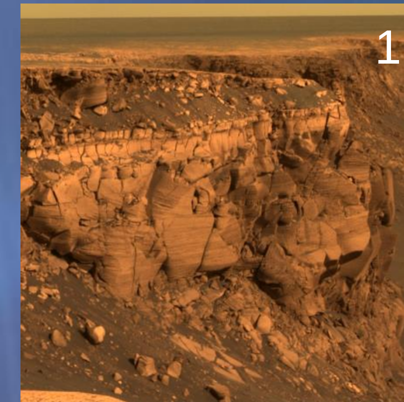
- Cratering rate (1)
- Late Heavy Bombardment (2)
- Material embays/fills some craters
- Distributions on Highlands and Mare
- Bright ejecta rays
- Dark-halo craters - evidence for buried mare volcanism

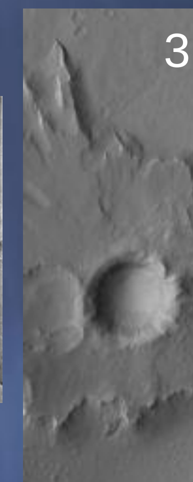
Resources: Ch. 10, *New Solar System*; Bell & Hawke, 1984; Neukum et al, 2001; Kring & Cohen, 2002; Cohen et al., 2000; Gomez et al., 2005; photojournal.jpl.nasa.gov



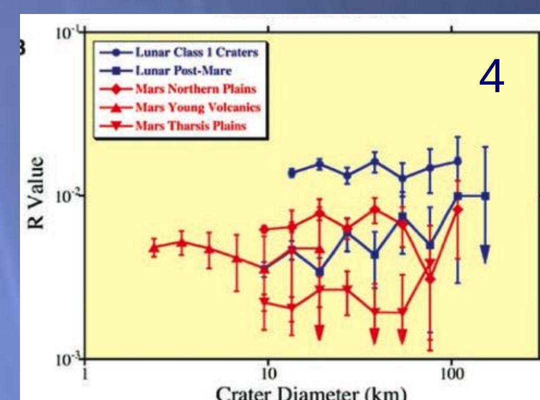
Mars

- Lightly to Heavily Cratered
- Mariners: 1960’s & 70’s
- Vikings: 1976
- Pathfinder: 1997
- MER & MRO: now



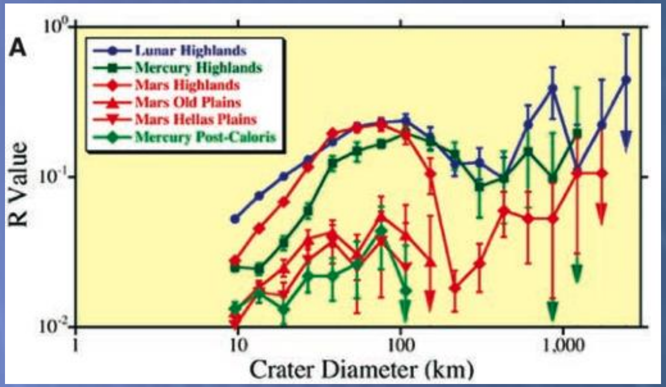


- Look into past crustal layers - evidence for water! (1)
- Fluidized ejecta (2)
- Pedestal craters (3)
- Units with very different crater densities (4)
- Evidence of faster erosion
- Embayed craters



Resources: Ch. 11, *New Solar System*; www.lpi.usra.edu ; photojournal.jpl.nasa.gov

