Hayabusa at Itokawa:
first visit to a rubble pile asteroid, or

How do we know it's a rubble pile, and what does that mean?

A. F. Cheng, O Barnouin-Jha, N. Hirata, H. Miyamoto, R. Nakamura, H. Yano and the Hayabusa Team

NASA HQ, JHU/APL, ISAS, Univ. of Aizu, Univ. of Tokyo, Nat. Inst. Adv. Ind. Sci. Technology

Asteroids as Building Blocks of the Solar System

- What are the populations?
  - Physical properties and compositions
- How did they form and evolve?
  - Collisional evolution
  - Differentiation?
- How did they make planets?
- How have they affected planetary evolution (and biosphere evolution)?

HAYABUSA AT ASTEROID ITOKAWA

REPORT

The Rubble-Pile Asteroid Itokawa as Observed by Hayabusa

A. Fujiwara,[1*] J. Kawaguchi,[1] D. K. Yeomans,[2] M. Abe,[1] T. Mukai,[3] T. Okada,[1] J. Saito,[1] H. Yano,[1] M. Yoshikawa,[1] D. J. Scheeres,[4] O. Barnouin-Jha,[5] A. F. Cheng,[5] H. Demura,[6] R. W. Gaskell,[2] N. Hirata,[3] H. Ikeda,[1] T. Kominato,[7] H. Miyamoto,[8] A. M. Nakamura,[3] R. Nakamura,[9] S. Sasaki,[10] K. Uesugi[1]

During the interval from September through early December 2005, the Hayabusa spacecraft was in close proximity to near-Earth asteroid 25143 Itokawa, and a variety of data were taken on its shape, mass, and surface topography as well as its mineralogic and elemental abundances. The asteroid's orthogonal axes are 535, 294, and 209 meters, the mass is 3.51×10^{10} kilograms, and the estimated bulk density is 1.9 ± 0.13 grams per cubic centimeter. The correspondence between the smooth areas on the surface (Muses Sea and Sagamihara) and the gravitationally low regions suggests mass movement and an effective resurfacing process by impact jolting. Itokawa is considered to be a rubble-pile body because of its low bulk density, high porosity, boulder-rich appearance, and shape. The existence of very large boulders and pillars suggests an early collisional breakup of a preexisting parent asteroid followed by a re-agglomeration into a rubble-pile object.

Science, vol. 312, 2006

Science, vol. 316, 2007

Regolith Migration and Sorting on Asteroid Itokawa

Hideaki Miyamoto,[1,2,3,4*] Hajime Yano,[5] Daniel J. Scheeres,[6] Shinsuke Abe,[7] Olivier Barnouin-Jha,[8] Andrew F. Cheng,[8] Hirohide Demura,[9] Robert W. Gaskell,[10] Naru Hirata,[9] Masateru Ishiguro,[11] Tatsuhiro Michikami,[12] Akiko M. Nakamura,[7] Ryosuke Nakamura,[13] Jun Saito,[5,14] Sho Sasaki[15]

High-resolution images of the surface of asteroid Itokawa from the Hayabusa mission reveal it to be covered with unconsolidated millimeter-sized and larger gravels. Locations and morphologic characteristics of this gravel indicate that Itokawa has experienced considerable vibrations, which have triggered global-scale granular processes in its dry, vacuum, microgravity environment. These processes likely include granular convection, landslide-like granular migrations, and particle sorting, resulting in the segregation of the fine gravels into areas of potential lows. Granular processes become major resurfacing processes because of Itokawa's small size, implying that they can occur on other small asteroids should those have regolith.

GRL, vol. 34, 2007

GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L09201, doi:10.1029/2007GL029559, 2007

Fundamentally distinct outcomes of asteroid collisional evolution: Itokawa and Eros

A. F. Cheng,[1] O. Barnouin-Jha,[1] N. Hirata,[2] H. Miyamoto,[3] R. Nakamura,[4] and H. Yano[5]

Asteroids as Building Blocks of the Solar System (cont'd)

- Which asteroids are undifferentiated (never heated to melting)?
- Asteroids are collisionally evolved
  - Only the largest asteroids date back to epoch of planetary accretion; most smaller objects are collisional fragments
  - The near-Earth population consists of objects whose orbits evolved out of the main belt due to gravitational and non-gravitational perturbations
- Asteroids dominated the late heavy bombardment of the [inner] solar system, which may have affected the emergence of life
- Asteroids continue to pose a planetary hazard
  - For mitigation, it is important to know physical properties and interior structure of hazardous asteroids

Asteroids are shaped by collisional evolution, but …

- “what is the balance between accretion and collisional destruction…?” *
- “what is the time history of collisional events…” *
- A key objective of the NEAR and Hayabusa missions was to infer collisional history and interior structure

*2003 Decadal Survey questions

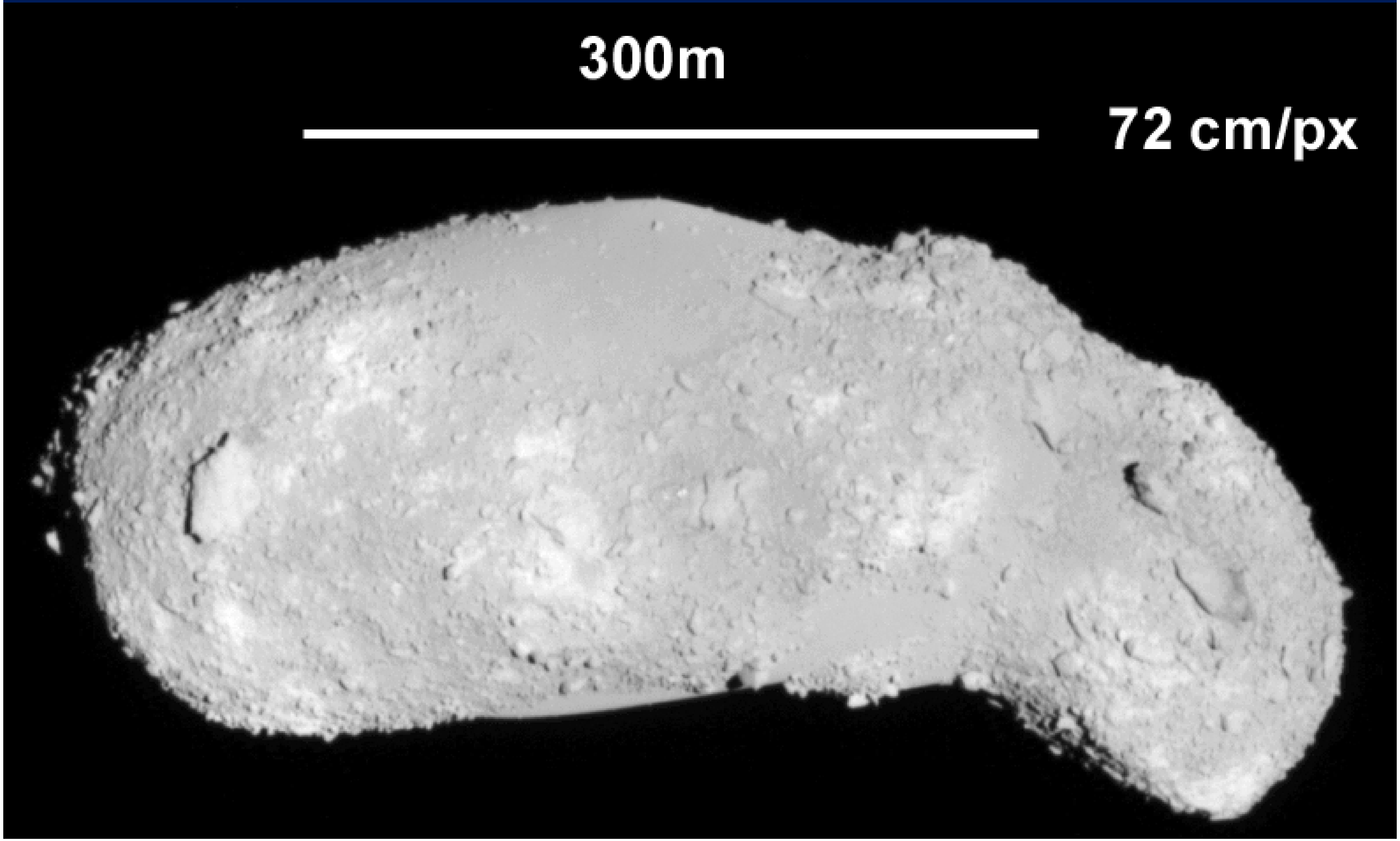
Asteroids are shaped by collisional evolution, but …

- Are most asteroids >1 km gravitational aggregates (“rubble piles”), whereas much smaller asteroids are intact fragments?
  - *Asteroids III* theoretical prediction
- What should a “rubble pile” look like?
  - What is the surface geology that signifies “rubble”?
- NEAR visited Mathilde [53km object] and landed on Eros [18 km object]
- Hayabusa at Itokawa was the ***first visit*** to an asteroid <1 km

