Morphology and Geology of Short-Period Comet 67P/Churyumov-Gerasimenko

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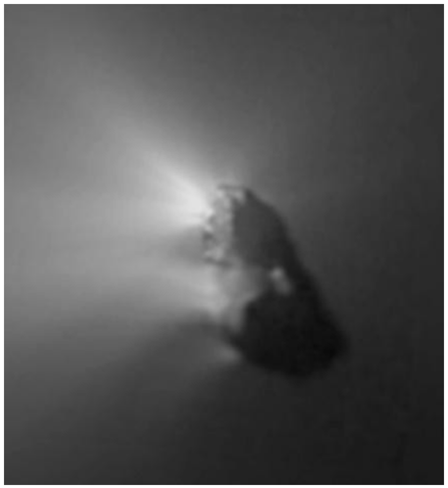
Outline

- Various morphological features on 67P

- The nucleus formed by a merger of two “onion-layered” lobes
- Consolidated terrain form near the surface by solar processing
- Smooth terrain form by backfall of coma particles

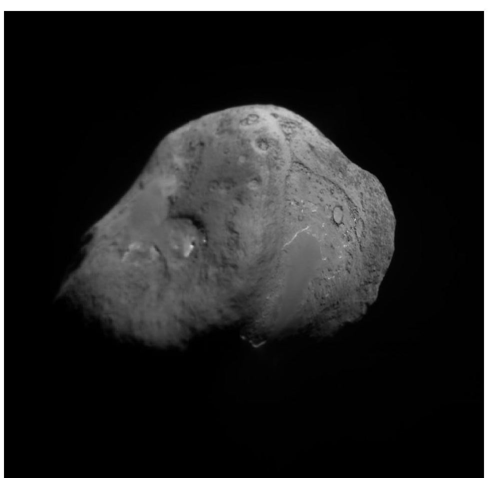
Comet nuclei imaged by spacecraft



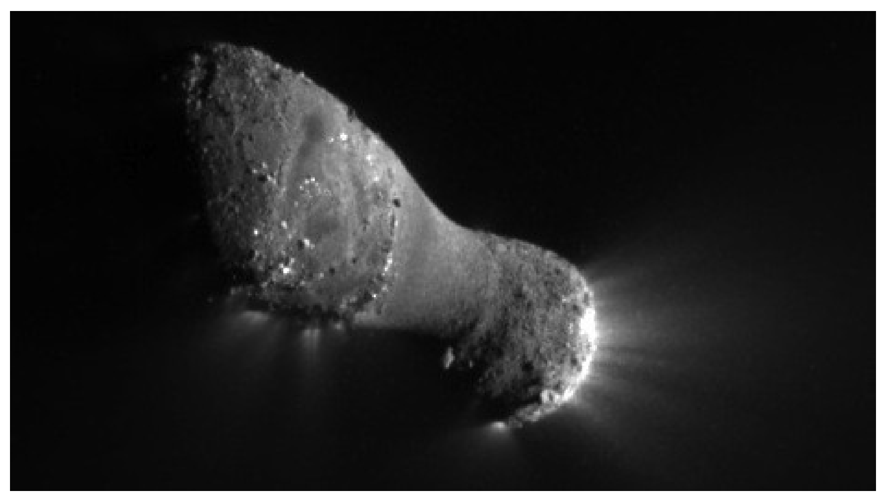
1P/Halley from 600km
Giotto, 1986

19P/Borrelly from 2200km
Deep Space 1, 2001

81P/Wild 2 from 240km
Stardust, 2004



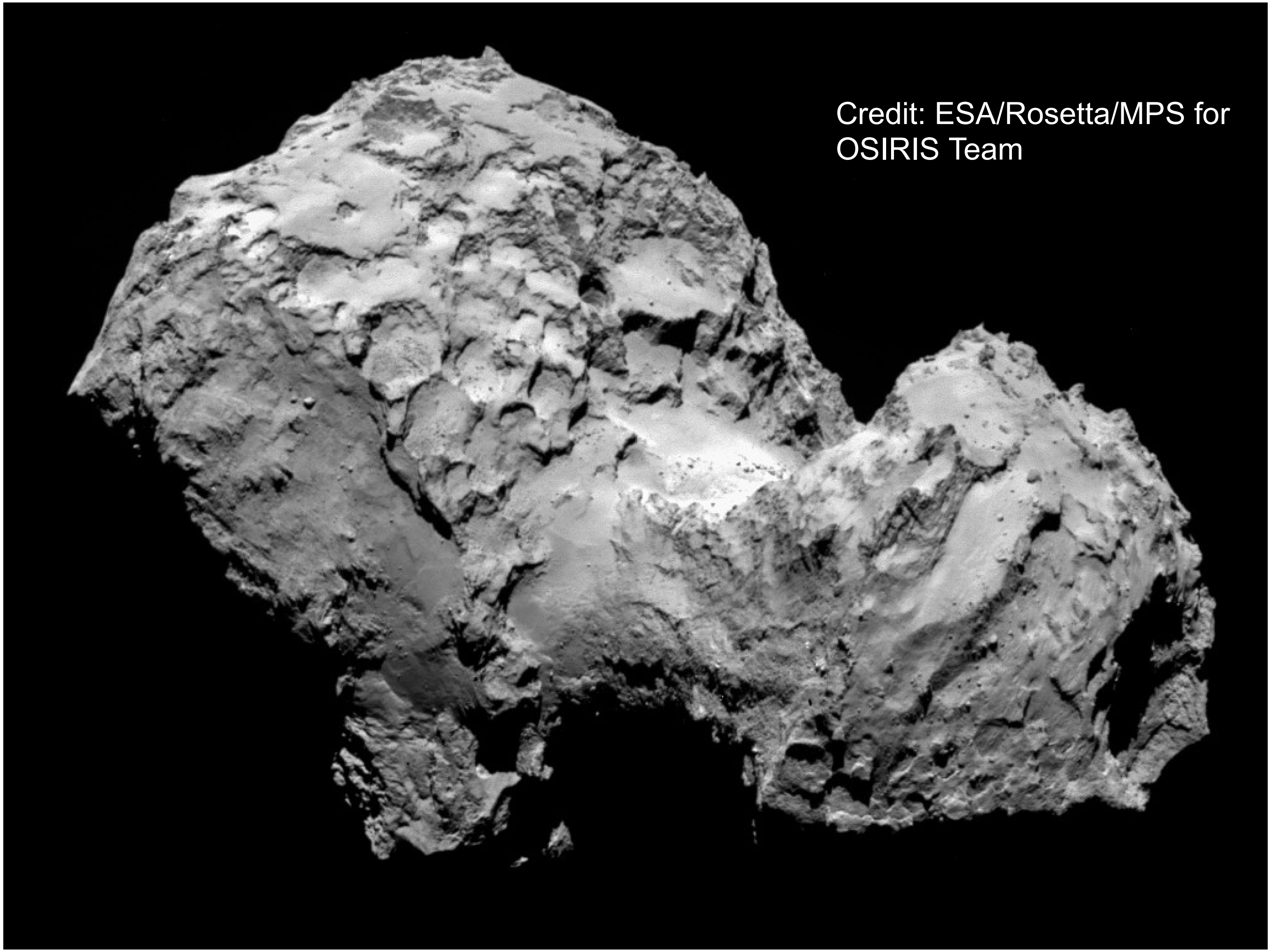
9P/Tempel 1 from 500/180km
Deep Impact/Stardust-Next, 2005/2011



103P/Hartley 2 from 700km
EPOXI, 2010

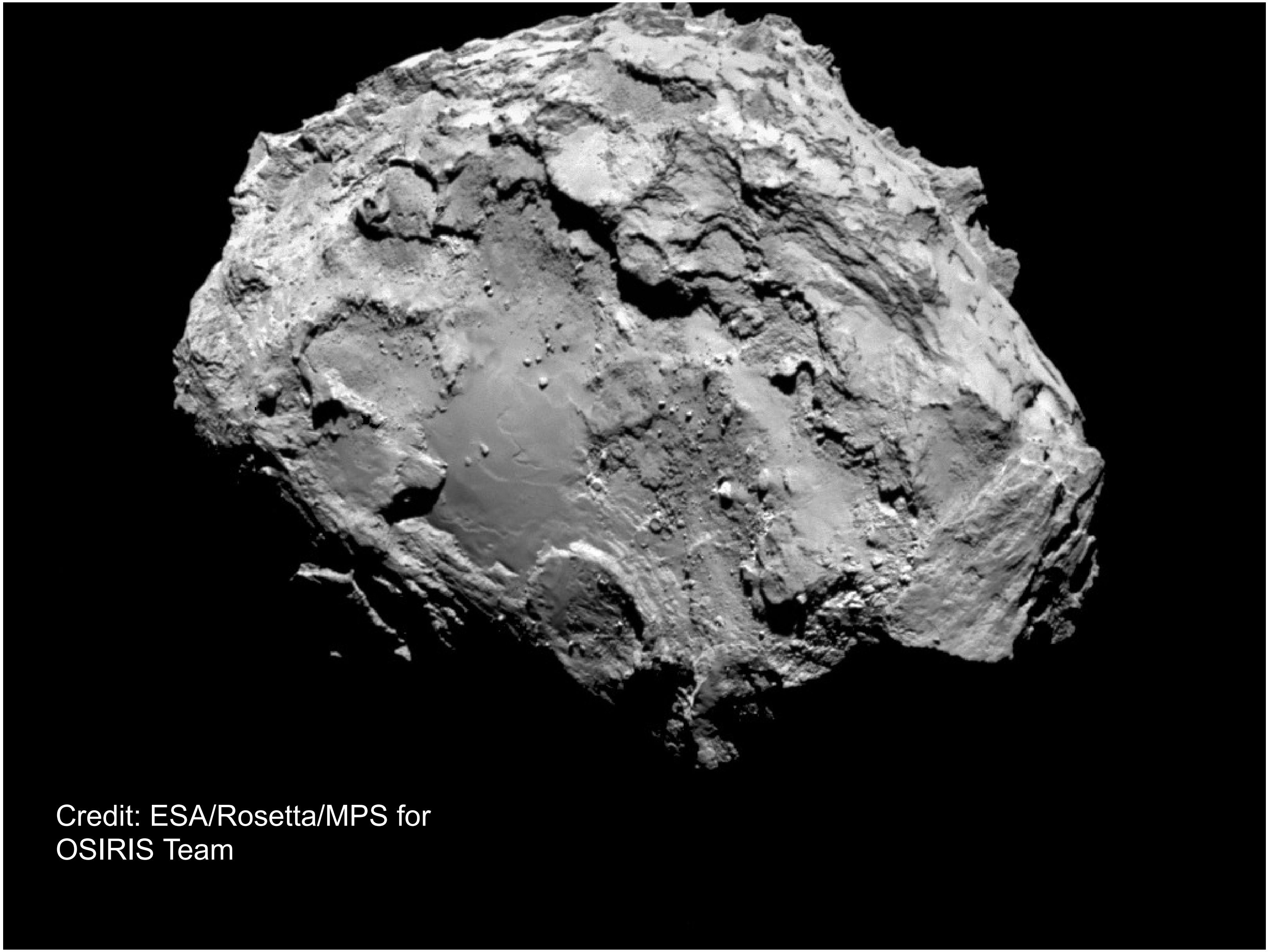
Credit:
ESA
NASA
JPL/Caltech
UMD

67P is a bi-lobed comet nucleus

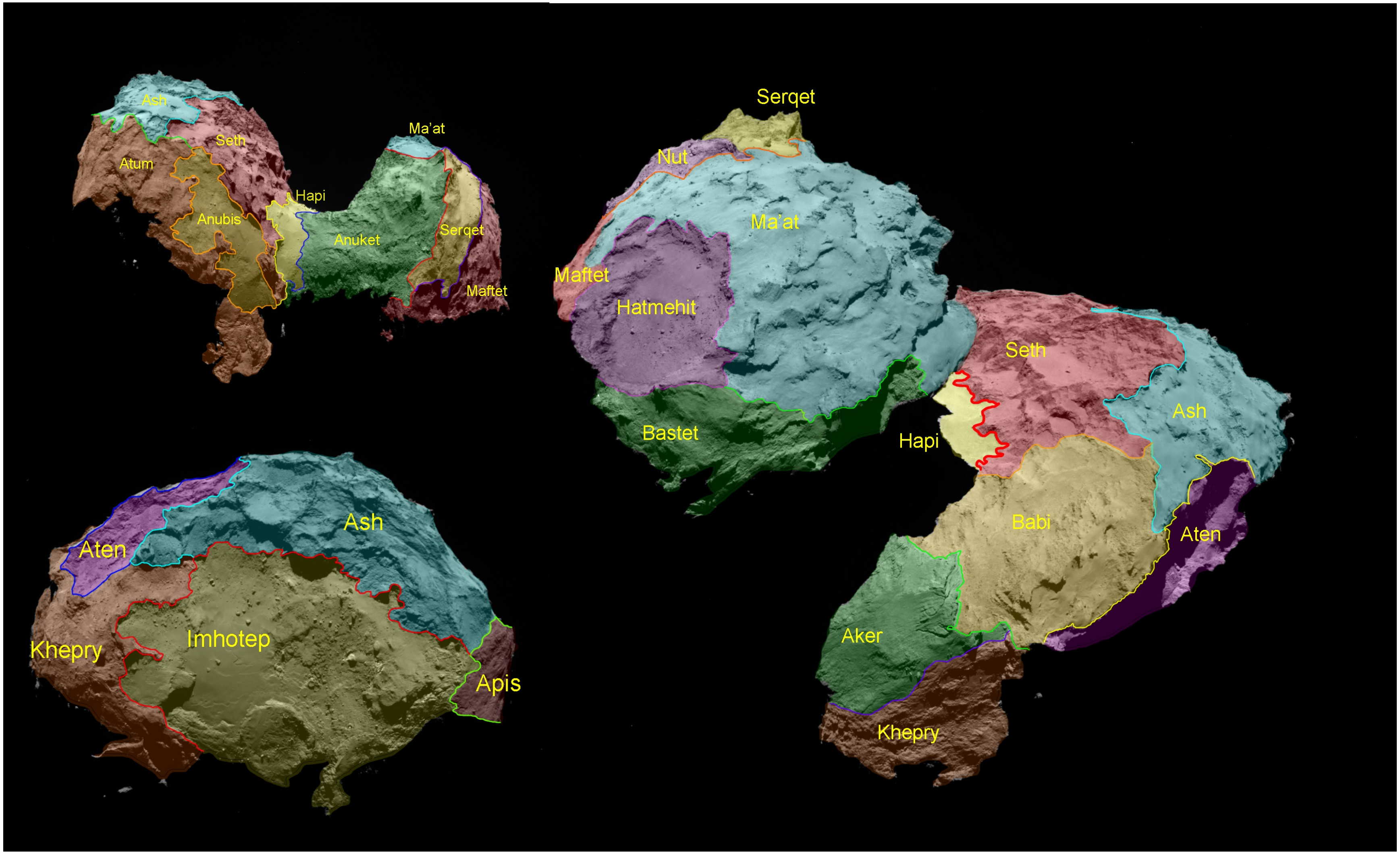


Small lobe: 2.70 x 2.24 x 1.64 km
Large lobe: 4.20 x 3.22 x 1.80 km (Jorda *et al.* 2016, *Icarus* **277**, 257-278).