Inner Solar System Comparisons



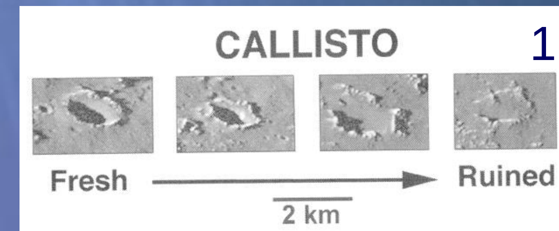
- Ancient terrains all show a similar size-frequency distribution (SFD) - shape & density - implying one impactor population, likely main-belt asteroids (MBA) which also have a similar SFD (Woronow et al., *Satellites of Jupiter*, 1982; Neukum et al., Chronol. & Evol. Mars, 2001; Strom et al., Science, 2005)
- This similarity also implies that the late heavy bombardment that occurred on the Moon occurred throughout the ISS and was due to the scattering of MBA by orbital migration of the gas giants (Strom et al., Science, 2005; Gomez et al., Nature, 2005)
- The transition diameter between simple/complex for Mercury & Moon is different than for Earth & Mars implying that impacts can be different into "dry" targets than "wet" (Pike, *Mercury*, 1988)
- Ring spacing for basins is similar on all bodies implying that target properties is not an important factor for basin rings formation (Pike, *Mercury*, 1988)
- Some bodies have been more recently active than others: Venus ~0.5 Ga, Mars ~0.5-2 Ga, Moon ~3 Ga, Mercury > 4 Ga (*The New Solar System*, 1999)

Crater Studies in the Outer Solar System

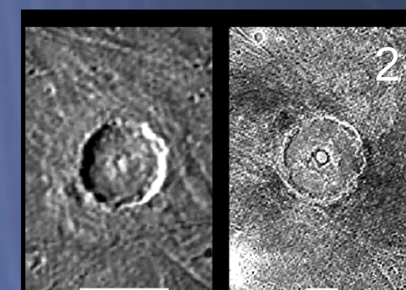

Ganymede
5262 km
Titan
5150 km
Mercury
4880 km
Callisto
4806 km
Io
3642 km
Moon
3476 km
Europa
3138 km
Triton
2706 km
Pluto
2300 km
Titania
1580 km
The Largest Moons and Smallest Planets
© Copyrgiht 1999 by Calvin J. Hamilton

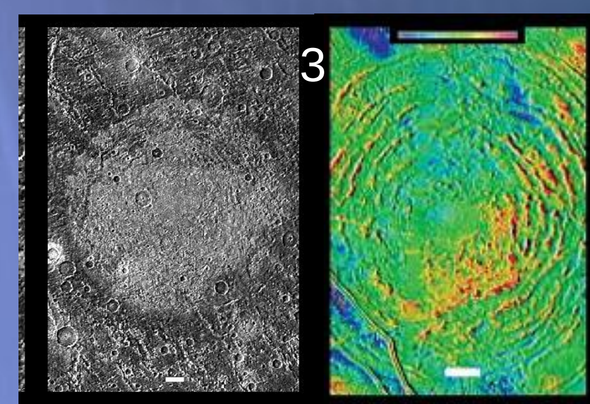
Jupiter’s Moons

- Lightly to Heavily Cratered
- Voyagers: 1979
- Galileo: 1995-2003



- Europa: secondaries may be an important influence on densities at smaller diameters
- Ganymede: strained craters
- Ganymede: terrains with different crater densities
- Ganymede: pedestal craters
- Callisto: unique degradation process/lack of small craters (1)
- All: central pit/dome craters (2)
- All: different color material, some crater floors level with exterior terrain & furrows - large impacts into thin layered crust over ductile ice/water (3)
- All: relaxed craters



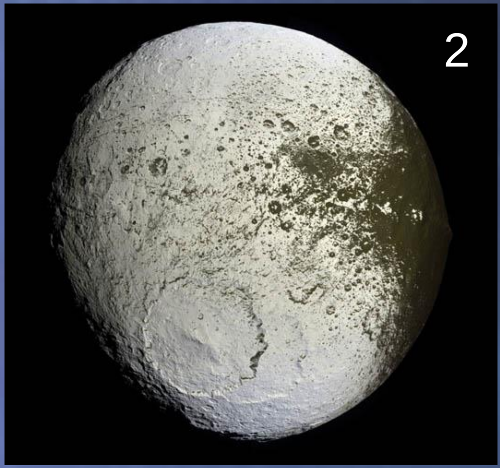


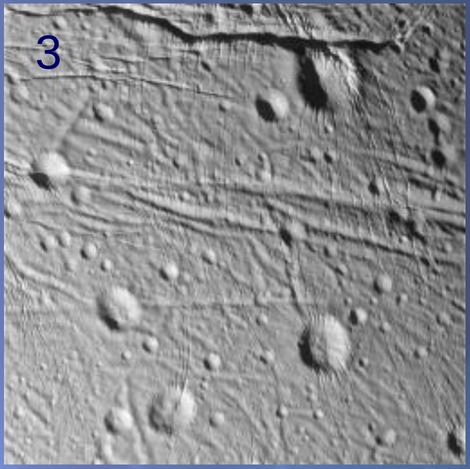
Resources: Ch. 18-19, *New Solar System*; Bierhaus et al., 2001; Pappalardo & Collins, 2005; Dombard & McKinnon, 2006; Chapman & McKinnon, 1986; photojournal.jpl.nasa.gov