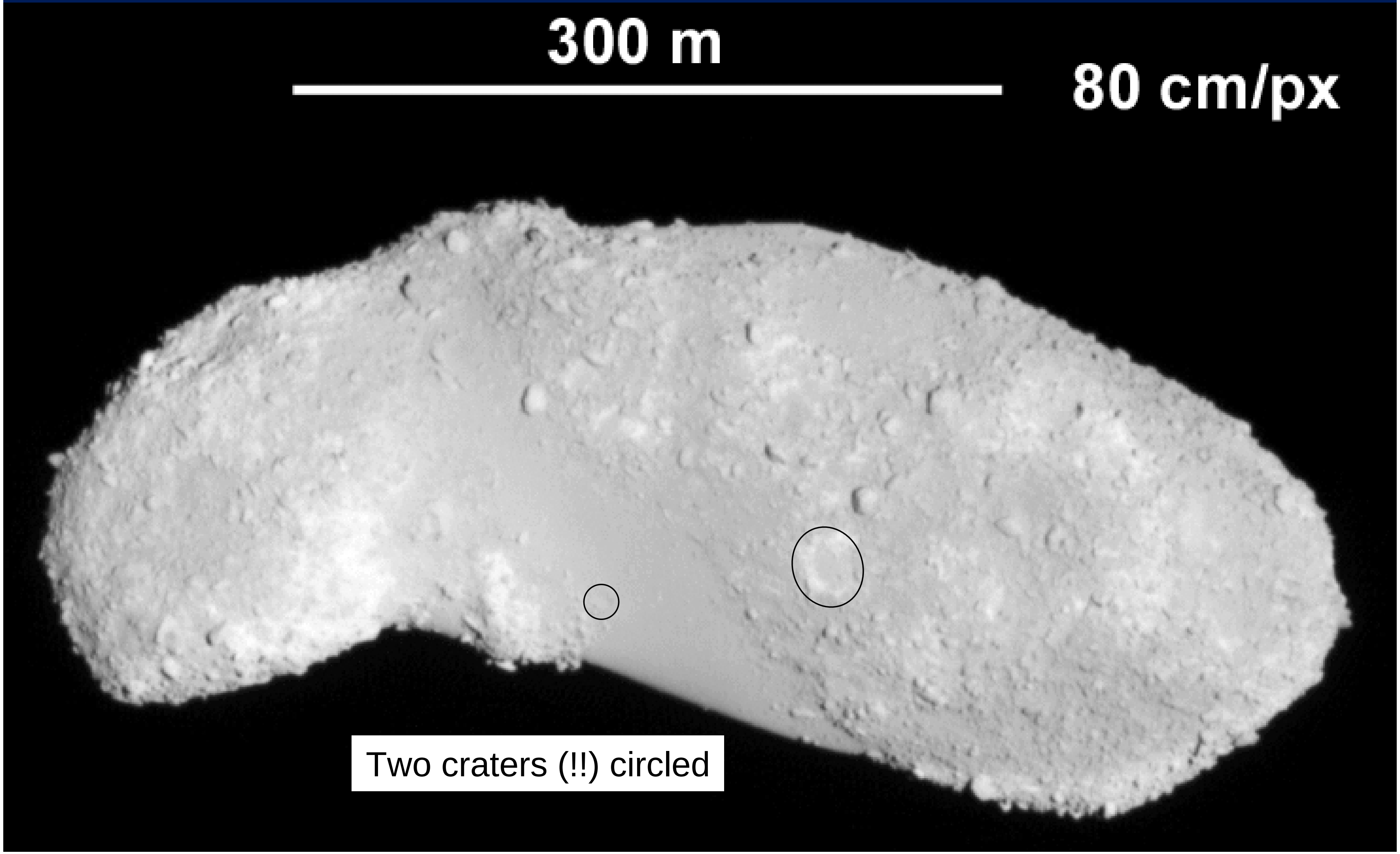
As reported in *Science* and *GRL*

- Itokawa has a low density of 1.9 gm/cc, significantly lower than Eros, despite similar composition (from VNIR and X-ray)
- Itokawa provides first close-up look at a rubble pile asteroid
- Small rubble piles are geologically active!

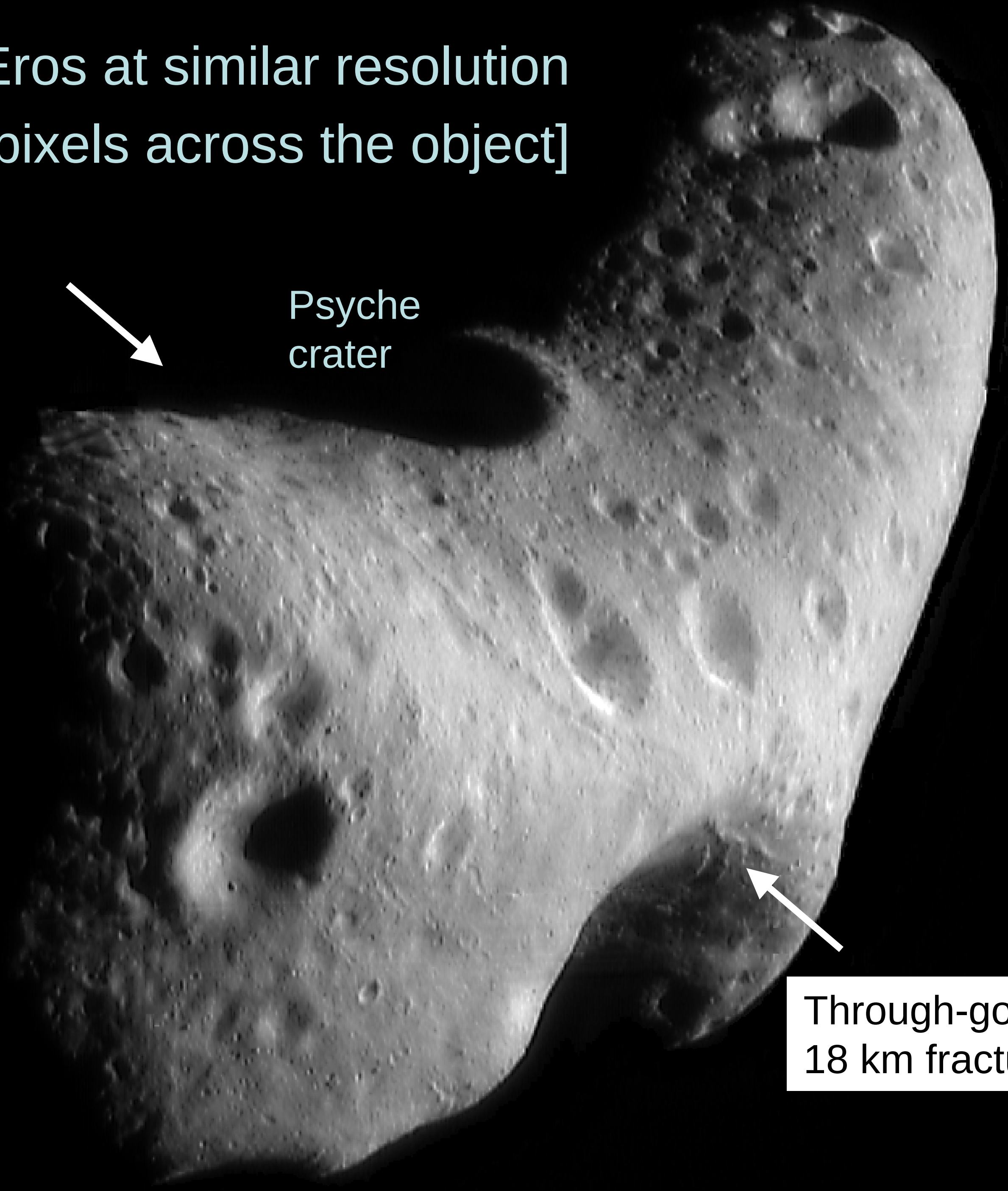
Itokawa: west

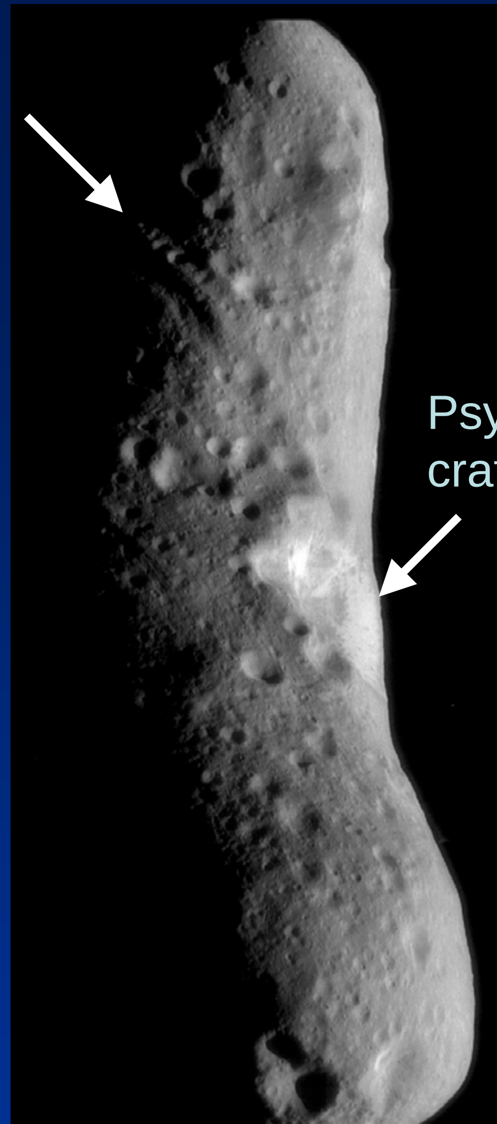


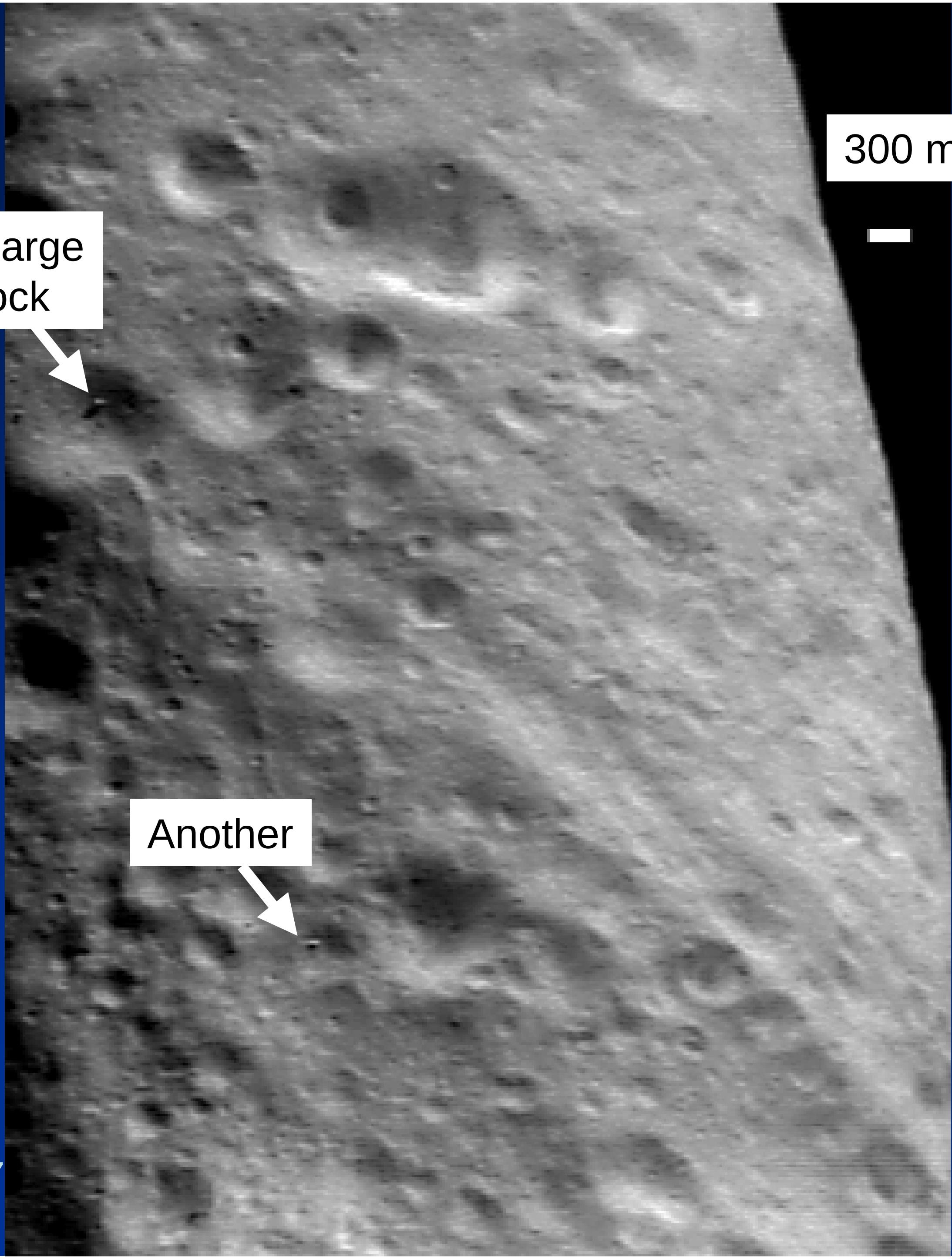
Itokawa: east



Eros at similar resolution [pixels across the object]