The lower side of the large lobe

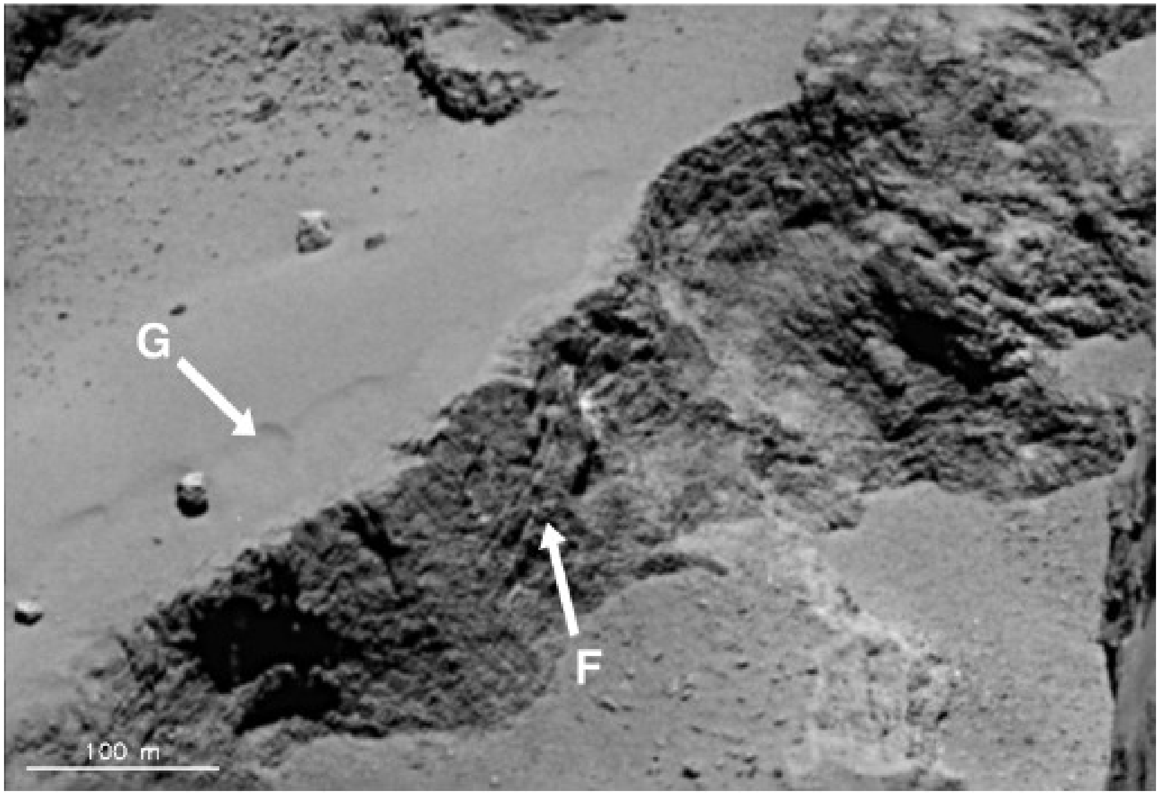


Morphological units: Northern hemisphere

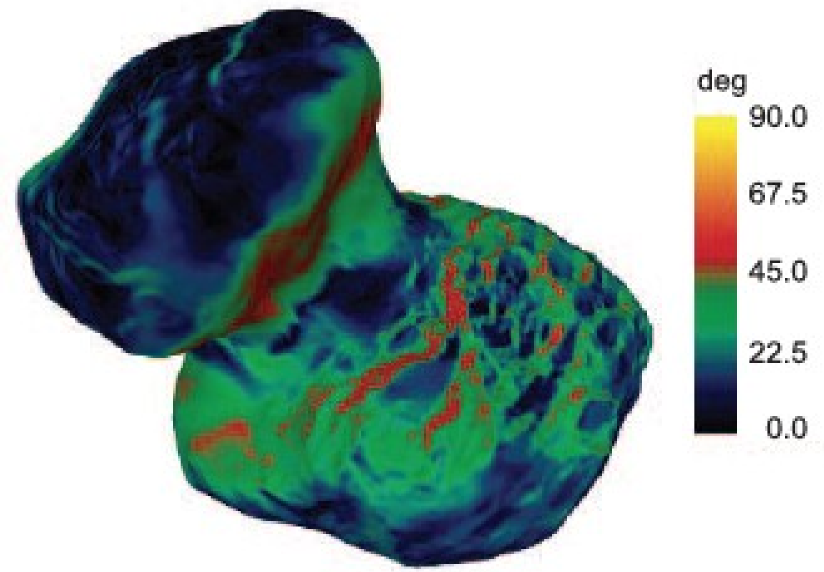


Credit: Thomas *et al.* (2015, *Science* **347**, aaa0440)

Terraces and cliffs

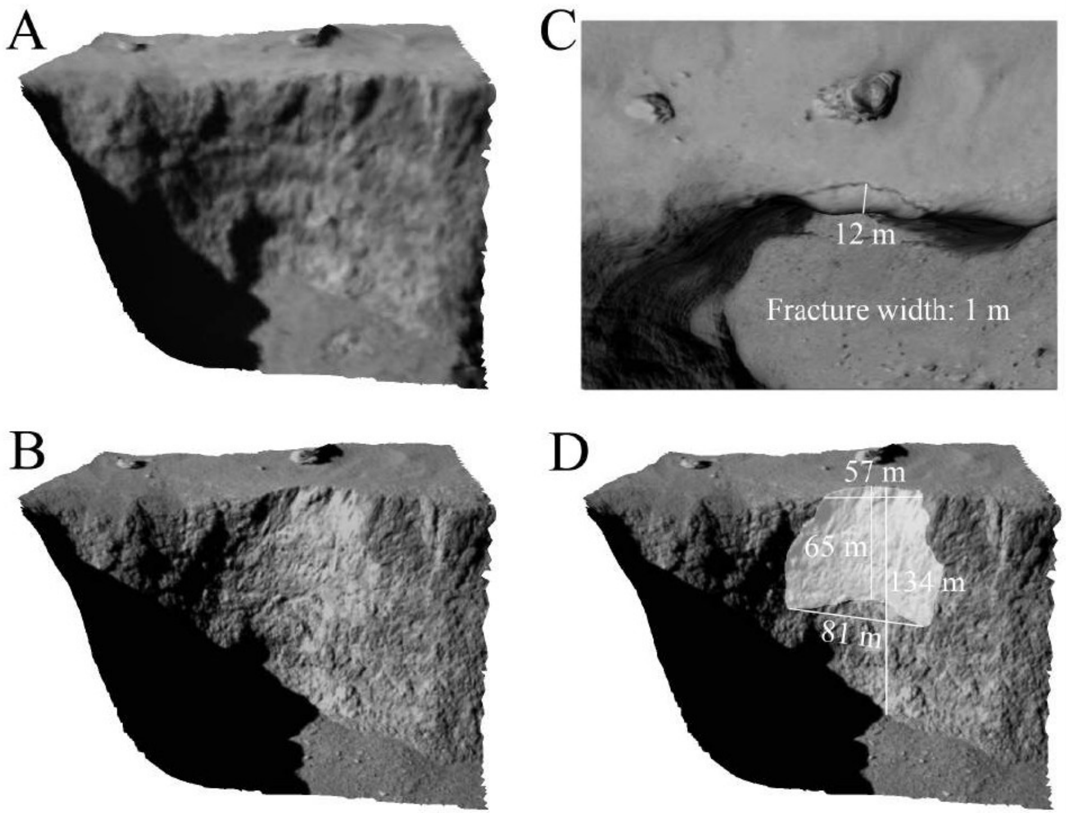


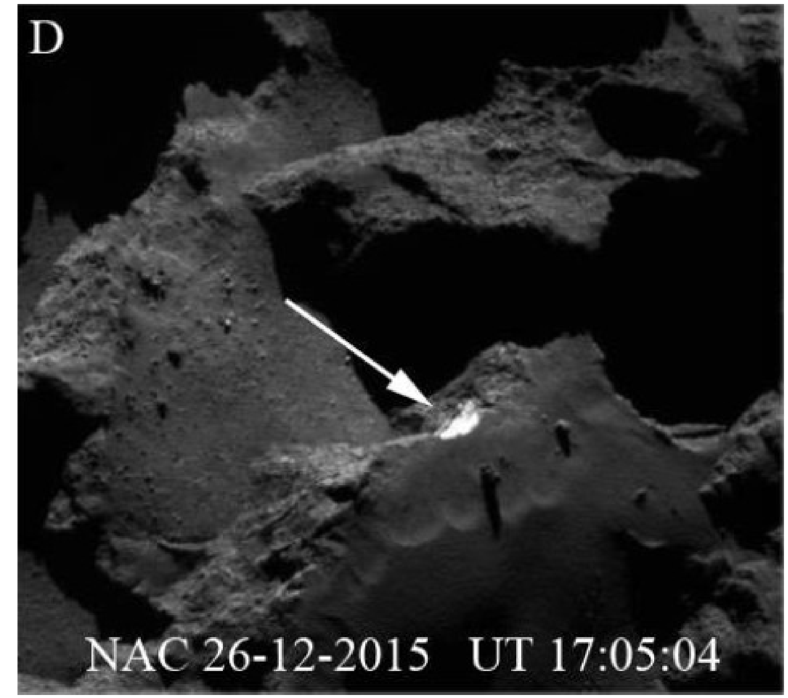
Credit: Thomas *et al.* (2015, *Science* **347**, aaa0440)



Credit: Sierks *et al.* 2015, *Science* **347**, aaa1044

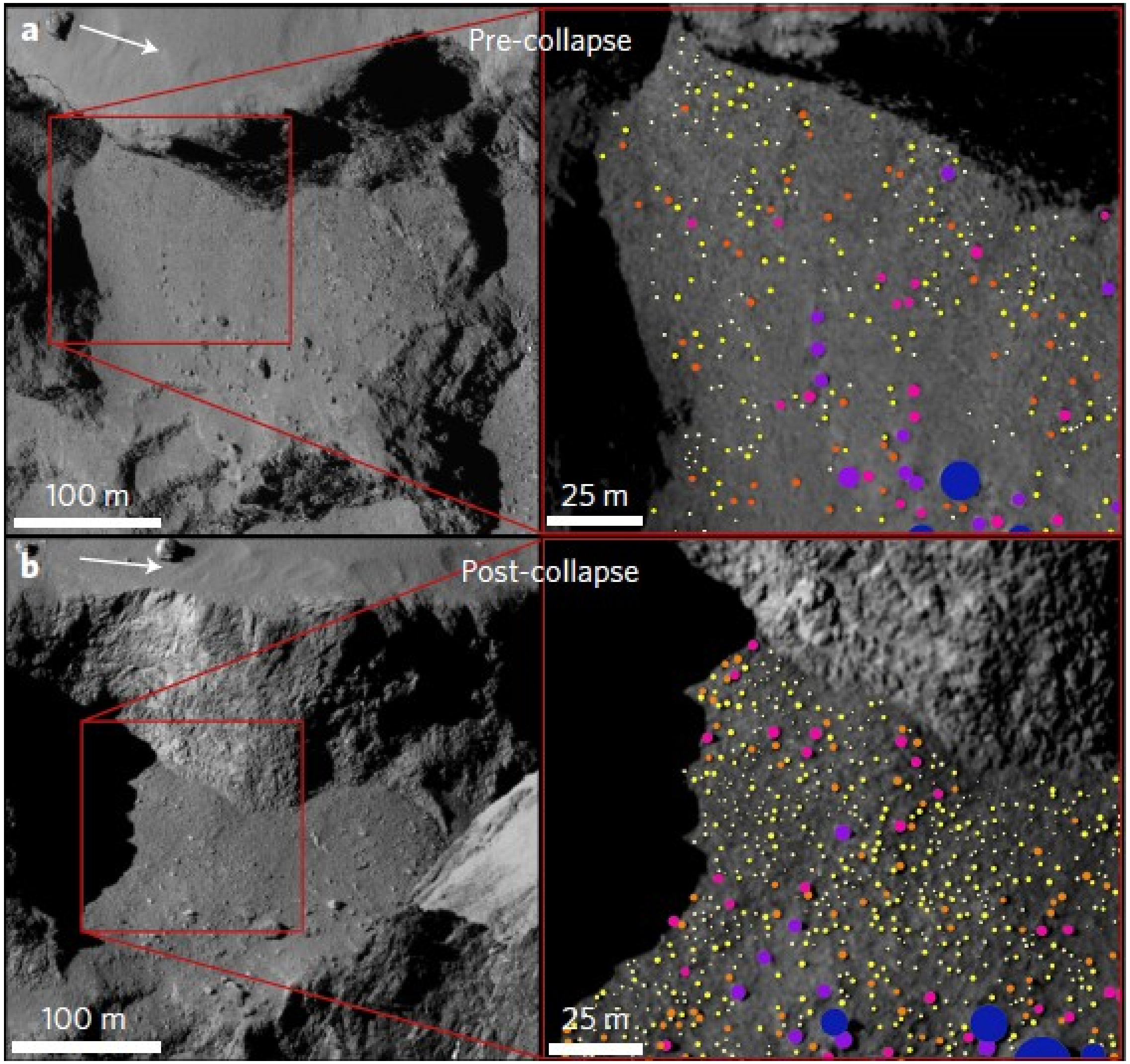
Cliff collapse

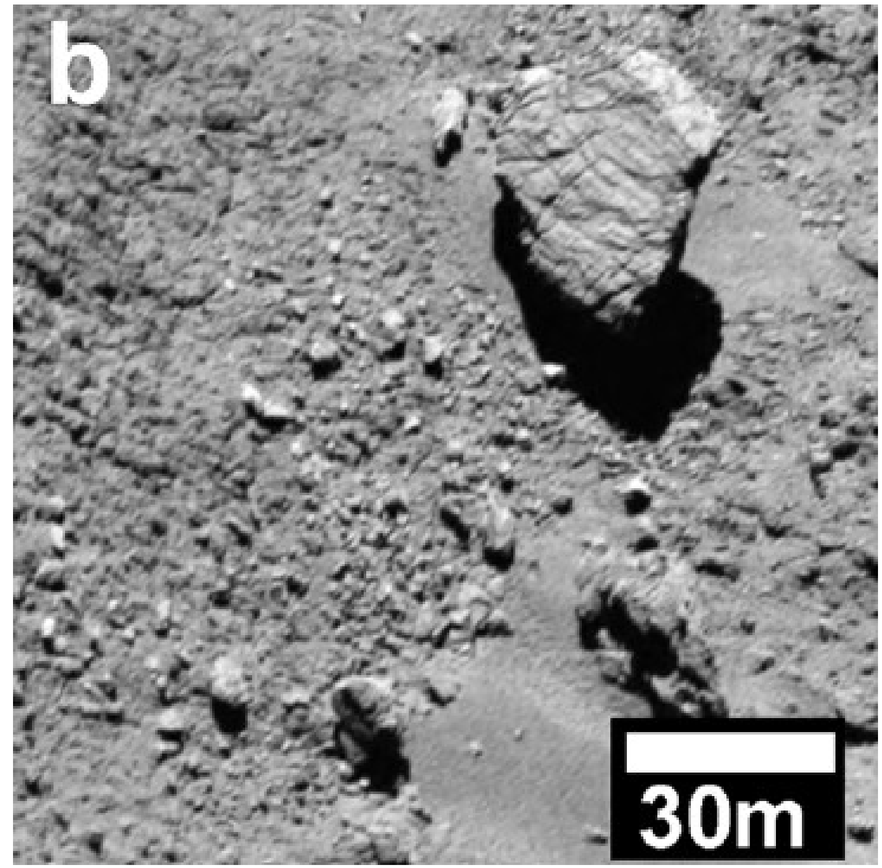




Credits: Pajola *et al.* (2017, *Nature Astronomy* **1**, 0092)

Boulders

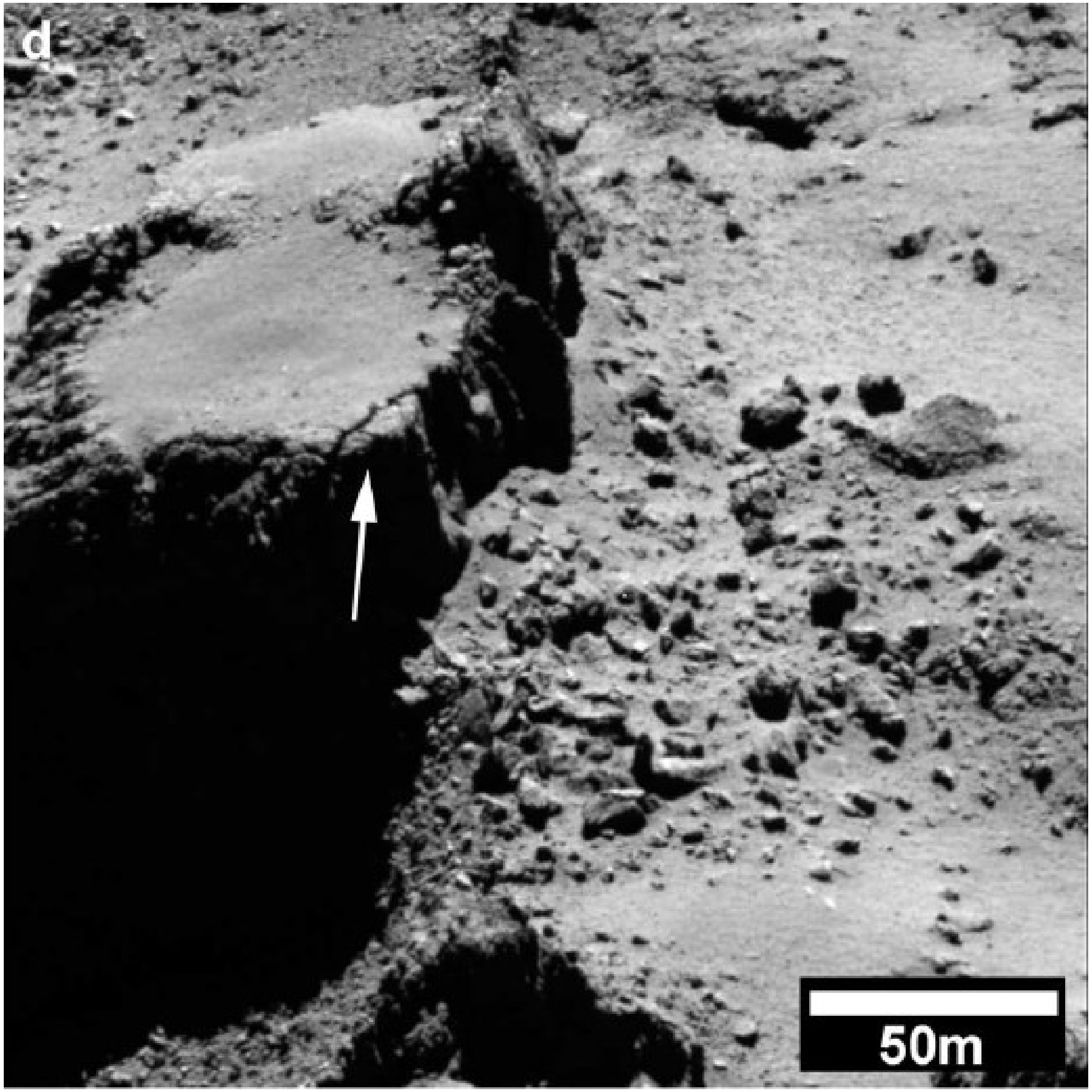




Credits: El-Maarry *et al.* (2015, *GRL* **42**, 5170)