Saturn's Moons

- Lightly to Heavily Cratered
- Voyagers: 1980
- Cassini: now

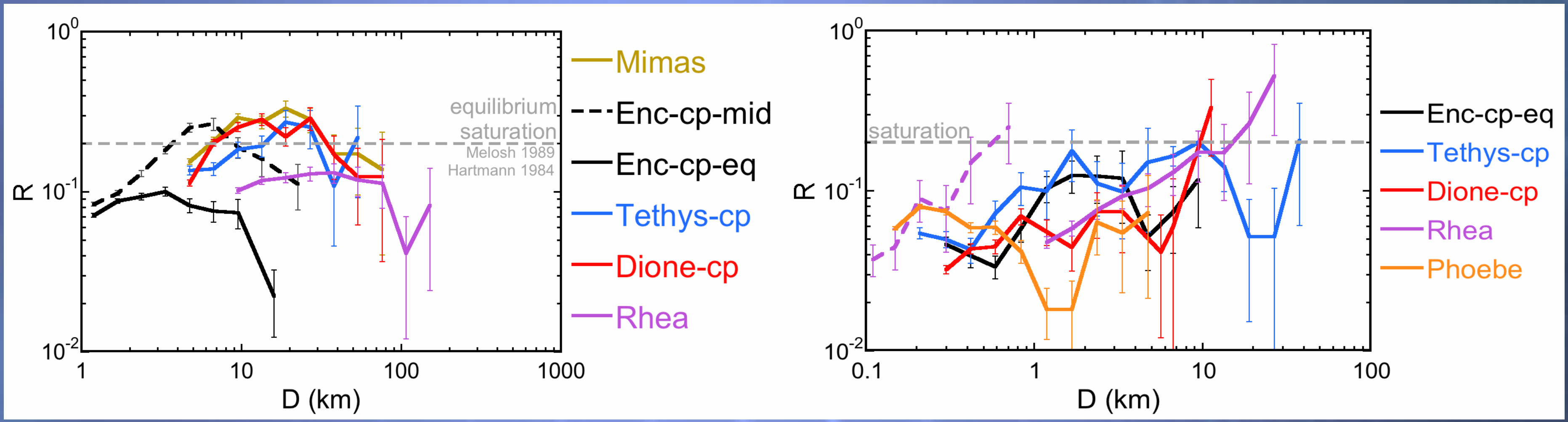
- Relaxed craters (1)
- Energy required for satellite breakup
- Iapetus: white floored craters in dark terrain; dark material in floors of craters in bright terrain (2)
- Rhea: abundance of small (D < 20 km) craters - another impactor population
- Relative decrease of larger craters on younger terrains - another impactor population
- Some: faulted and strained craters (3)
- Some: terrains of varying crater density