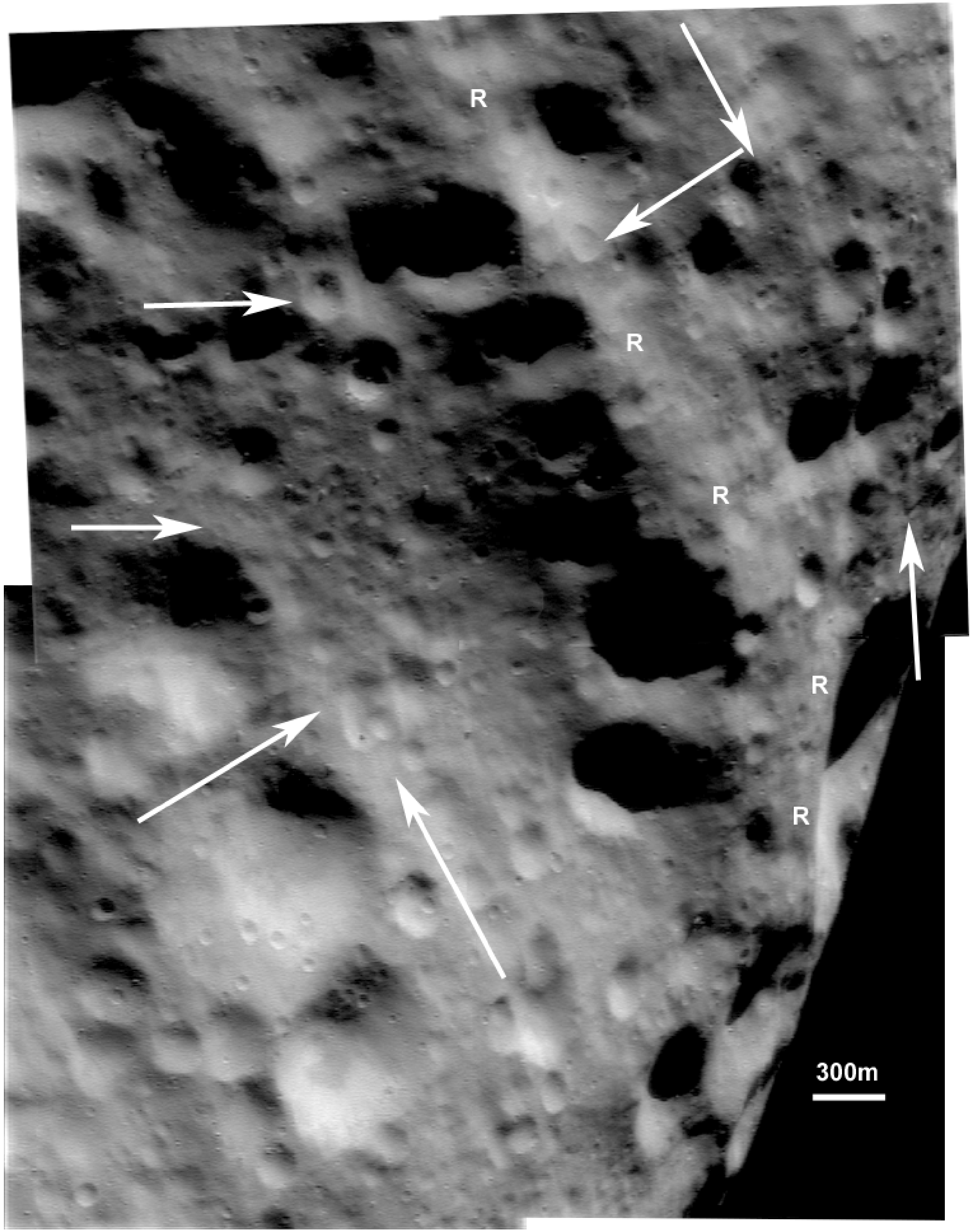




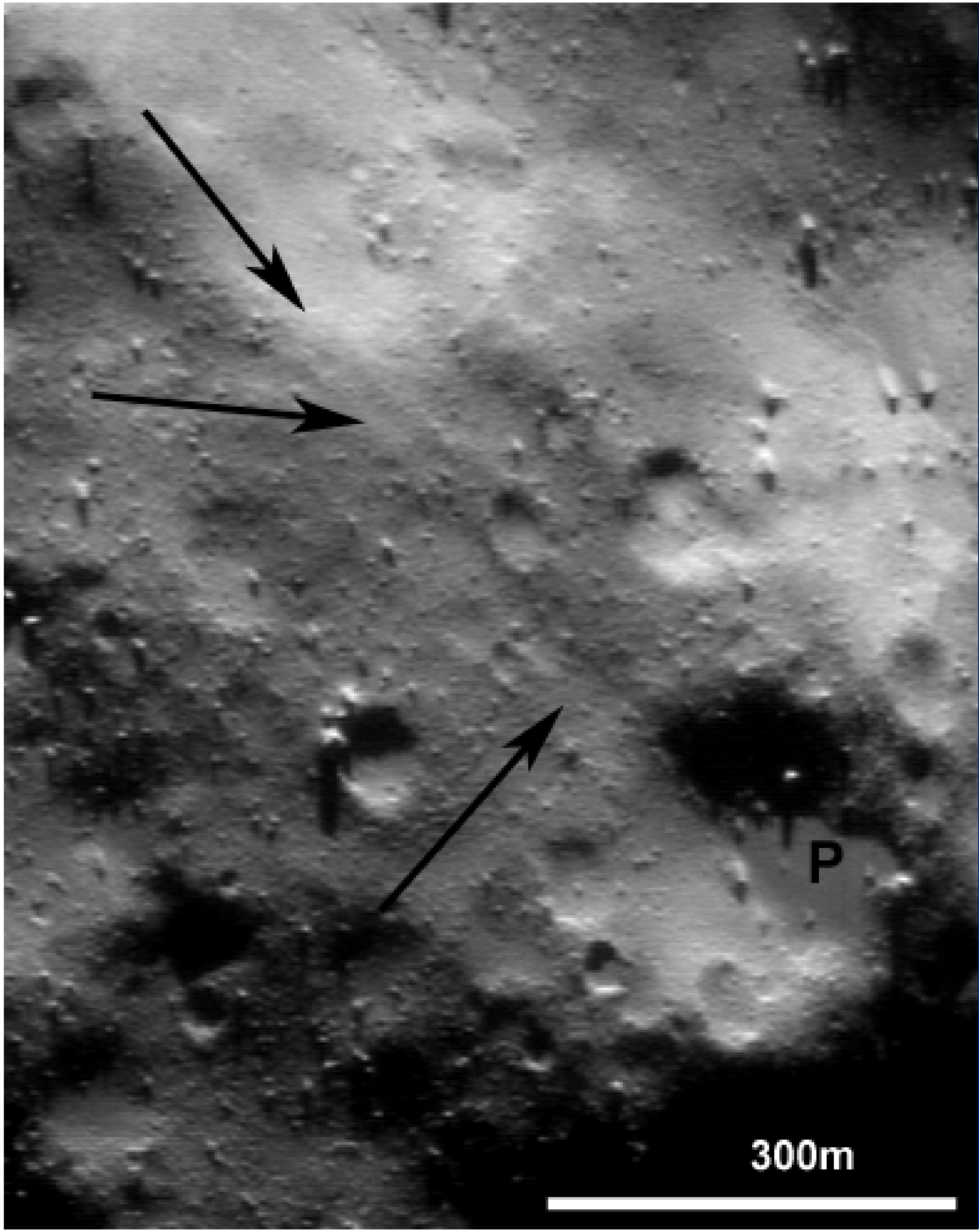


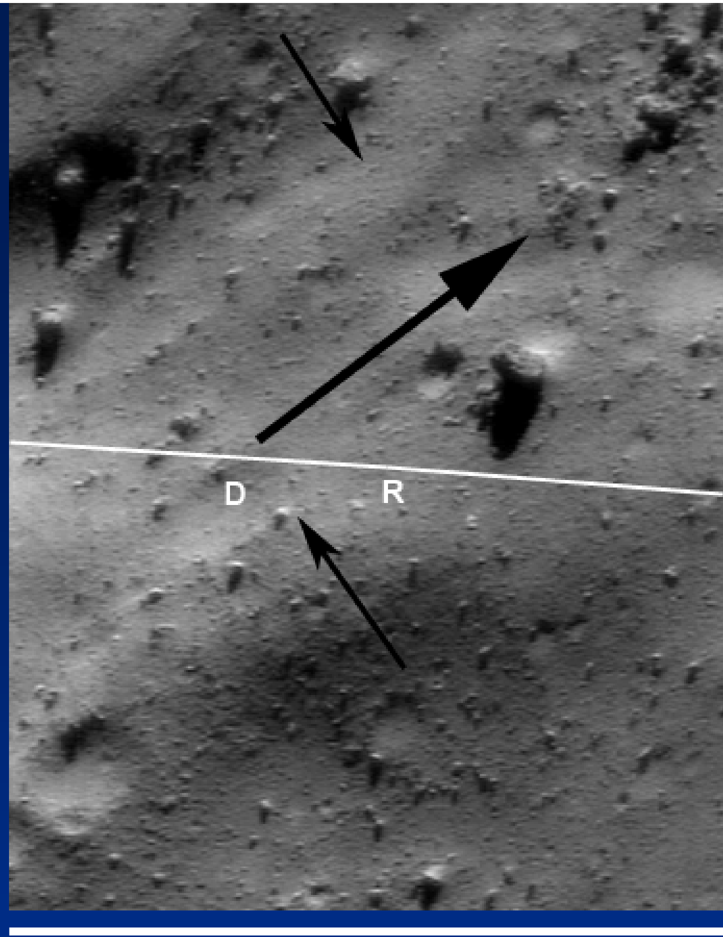
Eros:
heavily cratered;
blocks barely resolved;
ridges and grooves ⇒ completely distinct geology from Itokawa.

7 km ridge SW of Psyche is co-planar with through-going 18 km fracture



Eros image mosaic showing "twist" SW of Psyche crater, with 300 m scale bar (approximate mean diameter of Itokawa). Letters R indicate a ridge 120 m in elevation, ~7 km long. Arrows mark three systems of linear structural features: ridges and grooves or chains of degraded craters, many showing structural control. One lineation set trends from upper left to lower right; another trends from lower left to upper right; another trends across. Illumination from top of page.