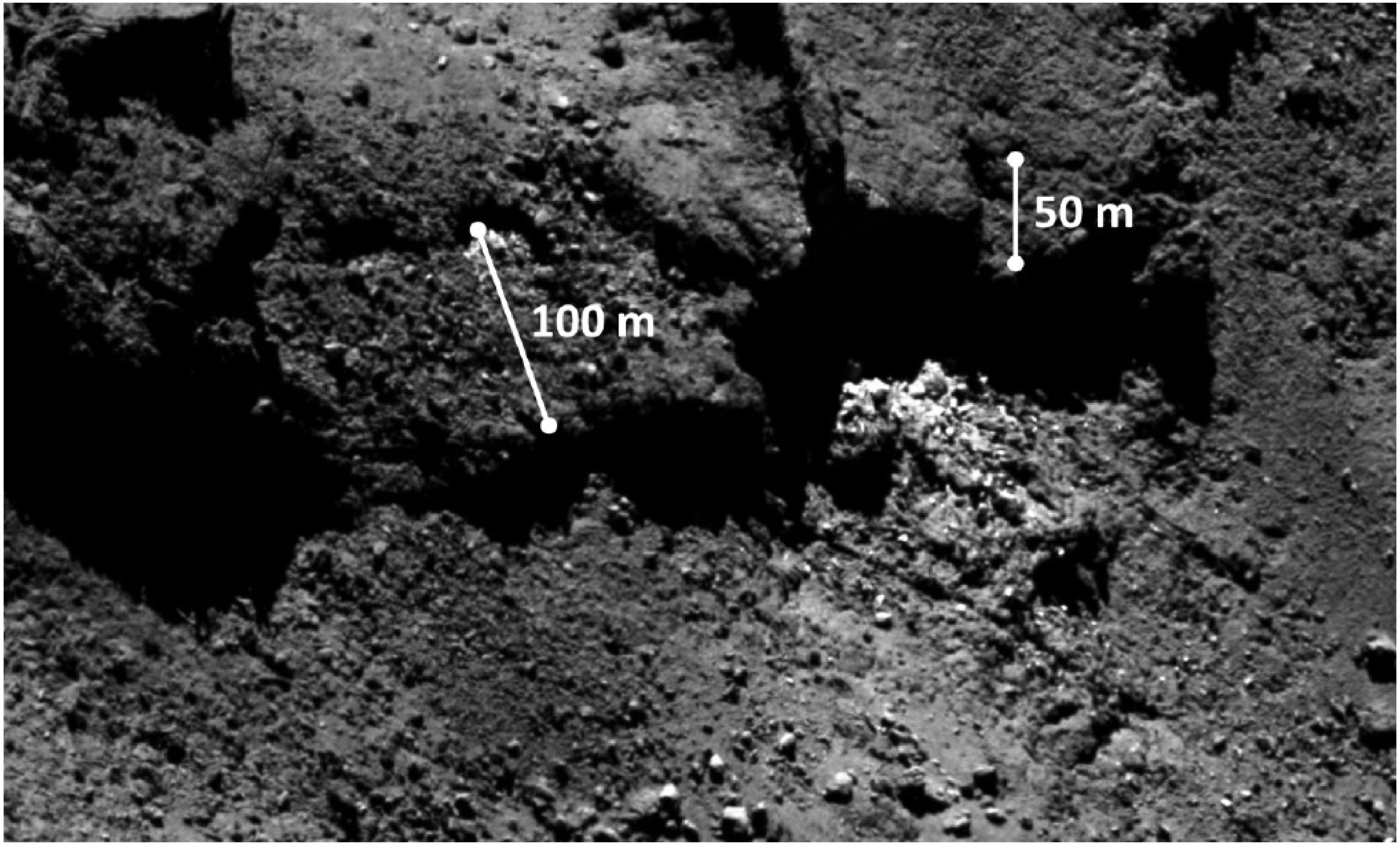
Credits: Pajola *et al.* (2017, *Nature Astronomy* **1**, 0092)

Thalus



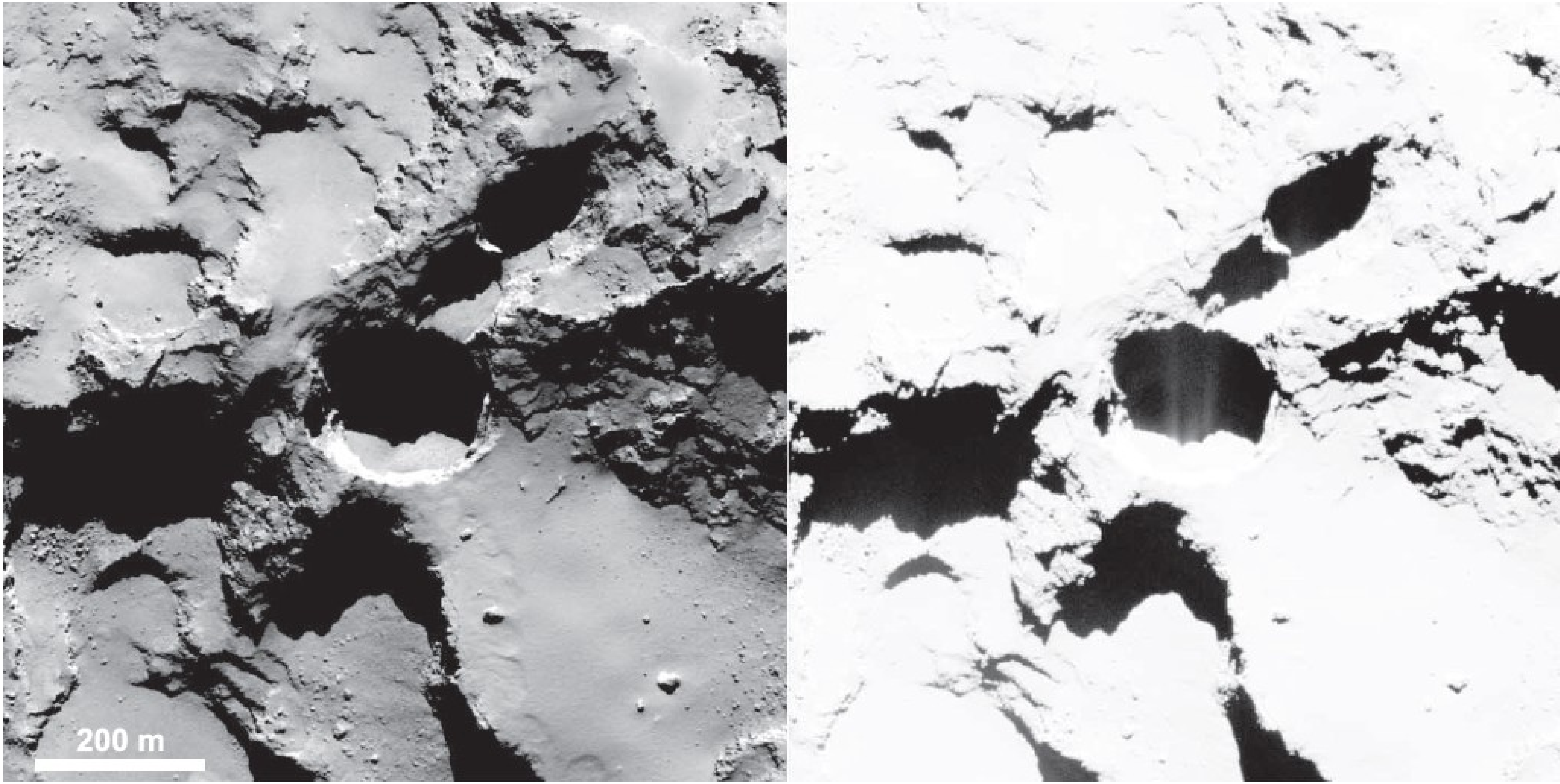
Credits: El-Maarry *et al.* (2015, *GRL* **42**, 5170)

Collapsed overhangs



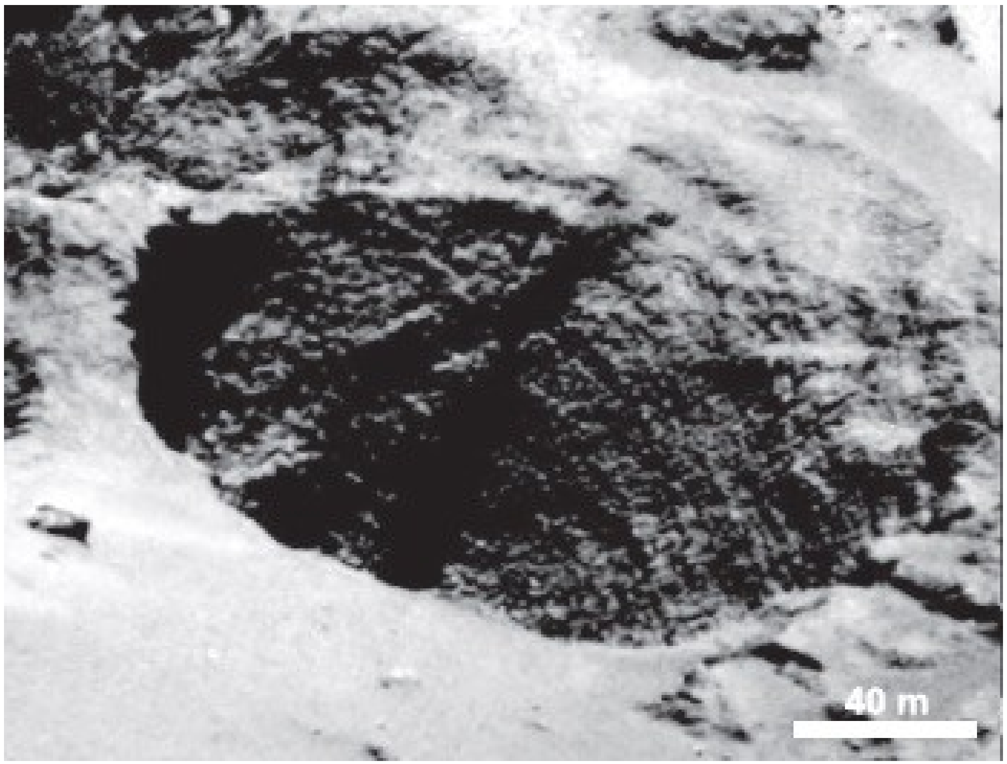
Credit: Groussin *et al.* 2015, *A&A* **583**, A32