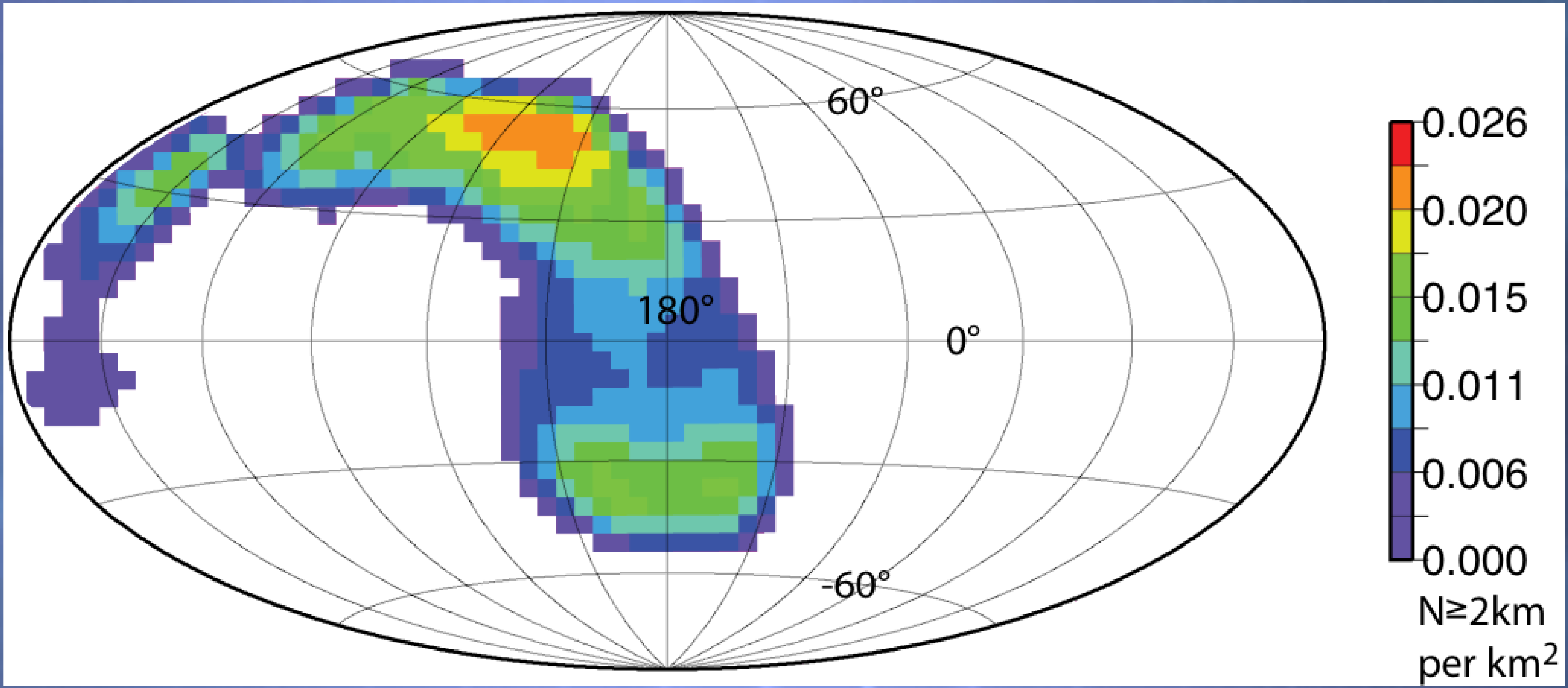
Resources: Ch. 22, *New Solar System*; Chapman & McKinnon, 1986; astro.wsu.edu; www.skyandtelescope.com; photojournal.jpl.nasa.gov

Cratered Plains Distributions



- ☼ similar shape ⇒ same impactor population
- ☼ except Enceladus ➔ steep drop off D≥6 km & D≤2 km
  - ➢ burial, different impactor population ??
  - ➢ viscous relaxation, different impactor population ??
- ☼ except Phoebe, dip at D≈1.5 km