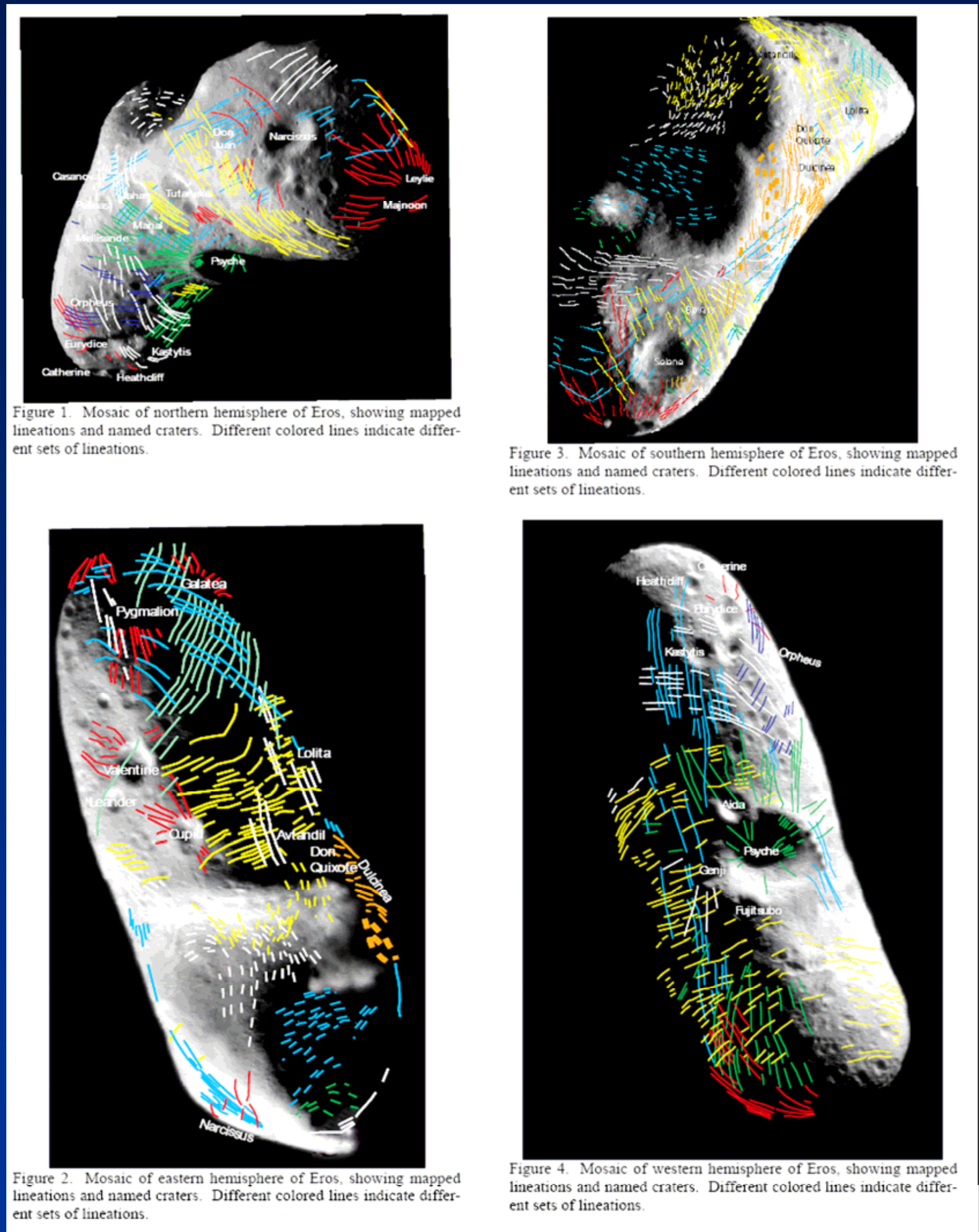


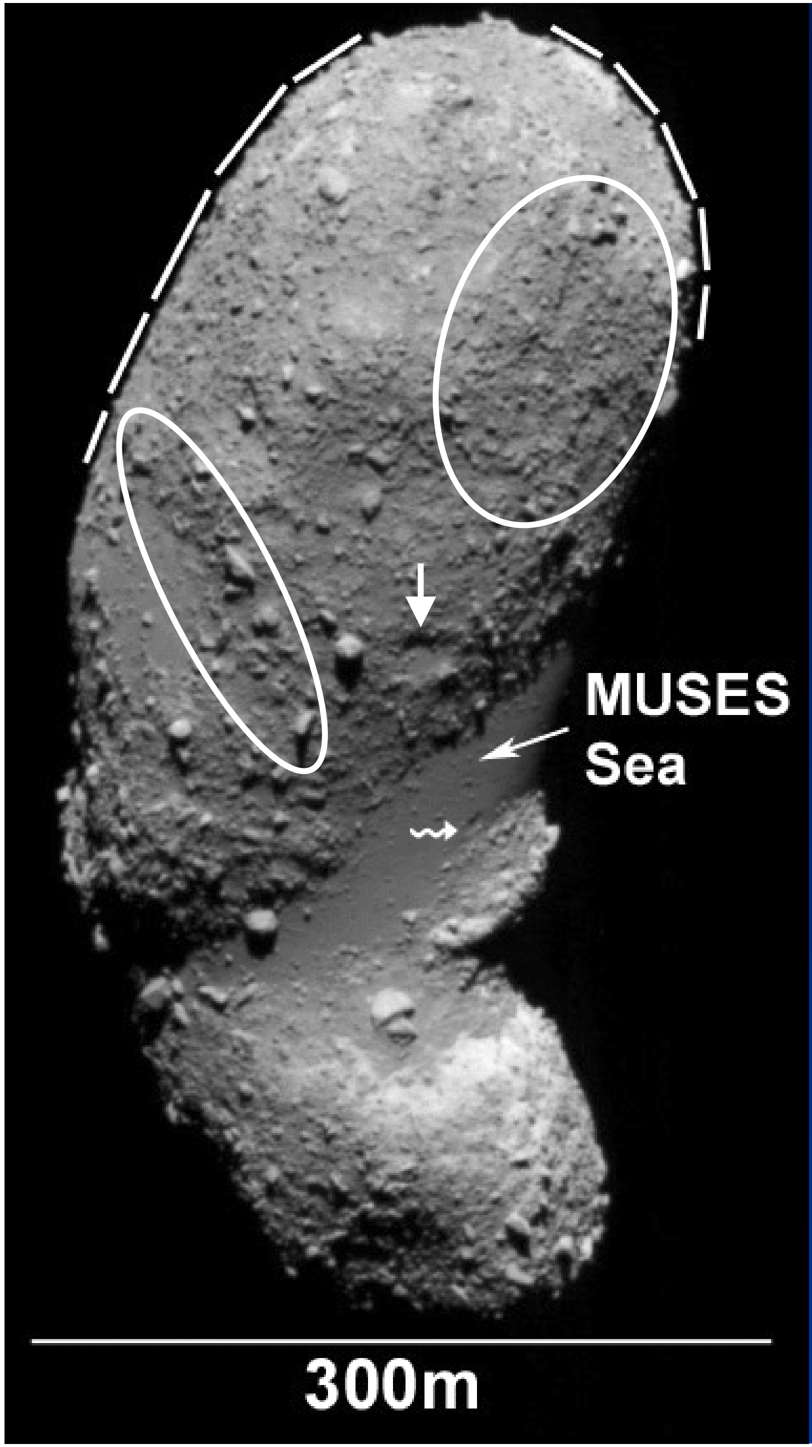


260 m

Global fabric on Eros from many km scales to 10s of meters, several meter blocks, and a pond [P]

Eros, global lineament fabric: some fractures are related to impacts on the body, some are not





Itokawa

A gravitational aggregate: no global lineament fabric, block and crater distributions inconsistent with collisional evolution of an intact fragment, and regolith inconsistent with crater population

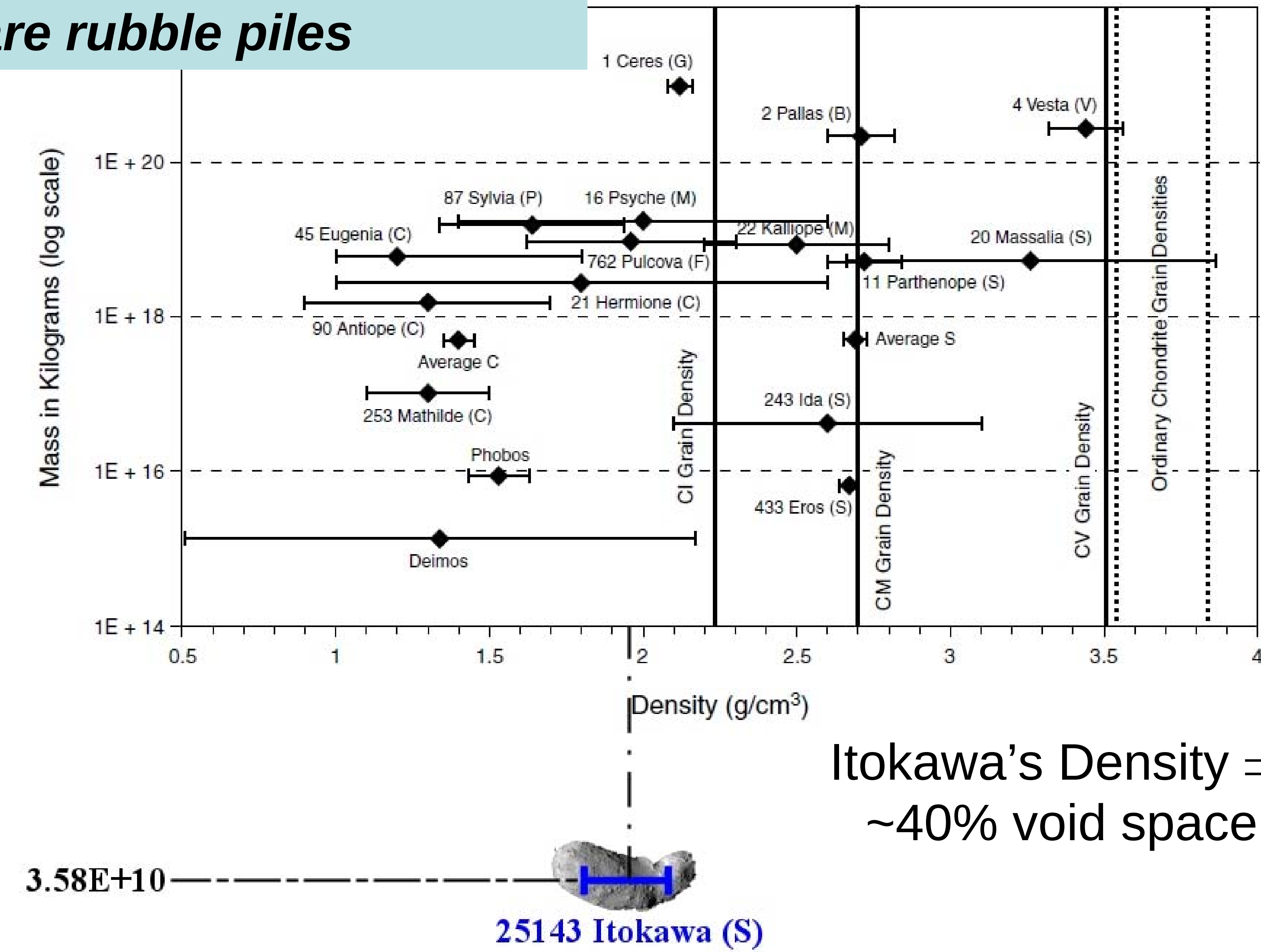
Why the difference is surprising

- Cratering flow velocity $\propto \sqrt{gR_c}$
- Escape velocity $\propto \sqrt{gR_a}$
- Giant craters common $R_{c,giant} \approx 0.5R_a$
- Recaptured ejecta, making regolith, dominated by largest crater (giant crater)
- Then regolith depth $\propto R_a$
- Also largest block size $\propto R_c$ or $\propto R_a$
- Itokawa as scaled down Eros -- fractal