Active pits

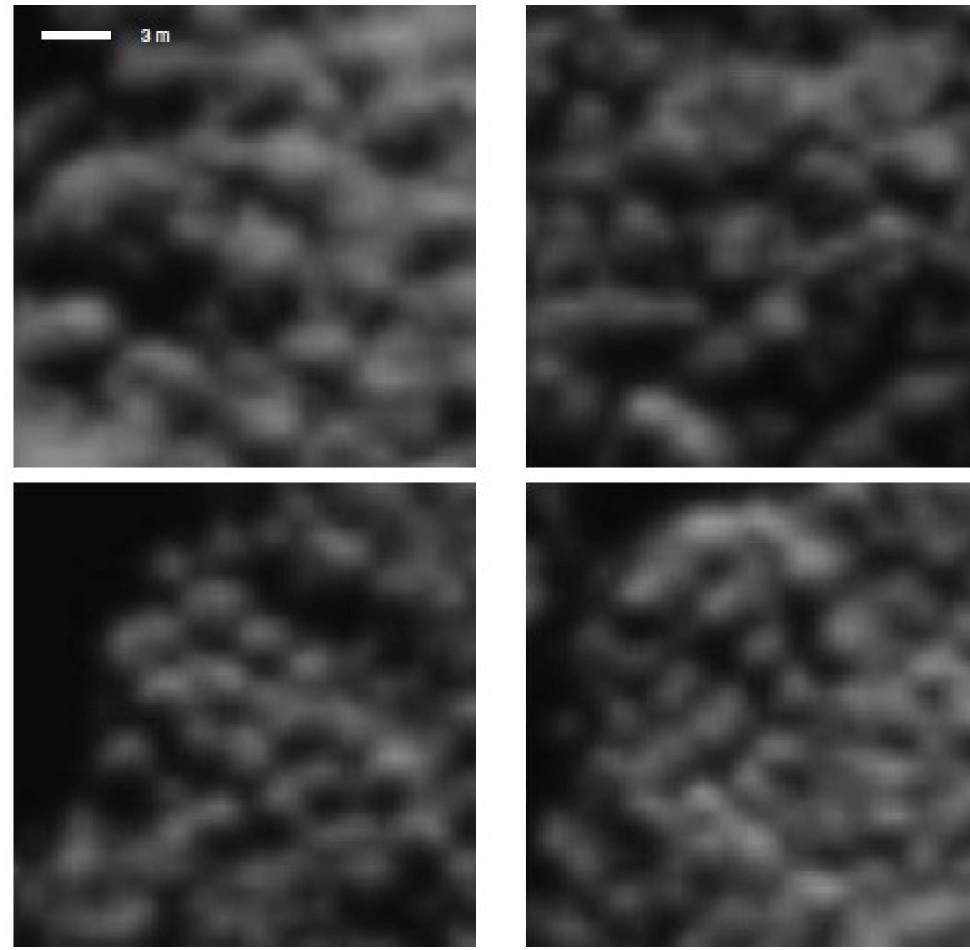


Credit: Sierks *et al.* 2015, *Science* **347**, aaa1044

Pits and goose bumps

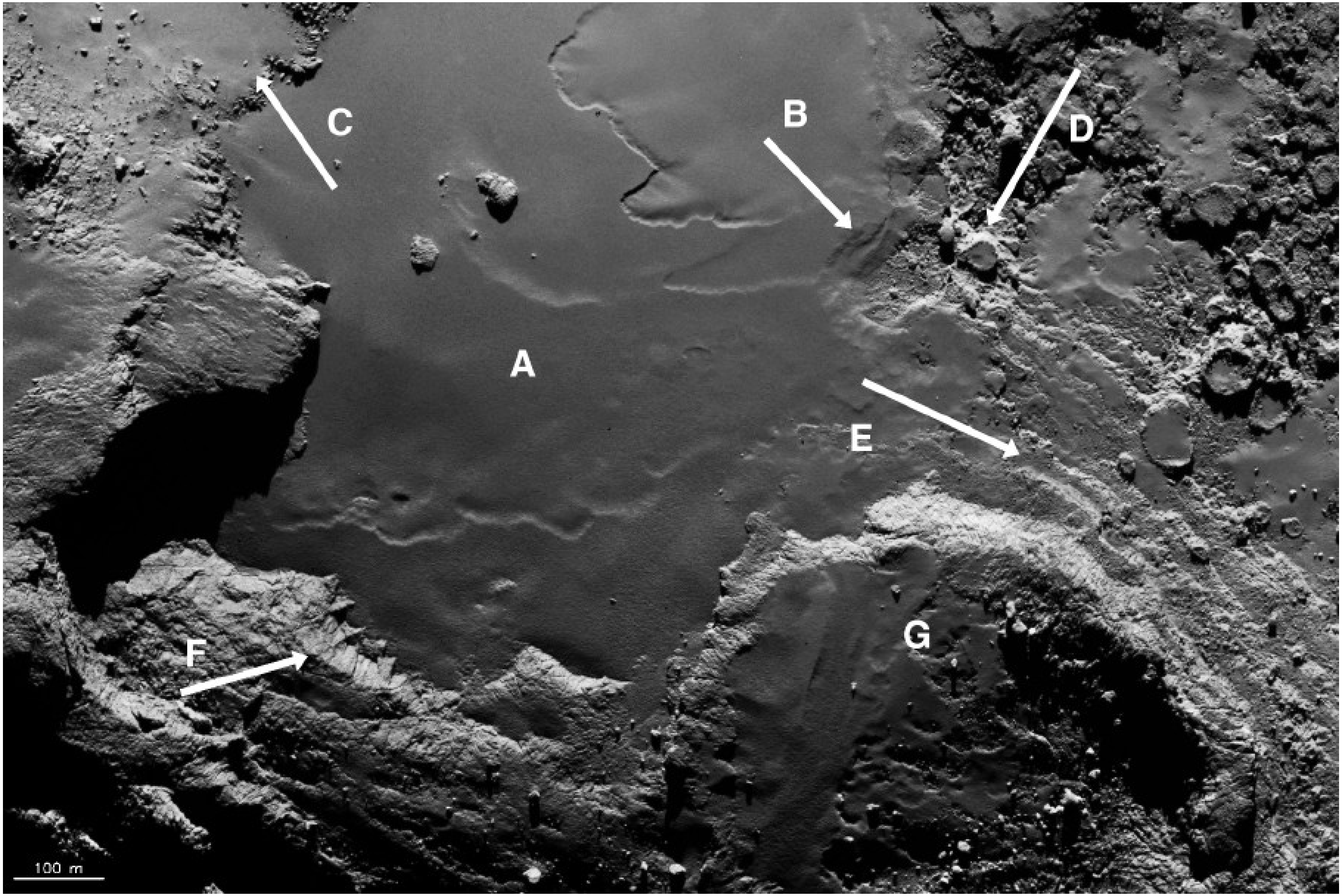


Credit: Sierks *et al.* 2015, *Science* **347**, aaa1044



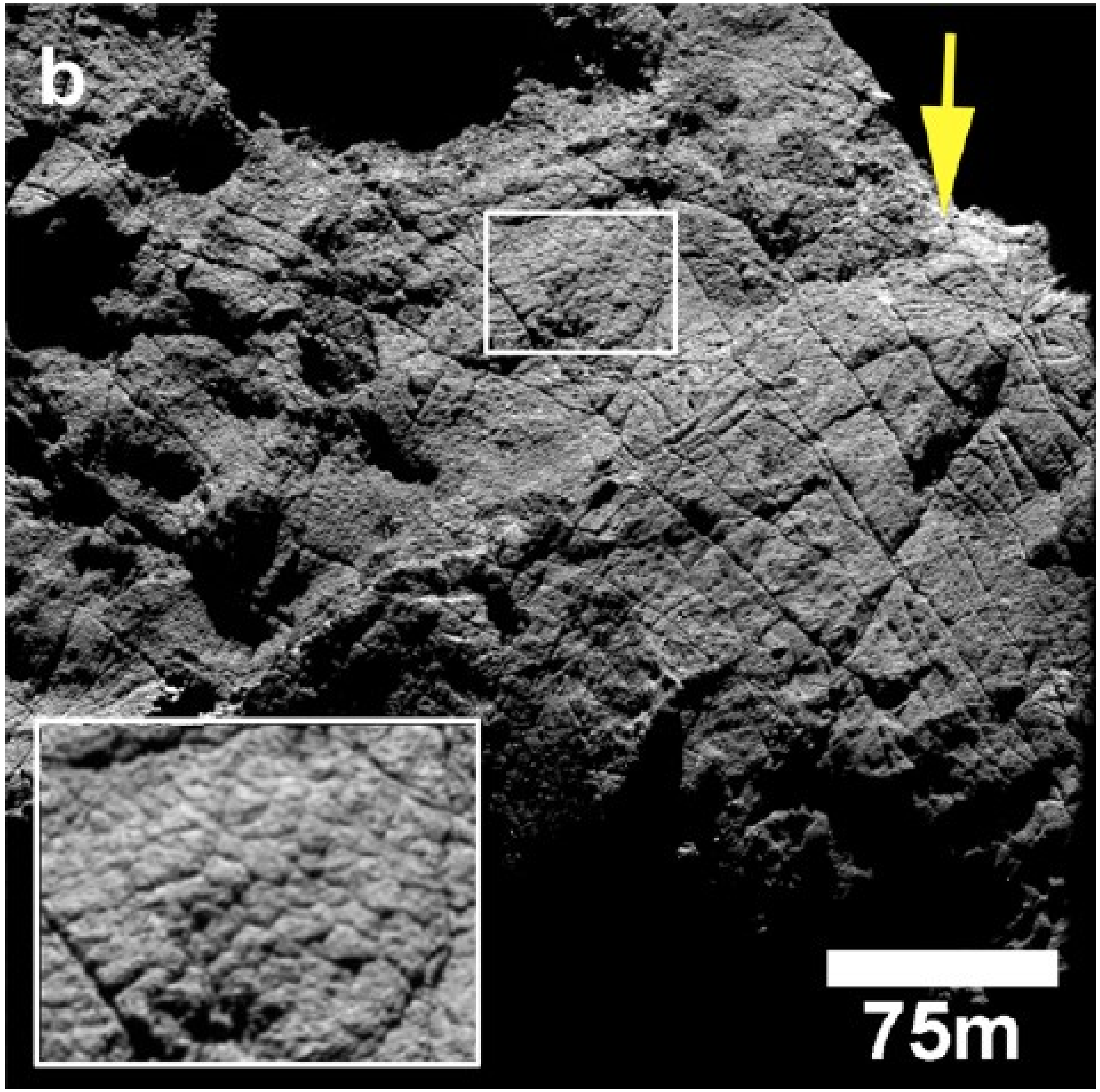
Credit: Davidsson *et al.* 2016, *A&A* **592**, A63

Smooth terrain



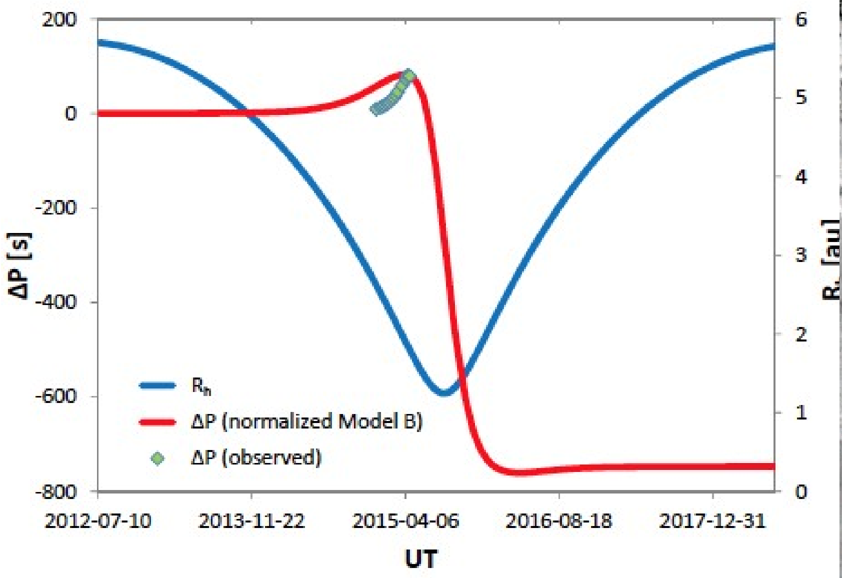
Credit: Thomas *et al.* (2015, *Science* **347**, aaa0440)

Consolidated and cracked terrain

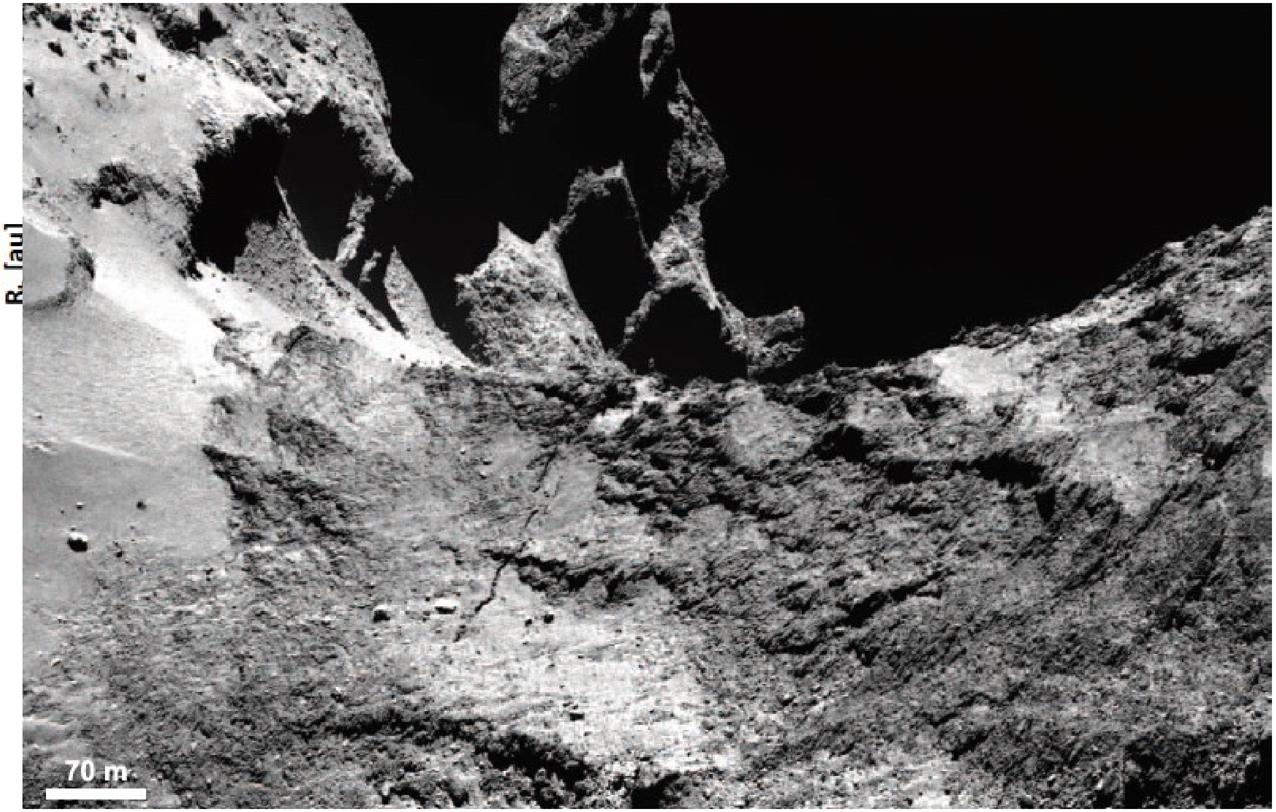


Credits: El-Maarry *et al.* (2015, *GRL* **42**, 5170)

Cracking by sublimation torques

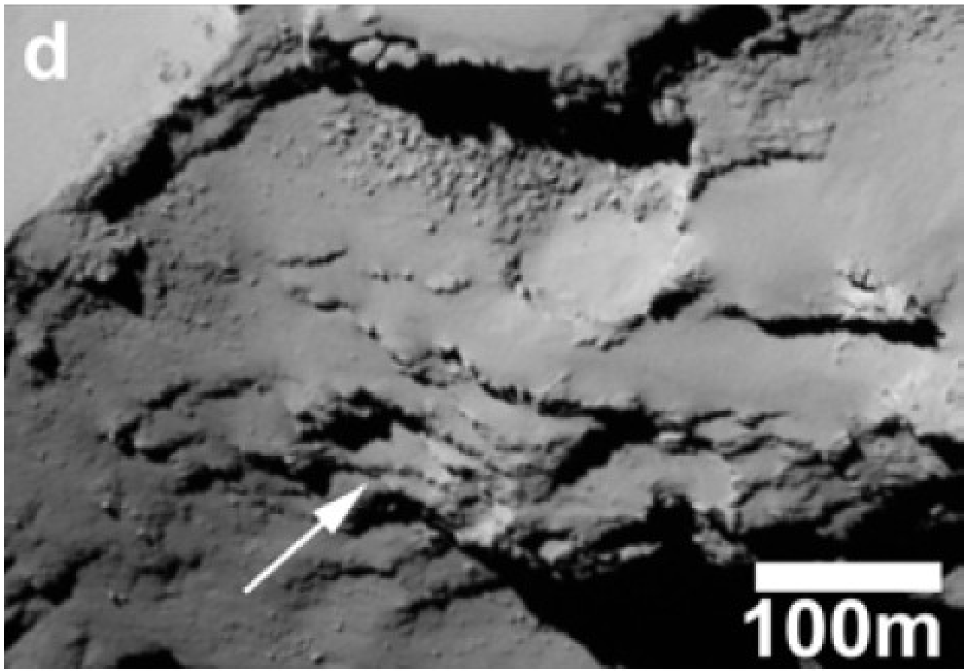


Credit: Keller *et al.* (2015, *A&A* **579**, L5)

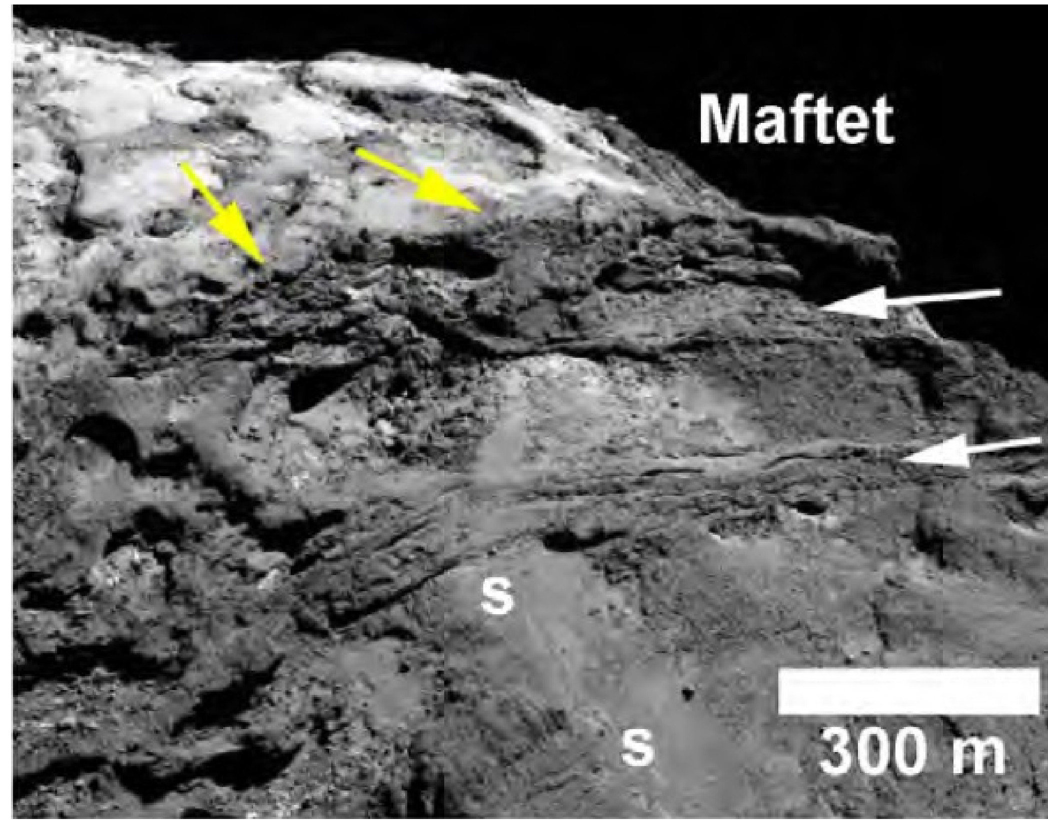


Credit: Sierks *et al.* 2015, *Science* **347**, aaa1044

Layering



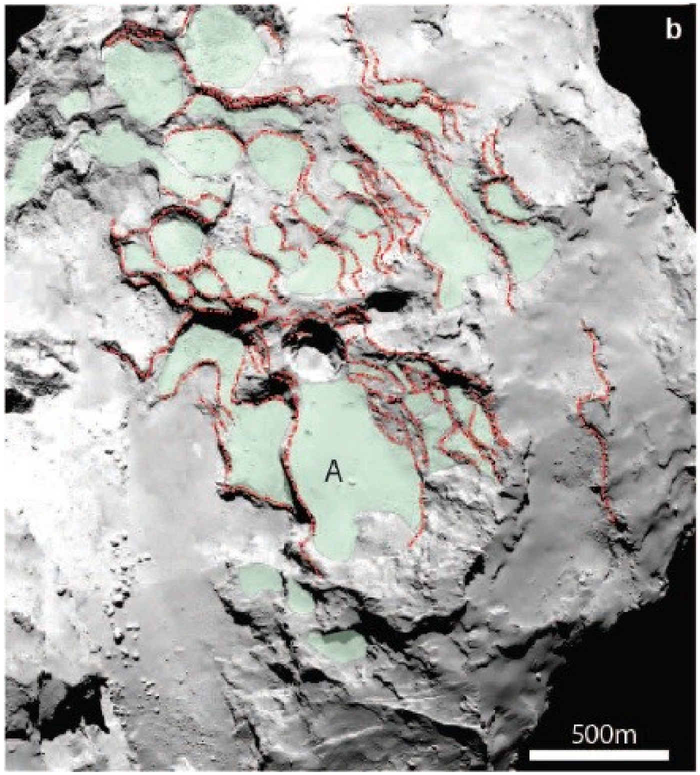
Credits: El-Maarry *et al.* (2015 *A&A* **583**, A26)

