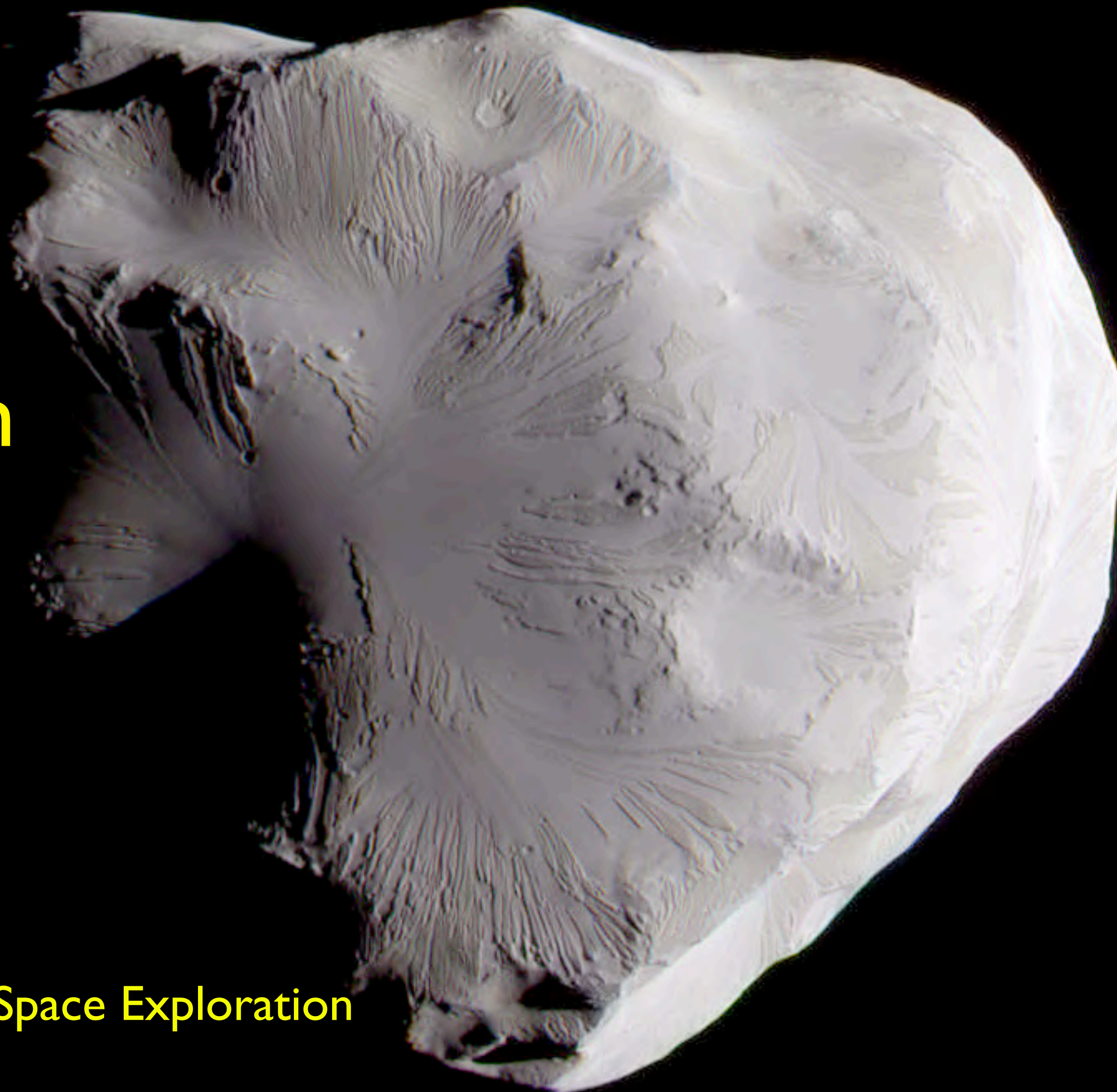
Surface Geology & Geologic Processes on Primitive Bodies



NASA/JPL/SSI/Cassini Mission

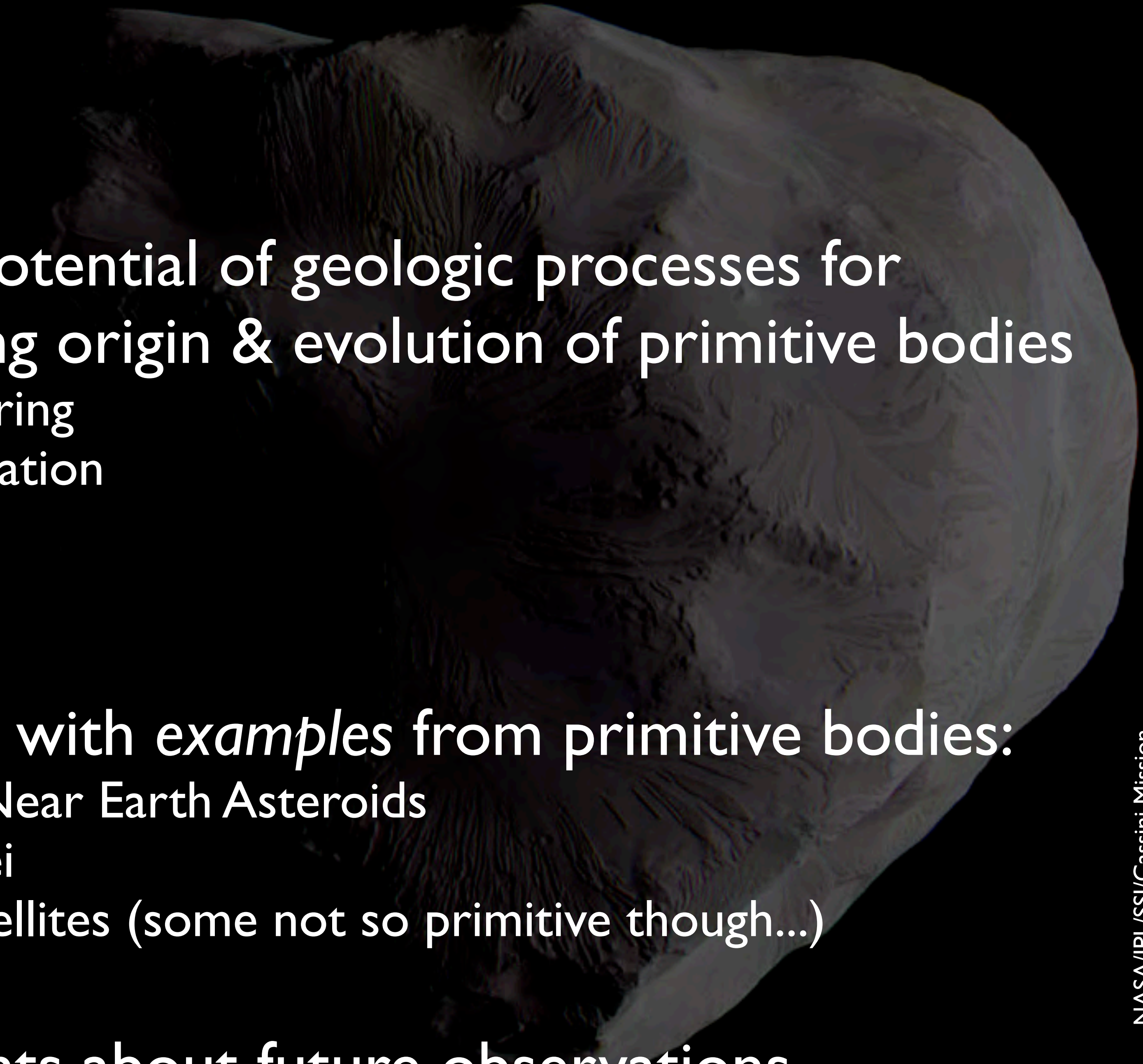
Jim Bell
ASU/School of Earth & Space Exploration
Tempe, Arizona

Outline

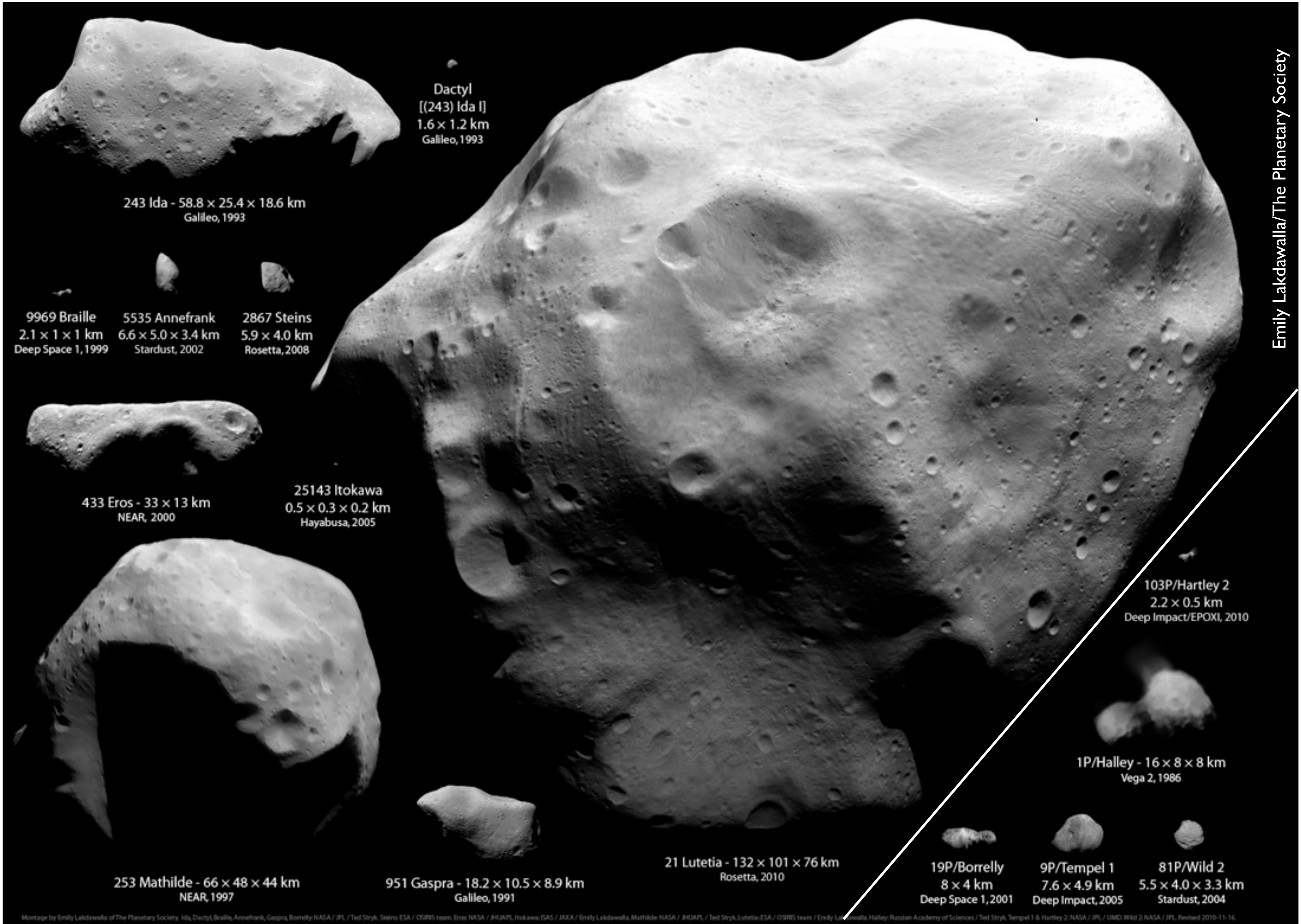
- Diagnostic potential of geologic processes for understanding origin & evolution of primitive bodies
  - Impact Cratering
  - Erosion/Gradation
  - Tectonism
  - Volcanism

- Interspersed with *examples* from primitive bodies:
  - Main Belt & Near Earth Asteroids
  - Comet Nuclei
  - Planetary Satellites (some not so primitive though...)

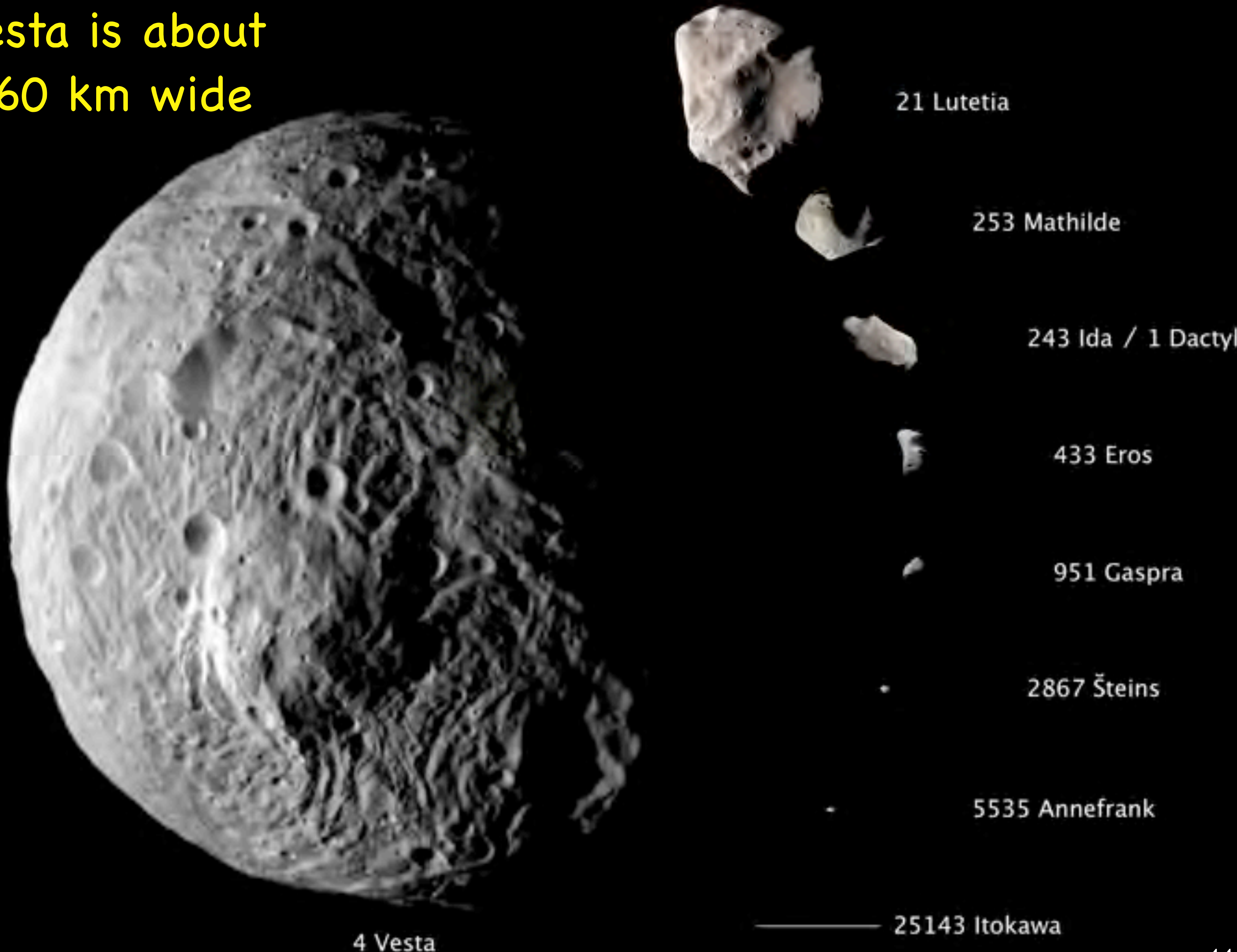
- Some thoughts about future observations

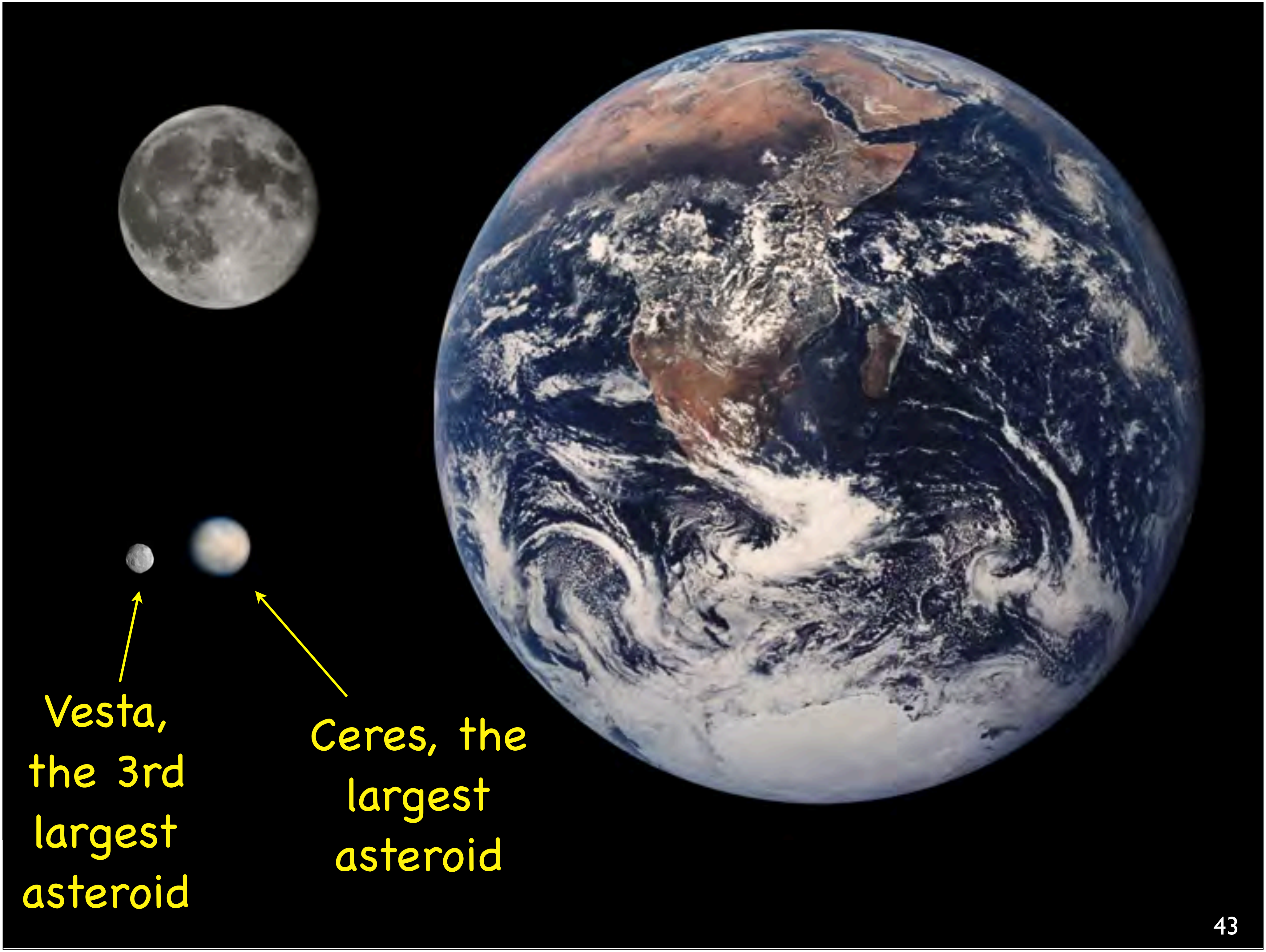


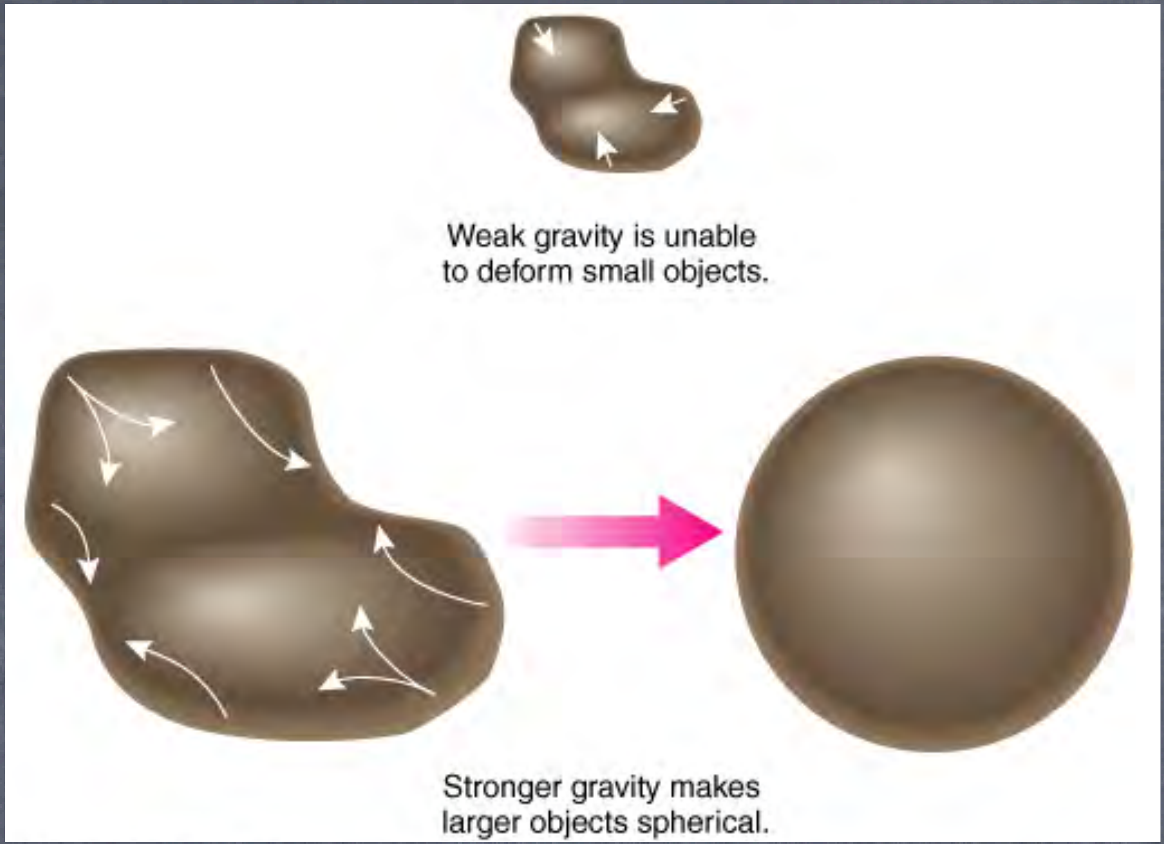
NASA/JPL/SSI/Cassini Mission


Emily Lakdawalla/The Planetary Society
243 Ida - 58.8 × 25.4 × 18.6 km
Galileo, 1993
Dactyl
[(243) Ida I]
1.6 × 1.2 km
Galileo, 1993
9969 Braille
2.1 × 1 × 1 km
Deep Space 1, 1999
5535 Annefrank
6.6 × 5.0 × 3.4 km
Stardust, 2002
2867 Steins
5.9 × 4.0 km
Rosetta, 2008
433 Eros - 33 × 13 km
NEAR, 2000
25143 Itokawa
0.5 × 0.3 × 0.2 km
Hayabusa, 2005
253 Mathilde - 66 × 48 × 44 km
NEAR, 1997
951 Gaspra - 18.2 × 10.5 × 8.9 km
Galileo, 1991
21 Lutetia - 132 × 101 × 76 km
Rosetta, 2010
103P/Hartley 2
2.2 × 0.5 km
Deep Impact/EPOXI, 2010
1P/Halley - 16 × 8 × 8 km
Vega 2, 1986
19P/Borrelly
8 × 4 km
Deep Space 1, 2001
9P/Tempel 1
7.6 × 4.9 km
Deep Impact, 2005
81P/Wild 2
5.5 × 4.0 × 3.3 km
Stardust, 2004
Montage by Emily Lakdawalla of The Planetary Society. Ida, Dactyl, Braille, Annefrank, Gaspra, Borrelly: NASA / JPL / Ted Stryk. Steins: ESA / OSIRIS team. Eros: NASA / JHUAPL. Itokawa: ISAS / JAXA / Emily Lakdawalla. Mathilde: NASA / JHUAPL / Ted Stryk. Lutetia: ESA / OSIRIS team / Emily Lakdawalla. Halley: Russian Academy of Sciences / Ted Stryk. Tempel 1 & Hartley 2: NASA / JPL / UMD. Wild 2: NASA / JPL. Revised 2010-11-16.