Fractal Scaling Fails Badly, Eros→Itokawa

- Eros and Itokawa have totally different surface geology
- Itokawa has the same composition, but much lower density, than Eros
- Interpretation is that Itokawa is a rubble pile, but Eros is an intact but fractured collisional fragment
- Both objects were once part of much larger parent bodies

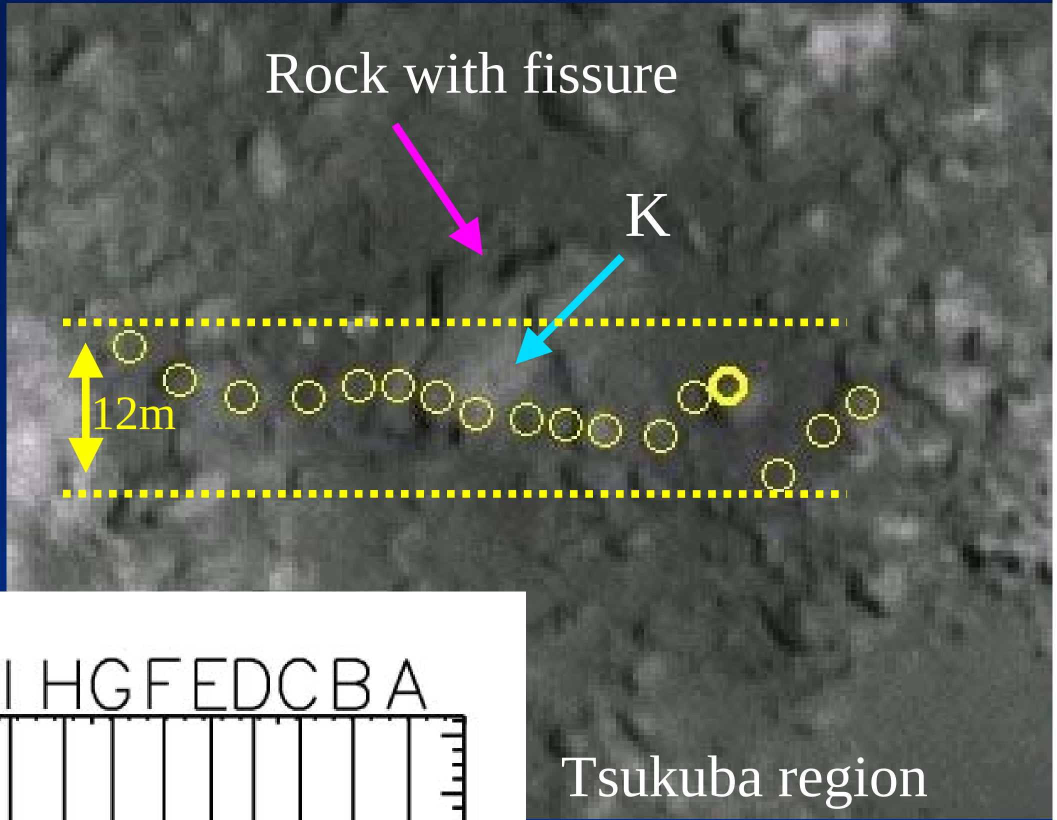
Many (most?) asteroids are rubble piles

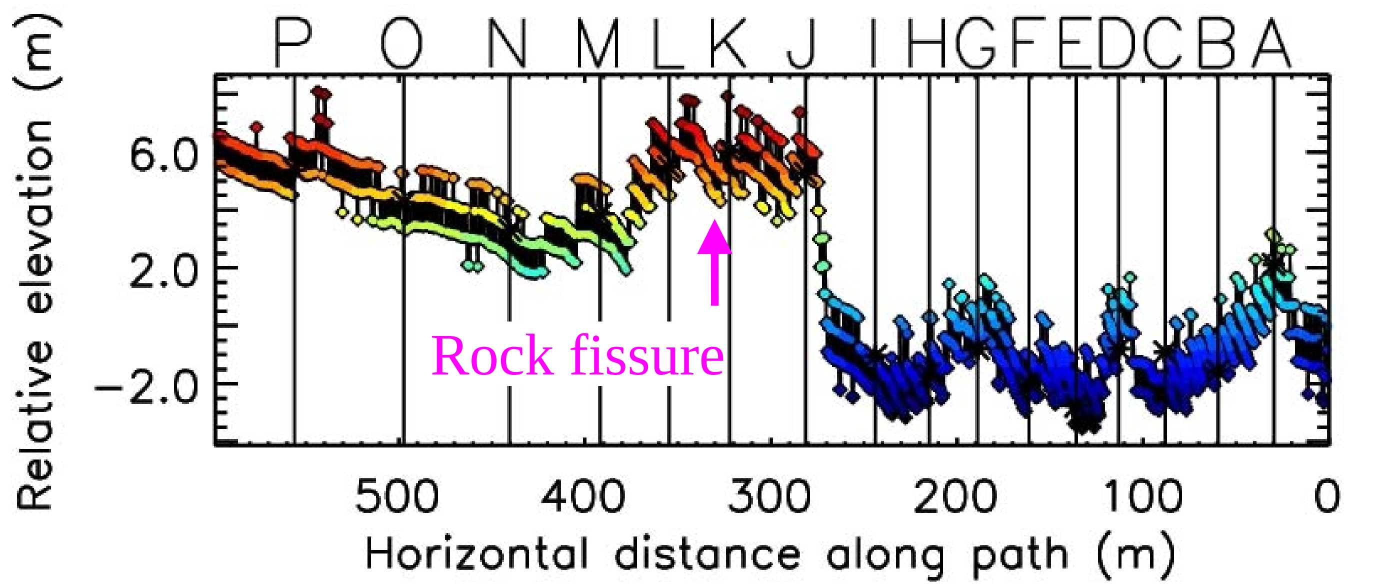


Itokawa's Density ⇒ ~40% void space

Hayabusa LIDAR

- Ranging to surface
- Correlation with images to find relative boresights





Spot ~ 7m

Density Determination

- Direct measurement of gravitational acceleration in free fall using LIDAR
- Required simultaneous solution of body shape, body rotation, spacecraft position and instrument pointing

Science, vol. 312, 2006

REPORT

Mass and Local Topography Measurements of Itokawa by Hayabusa

Shinsuke Abe,[1*] Tadashi Mukai,[1] Naru Hirata,[1,3] Olivier S. Barnouin-Jha,[2] Andrew F. Cheng,[2] Hirohide Demura,[3] Robert W. Gaskell,[4] Tatsuaki Hashimoto,[5] Kensuke Hiraoka,[1] Takayuki Honda,[1] Takashi Kubota,[5] Masatoshi Matsuoka,[6] Takahide Mizuno,[5] Ryosuke Nakamura,[7] Daniel J. Scheeres,[8] Makoto Yoshikawa[5]

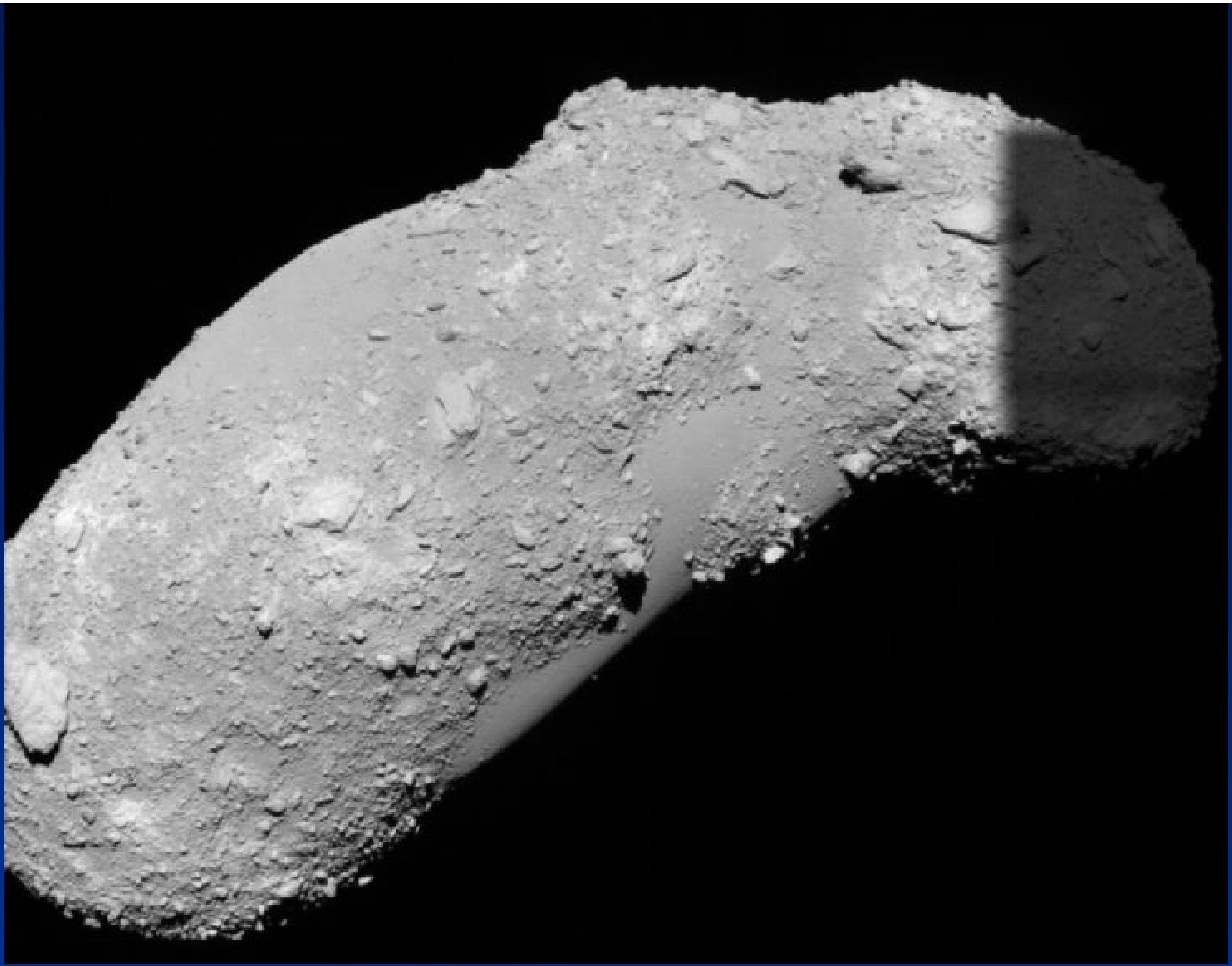
The ranging instrument aboard the Hayabusa spacecraft measured the surface topography of asteroid 25143 Itokawa and its mass. A typical rough area is similar in roughness to debris located on the interior wall of a large crater on asteroid 433 Eros, which suggests a surface structure on Itokawa similar to crater ejecta on Eros. The mass of Itokawa was estimated as $(3.58 \pm 0.18) \times 10^{10}$ kilograms, implying a bulk density of (1.95 ± 0.14) grams per cubic centimeter for a volume of $(1.84 \pm 0.09) \times 10^{7}$ cubic meters and a bulk porosity of ~40%, which is similar to that of angular sands, when assuming an LL (low iron chondritic) meteorite composition. Combined with surface observations, these data indicate that Itokawa is the first subkilometer-sized small asteroid showing a rubble-pile body rather than a solid monolithic asteroid.