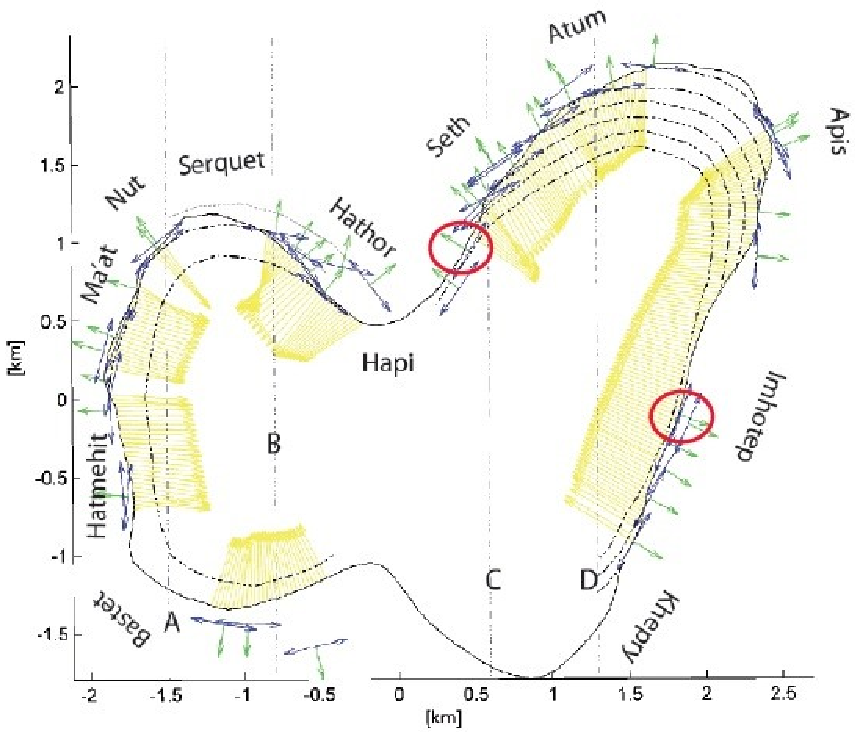


Credits: El-Maarry *et al.* (2016 *A&A* **593**, A110)

Why does the comet look like this?

Layering





Credit: Massironi *et al.* (2015, *Nature* **526**, 402)

Numerous terraces: onion-shell stratification (650 m thick)

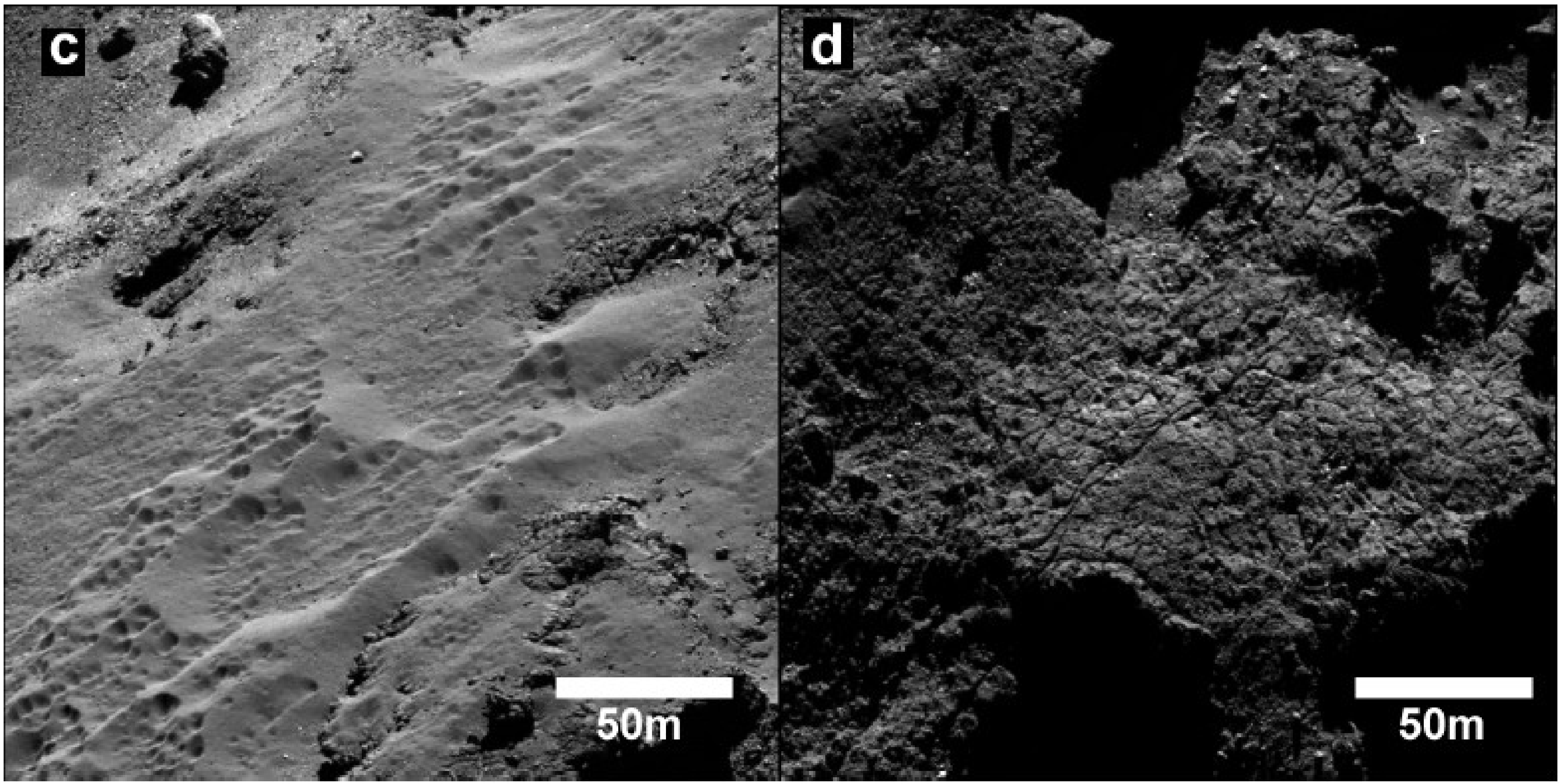
Lobes are *individually* layered: merger of two bodies

Layering probably created during accretion by smeared cometesimals, as in the “talps model” (Belton *et al.* 2007 *Icarus* **187**, 332)

Terraces, cliffs, overhangs, pits

- The nucleus has a primordial layered structure
- Solar heating causes differential erosion of the layers
- This erosion gives rise to overhangs that collapse, cliffs, and terraces
- Pits may be gradually excavated by this mechanism, or formed as “sink holes” when roofs over sub-surface cavities collapse

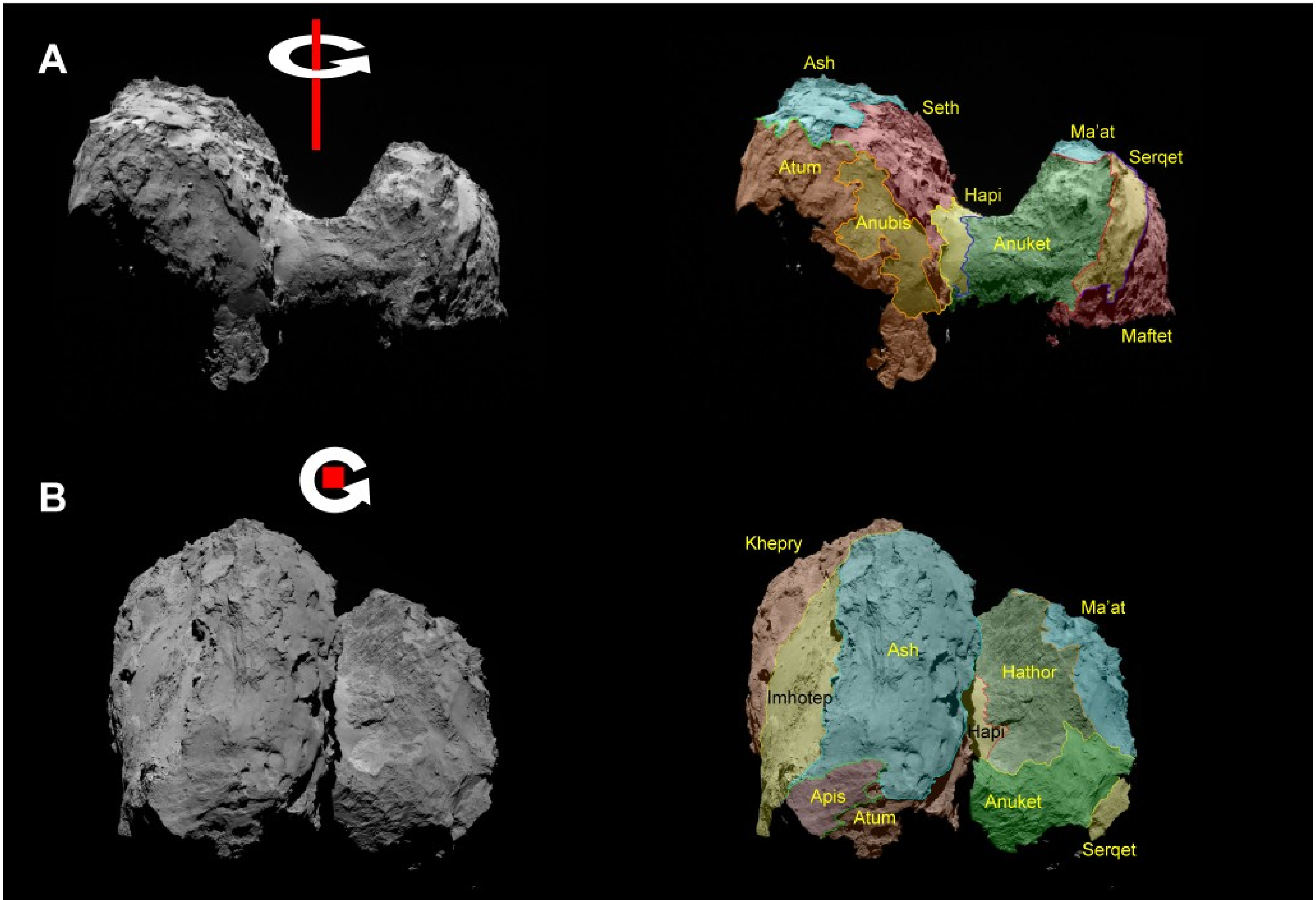
Two very different terrain types on 67P/C-G



Smooth terrain Consolidated terrain

Image credits: El-Maarry *et al.* (2015 *A&A* **583**, A26)

Smooth terrain dominates the north



<u>Smooth plains</u>

Hapi
Anubis
Imhotep

<u>Dust-covered consolidated terrain</u>

Seth
Ash
Ma'at
Maftet

<u>Consolidated</u>

Atum
Apis

Image credits: El-Maarry *et al.* (2015 *A&A* **583**, A26)

Consolidated terrain dominates the south

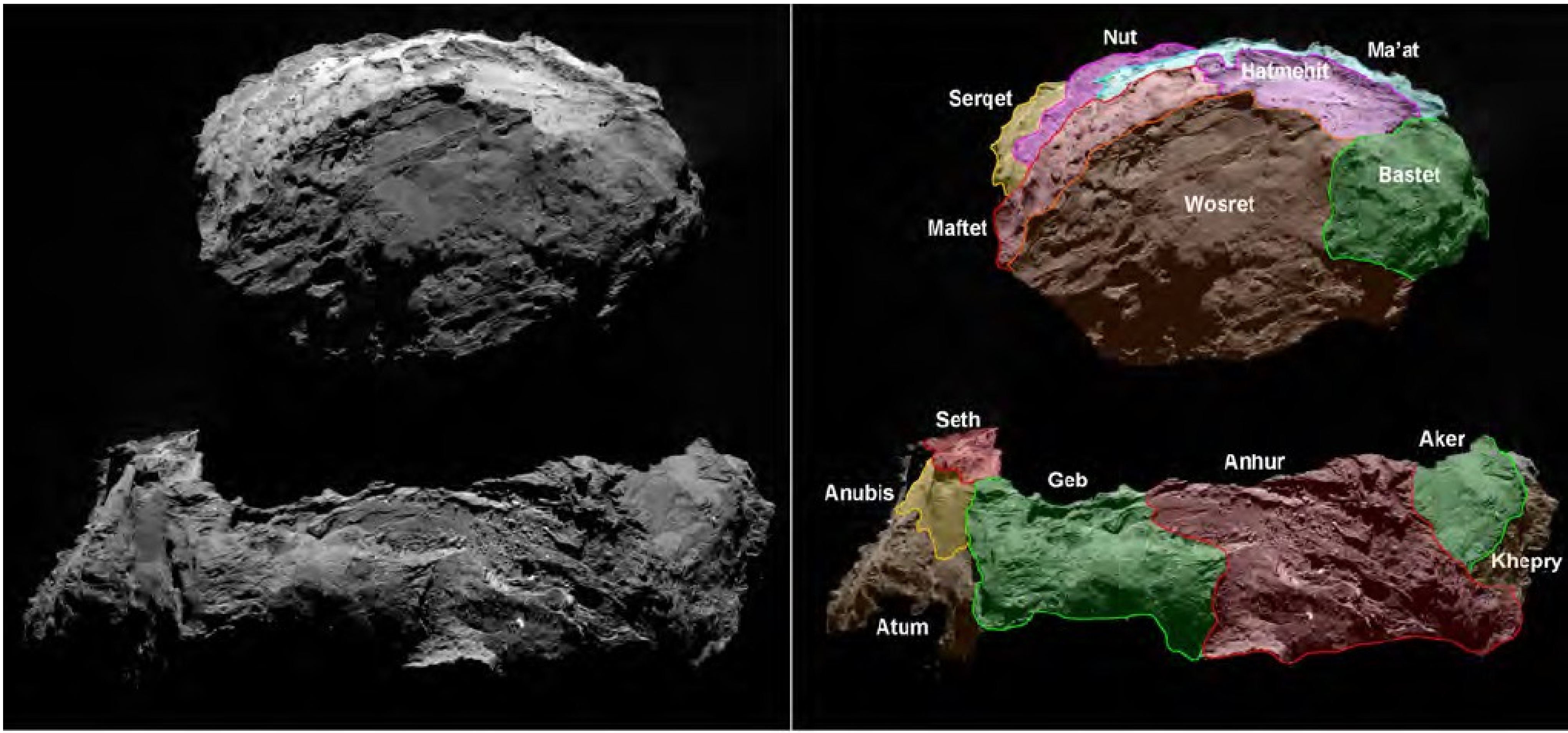
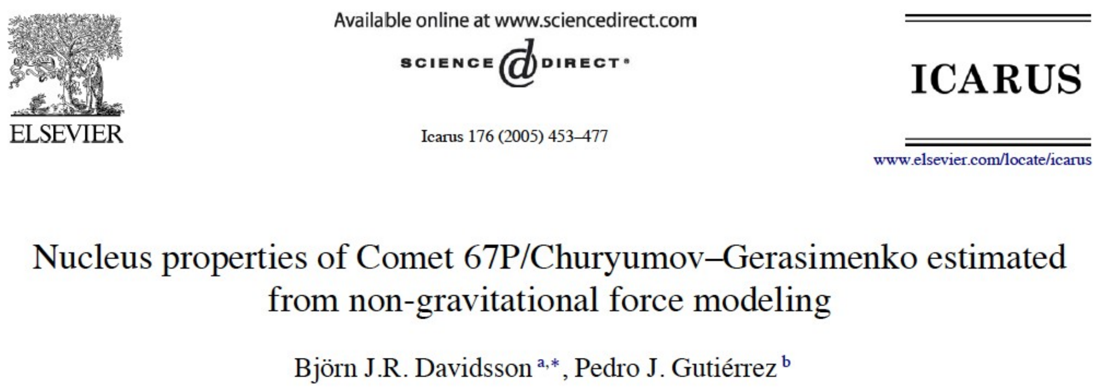