Vesta is about 560 km wide




Vesta, the 3rd largest asteroid
Ceres, the largest asteroid



- Where does "geology" begin to be expressed?
  - At large enough sizes, objects can preserve impact craters without being completely destroyed
  - Above a threshold size, self-gravity leads to a spherical shape because of internal heating/relaxation. Differentiation? Gradational processes?
  - Larger sizes, more internal heating: Volcanism? Tectonism? Gradation?
  - Note: Somewhere in here is where some people define "planet"...

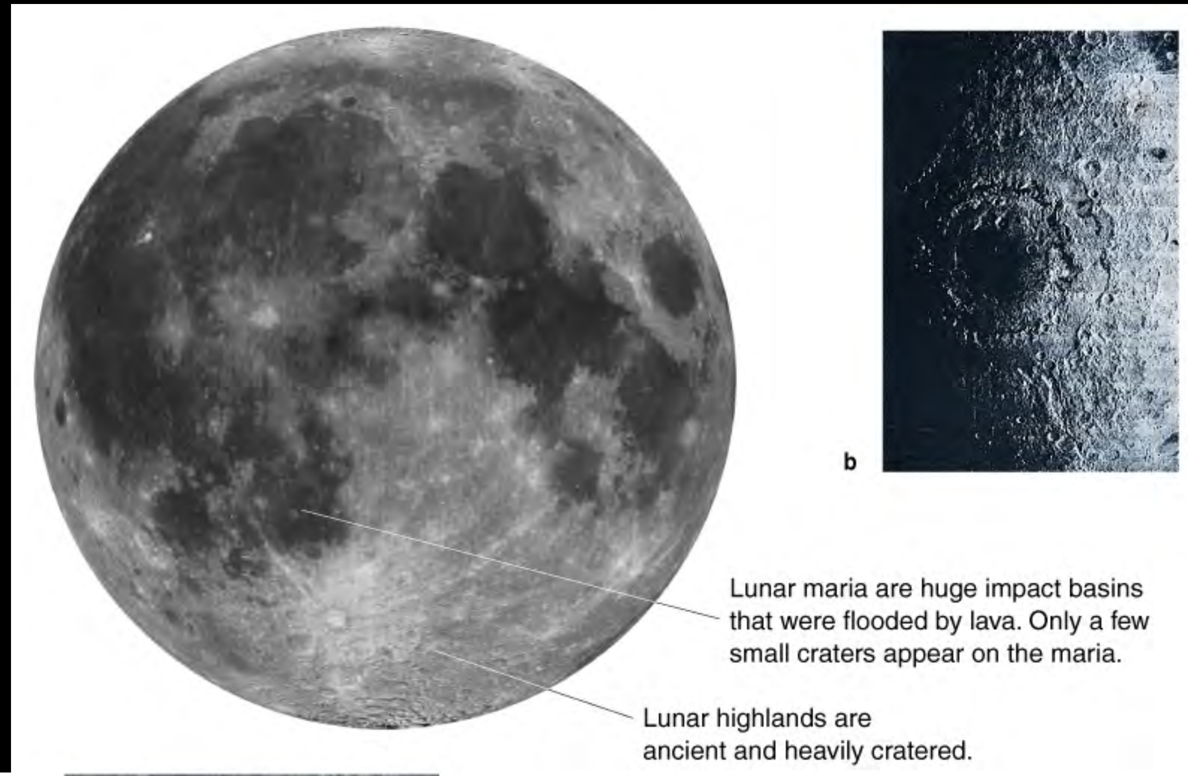
Planetary Surface Processes

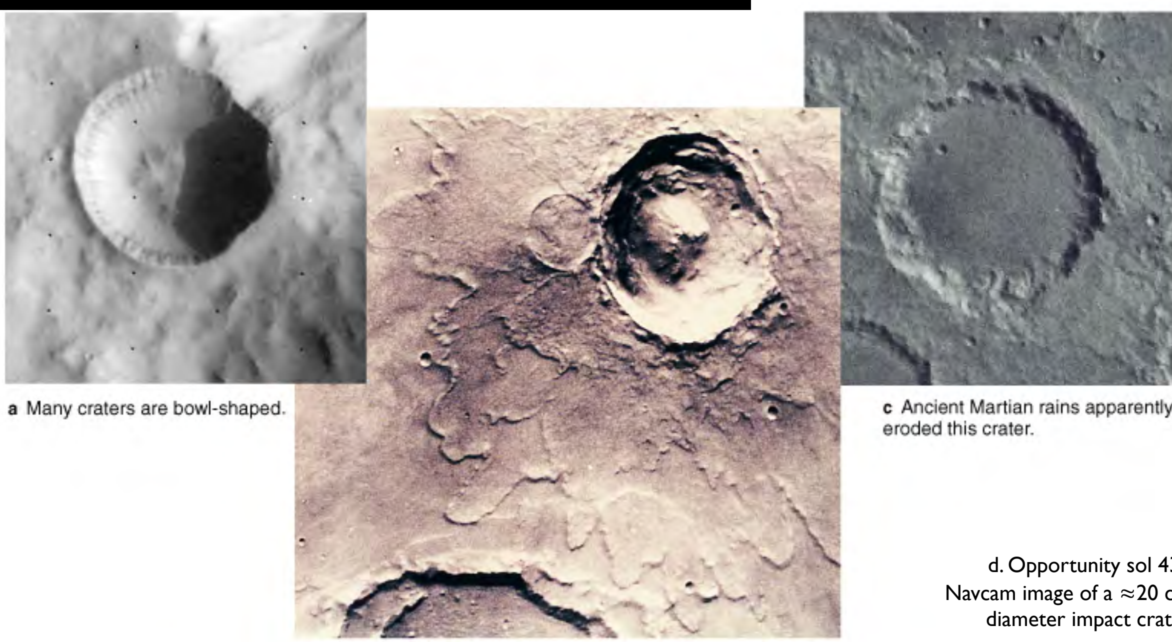
- Four major *geologic* processes:
  - Impact Cratering
  - Volcanism
  - Tectonism
  - Erosion (also called "Gradation")

- The combination of these processes, working over a variety of timescales, is responsible for producing what we see on solar system surfaces today with spacecraft and telescopes

Impact Craters:

Common geologic landforms on all spatial scales





a Many craters are bowl-shaped.

b Impacts into icy ground may form muddy ejecta.

c Ancient Martian rains apparently eroded this crater.

d. Opportunity sol 433 Navcam image of a ≈20 cm diameter impact crater

Key Morphologic Parameters

- **Crater diameter**
- **Crater depth** (relative to surroundings...)
- **Floor** diameter (if there is a "floor")
- Degree and type of **failure** of the inner walls
- Radial **range of the ejecta** (including possible **impact melt**)

Melosh (1989)

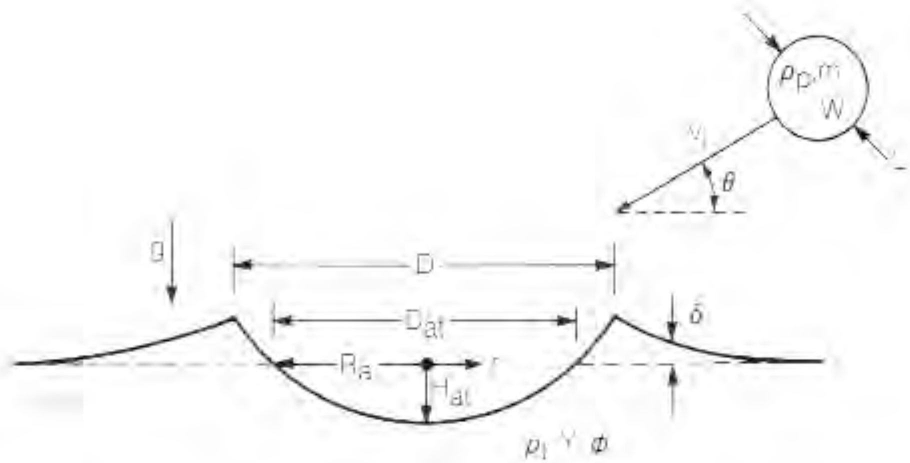
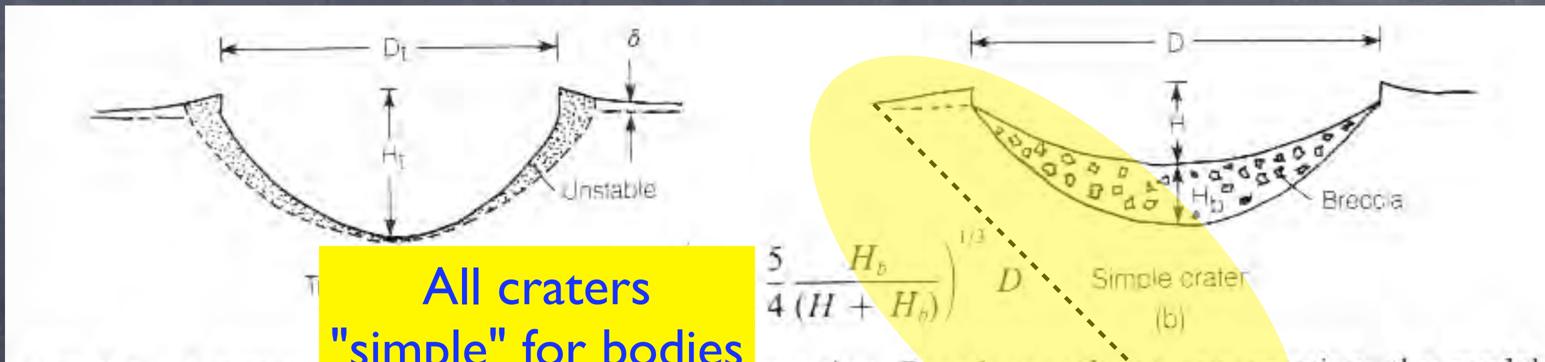


Fig. 7.1 Variables and parameters important in impact crater scaling relations. These quantities are divided into three groups: Projectile variables are density ρ_p, diameter L, mass m, impact velocity v_i, kinetic energy W, and angle of impact θ. Transient crater descriptors are apparent diameter D_{at}, radius $R_a = D_{at}/2$, distance from the crater's center r, crater depth H_{at}, crater volume V and ejecta blanket thickness δ. Target variables are density ρ_t, yield strength Y, porosity ϕ, and the acceleration of gravity g. Not all of these quantities are independent, but the different forms are used where convenient in this chapter.

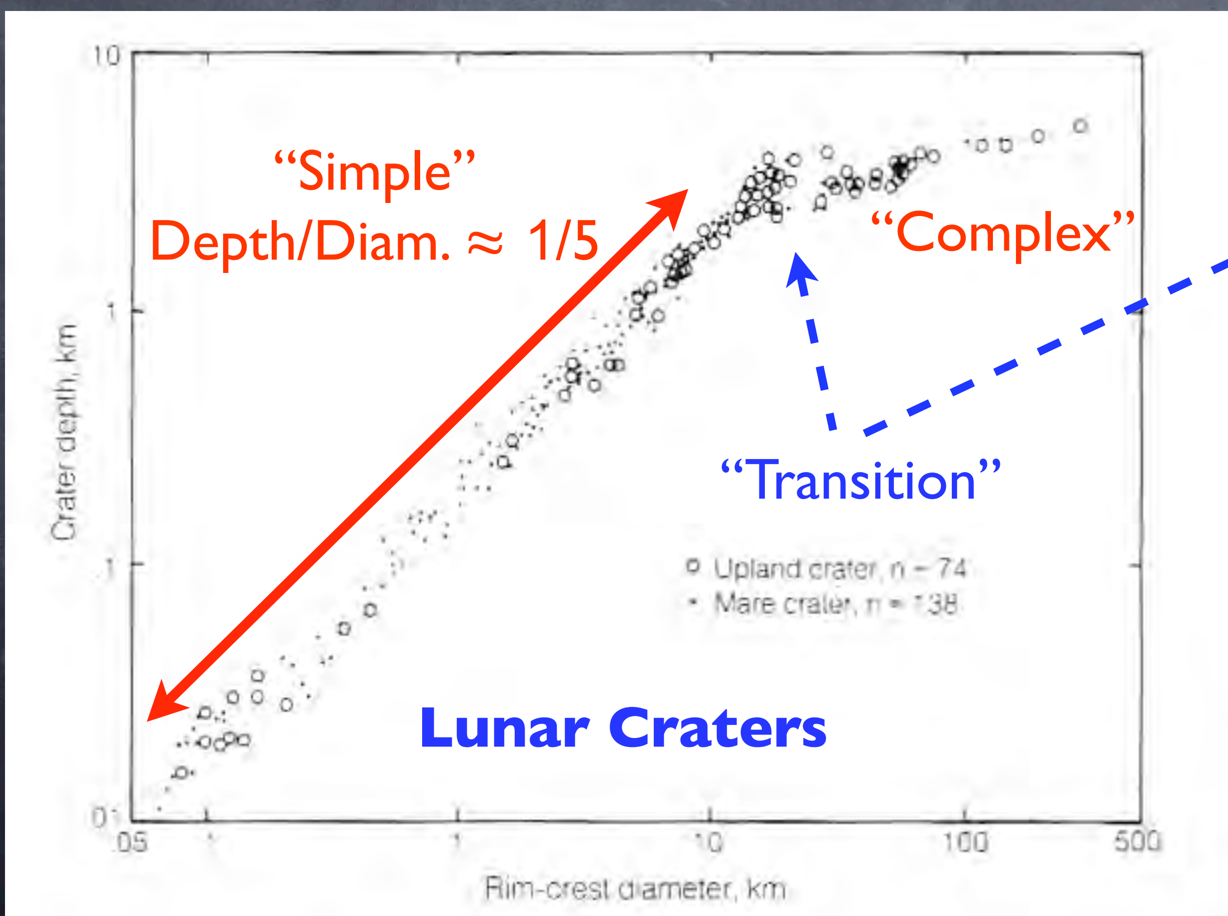
Depth to Diameter Ratio

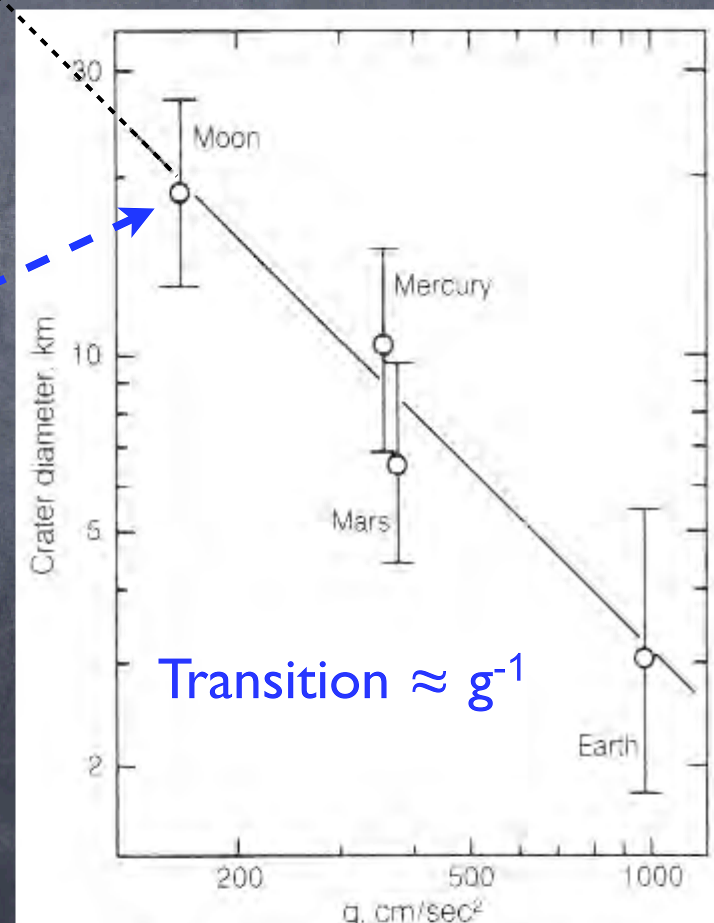


$\frac{5}{4} \frac{H_b}{(H + H_b)})^{1/3} D$

Fig. 8.3 A geomet... ...rmation. Based on volume conservation, the model relates the depth H... ...sient crater to the depth H, diameter D, and breccia lens thickness H_b of... ...rim thickness δ is taken into account by this model.

All craters "simple" for bodies smaller than a few hundred km...