Itokawa must be a rubble pile

- Blocks on Itokawa are too large to have formed on a body the size of Itokawa
- Regolith fill in smooth areas has too large a volume for craters on Itokawa
  – This fill is gravel (from landing site data)
  – If all gravel, regolith volume fits on boulder size distribution suggesting fragmentation
- Global fabric, such as from fragmentation of an Eros-like parent body, would have been observed but is NOT seen on Itokawa
- In contrast, blocks and regolith are consistent with having formed predominantly in a single giant crater on Eros (Shoemaker), and the lineament fabric is ubiquitous

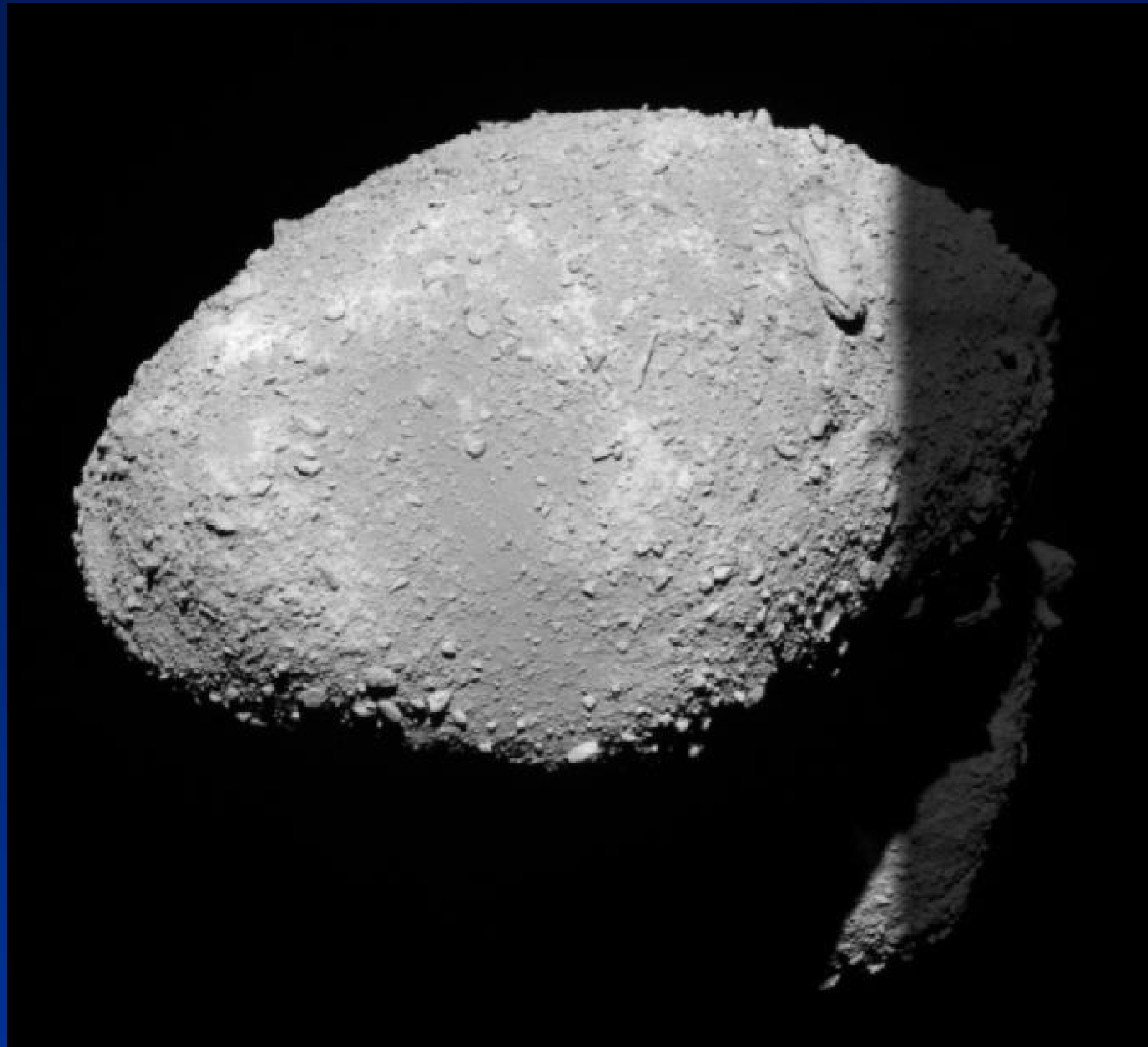
Itokawa's Suggested History

- Itokawa's blocks and regolith formed as result of catastrophic breakup of the much larger parent body (>2 km?)
- Head and body of Itokawa coalesced
- Finer regolith and blocks segregated subsequently
- How can a small rubble pile become geologically active?



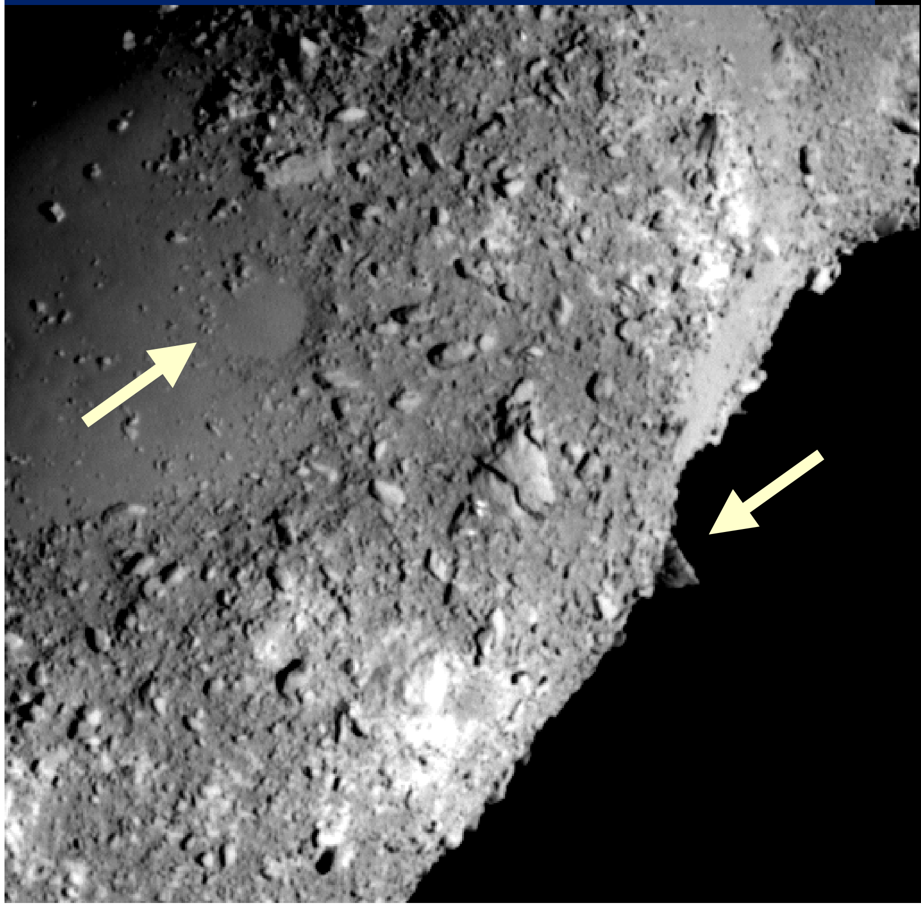
- Boulders too large to be formed from any observed craters
- Sharply defined “smooth” areas at gravitational lows

- Few structural lineaments (compared to Eros)
- Suggested facets



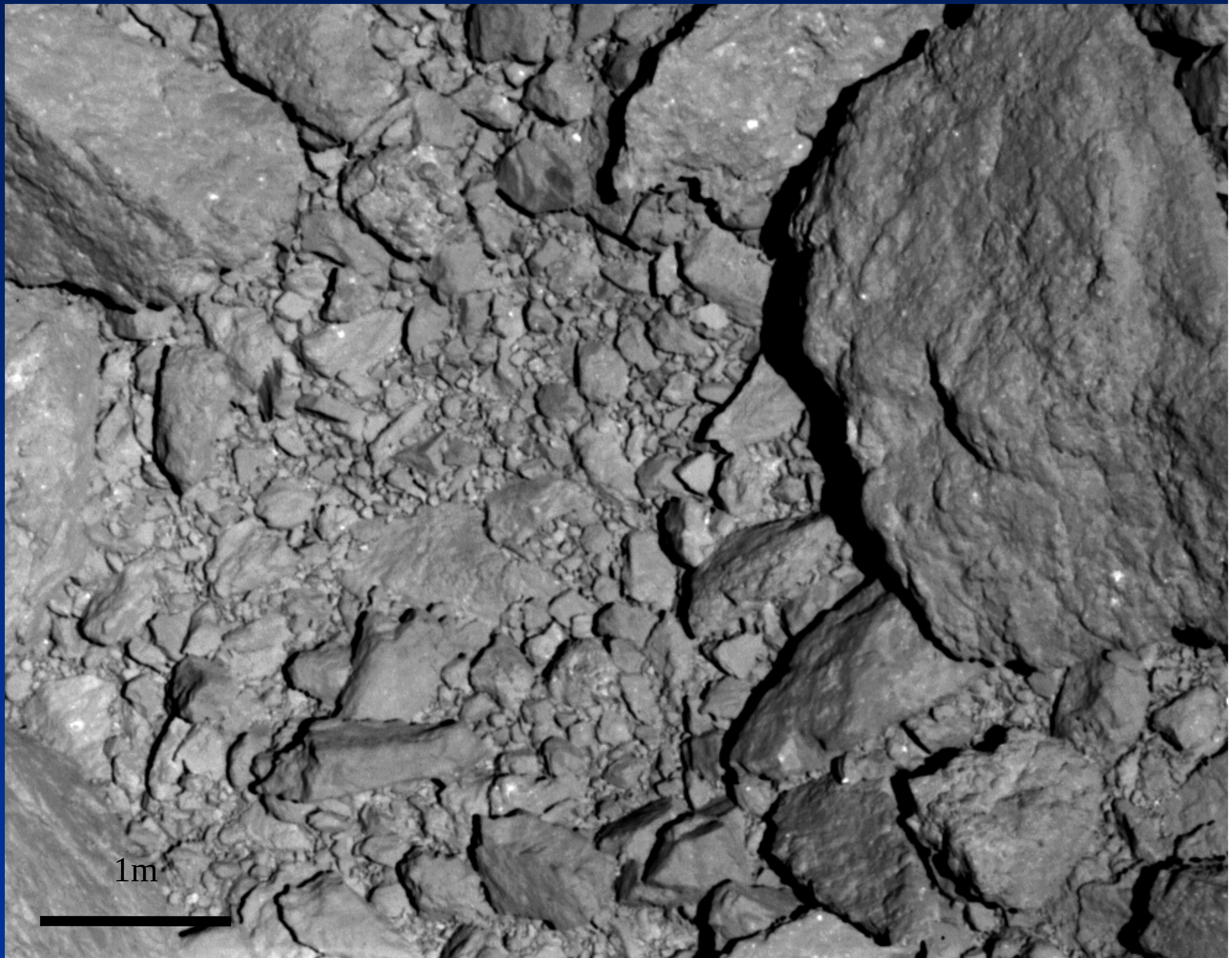
- Many perched boulders
- A pond

- Head and Body? [contact binary]