Image credits: El-Maarry *et al.* (2016 *A&A* **593**, A110)

The deep interior: bulk density and porosity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Icarus 176 (2005) 453–477

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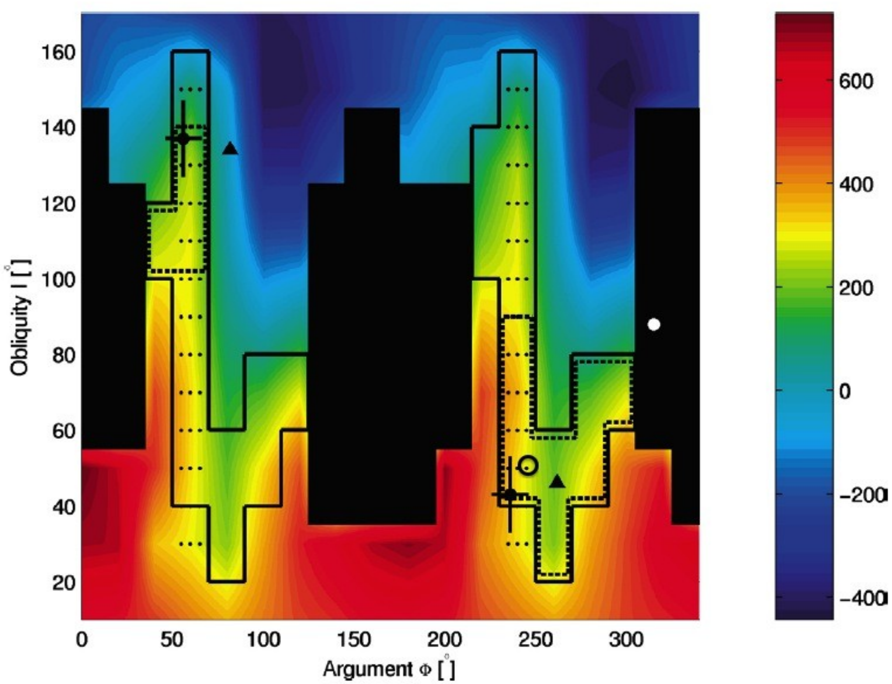
Nucleus properties of Comet 67P/Churyumov–Gerasimenko estimated from non-gravitational force modeling

Björn J.R. Davidsson[a,*], Pedro J. Gutiérrez[b]



For the spin axis orientation "CM" about 7° from correct one.

M=$1.1\cdot10^{13}$ kg
(range 0.9-$1.4\cdot10^{13}$ kg)

Corresponding density for *assumed* volume:
ρ=330 kg m^{-3}
(range 270-420 kg m^{-3})

In situ measurements by Rosetta/RSI (Pätzold *et al.* 2016, *Nature* **530**, 63)

M=$9.982\cdot10^{12}$ kg
ρ= 535 kg m^{-3} (correct volume)

Dust/ice mass ratio 4±2 (Rotundi *et al.* 2015, *Science* **347**, aaa3905): ρ_{comp}≈1800 kg m^{-3}, porosity is ~70%!

The deep interior versus the surface

Non-gravitational force modeling:

1P/Halley: 500-600 kg m^{-3}
(Skorov & Rickman 1999, *PSS* **47**, 935
Sagdeev *et al.* 1988, *Nature* **331**, 240)
19P/Borrelly: 180-300 kg m^{-3}
(Davidsson & Gutierrez 2004, *Icarus* **168**, 392)
81P/Wild 2: <600-800 kg m^{-3}
(Davidsson & Gutierrez 2006, *Icarus* **180**, 224)
9P/Tempel 1: 450 ± 250 kg m^{-3}
(Davidsson *et al.* 2007, *Icarus* **187**, 306
Richardson *et al.* 2007, *Icarus* **190**, 357)

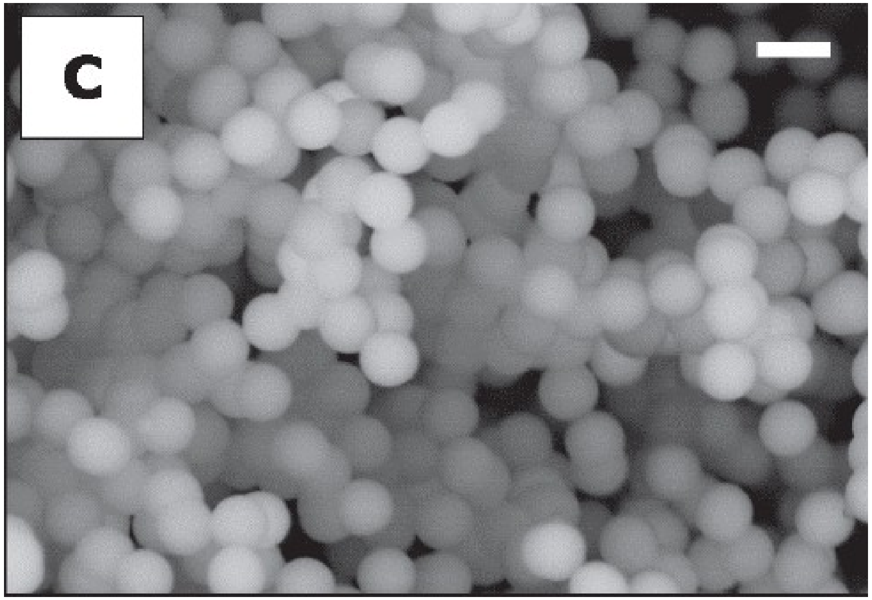


Image credits: Blum *et al.* (2006 *ApJ* **652**, 1768-1781)

Radar observations of comets:

C/1983 H1 (IRAS-Araki-Alcock): 900 kg m^{-3}
2P/Encke: 1200 kg m^{-3}
26P/Grigg-Skjellerup: 1300 kg m^{-3}
C/1983 J1 (Sugano-Saigusa-Fujikawa): 1500 kg m^{-3}
8P/Tuttle: 1800 kg m^{-3}

The deep interior is characterized by a highly porous fine-grained mixture of silicates, sulfides, organics, and ices.

The upper few dm-m appear compacted with respect to the deep interior.

The deep interior versus the surface

Nucleus: deep interior
CONSERT: dielectric constant $\varepsilon=1.27$,
porosity $\psi=75\text{-}85\%$
(Kofman *et al.* 2015, *Science* **349**, aab0639)

The consolidated material is a thin surface skin, like the crust on a loaf of bread

Nucleus: shallow depth (upper 2.5m)
Groundbased radar: $\varepsilon=1.9\text{-}2.1$,
$\psi=55\text{-}65\%$
(Kamoun *et al.* 2014, *A&A* **568**, A21)

Nucleus: surface (upper 1m)
SESAME/MUPUS: $\varepsilon=2.45$,
$\psi=40\text{-}55\%$,
compressive strength >2MPa
(Lethuillier *et al.* 2016, *A&A* **591**, A32,
Spohn *et al.* 2015, *Science* **349**, aab0464,
Biele *et al.* 2015 *Science* **349**, aaa9816)

Consolidated terrain: formation

Icarus 201 (2009) 335–357

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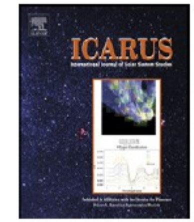


Physical properties of morphological units on Comet 9P/Tempel 1 derived from near-IR Deep Impact spectra

Björn J.R. Davidsson [a,*], Pedro J. Gutiérrez [b], Hans Rickman [a,c]

thermal inertia. These regions may have been devolatilized a long time ago, and there may not be enough gas welling up from the deep interior to loosen up the near-surface material. The porosity might gradually decrease as grains of minerals and organics settle into increasingly compact configurations, perhaps assisted by microvibrations by geological events taking place elsewhere. This material could consolidate further due to the presence of tar-like organics. As shown experimentally by Kömle et al. (1996), mixtures of silicate dust and organics develop into cohesive mantles upon solar heating, with substantially higher conductivity and thermal inertia than pure silicate powder. The reason is that plastically

Consolidated terrain:
result of solar heating/cooling cycles leading to compaction and sintering by ice and/or organics

Laboratory experiment: sintering by organics

Extractable organics
(e.g., abundant carboxylic
acids in carbonaceous chondrites)
have melting points of ~300K
and are prone to sintering.

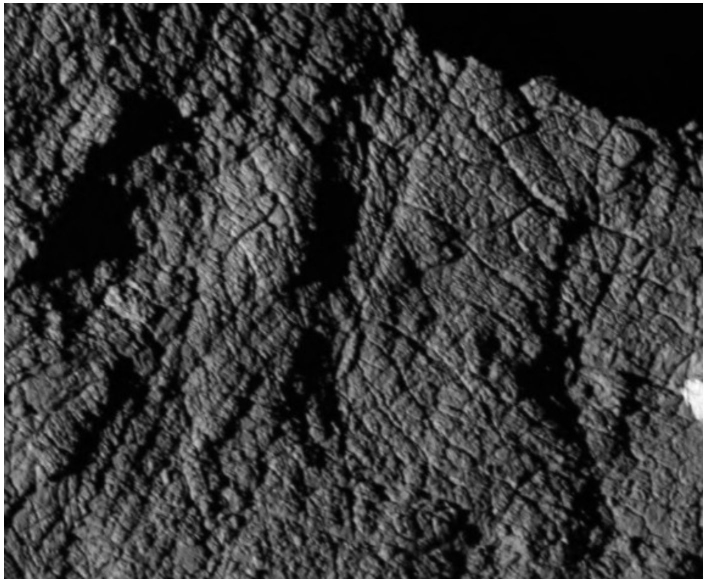
Note cracks and coherent chunks
of material after heating/cooling
cycles of granular silicate / organics
mixture.

Image credits: Kömle *et al.* (1996, *PSS* **47**, 675)
G. Kargl: Physical processes on the surface of a cometary nuceus: Experimental investigations of the influence of organic constituents on the thermal properties., PhD Thesis, Karl-Franzens-University Graz, Austria (1998)

Formation of consolidated terrain

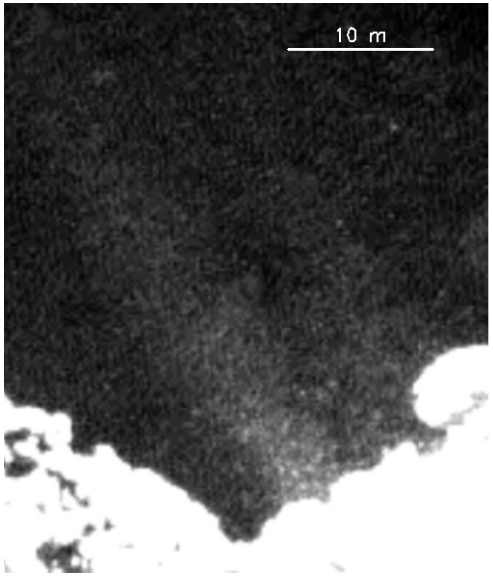
- The primordial nucleus is a highly porous and weakly bound aggregate of micrometer-sized grains
- Solar heating causes compaction and sintering of a *surface layer* that may be a few meters thick
- This is what we see as “rock-like” consolidated terrain
- It may crack and eventually crumble into boulders at cliffs

Smooth terrain: formation



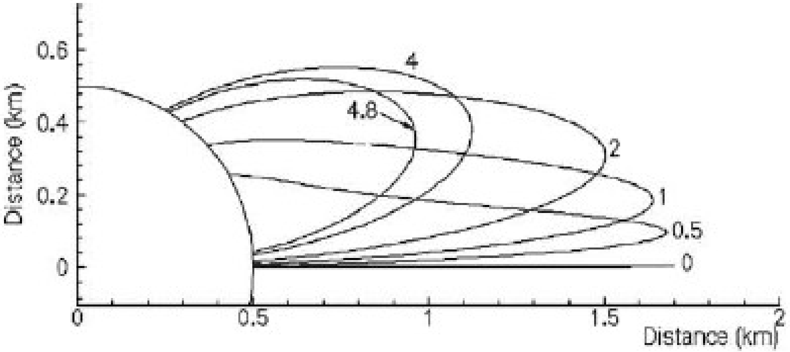
Cracking of consolidated material

⇒



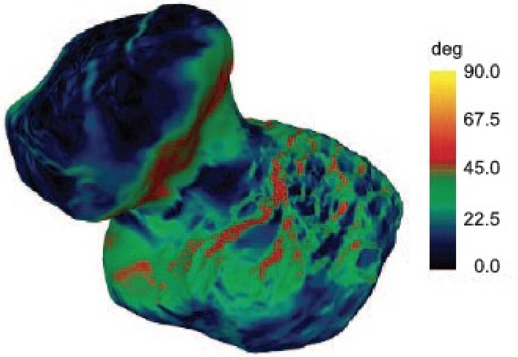
Lift-off of cm-dm chunks

⇒



Ballistic flight and fall back

⇒



Deposition on level surfaces

Image credits: UL: El-Maarry *et al.* (2015, *GRL* **42**, 5170); UR: Thomas *et al.* (2015, *A&A* **583**, A17); LL: Crifo *et al.* (2005, *Icarus* **176**, 192); LR: Sierks *et al.* (2014, *Science* **347**, aaa1044)

Transport: south to north

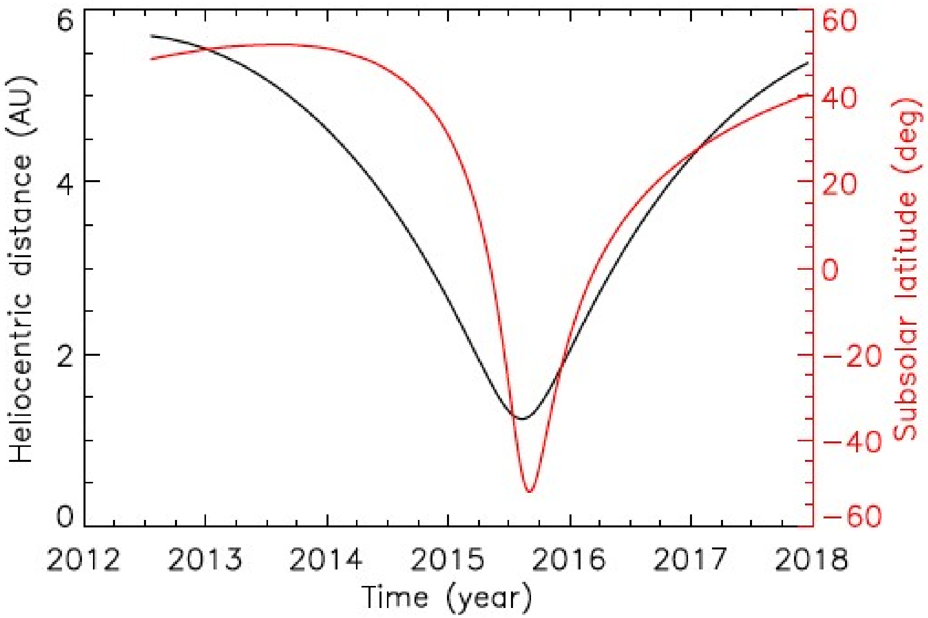


Image credit: Keller *et al.* (2015, *A&A* **583**, A34)