Melosh (1989)

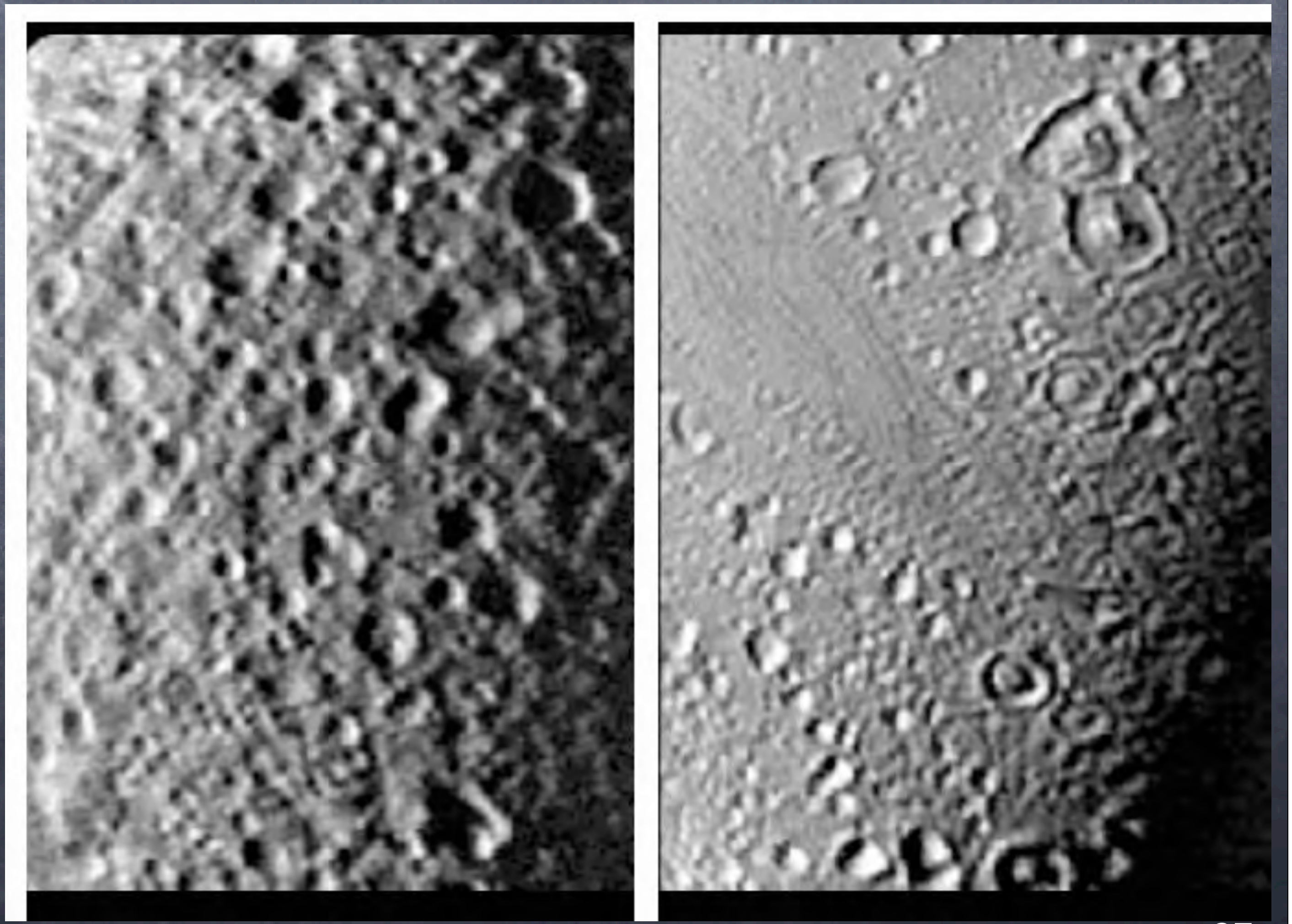
Ages of Planetary Surfaces

- ***Relative ages*** often determined by impact crater number density [craters/km^2]

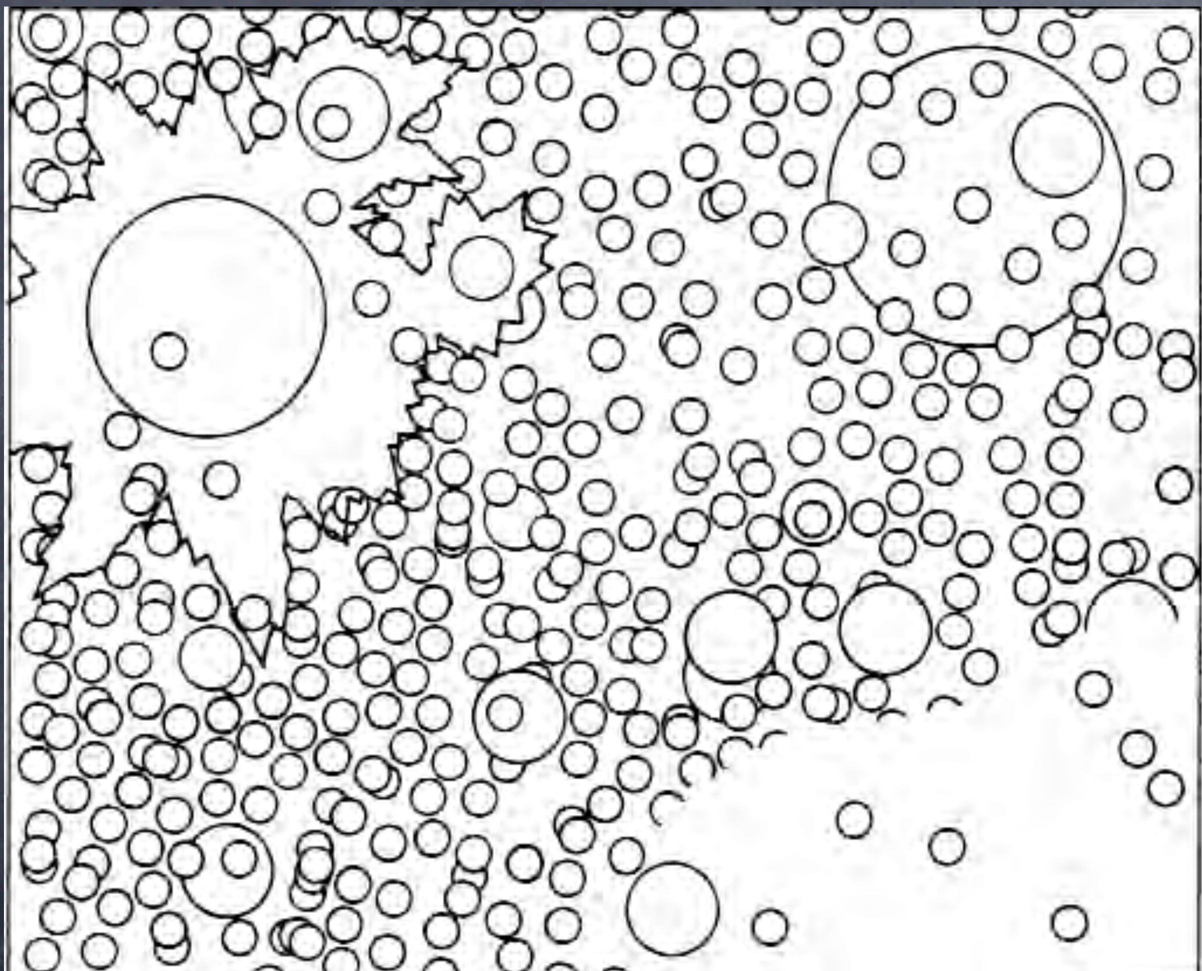
If these two images are of the same-sized regions on the same planet, which area is likely older?

Why?

What assumptions are required?

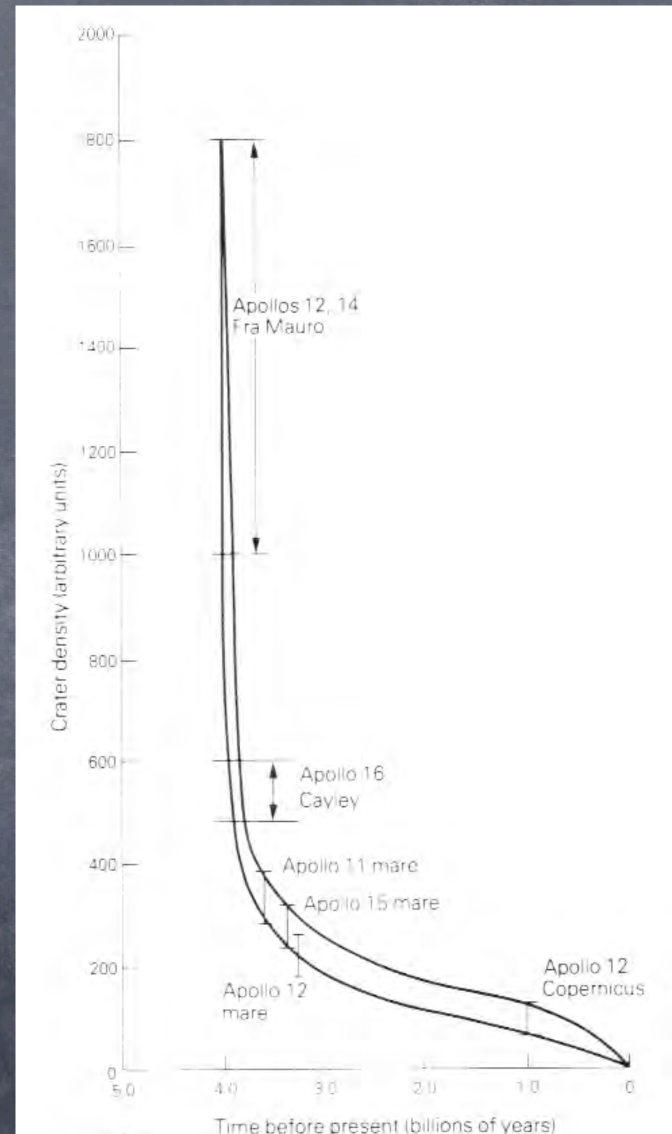


Relative Age Dating from Impact Craters:
“Crater Retention Age”



Example/Idealized Surface

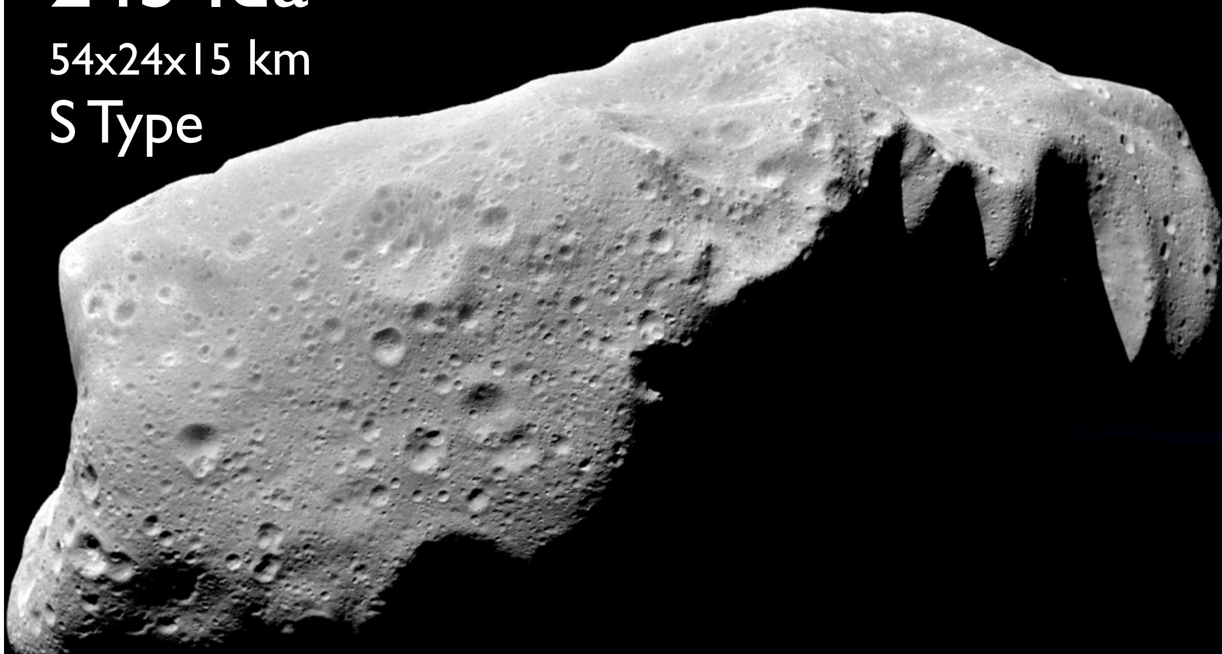
Hartmann (1977)



Actual/Absolute Dates
Soderblom et al. (1974)

243 Ida

54x24x15 km
S Type



NASA/JPL-Caltech/Galileo Mission

3 populations of craters:

(1) "Fresher" (young) craters < 1 km diameter
(2) Degraded craters < 6 km
(3) Degraded craters > 10 km

→ Change in early large impactor flux/environment?

2 populations of craters:

(1) "Fresher" (young) craters < 1 km diameter
(2) Degraded larger craters

→ Role of last major impact?

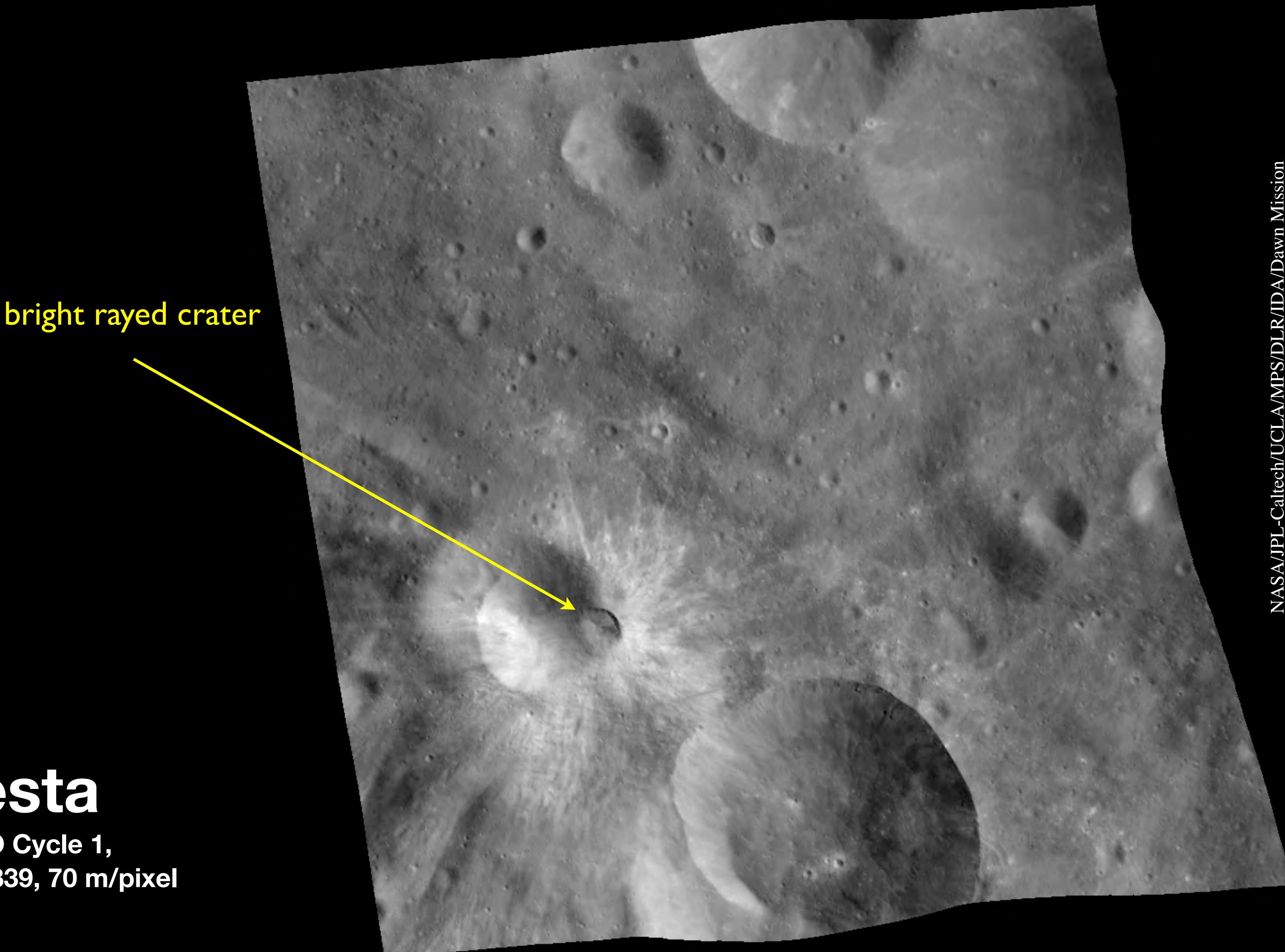
Sullivan *et al.* (2002)

NASA/JPL-Caltech/Galileo Mission

951 Gaspra

18x11x9 km
S Type

Impacts can also reveal stratigraphy...



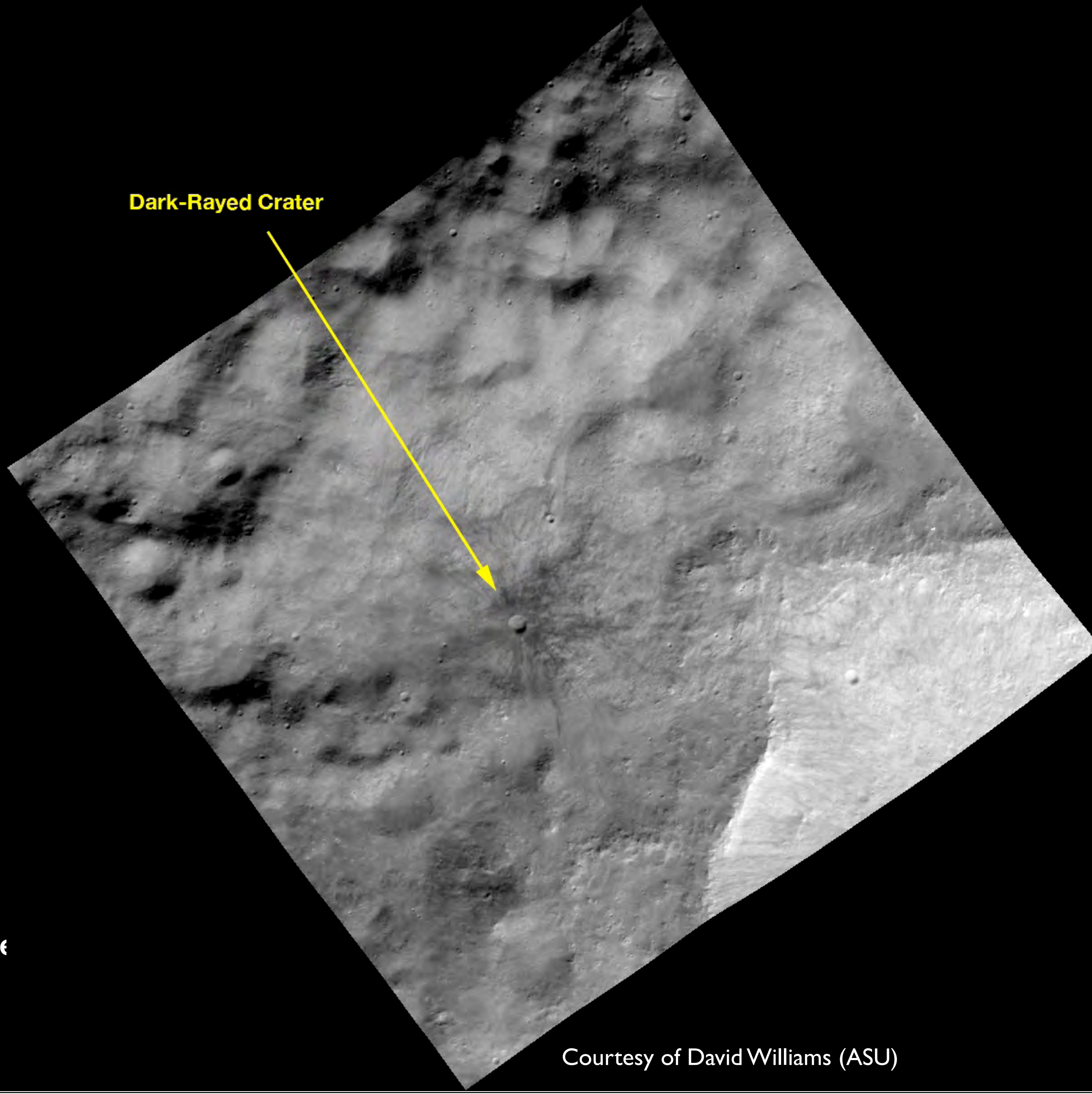
NASA/JPL-Caltech/UCLA/MPS/DLR/IDA/Dawn Mission

Vesta

HAMO Cycle 1,
F2_372565839, 70 m/pixel

Courtesy of David Williams (ASU)

Impacts can also reveal stratigraphy...



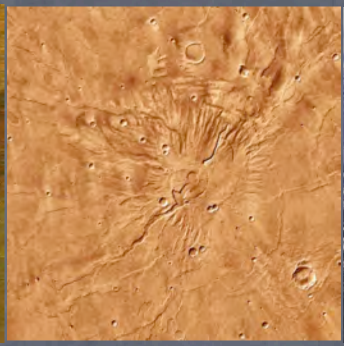
NASA/JPL-Caltech/UCLA/MPS/DLR/IDA/Dawn Mission

Vesta

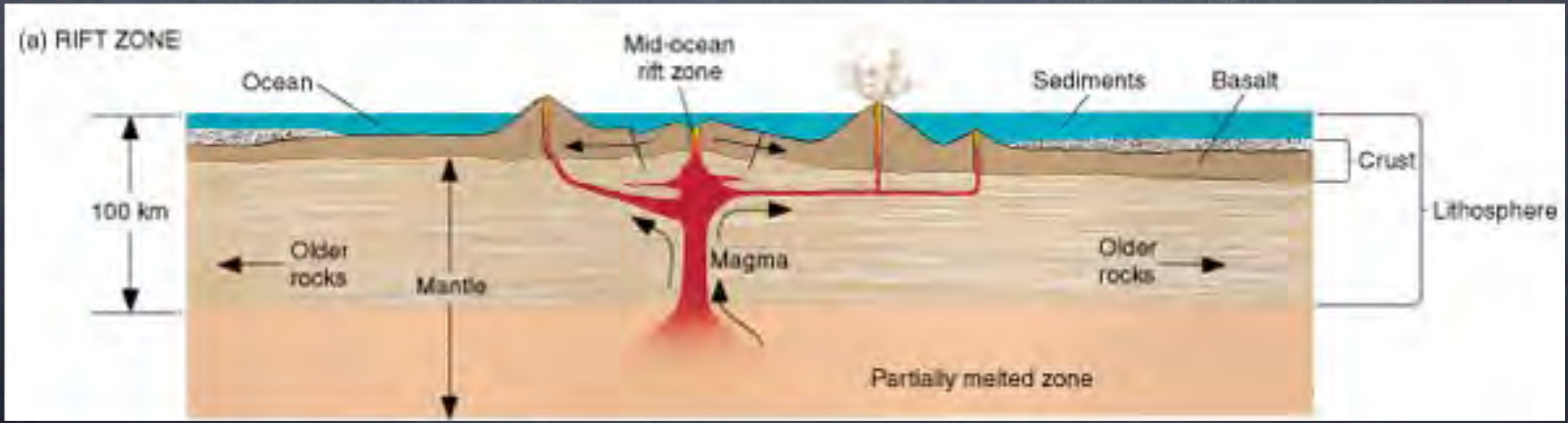
HAMO Cycle 1,
F2_370834998, 70 m/pix

Courtesy of David Williams (ASU)