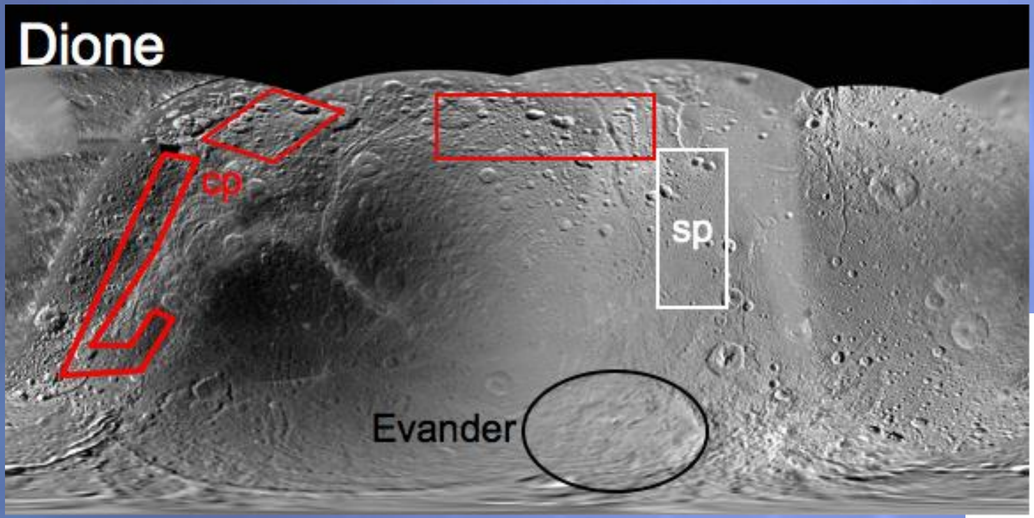
Enceladus

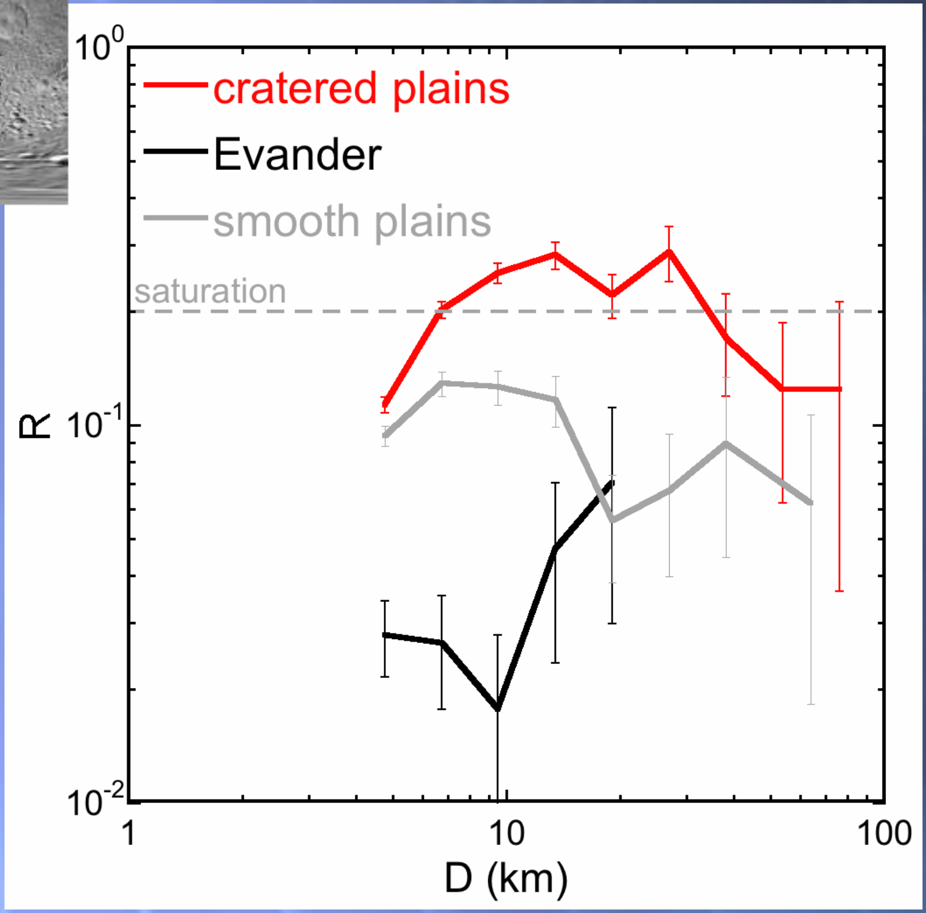


Crater Density Map: No. of craters ≥2 km per unit area in the cratered plains (cp) unit; created with counting circle analysis (R=10°)

➔ In cratered plains have low density at equator; higher density (~2x) at mid-latitudes