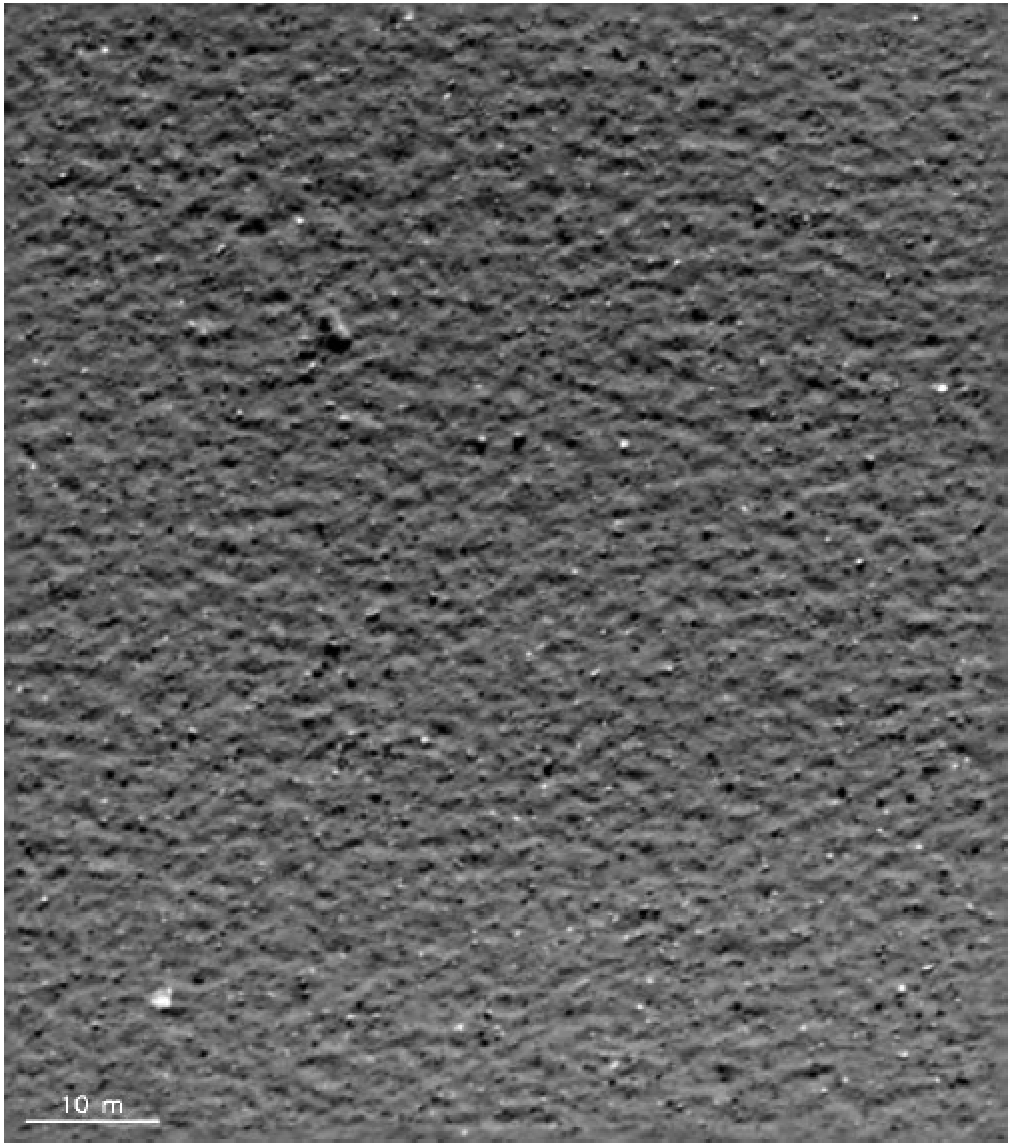
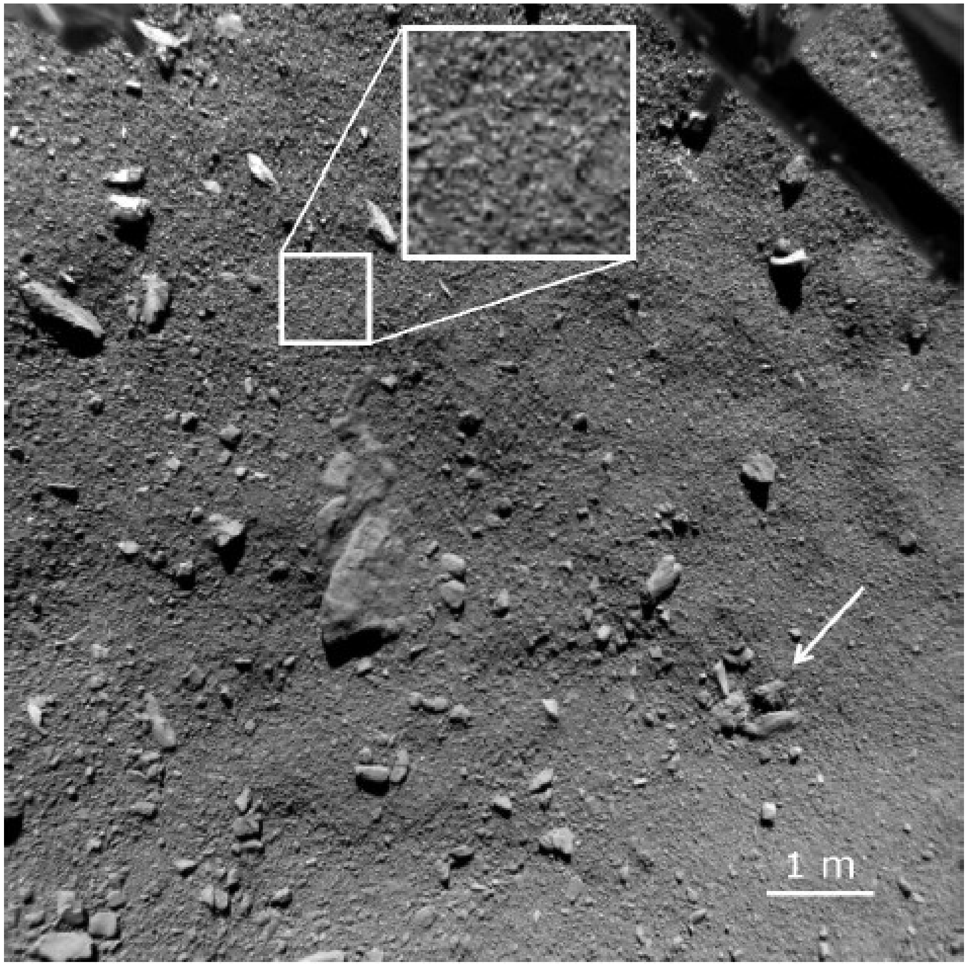


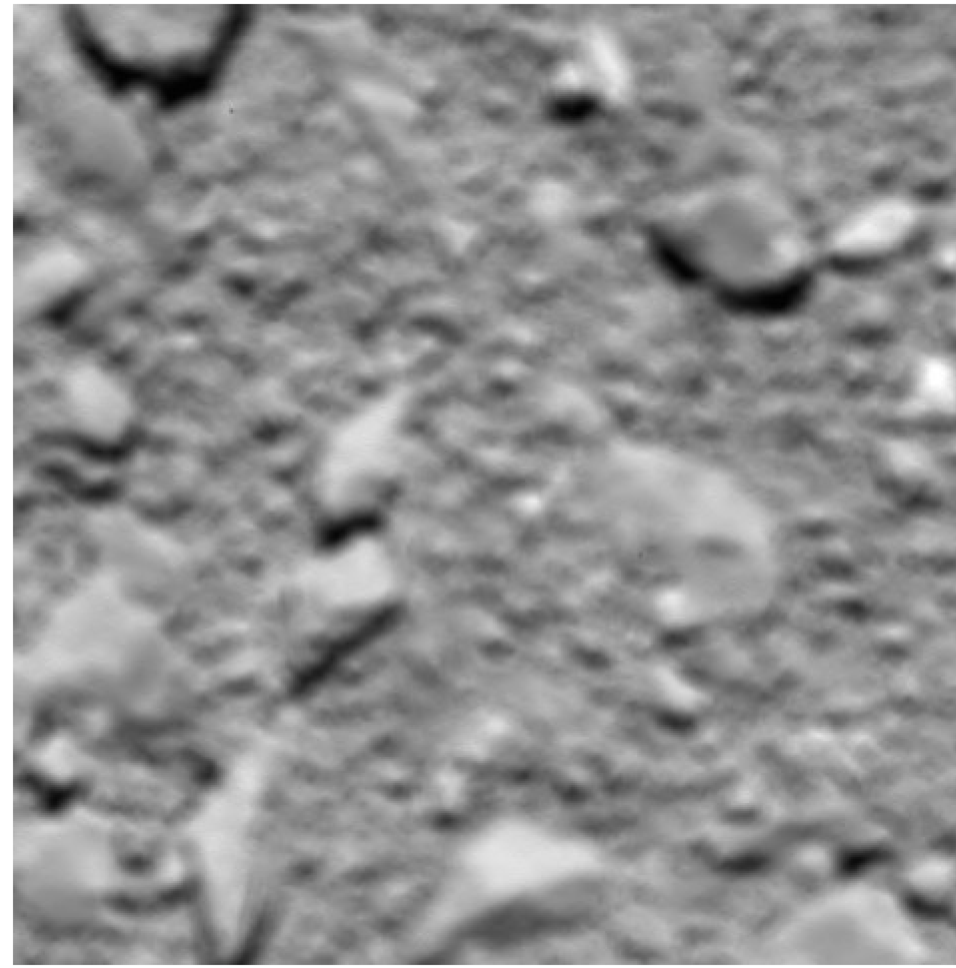
Image credits: Thomas *et al.* (2015, *A&A* **583**, A17)

At 0.14 m px^{-1} resolution (left) smooth terrains appear pitted and dm-sized boulders are visible

Close-up images: Angular and facetted boulders

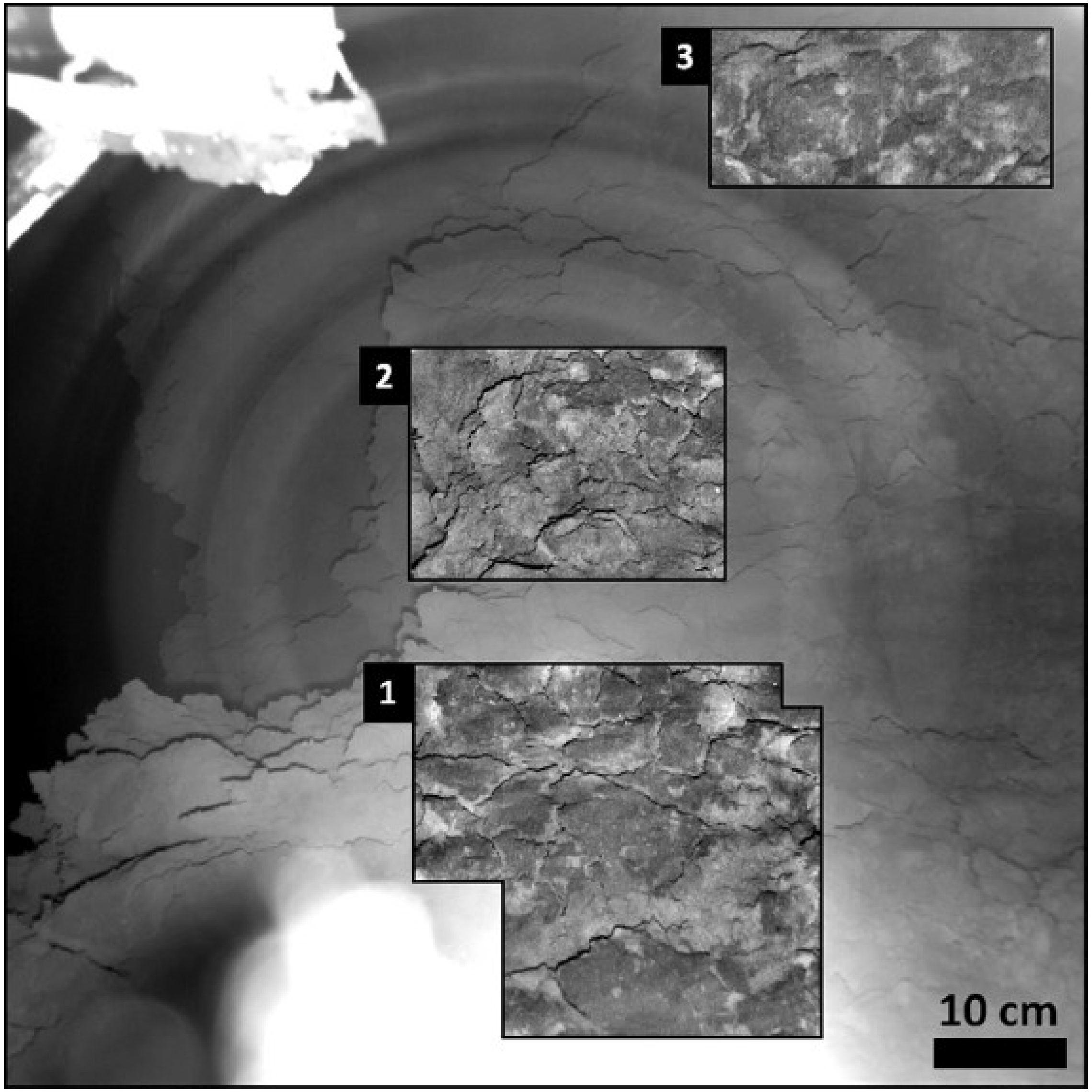


Agilkia at 0.95 m px^{-1} resolution (ROLIS)
(Image credits: Mottola *et al.* 2015, *Science* **349**, aab0232)



Sais at 0.002 m px^{-1} resolution (OSIRIS)
(Image credits: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA)

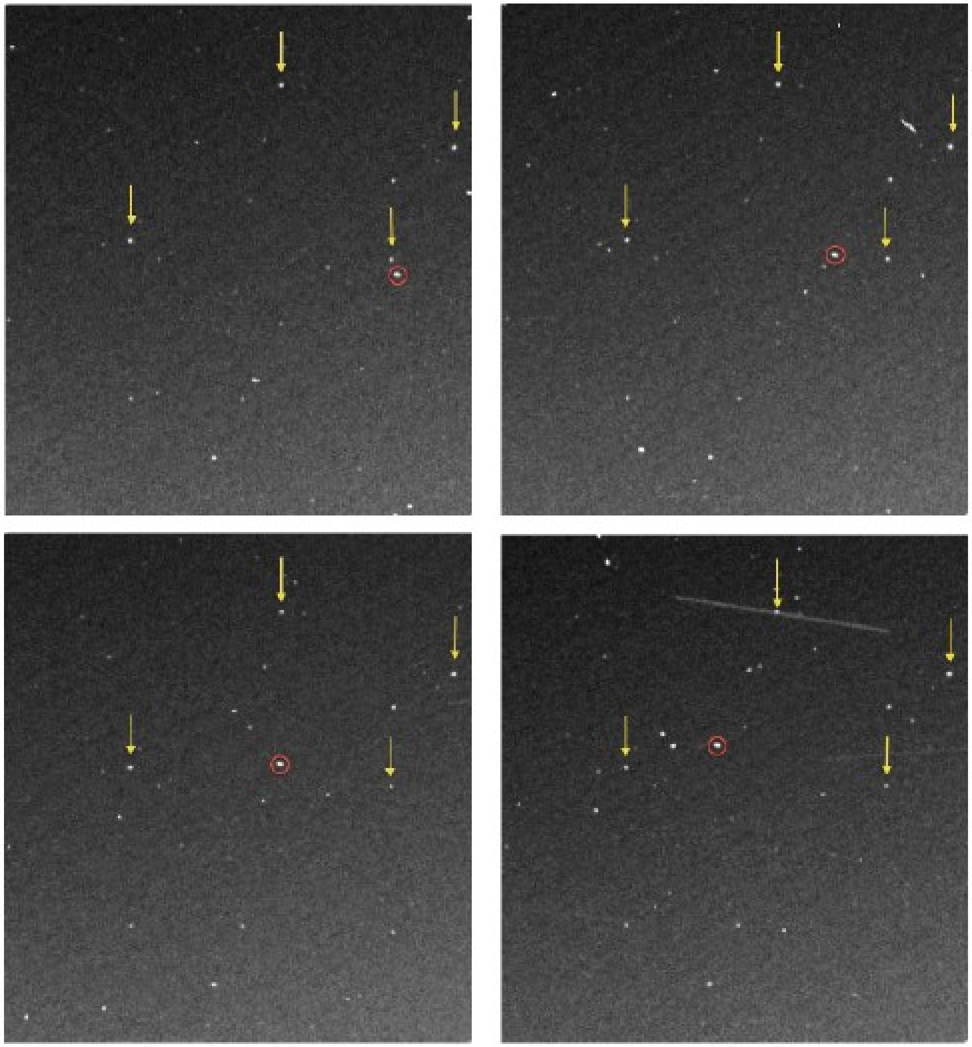
Breaking up consolidated material: thermal cracking



Cracked consolidated material at Abydos – final resting place of Philae

Image credits: Schröder *et al.* (2017, *Icarus* **285**, 263)

Ballistic trajectories



September 10, 2014. 67P was 3.39 AU from the Sun, moving inbound.