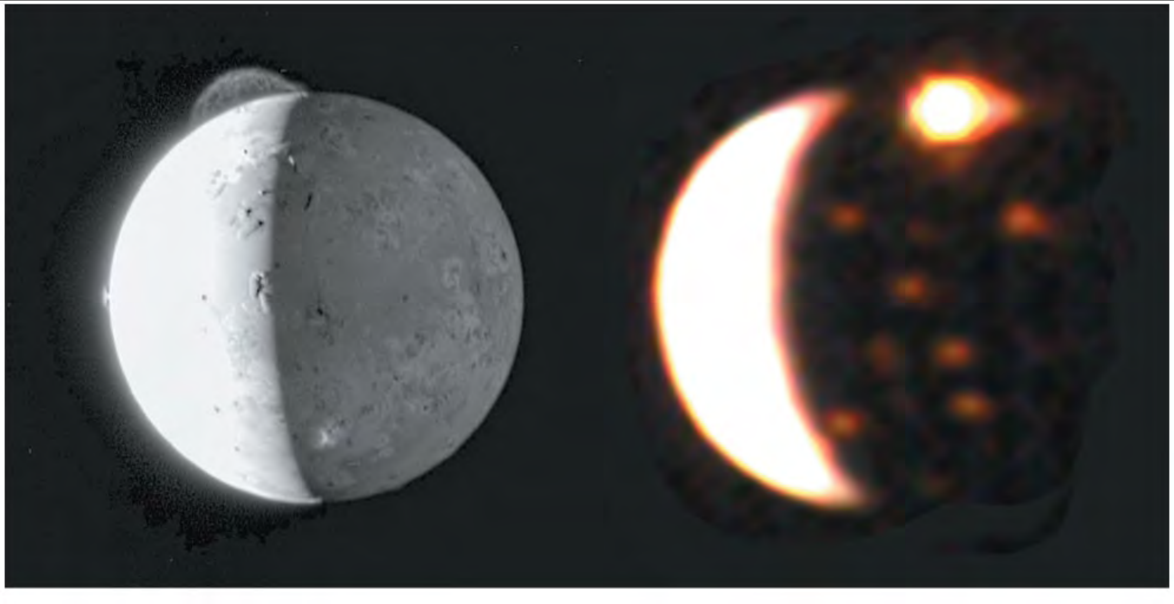
Volcanism



- Volcanism is the melting of materials within a planet and the transport or eruption of these materials onto a planetary surface
- On the terrestrial planets, the molten material, or magma, is silicate rock. For some outer planet asteroids, satellites, and dwarf planets, the magma could be water ice or molten sulfur

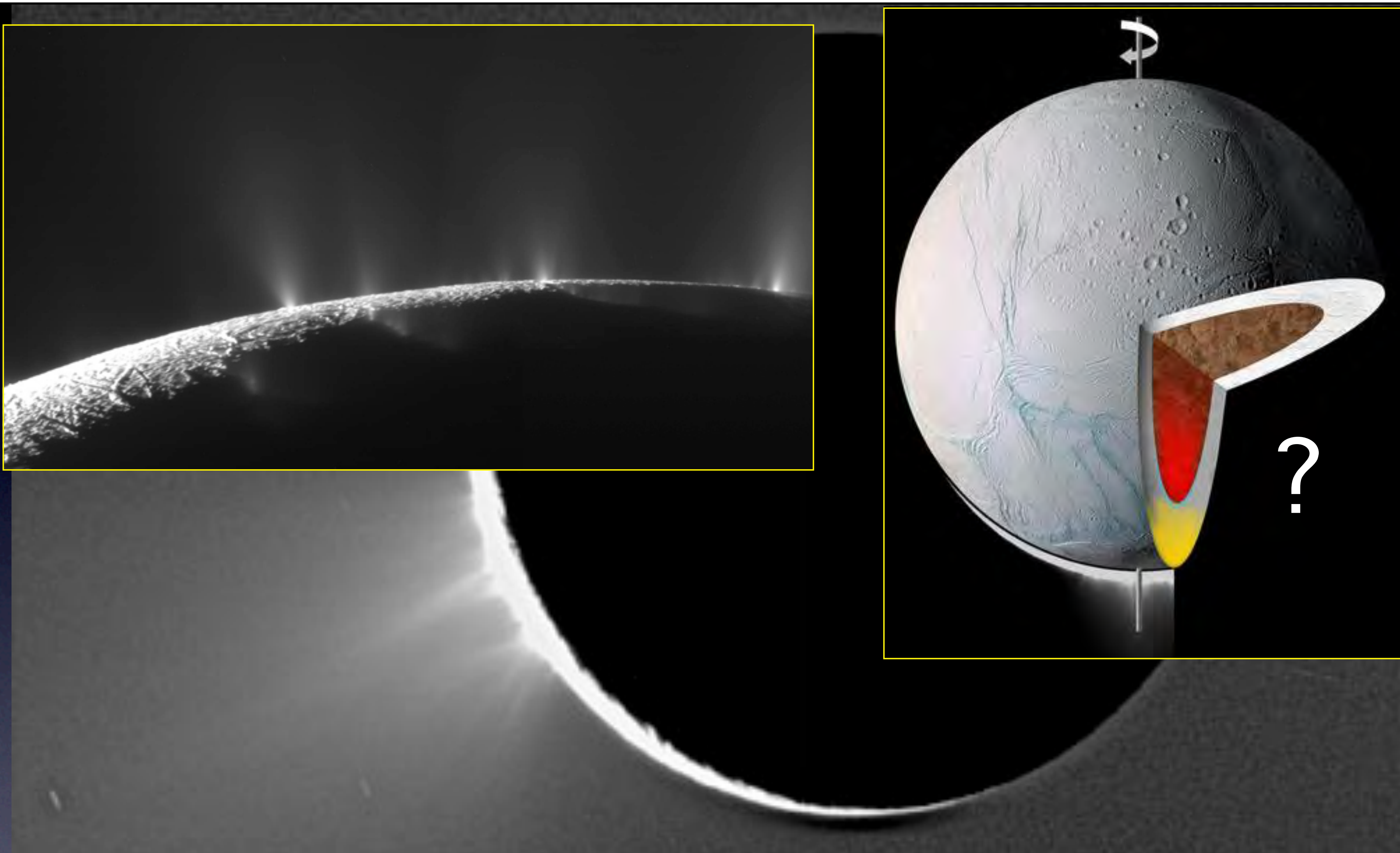


Io's silicate volcanism



Icy satellite volcanic resurfacing?

NASA/JPL Voyager & Cassini Missions

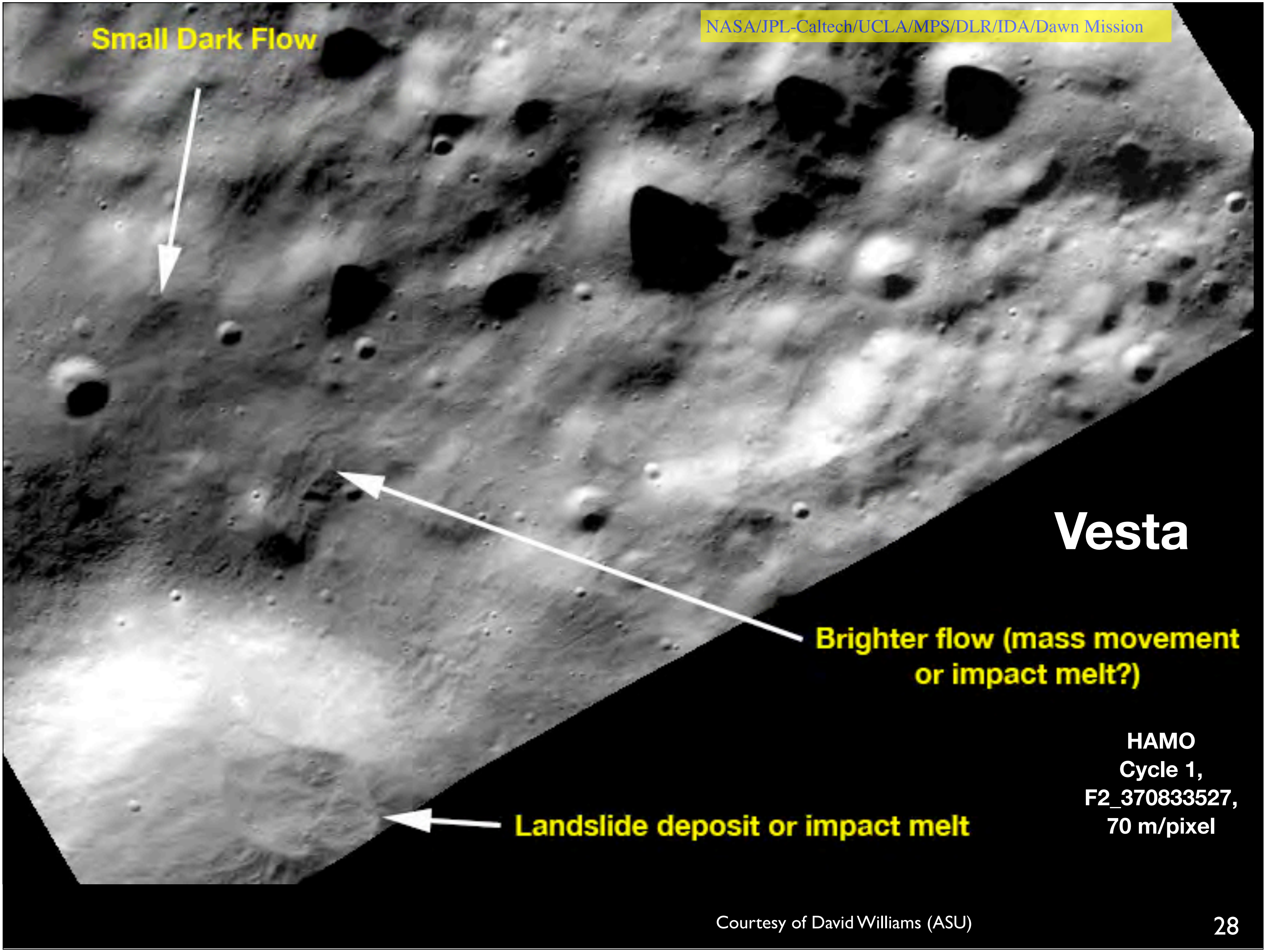


NASA/JPL/SSI Cassini Mission

Enceladus "Volcanic" Plumes...

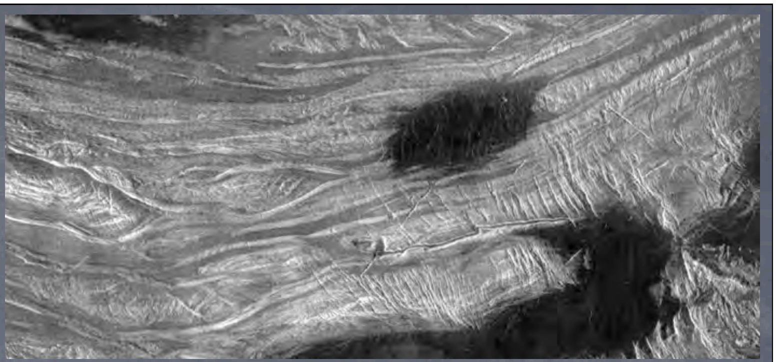
- Satellite is only 500 km diameter, yet internally active!
- Subsurface liquid water? Newest astrobiology “hotspot” in the solar system...

NASA/JPL/SSI/UCLA Cassini and Dawn Missions



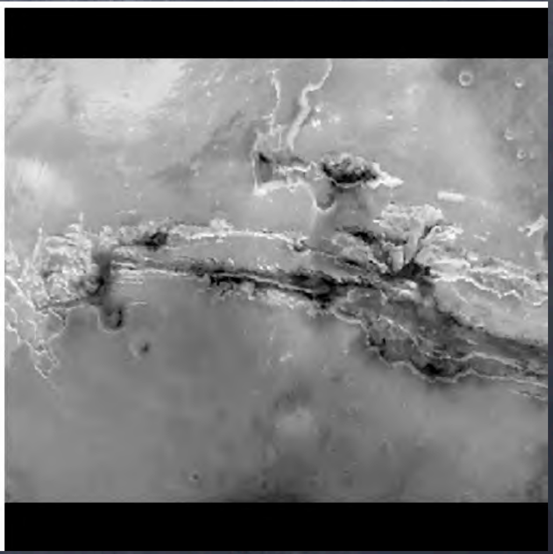
Courtesy of David Williams (ASU)

Tectonism

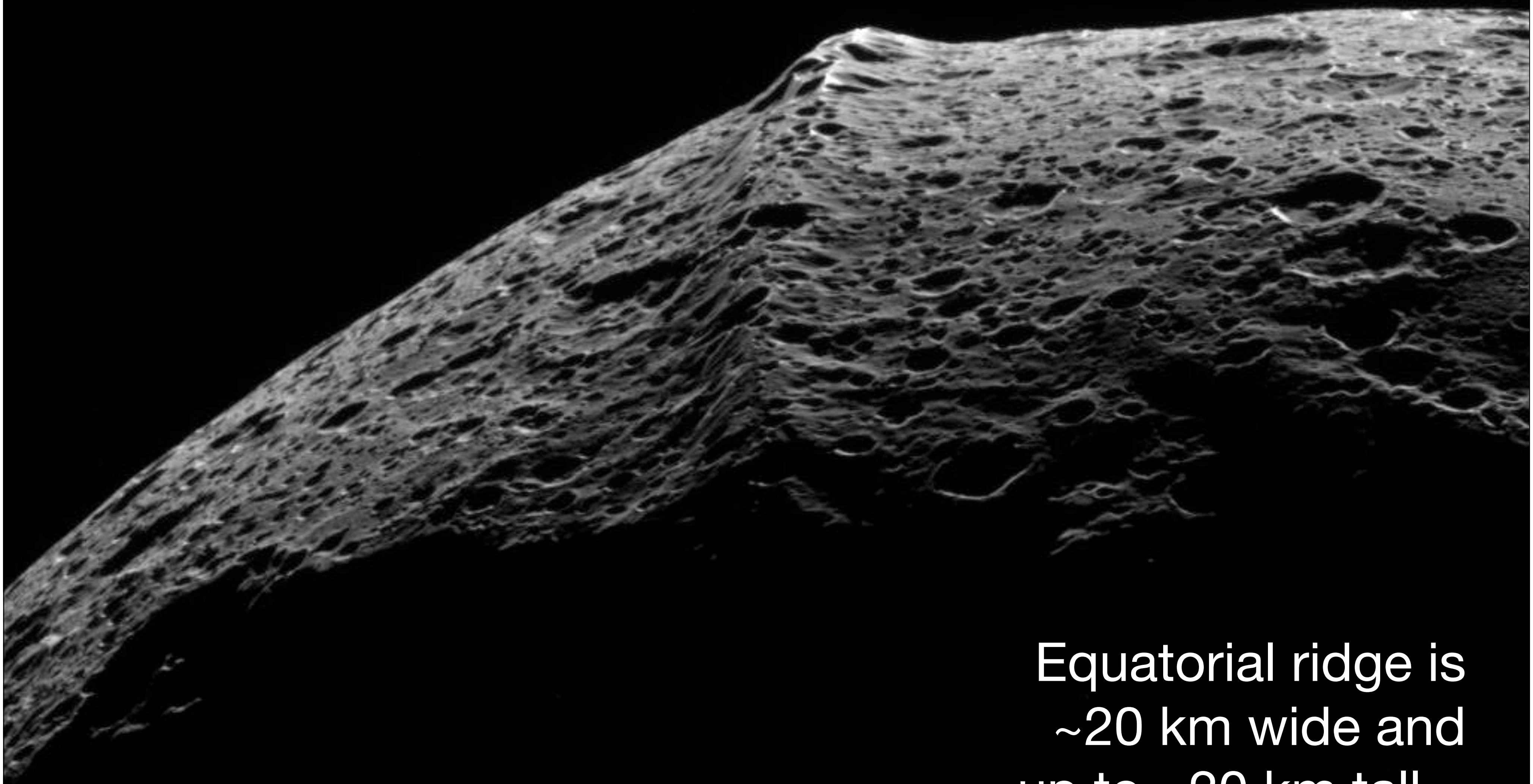


- Tectonism is the deformation of the surface and interior of a planet, driven by either internal (volcanic, tidal, etc.) or external (impact) forces

- Tectonic processes produce faults, fractures, and folds with morphologies dependent upon the style of local deformation as well as the physical properties/conditions of the surface materials



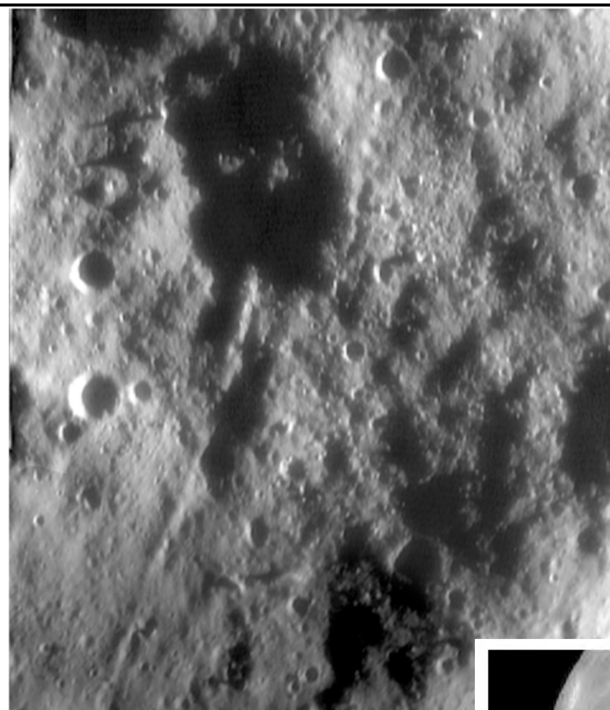
Iapetus

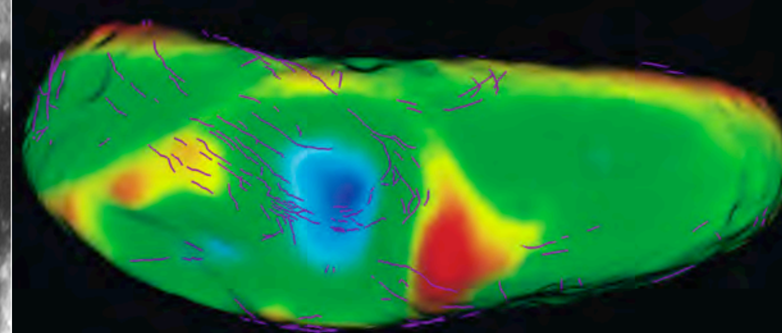


Equatorial ridge is
~20 km wide and
up to ~20 km tall...

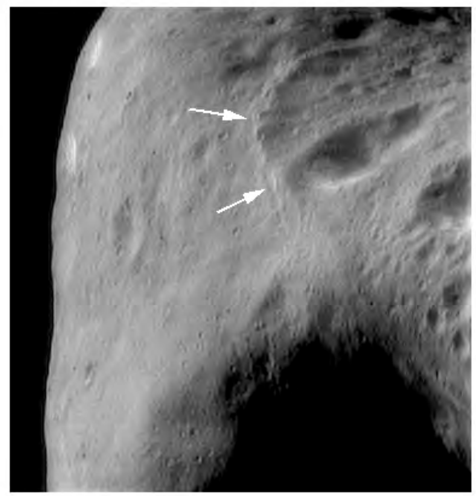
NASA/JPL/SSI/Cassini Mission

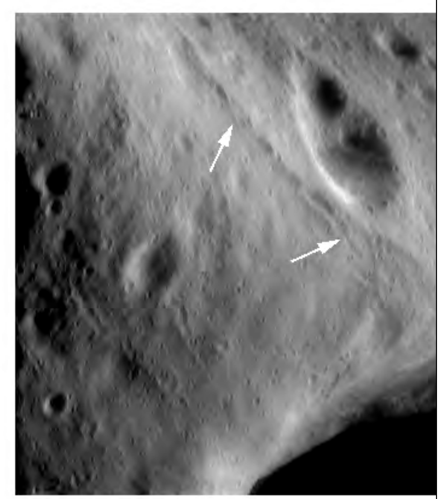
Structural features on Eros



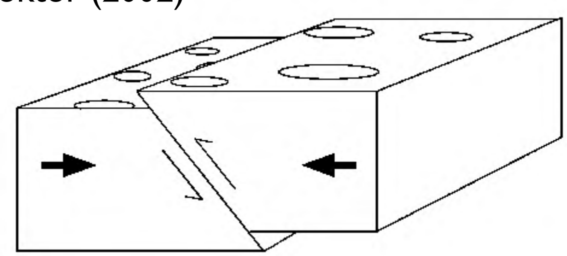


Thomas *et al.* (2002)





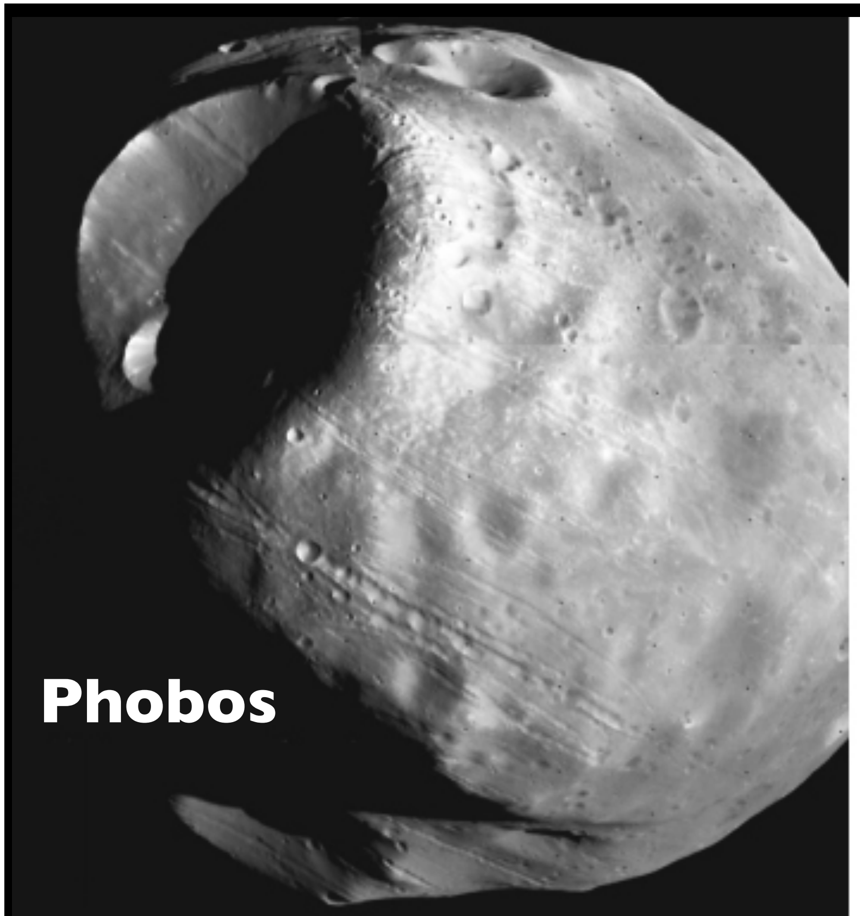
Robinson & Proktor (2002)



NASA/JHU-APL/Cornell/NEAR Mission

Ridges, Grooves, and Fractures

Tidally-forced tectonism?