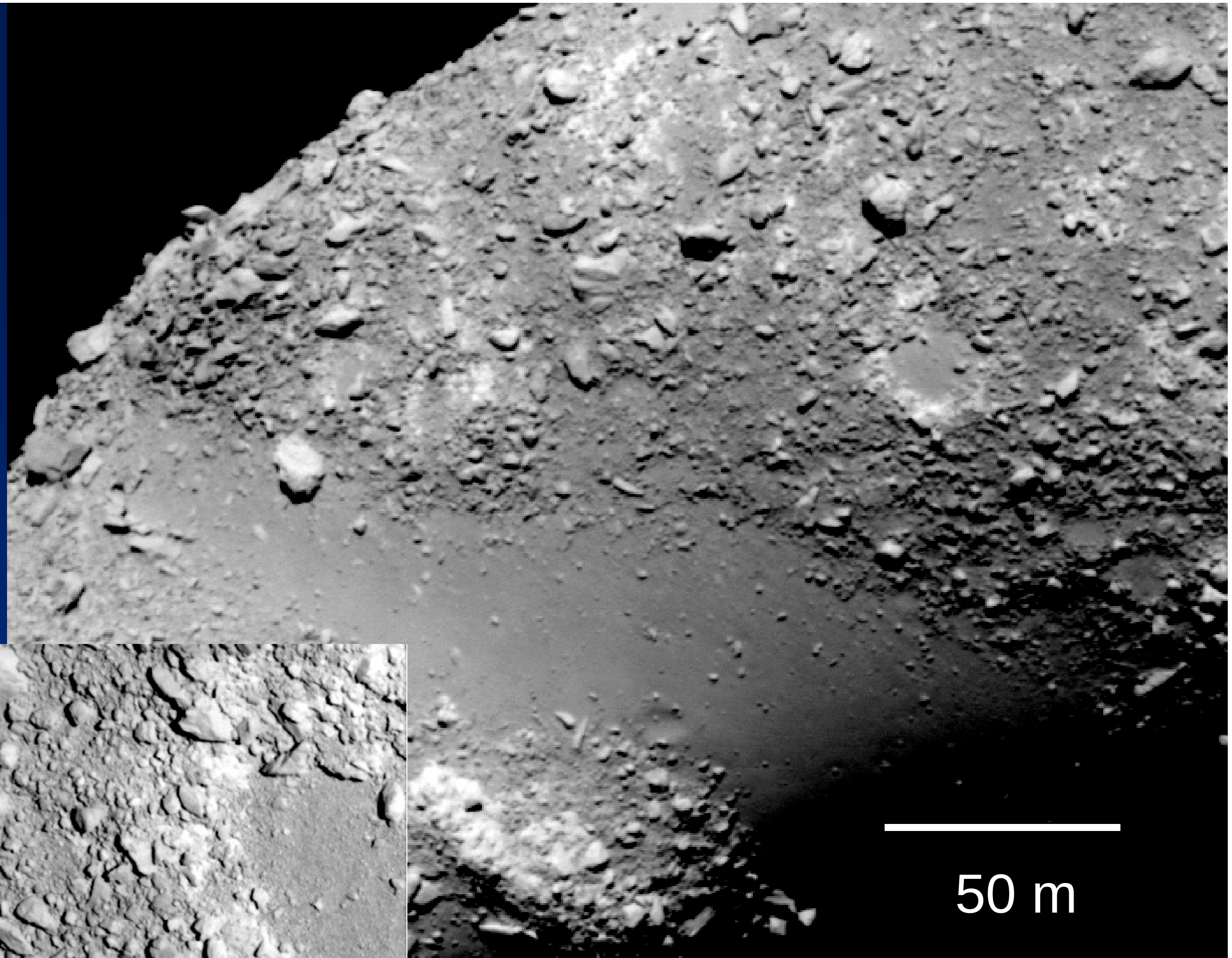


Itokawa Up Close

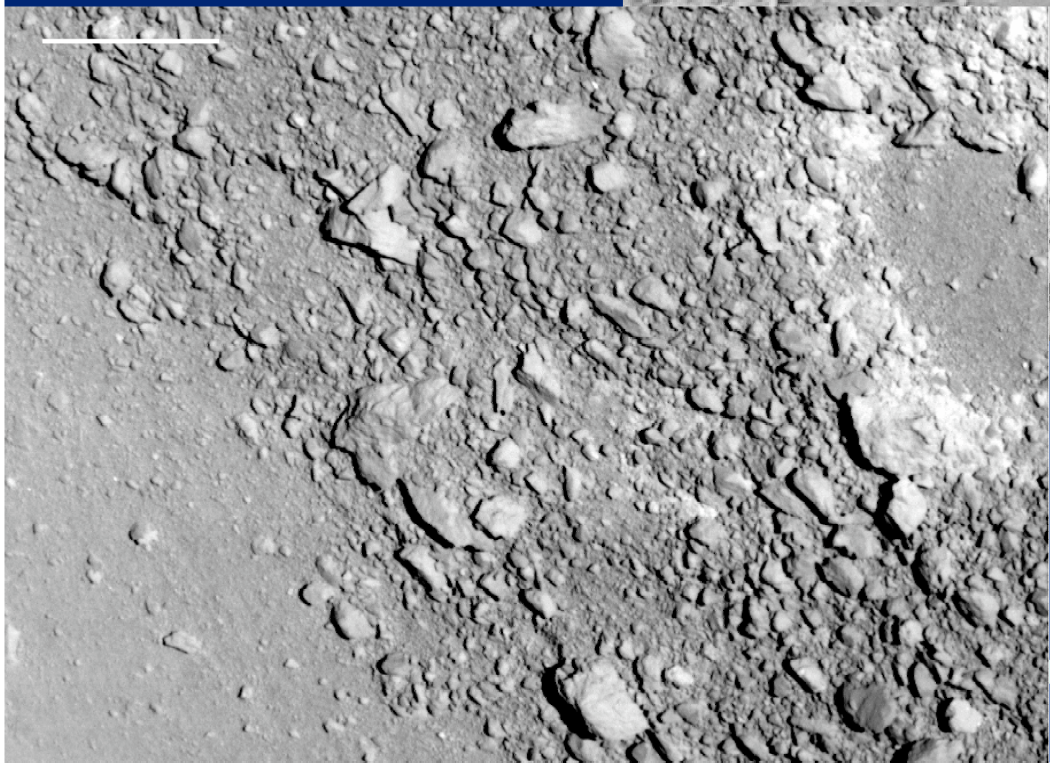
- No apparent fine grained material
  - Where has it gone?