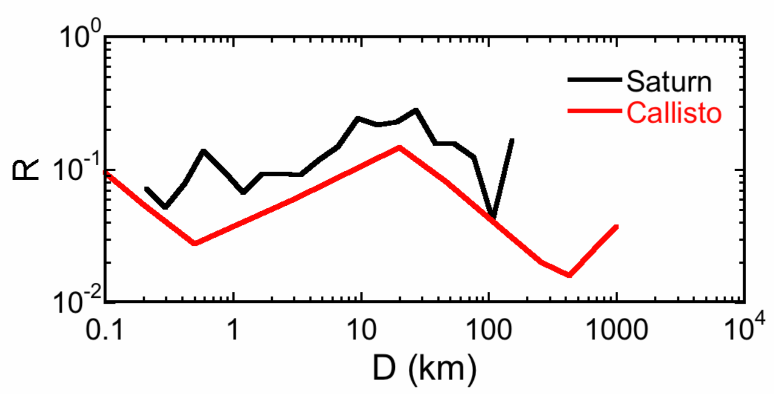
Dione





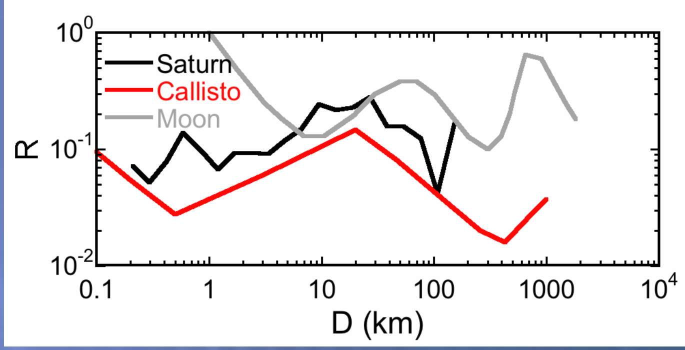
- shapes comparable ⇒ impactor population may be same over time

Outer Solar System Comparisons



- Unlike past work (Chapman & McKinnon, *Satellites*, 1986), I have found that SFD are similar for Saturn's and Jupiter's satellites implying one primary impactor population for the OSS.
- The similarity of the Uranus' satellites to Jupiter's and Saturn's (McKinnon, *Uranus*, 1991) further supports this argument.
- The crusts of icy satellites are generally layered evidenced by the bright or dark ejecta that sometimes surround craters (Chapman & McKinnon, *Satellites*, 1986)
- Central pit craters common on Ganymede & Callisto, but not others - formation is likely a strong function of gravity and may rely on a warmer lithosphere (Chapman & McKinnon, *Satellites*, 1986)
- Multiringed basin structure varies - dependant on rheology of the interior (Chapman & McKinnon, *Satellites*, 1986)
- Some of these bodies have been more recently active than others: Enceladus & Io current, Europa ~60 Ga, Ganymede ~2 Ga, Tethys & Dione ~4 Ga (Zahnle et al., Icarus, 2003)

ISS/OSS Comparisons



- SFD shapes are not similar implying different impactor populations for the inner and outer solar systems
- Simple craters have similar depths implying cratering mechanics is same on rocky and icy bodies (Schenk et al., *Jupiter*, 2004)
- Complex craters are generally shallower - modification is different depending on rock/ice and gravity (Schenk et al., *Jupiter*, 2004)
- Transition diameters generally occur at smaller values for icy satellites than rocky bodies most likely due to that ice is weaker than rock (Schenk et al., *Jupiter*, 2004)
- Central pit in OSS (& rarely Mars) vs. peak ring in ISS - Implication of water rheology (Chapman & McKinnon, *Satellites*, 1986)

Conclusions

- Impact craters are a common geologic feature in our solar system and studying them has provided and will provide many important insights into a wide variety of questions about our solar system.
- Some bodies in our solar system have been recently active.
- The gas giants likely underwent a major migration of their orbits early in solar system history that lead to a heavy bombardment of the ISS.
- The inner and outer solar system have been impacted by different populations.
- The physics of hypervelocity impacts is cool!

Open Questions

- Is there a different impactor population for old and young terrains in the ISS?
  - Strom et al., Science, 2005 argue yes - NEO
  - Neukum et al., Chronol. & Evol. Mars, 2001 argue no
- Are there two impactor populations in the OSS?
- Is contamination by secondaries considerably affecting crater counts at small diameters?
  - McEwen & Bierhaus, 2006 argue yes
  - Neukum et al., argue no
- What is the cratering rate for the OSS?
- Is the rate for the inner solar system truly determined?
- What specifically are the causes for the morphology differences between the inner and outer solar system?
- Why and how do peak/peak rings/pits/multirings develop?