NASA/JPL-Caltech/Viking and MRO Missions

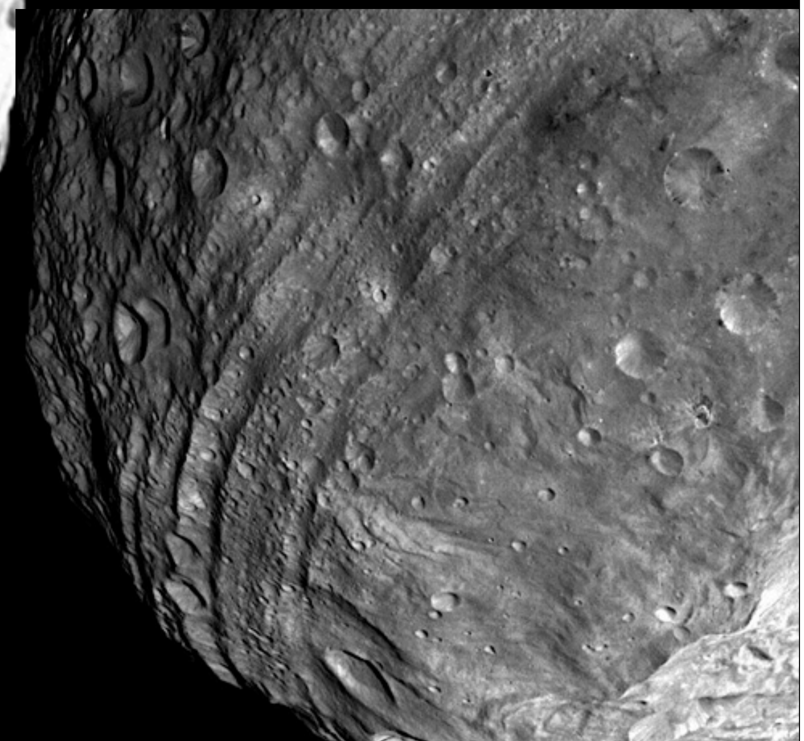
Ridges, Grooves, and Fractures

Impact-forced tectonism?

Vesta

Concentric and radial grooves related to large basins

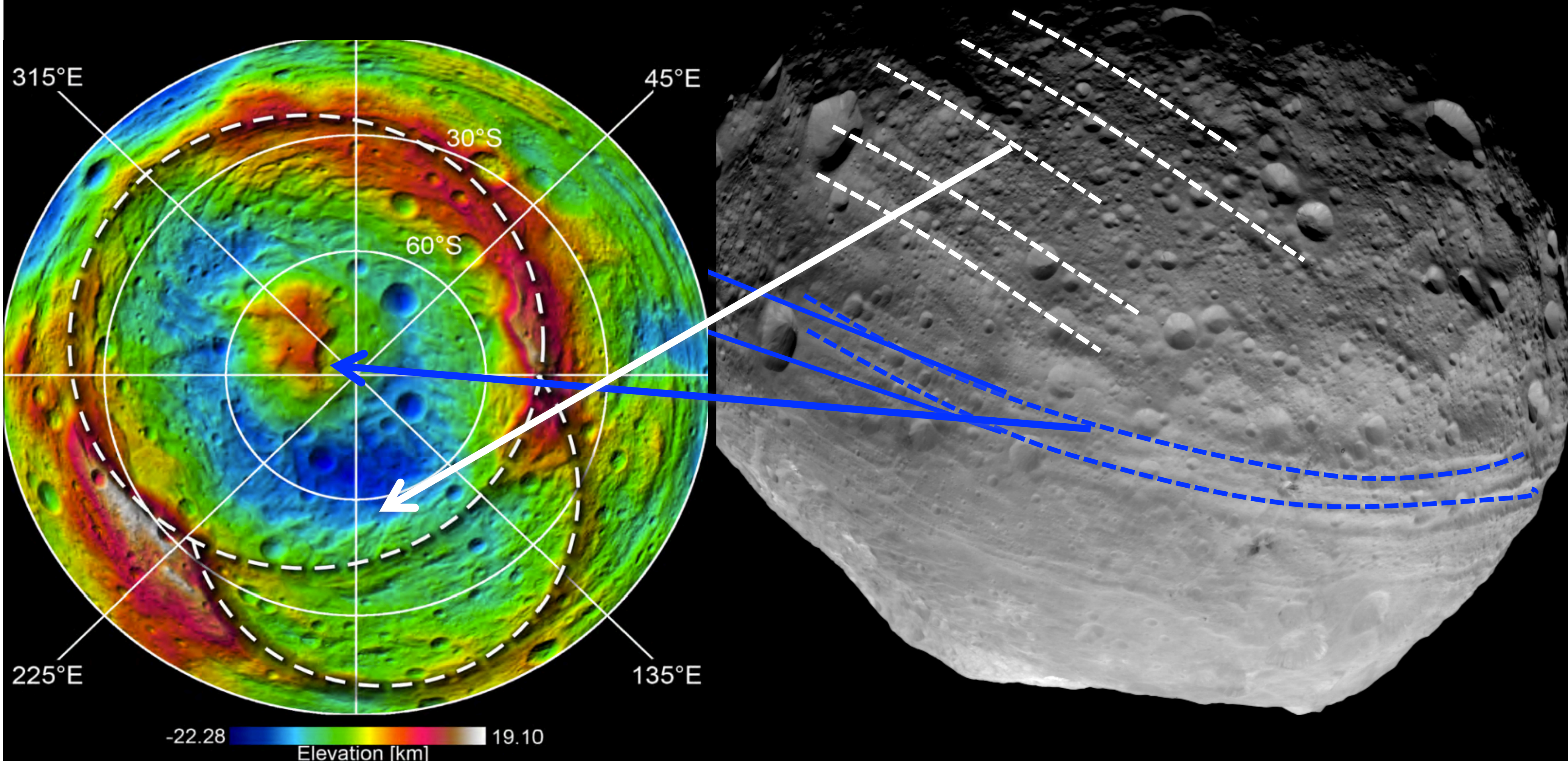
NASA/JPL-Caltech/UCLA/MPS/DLR/IDA/Dawn Mission



NASA/JPL-Caltech/UCLA/MPS/DLR/IDA/Dawn Mission

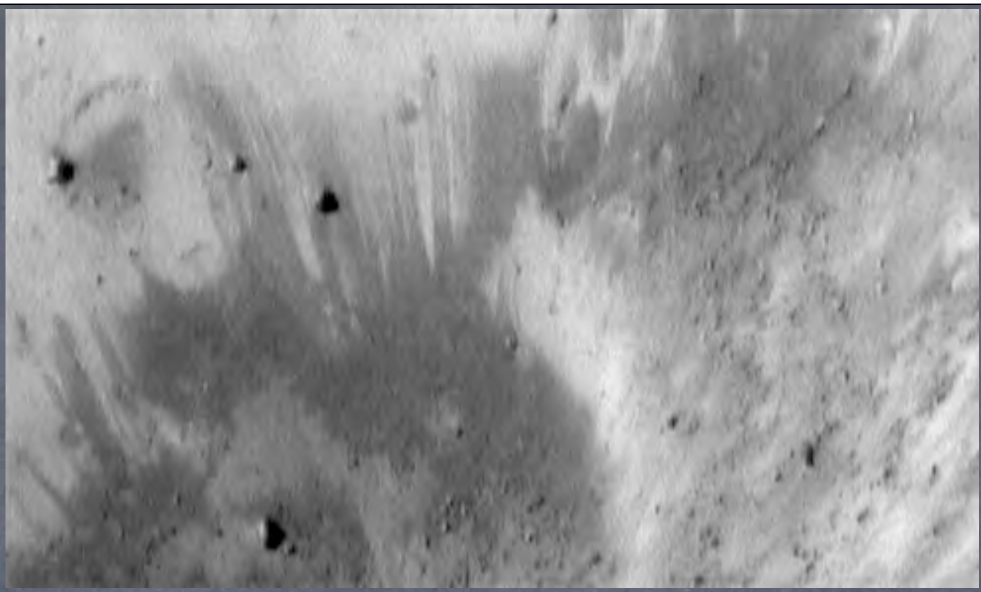
Tectonic features related to
(1) impact disruption
(2) differentiation (?)
(3) volcanic processes (?)

Vesta



Courtesy of David Williams (ASU)

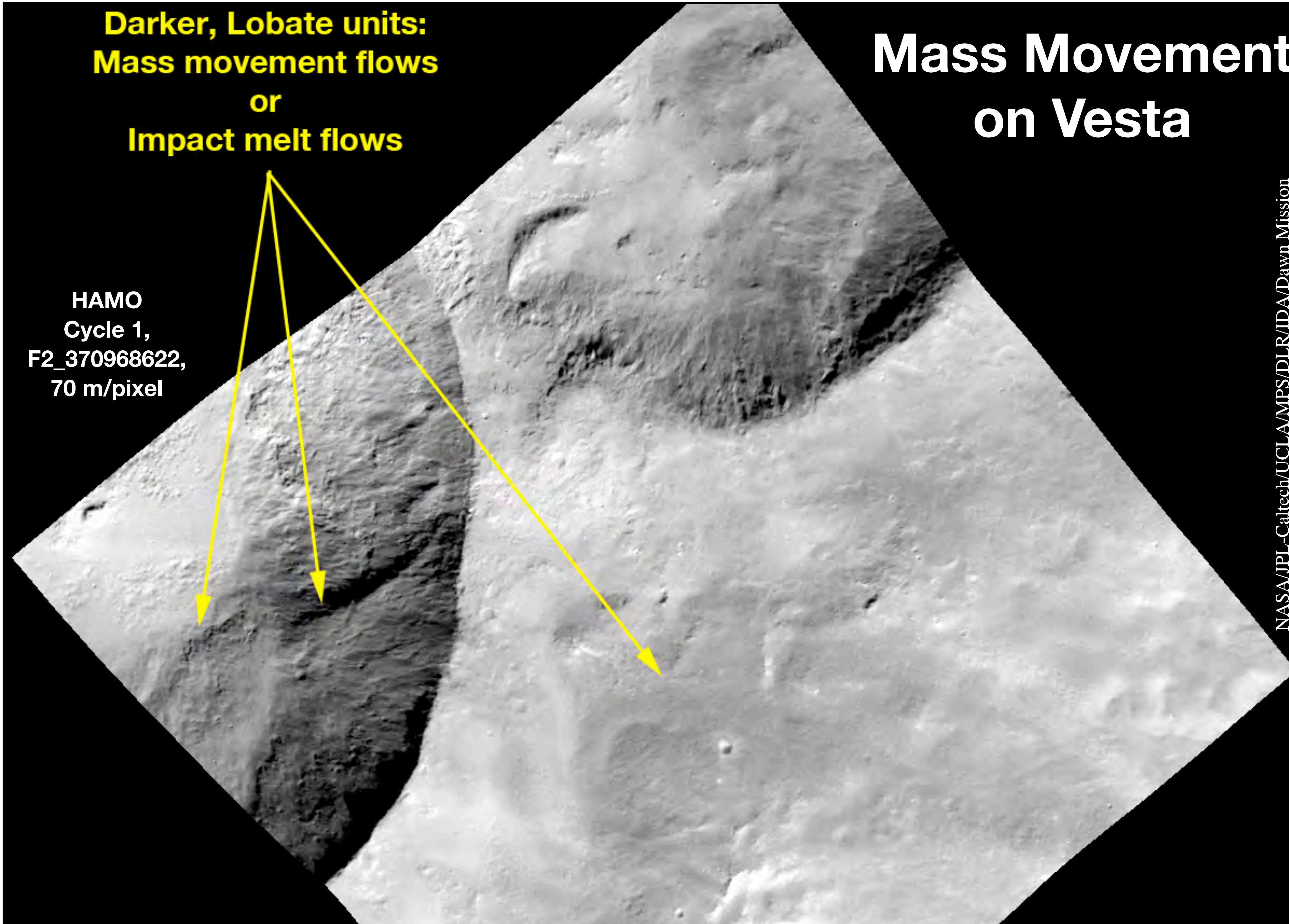
Erosion



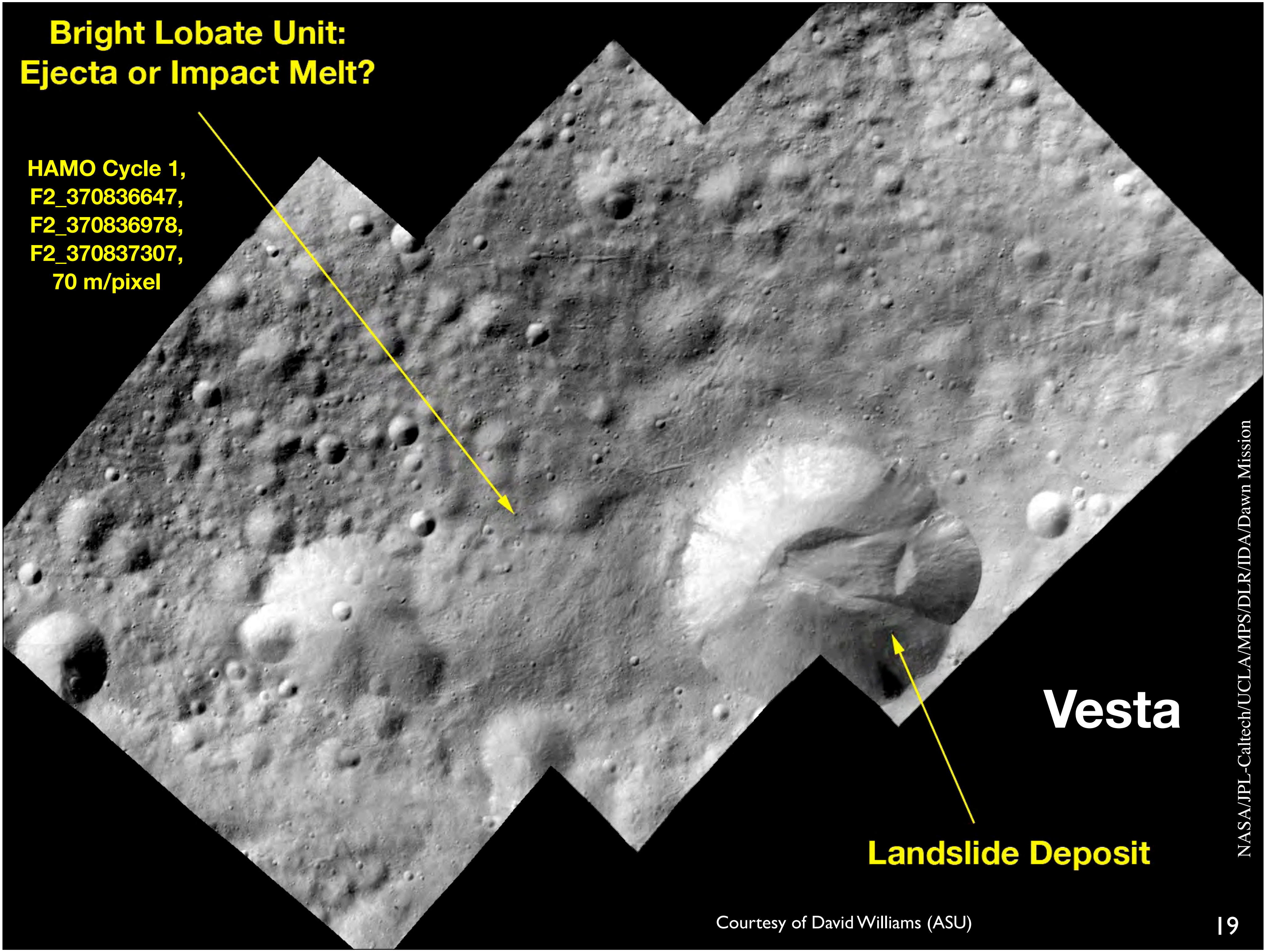
NASA/JHU-APL/Cornell/NEAR Mission

- *Erosion* or *gradation* is the wearing down of high places and the filling in of low places on a planetary surface
- For airless bodies, these erosional and depositional processes are driven by gravity
- The primary means of moving materials by gradation on airless bodies is via "mass wasting", or the downslope movement of surface materials
- On airless bodies, gradational processes can produce landslides, talus cones, slope streaks, and sediment "ponds"

Mass Movement on Vesta

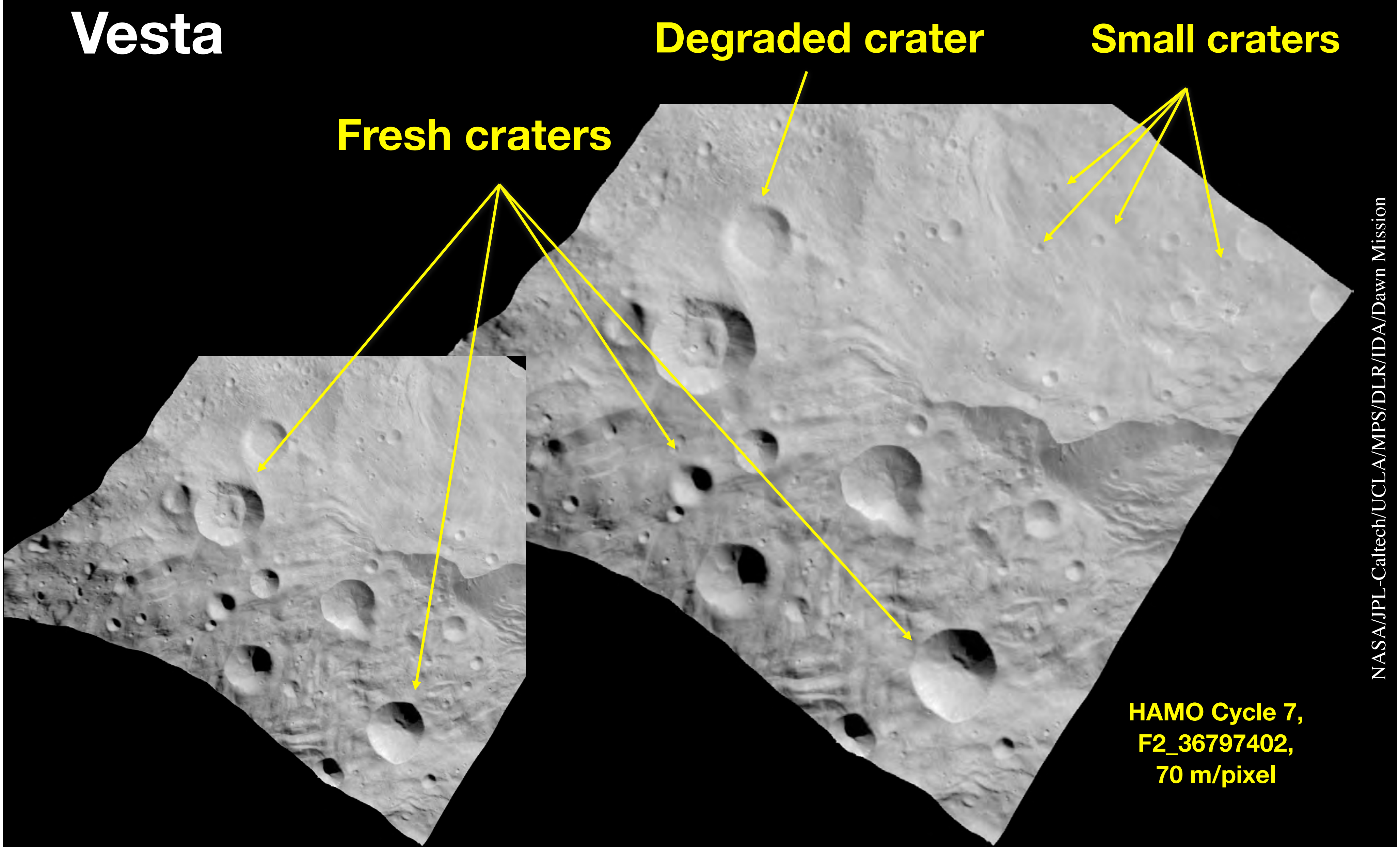


Courtesy of David Williams (ASU)