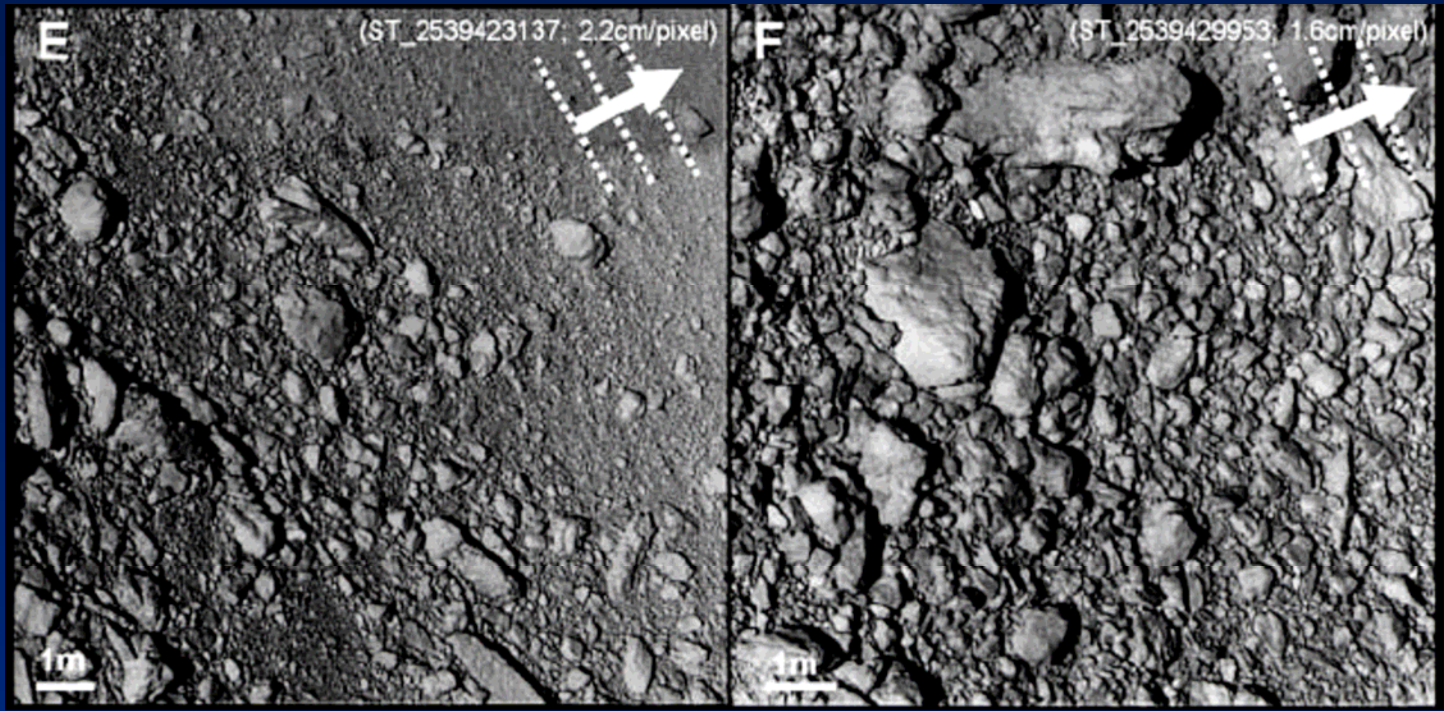
- Ponding in gravitational lows



10 m

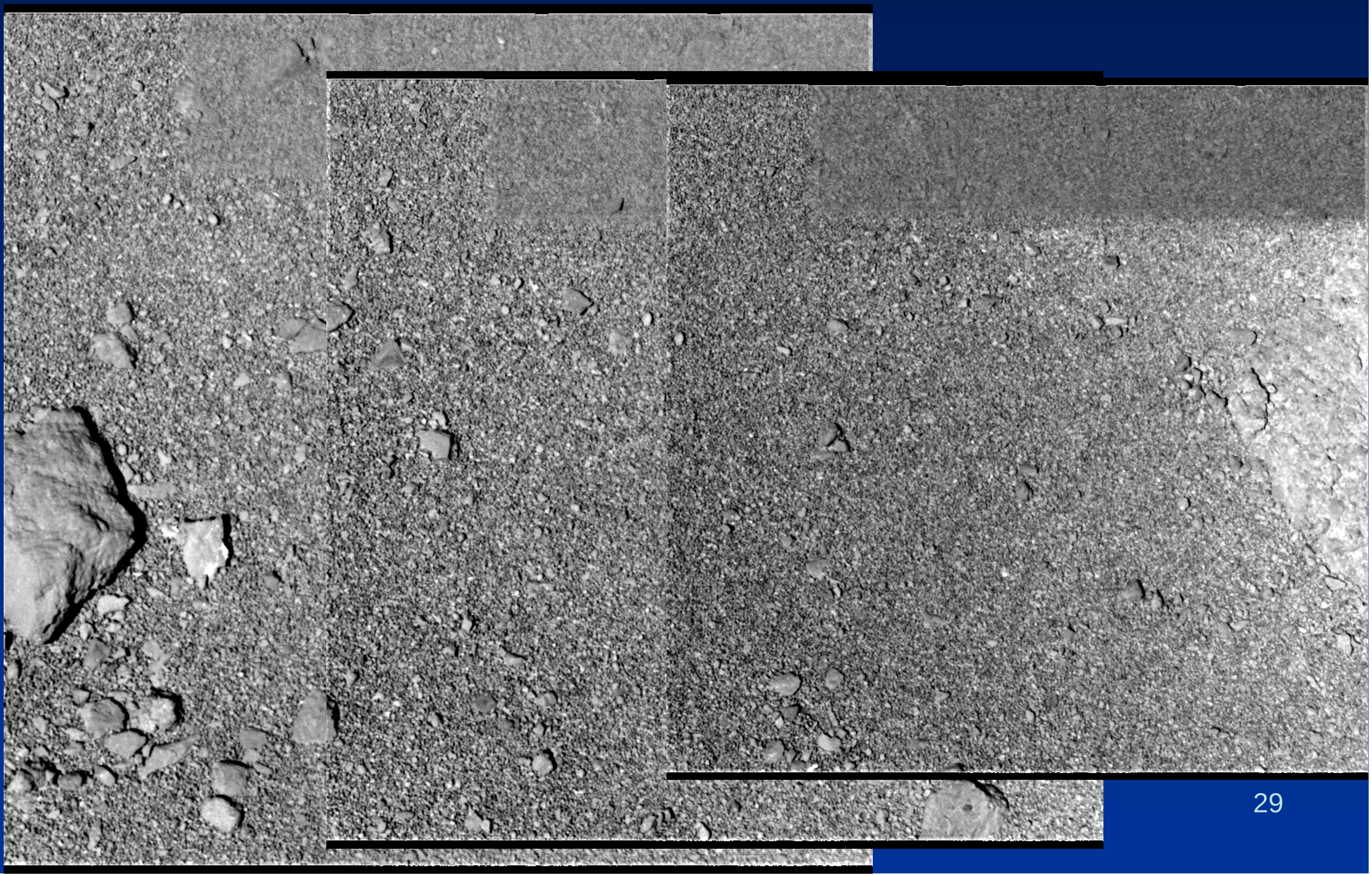


- Evidence for mass motion (imbrication)

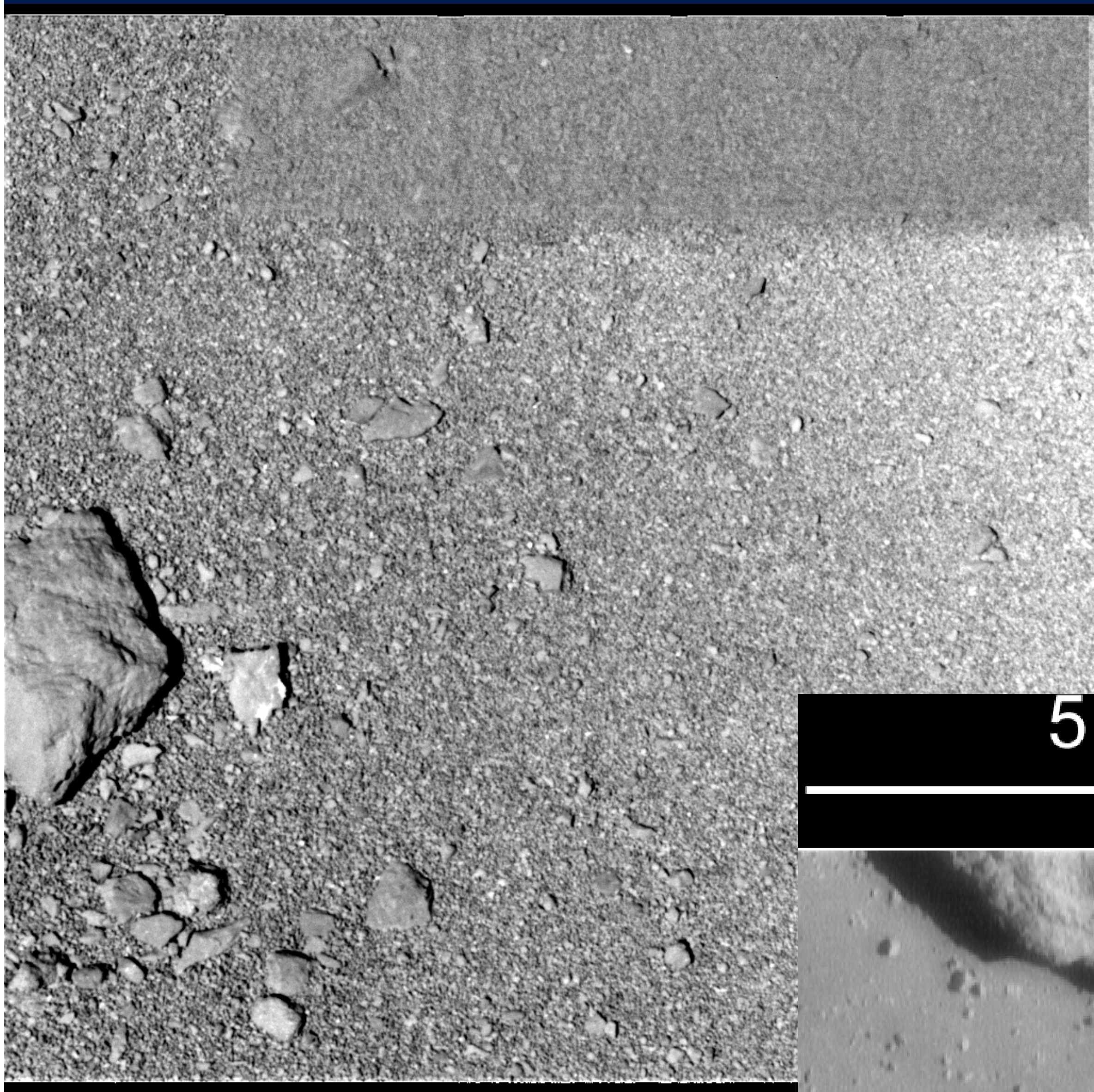


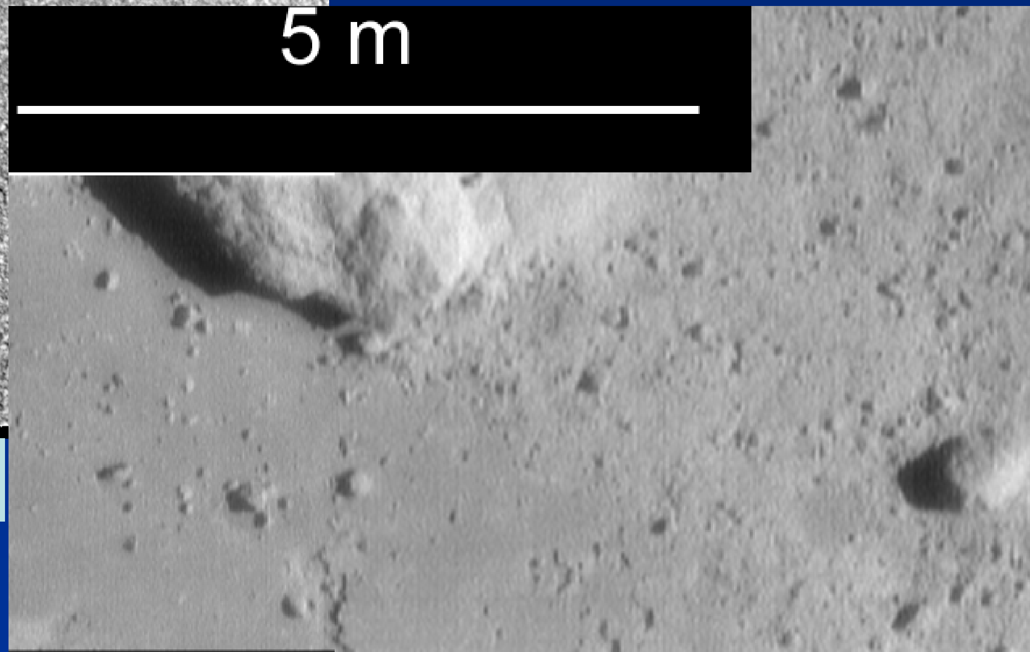
- More examples of imbrication, from Miyamoto et al.
- What causes mass motion on a small asteroid like Itokawa?
  - Seismic shaking from small impacts (which can also account for ponds on Eros [Cheng et al. 2002]
- Itokawa is probably ~O(10^6) yr old

The Hayabusa landing site – it was gravel, and it was *hard* (s/c bounced)



Strikingly different regolith on Eros (*below*) and Itokawa (*left*)





Images at same scale

Hayabusa at Itokawa

- First detailed study of a rubble pile asteroid
  - No longer a theoretical construct
- Rubble pile nature inferred from
  - Low density
  - Distinctive surface geology which is fundamentally different from lunar geology
- Recent geologic activity from seismic shaking caused by impacts
  - Even small asteroids have active surfaces

Hayabusa at Itokawa

- Fundamentally distinct outcomes of asteroid collisional evolution
  - Small asteroids are not all the same
  - Are most (how many?) asteroids rubble piles? Why are some (how many?) S asteroids not rubble piles? Does size matter?
- Both Eros and Itokawa are products of catastrophic disruption, but
  - Do outcomes tell us about collisions (i.e., low excess energy)? Or about target materials and/or parent body histories?