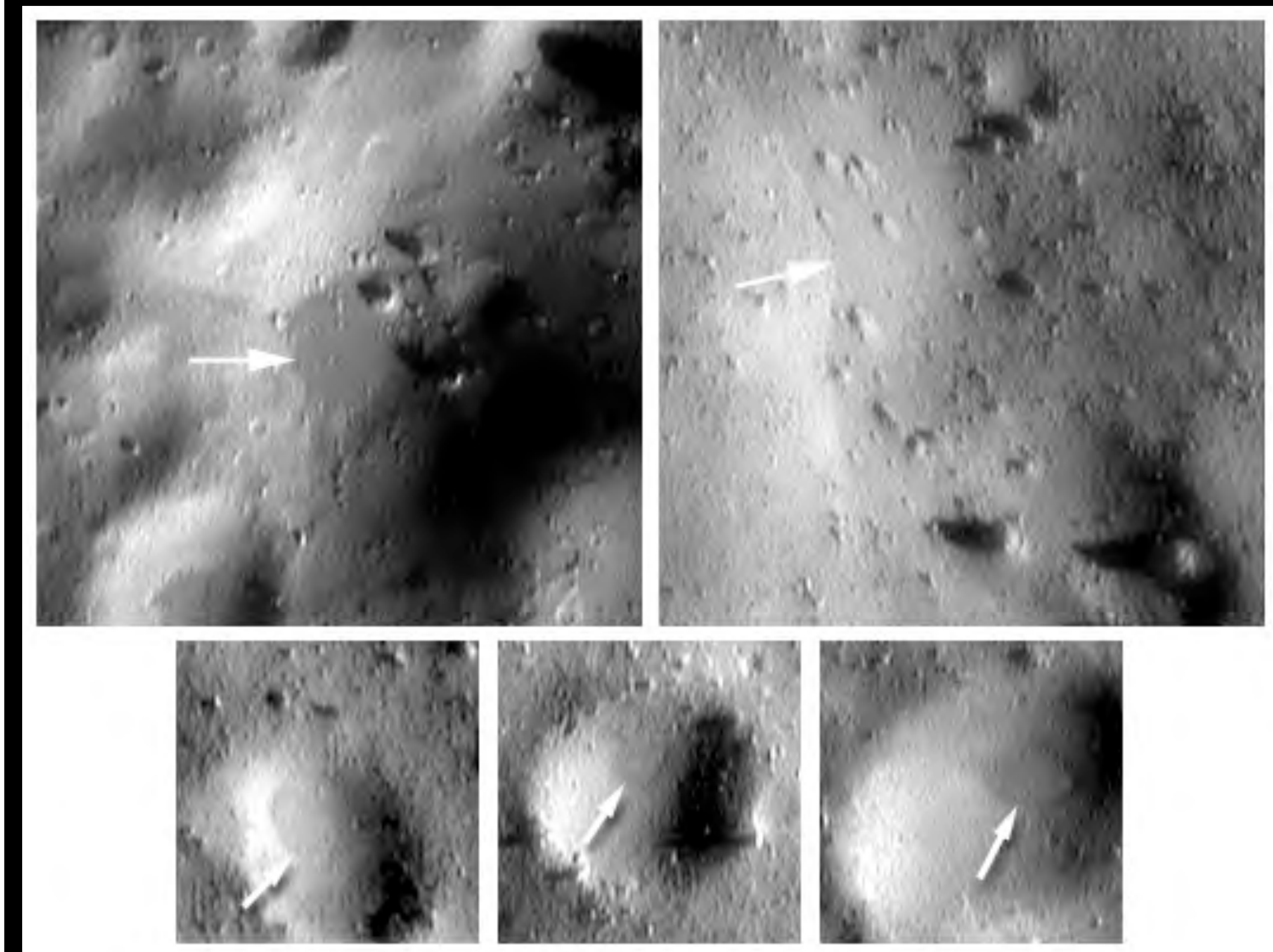
Courtesy of David Williams (ASU)

Crater Degradation State

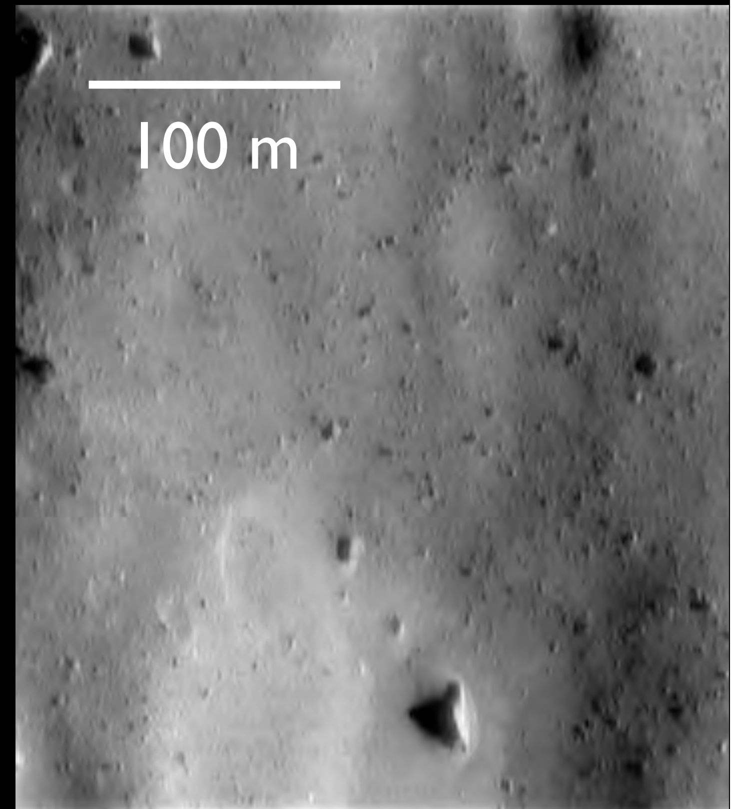


Courtesy of David Williams (ASU)

Sedimentary "ponds" on Eros



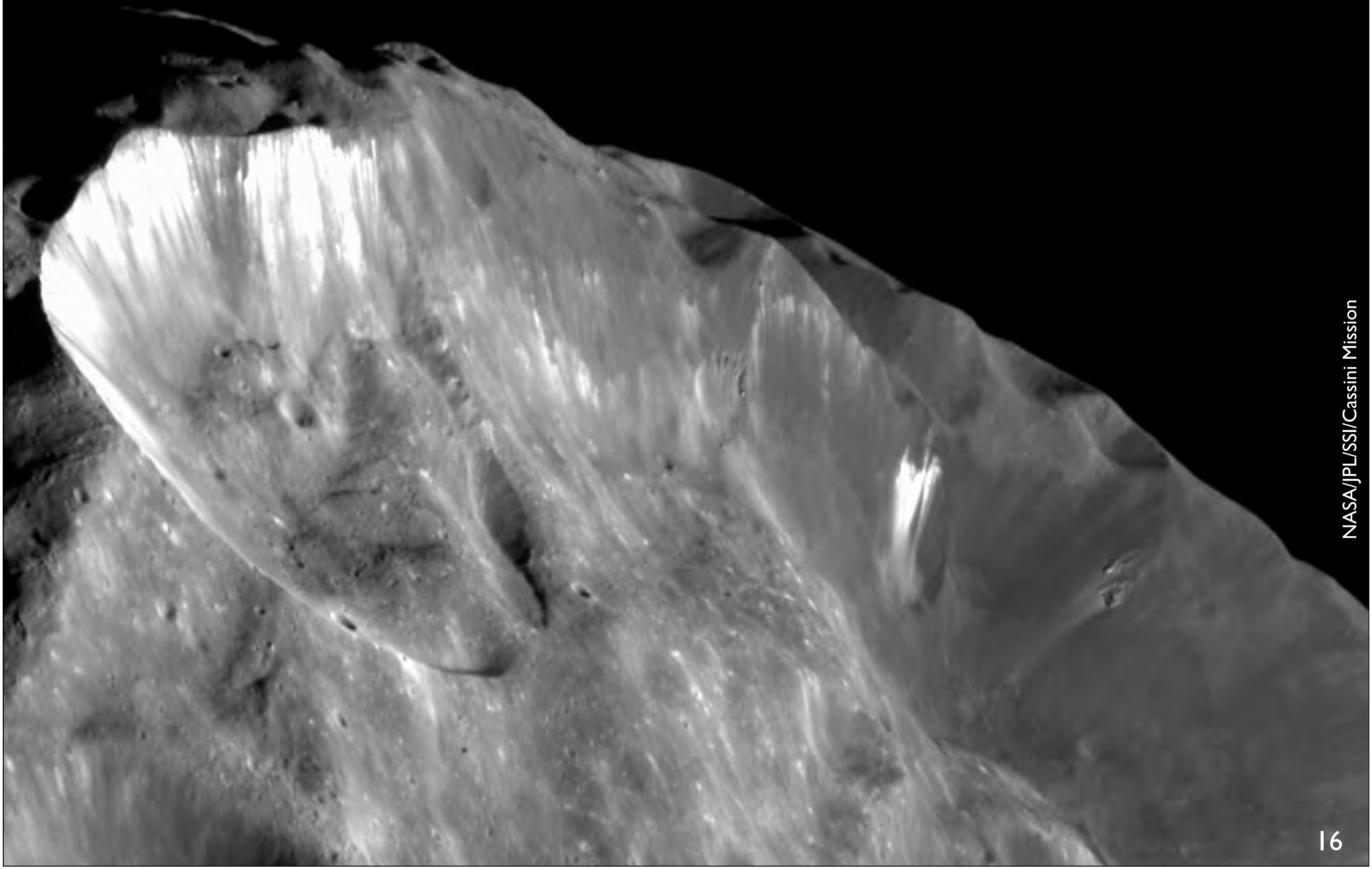
NASA/JHU-APL/Cornell/NEAR Mission



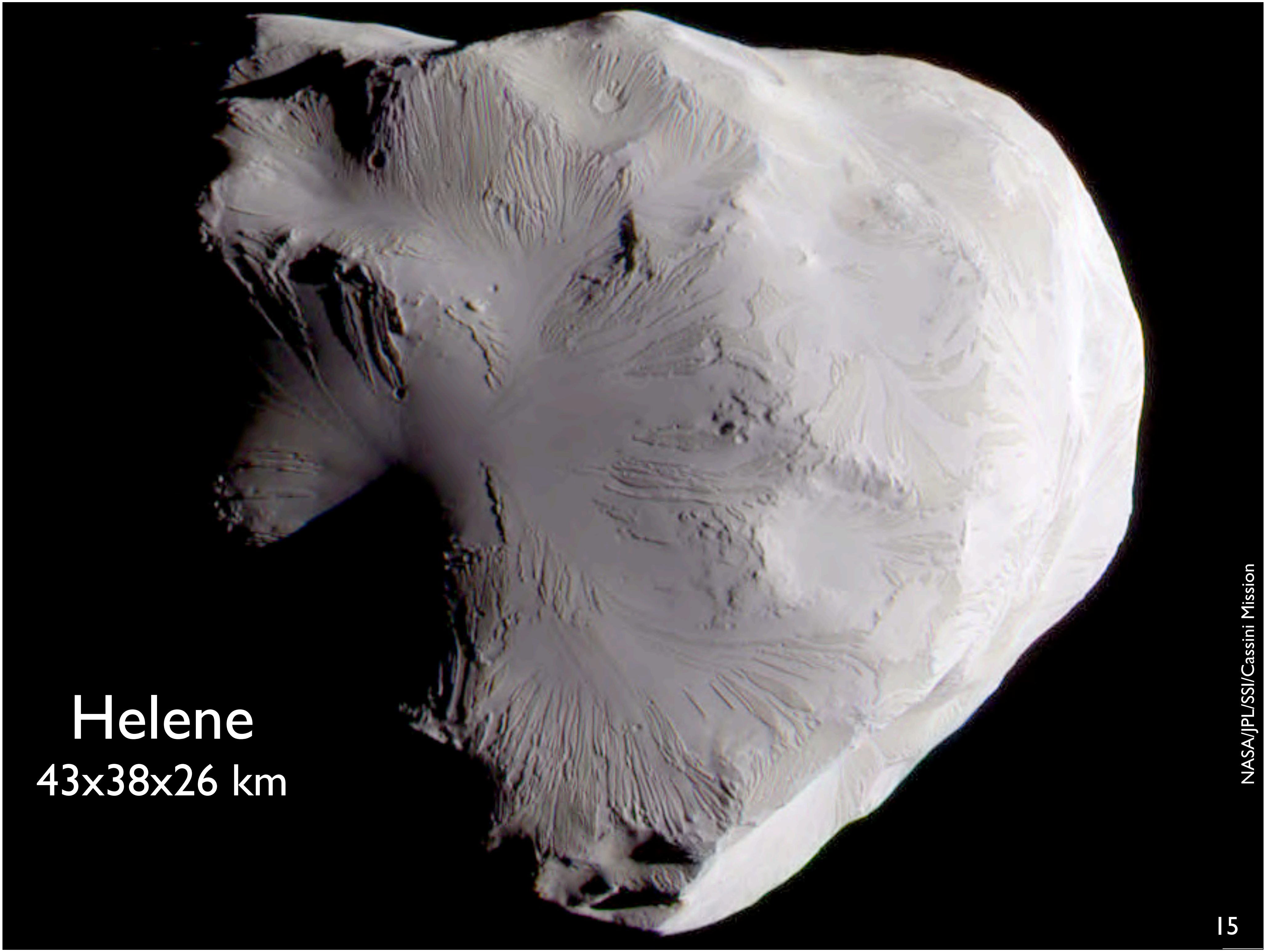
Robinson & Proktor (2002)

Phoebe
200 km diam.

Captured KBO?



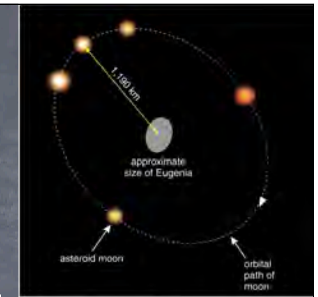
NASA/JPL/SSI/Cassini Mission


Helene
43x38x26 km
NASA/JPL/SSI/Cassini Mission

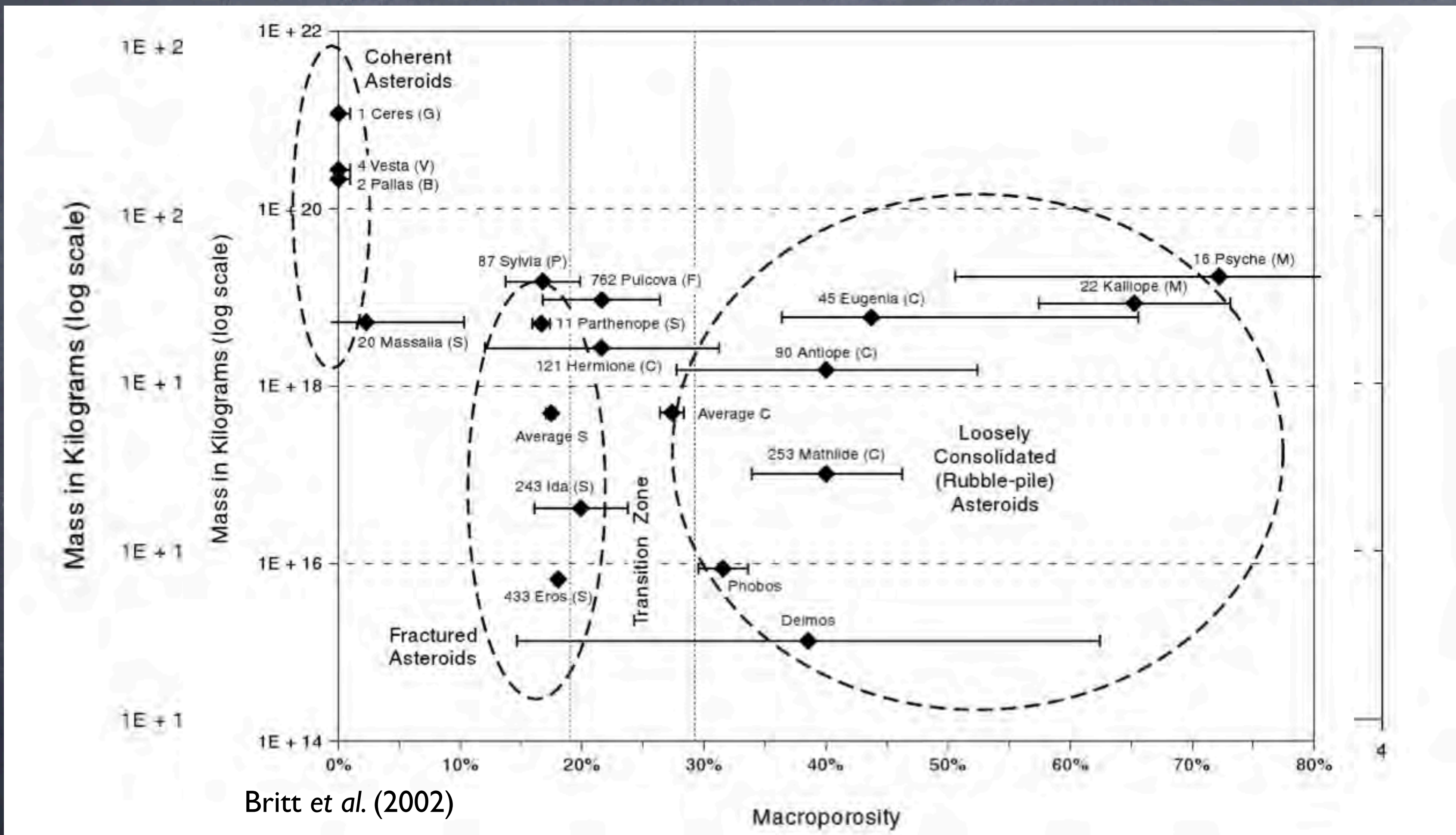
Other Clues about Process and Properties from Geologic Observations

- Imaging and topographic/shape data enable estimates of primitive body volume. Combined with mass estimates from spacecraft tracking gives an estimate of **density**
- Imaging and tracking of **asteroid satellites** is another way to determine mass and estimate density
- Mass and density combined with compositional data can enable an estimate of **porosity**
- Topographic/shape information combined with gravity mapping data (from orbital campaigns) enables an estimate of the locations and magnitudes of **crustal density anomalies**
- Considerable confusion about the geology of **comet nuclei**

Density & Porosity



Porous "rubble piles" <----> Solid rock



Britt *et al.* (2002)

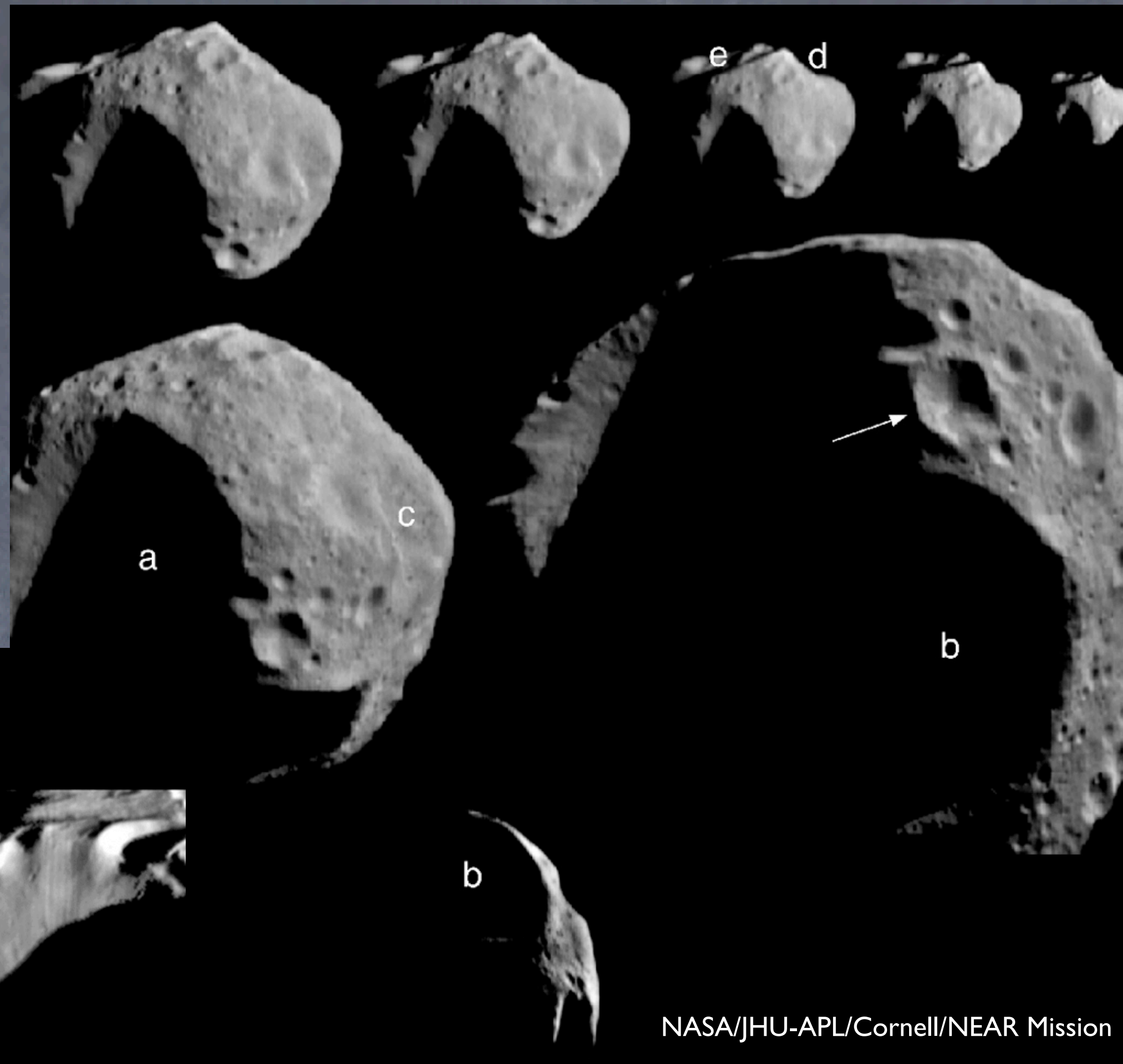
Most asteroids are rocky, many are very porous

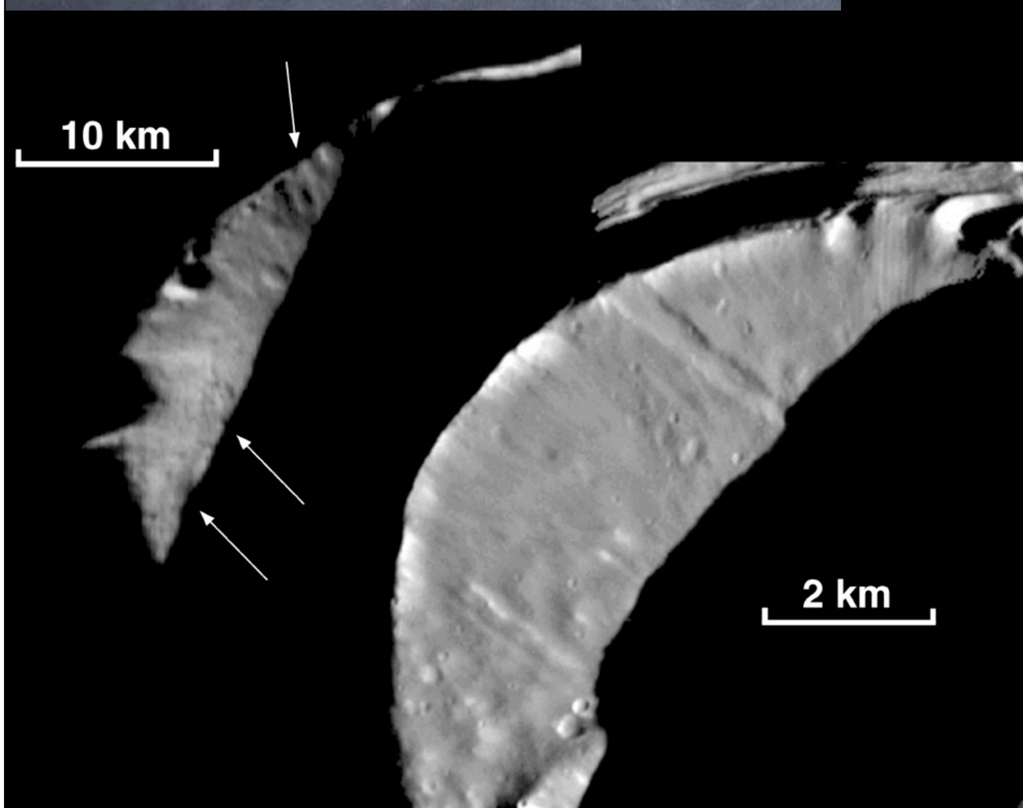
253 Mathilde

66x48x46 km

C Type

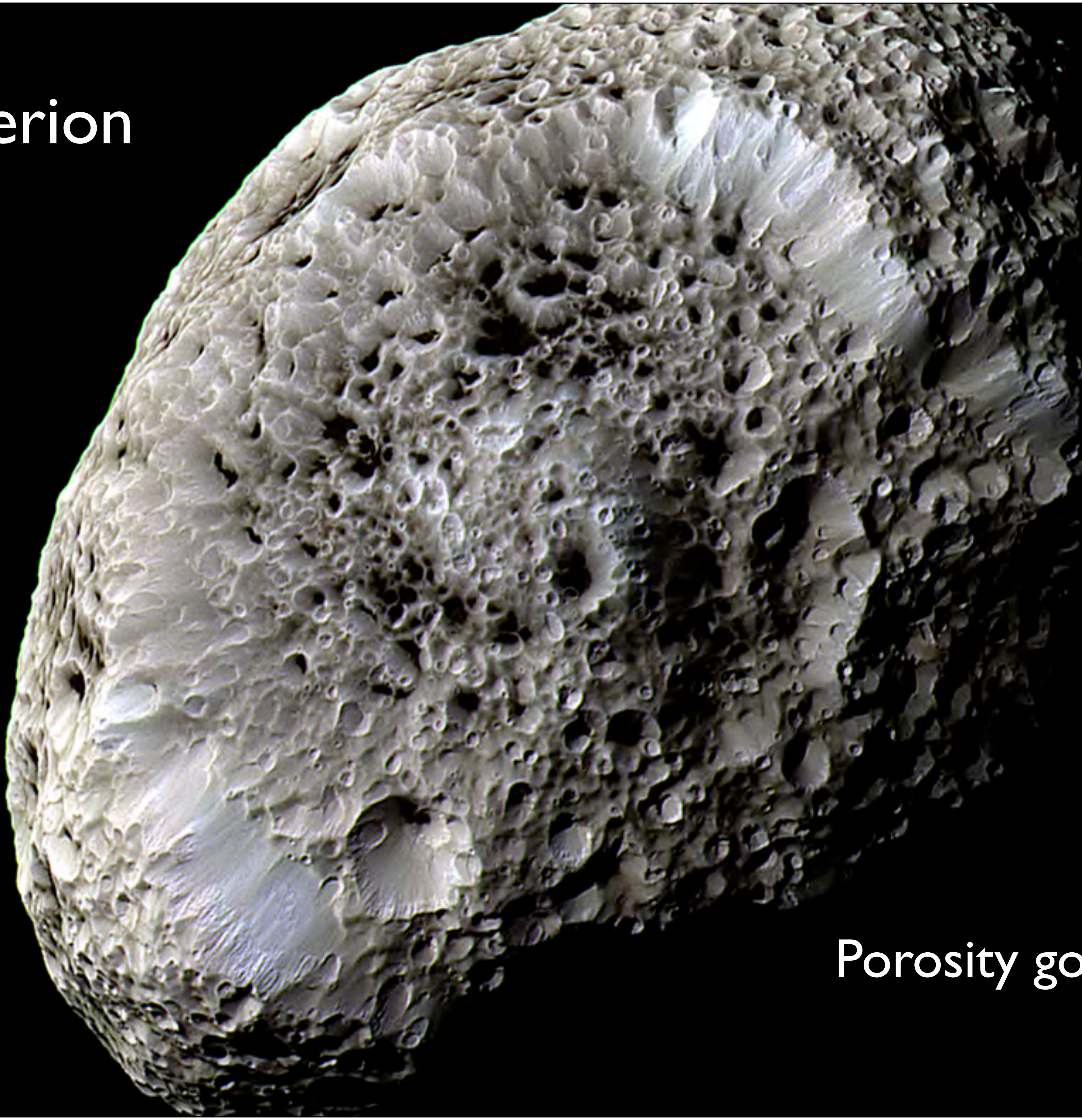
How can such a small object survive such an intense pounding?





Porous *rubble pile* nature of many asteroids absorbs impact shock

Hyperion



Porosity gone wild?

25143 Itokawa

535x294x209 *meters*

S Type, density = 1.9 g/cm^3

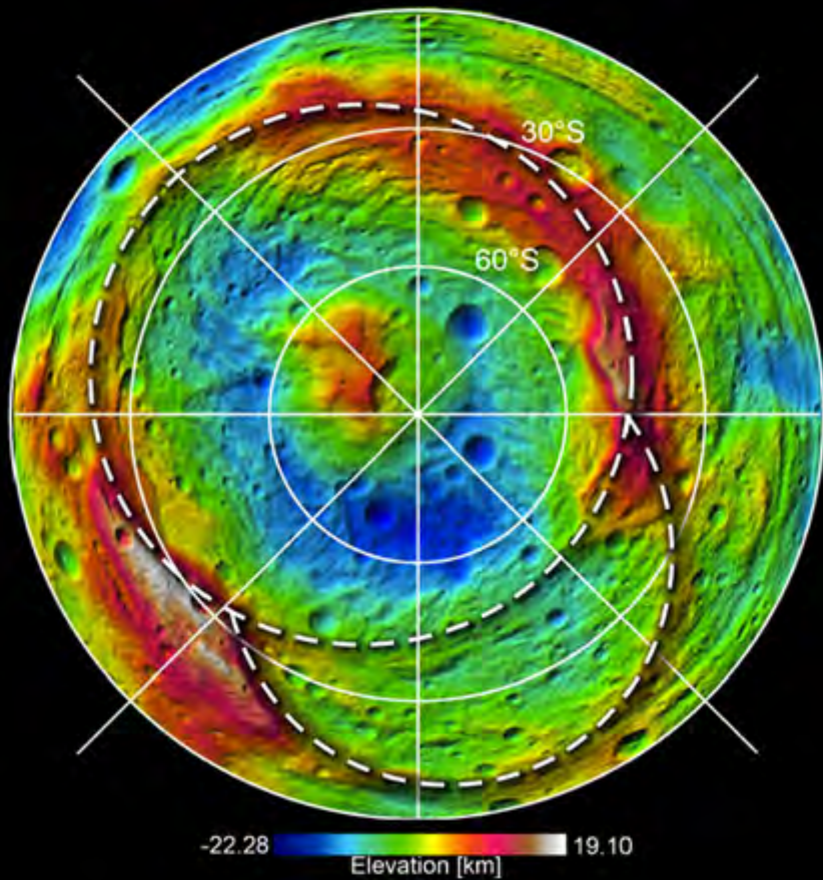
Where are the impact craters?

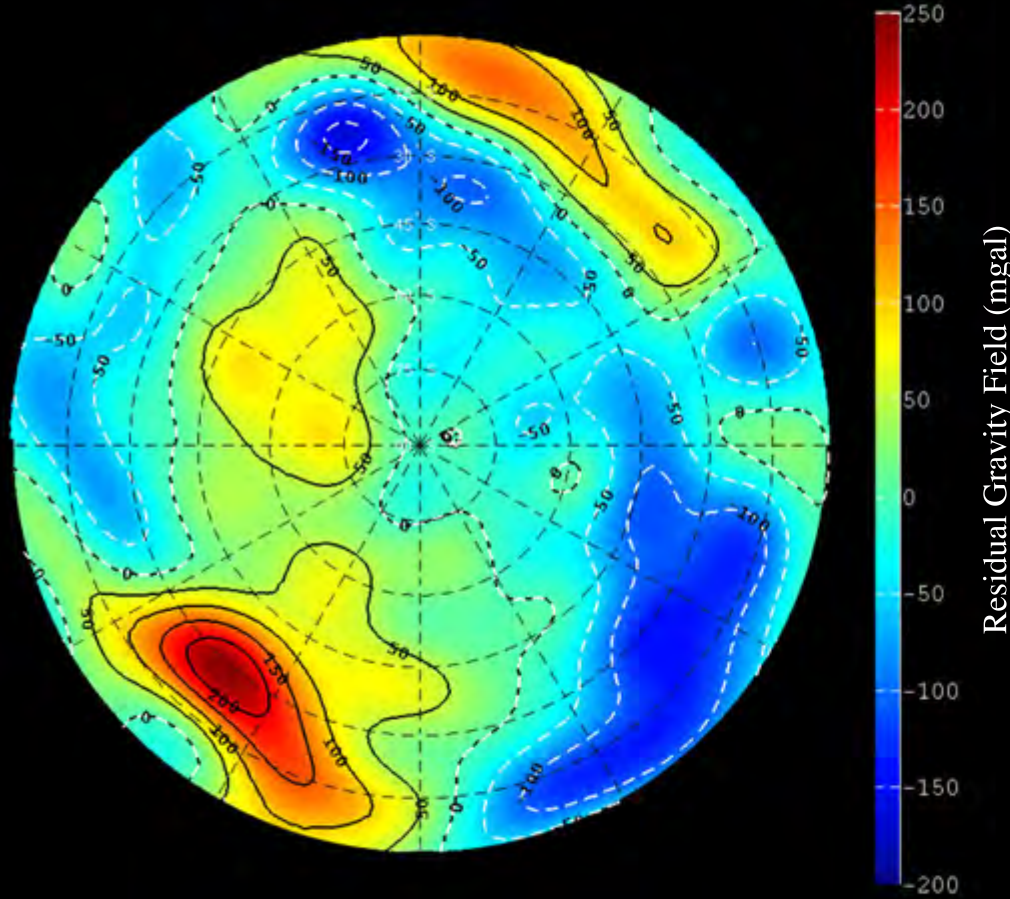
Is Itokawa a rubble pile?

JAXA/Hayabusa Mission

NASA/JPL-Caltech/UCLA/MPS/DLR/IDA/Dawn Mission

Vesta

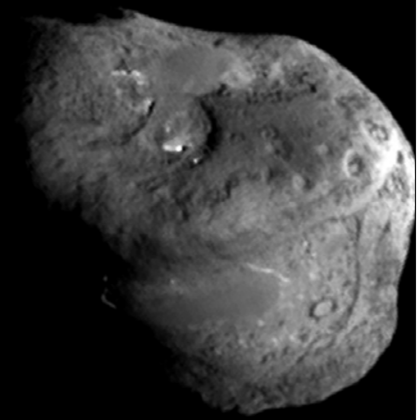
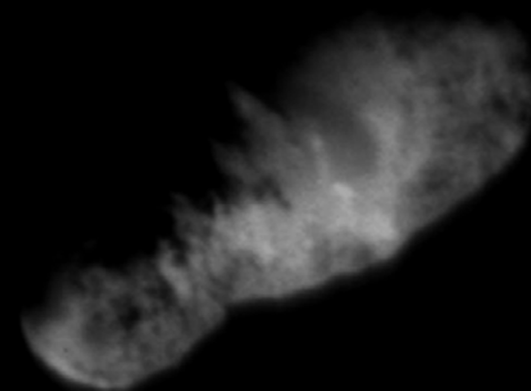
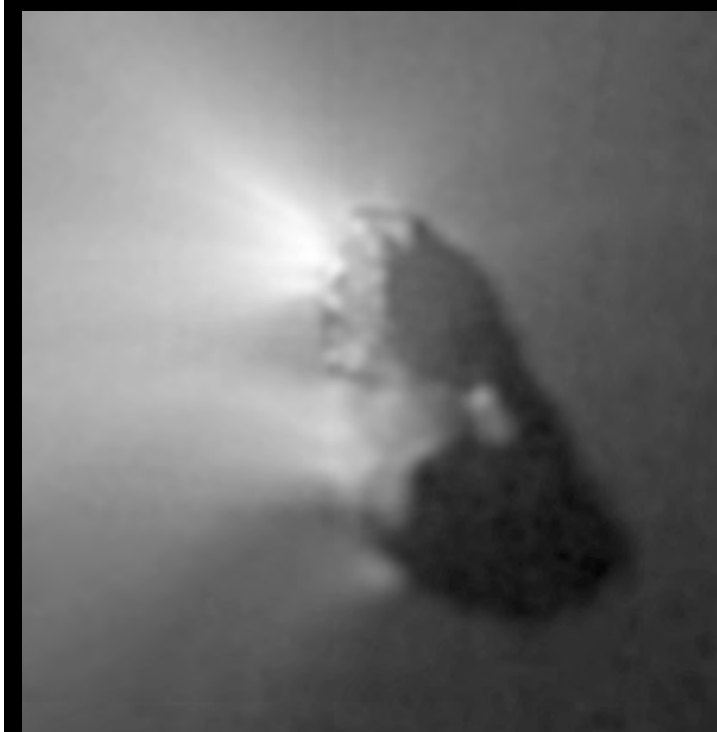




Topography from stereo imaging (left) can be removed from gravity signature to reveal crustal density anomalies (right)

Comets:
Increasing the sample imaged by spacecraft



Halley: 1985
Borrelly: 2001
Wild-2: 2004
Tempel-1: 2005, 2011
Hartley-2: 2010

ESA/IKI and NASA/JPL

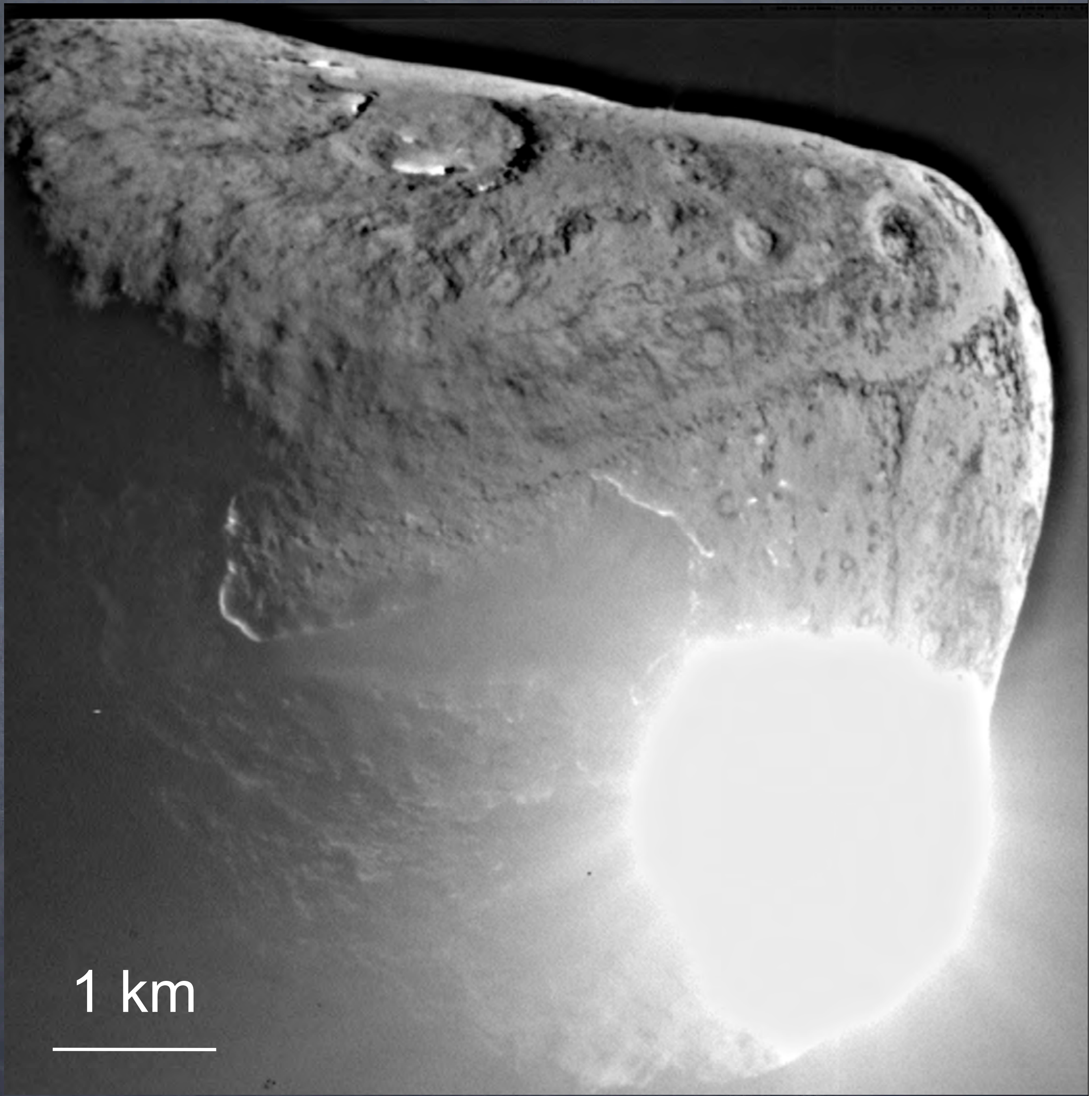
Comet Tempel-1

Deep layers wrap around, roughly parallel to “top” facet.

Regional differences in erosion and a wide variety of topographic forms

Why is the boundary between regions parallel to the layers? Draping? Regional erosion?

Many puzzles!

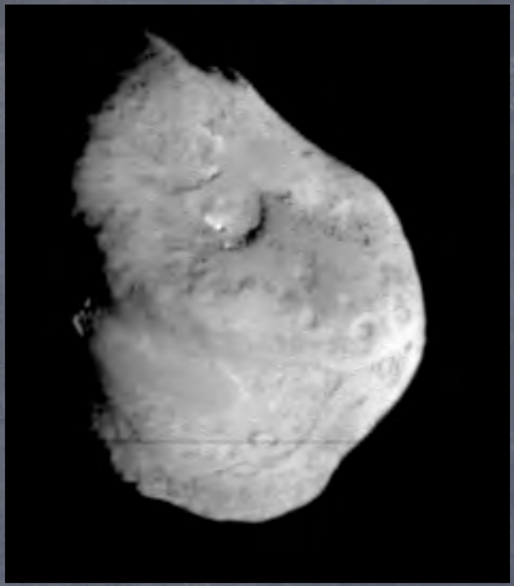


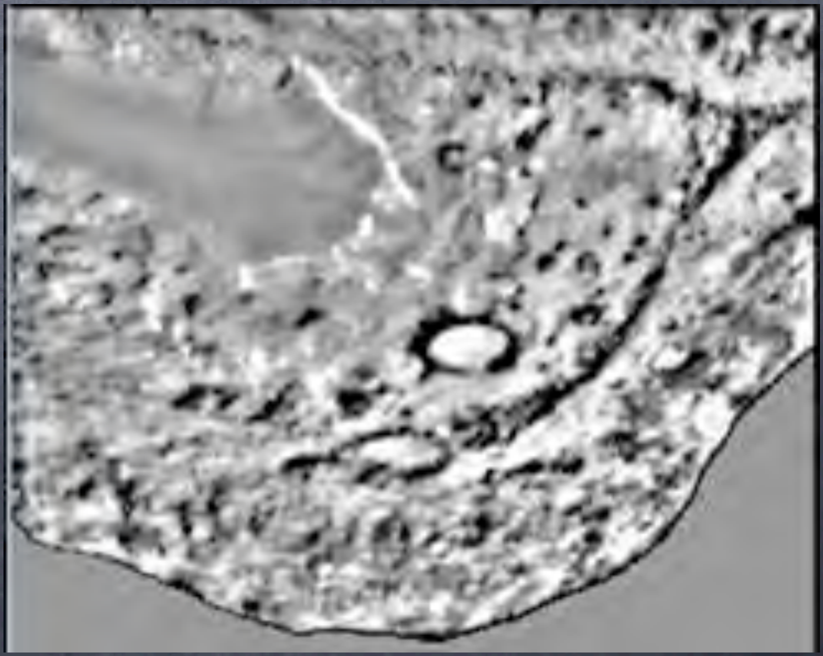
NASA/JPL Deep Impact Mission

Geology of Tempel 1

Physical character:
    mean density of 0.4 ± 0.2 g cm^{-3}
Geologic units
    layer structures: deep/shallow?
    “smooth” deposits and flows
    relation between types of layers
    (photometric variations?)
Processes
    venting, pitting, and deposition
    scarp retreat
    cratering
    regional variations
    relation to jet structures

Is this a pristine object? Puzzles...

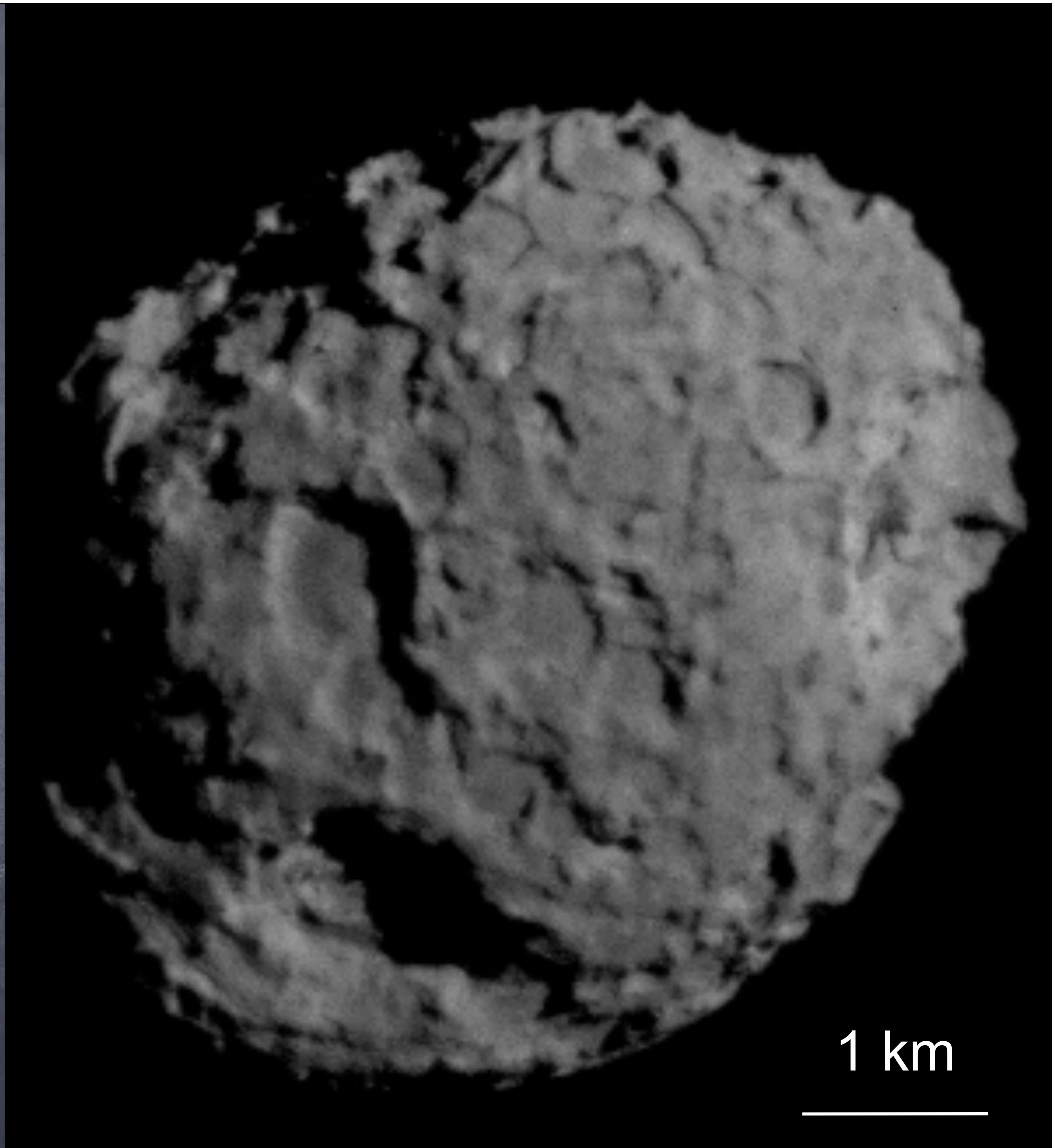




NASA/JPL/Cornell (P. Thomas), Deep Impact Mission

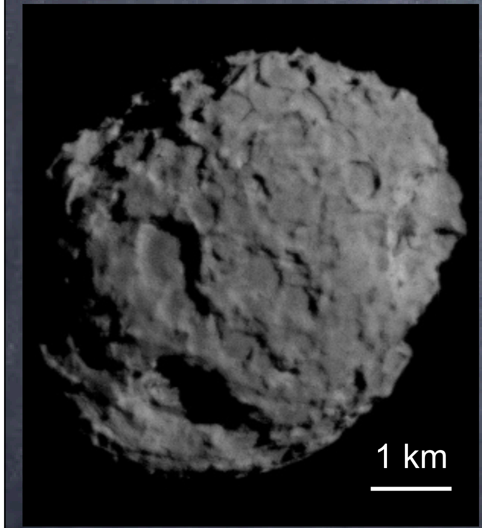
Wild-2:

- Rugged surface
- Circular depressions
- What are they?
- Craters?
- Sublimation pits?

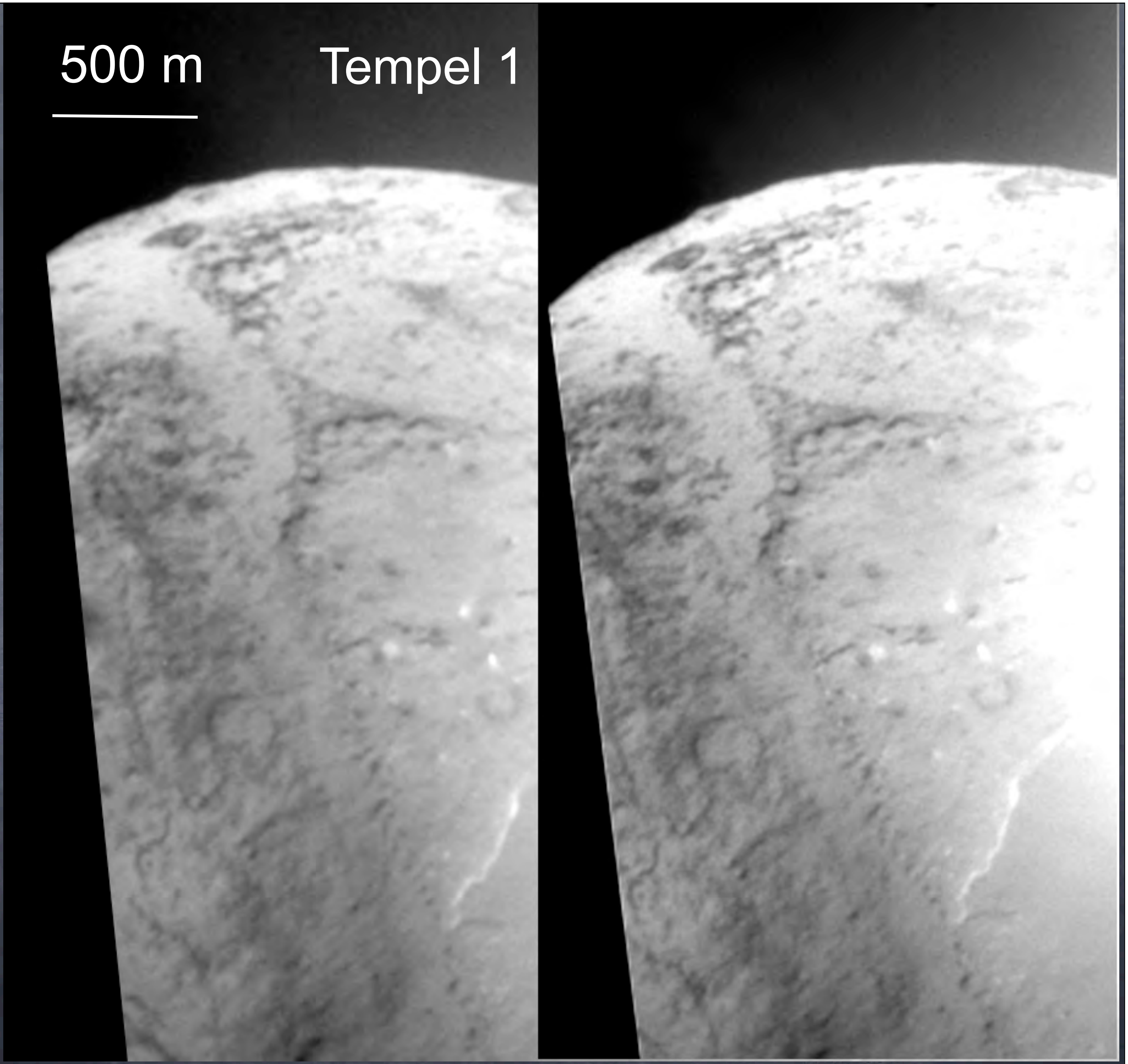


NASA/JPL Stardust Mission

The darker area with close round depressions is the part of Tempel 1 that most closely resembles Wild-2

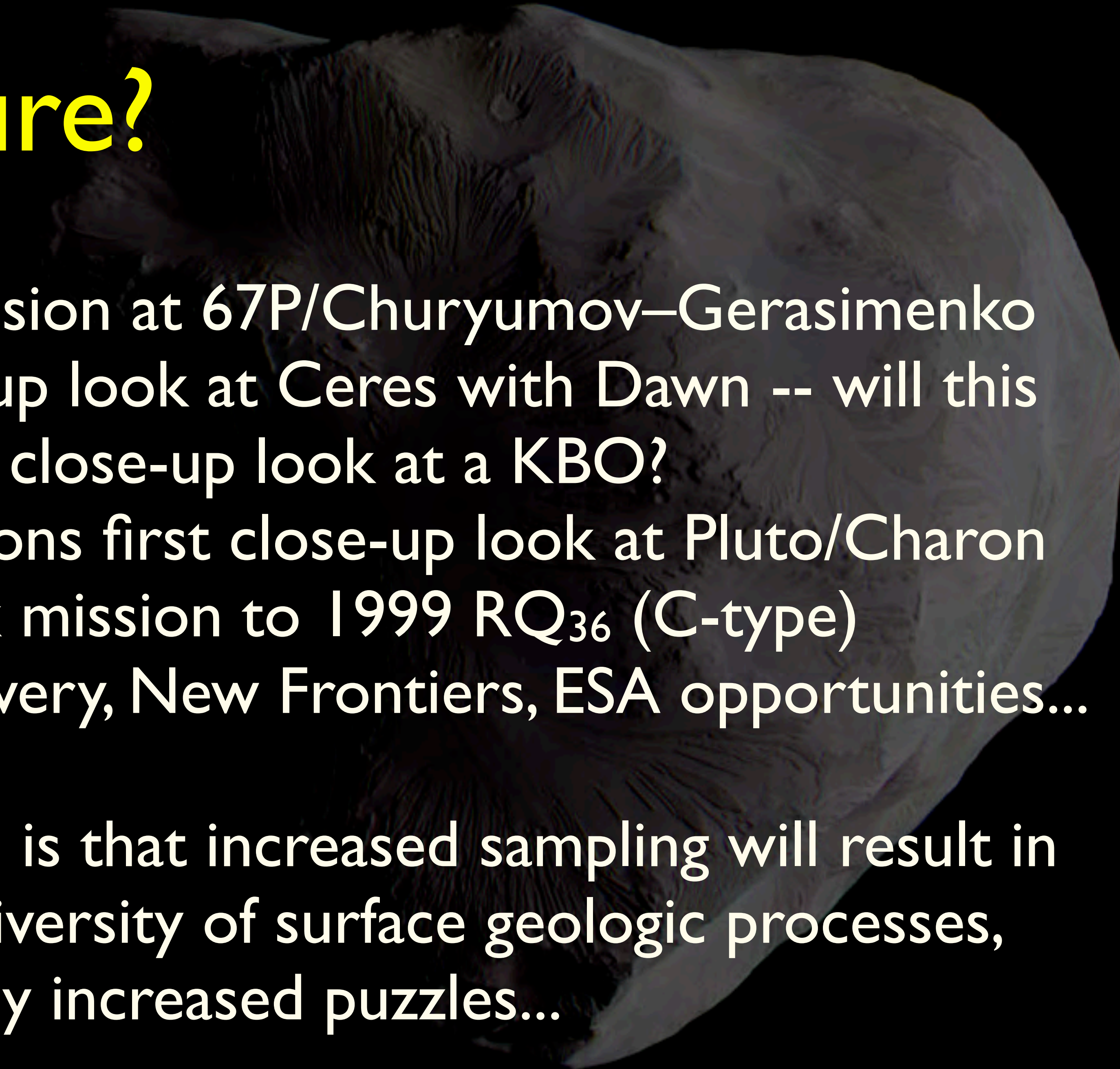


Wild-2



NASA/JPL Deep Impact and Stardust Missions

The Future?

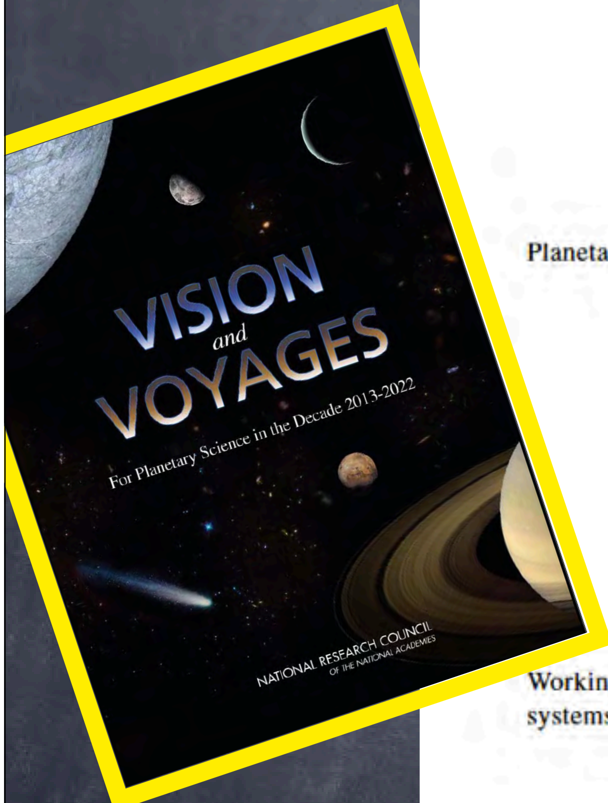


NASA/JPL/SSI/Cassini Mission

- Rosetta mission at 67P/Churyumov–Gerasimenko
- First close-up look at Ceres with Dawn -- will this be our first close-up look at a KBO?
- New Horizons first close-up look at Pluto/Charon
- OSIRIS-REx mission to 1999 RQ_{36} (C-type)
- New Discovery, New Frontiers, ESA opportunities...

- Expectation is that increased sampling will result in increased diversity of surface geologic processes, and probably increased puzzles...

NRC 2011 Planetary Decadal Survey



Primitive Bodies

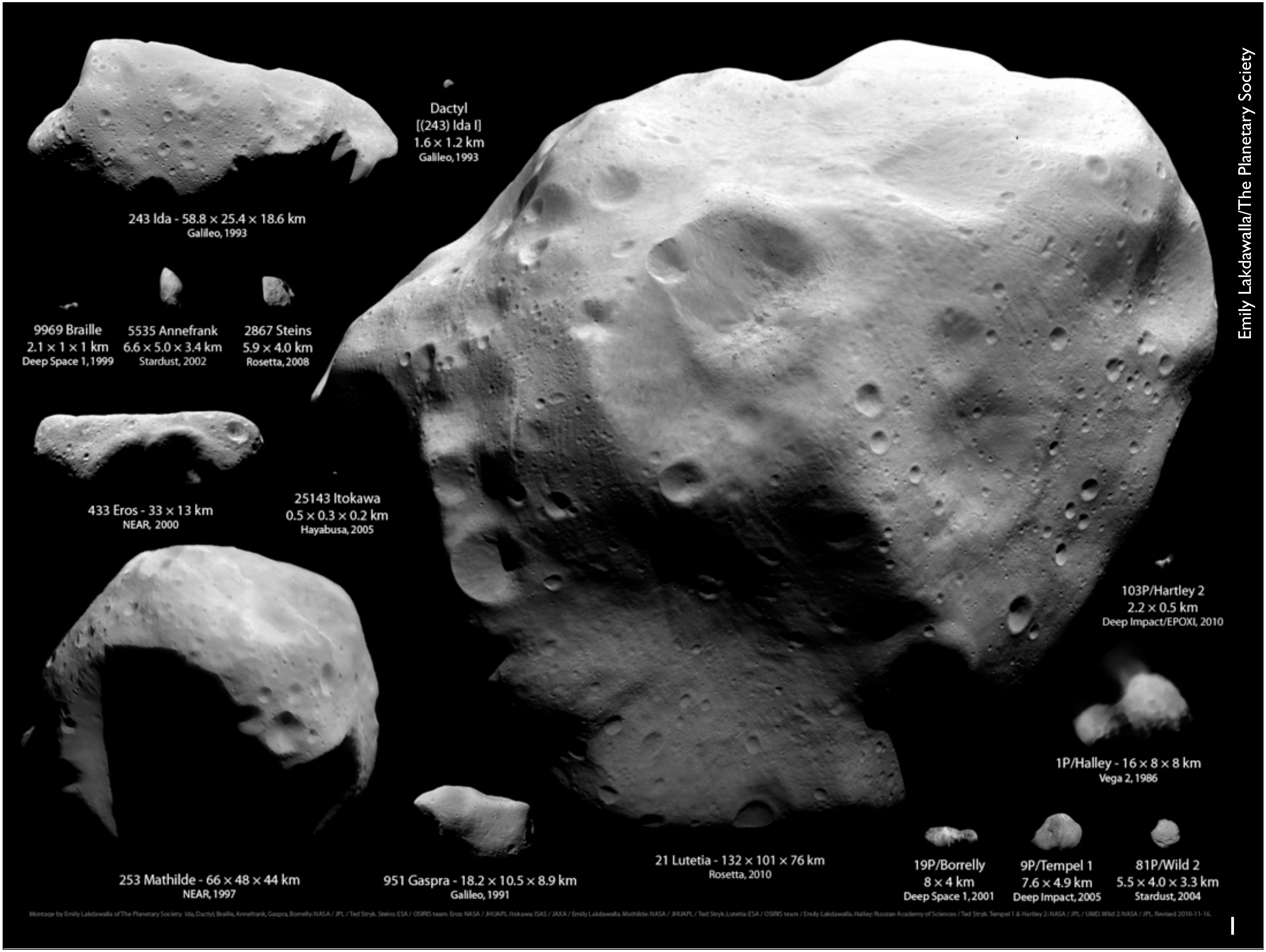
TABLE 3.1 The Key Questions and Planetary Destinations to Address Them

Crosscutting Themes	Priority Questions	Key Bodies to Study
Building new worlds	1. What were the initial stages, conditions and processes of solar system formation and the nature of the interstellar matter that was incorporated?	Comets, Asteroids, Trojans, Kuiper belt objects (see Chapter 4)
	2. How did the giant planets and their satellite systems accrete, and is there evidence that they migrated to new orbital positions?	Enceladus, Europa, Io, Ganymede, Jupiter, Saturn, Uranus, Neptune, Kuiper belt objects, Titan, rings (see Chapters 4, 7, and 8)
	3. What governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play?	Mars, the Moon, Trojans, Venus, asteroids, comets (see Chapters 4, 5, and 6)
Planetary habitats	4. What were the primordial sources of organic matter, and where does organic synthesis continue today?	Comets, asteroids, Trojans, Kuiper belt objects, uraniaun satellites, Enceladus, Europa, Mars, Titan (see Chapters 4, 5, 6, and 8)
	5. Did Mars or Venus host ancient aqueous environments conducive to early life, and is there evidence that life emerged?	Mars and Venus (see Chapters 5 and 6)
	6. Beyond Earth, are there modern habitats elsewhere in the solar system with necessary conditions, organic matter, water, energy, and nutrients to sustain life, and do organisms live there now?	Enceladus, Europa, Mars, Titan (see Chapters 6 and 8)
Workings of solar systems	7. How do the giant planets serve as laboratories to understand Earth, the solar system, and extrasolar planetary systems?	Jupiter, Neptune, Saturn, Uranus (see Chapter 7)
	8. What solar system bodies endanger Earth's biosphere, and what mechanisms shield it?	Near-Earth objects, the Moon, comets, Jupiter (see Chapters 4, 5, and 7)
	9. Can understanding the roles of physics, chemistry, geology, and dynamics in driving planetary atmospheres and climates lead to a better understanding of climate change on Earth?	Mars, Jupiter, Neptune, Saturn, Titan, Uranus, Venus (see Chapters 5, 6, and 8)
	10. How have the myriad chemical and physical processes that shaped the solar system operated, interacted, and evolved over time?	All solar system destinations. (see Chapters 4, 5, 6, 7, and 8)

Summary

- Geologic and geophysical observations of primitive (or "semi-primitive") bodies enable assessment of the role of impact, tectonic, erosional, and volcanic processes in their origin and evolution
- Some geologic observations, like density, porosity, and the spatial variations in impact crater size frequency distribution and degradation state, could provide constraints on formation models and surface/interior evolutionary pathways
- What surprises await among the giant unsampled populations of KBOs, Centaurs, and Trojans?

NASA/JPL/SSI/Cassini Mission


Emily Lakdawalla/The Planetary Society
243 Ida - 58.8 × 25.4 × 18.6 km
Galileo, 1993
Dactyl
[(243) Ida I]
1.6 × 1.2 km
Galileo, 1993
9969 Braille
2.1 × 1 × 1 km
Deep Space 1, 1999
5535 Annefrank
6.6 × 5.0 × 3.4 km
Stardust, 2002
2867 Steins
5.9 × 4.0 km
Rosetta, 2008
433 Eros - 33 × 13 km
NEAR, 2000
25143 Itokawa
0.5 × 0.3 × 0.2 km
Hayabusa, 2005
103P/Hartley 2
2.2 × 0.5 km
Deep Impact/EPOXI, 2010
1P/Halley - 16 × 8 × 8 km
Vega 2, 1986
253 Mathilde - 66 × 48 × 44 km
NEAR, 1997
951 Gaspra - 18.2 × 10.5 × 8.9 km
Galileo, 1991
21 Lutetia - 132 × 101 × 76 km
Rosetta, 2010
19P/Borrelly
8 × 4 km
Deep Space 1, 2001
9P/Tempel 1
7.6 × 4.9 km
Deep Impact, 2005
81P/Wild 2
5.5 × 4.0 × 3.3 km
Stardust, 2004
Montage by Emily Lakdawalla of The Planetary Society. Ida, Dactyl, Braille, Annefrank, Gaspra, Borrelly: NASA / JPL / Ted Stryk. Steins: ESA / OSIRIS team. Eros: NASA / JHUAPL. Itokawa: ISAS / JAXA / Emily Lakdawalla. Mathilde: NASA / JHUAPL / Ted Stryk. Lutetia: ESA / OSIRIS team / Emily Lakdawalla. Halley: Russian Academy of Sciences / Ted Stryk. Tempel 1 & Hartley 2: NASA / JPL / UMD. Wild 2: NASA / JPL. Revised 2010-11-16.
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