OSIRIS/WAC: astrometry for several boulders moving relative the stars

Preliminary orbits: Gauss method

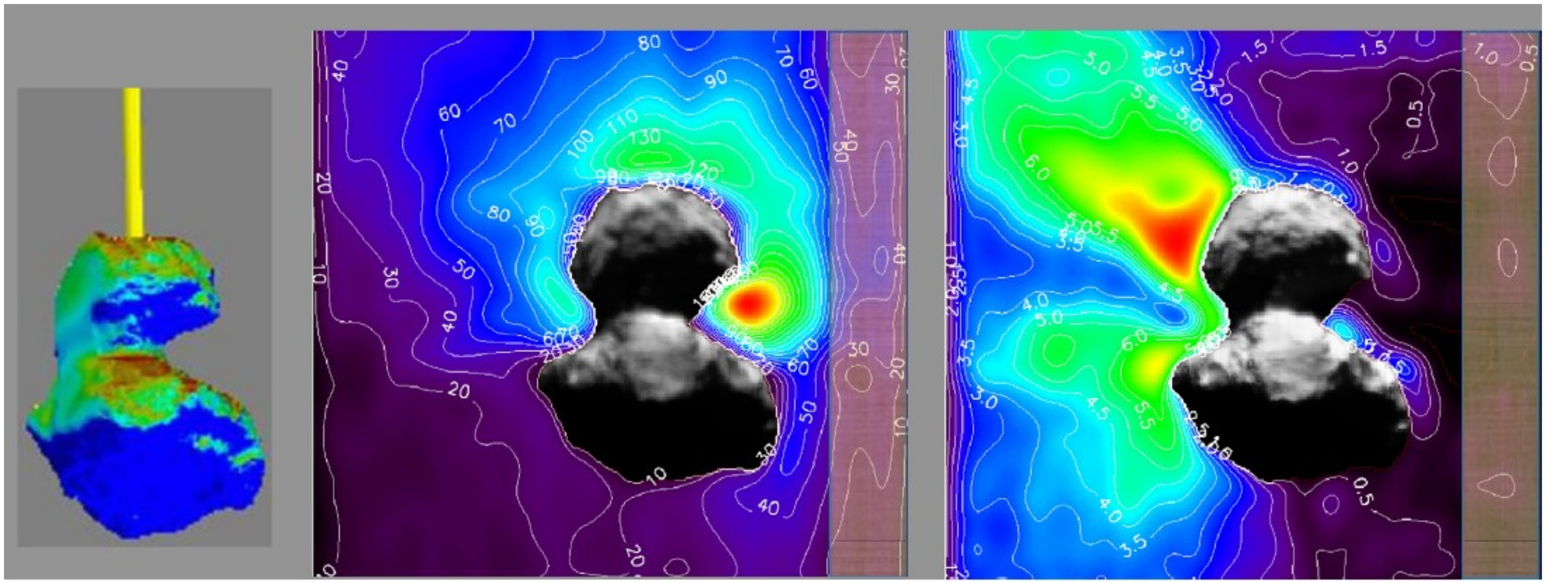
Orbit determination: pseudo-Newton variant of differential correction algorithm

Osculating orbital elements:
1) Hyperbolic escape trajectories
2) Bound elliptic orbits, some of which intercept nucleus (fallback)

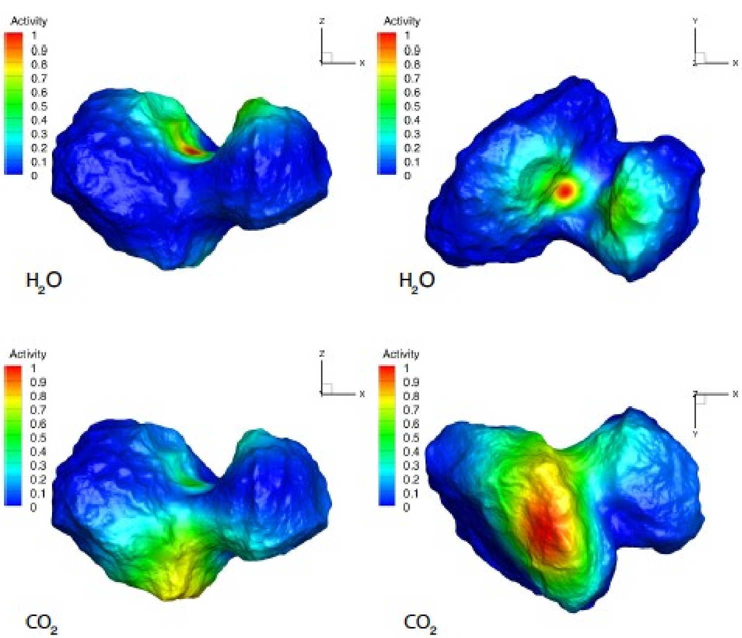
Diameters: 0.14-0.50 meters

Image credits: Davidsson *et al.* (2015, *A&A* **583**, A16)

Fall back: water ice present, supervolatiles lost



April 27, 2015
1.76 AU from the Sun



Hapi is a strong source of water but CO2 originates from the south.

Perihelion: fallback boulders loose their supervolatiles in the coma but retain their water ice.

That water is gradually lost on the inbound part of the orbit.

Image credits:
Up: Fink *et al.* (2016, *Icarus* **277**, 78)
Down: Fougere *et al.* (2016, *A&A* **588**, A134)

Fall back: water ice present, supervolatiles lost

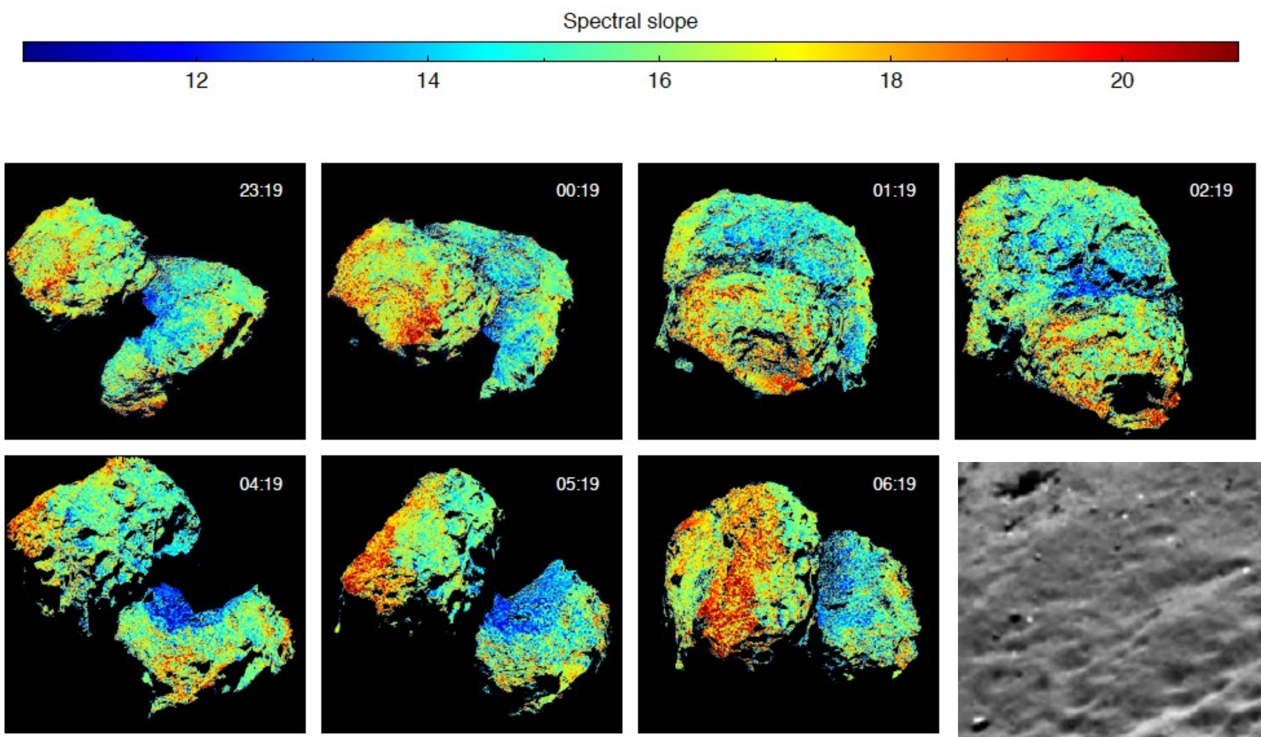
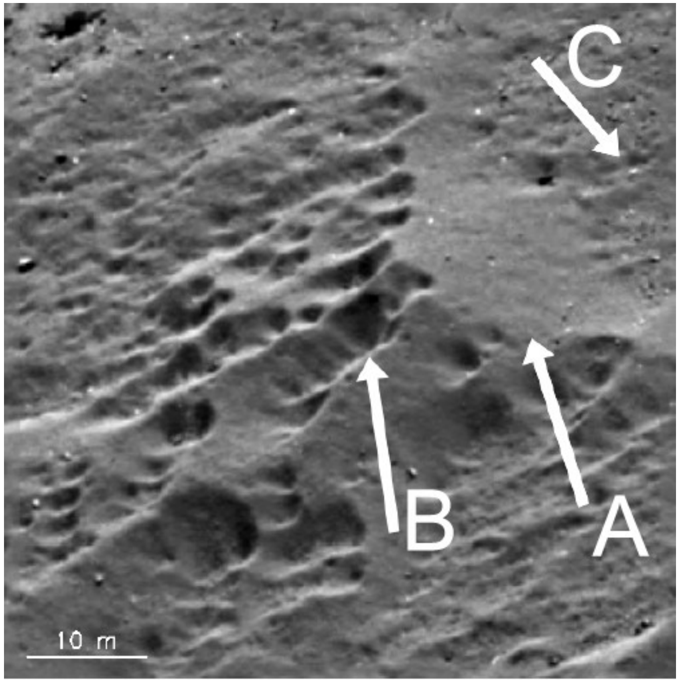


Image credits: Fornasier *et al.* (2015, *A&A* **583**, A60)

Spectral slope in 535-882 nm range: shallower slope (blue) indicative of water ice.



Sublimation pits in deposits of Maftet indicate presence of water ice.

Image credits: Thomas *et al.* (2015, *A&A* **583**, A17)

Formation of smooth terrain

- The consolidated “surface skin” cracks
- Bits and pieces are ejected into the coma
- Some material falls back on regions that have polar night (northern hemisphere during the perihelion passage)
- The fallback accumulates in gravitational lows as smooth terrain

Changes in smooth terrain: Imhotep

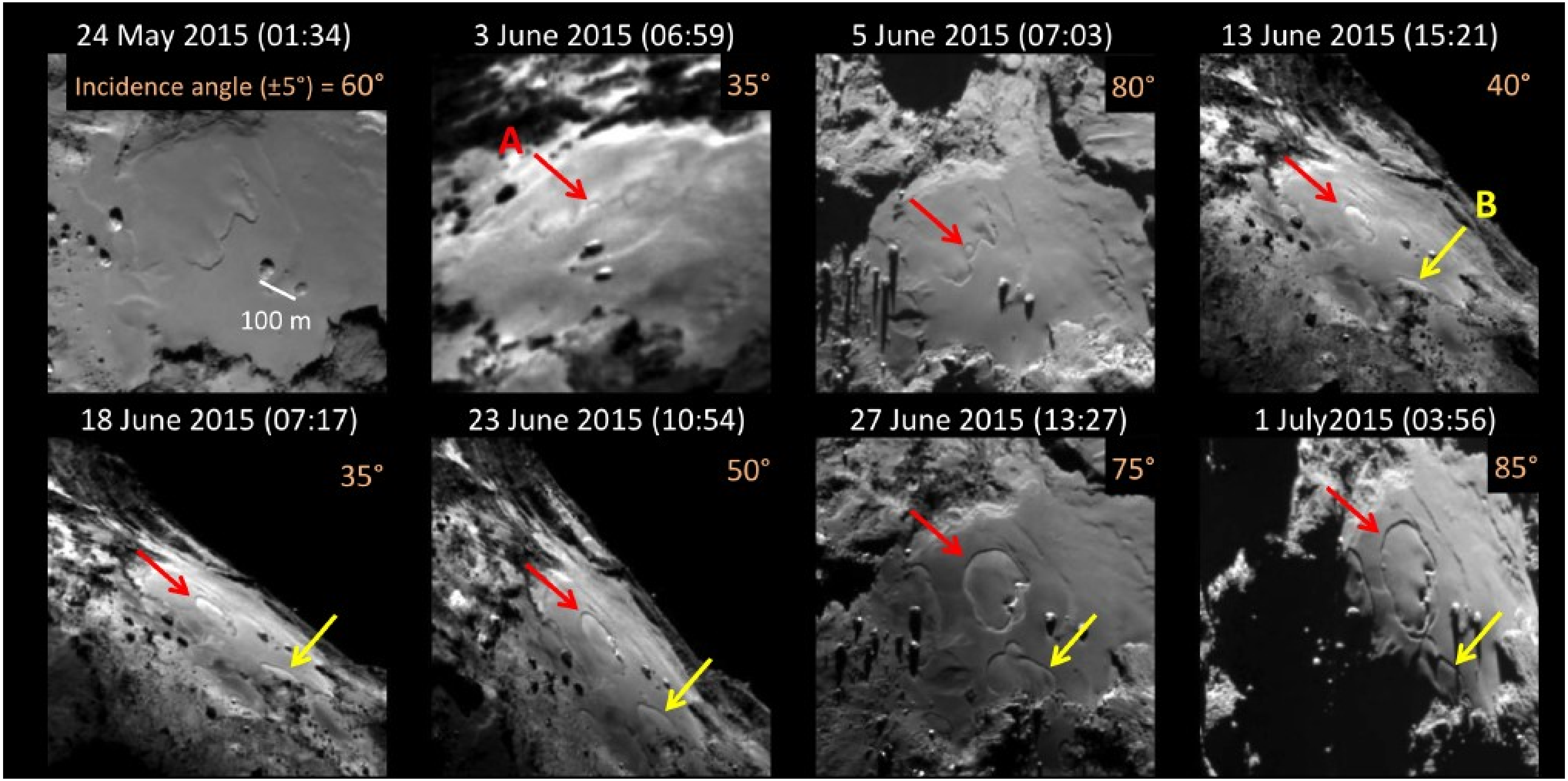
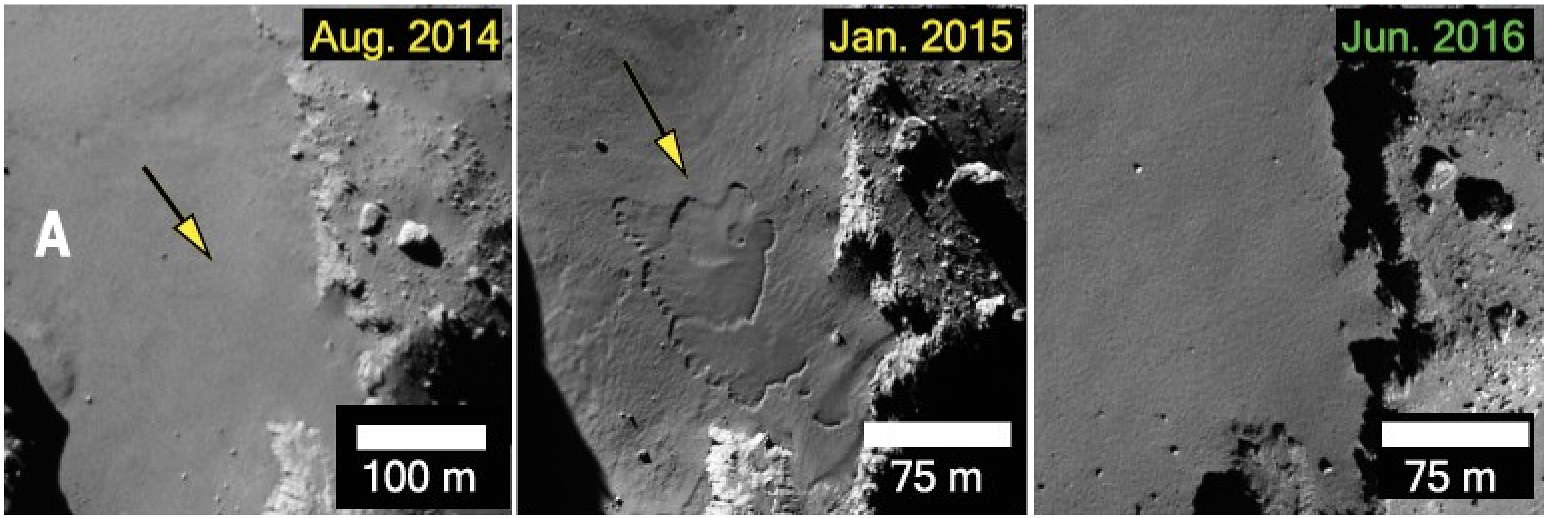
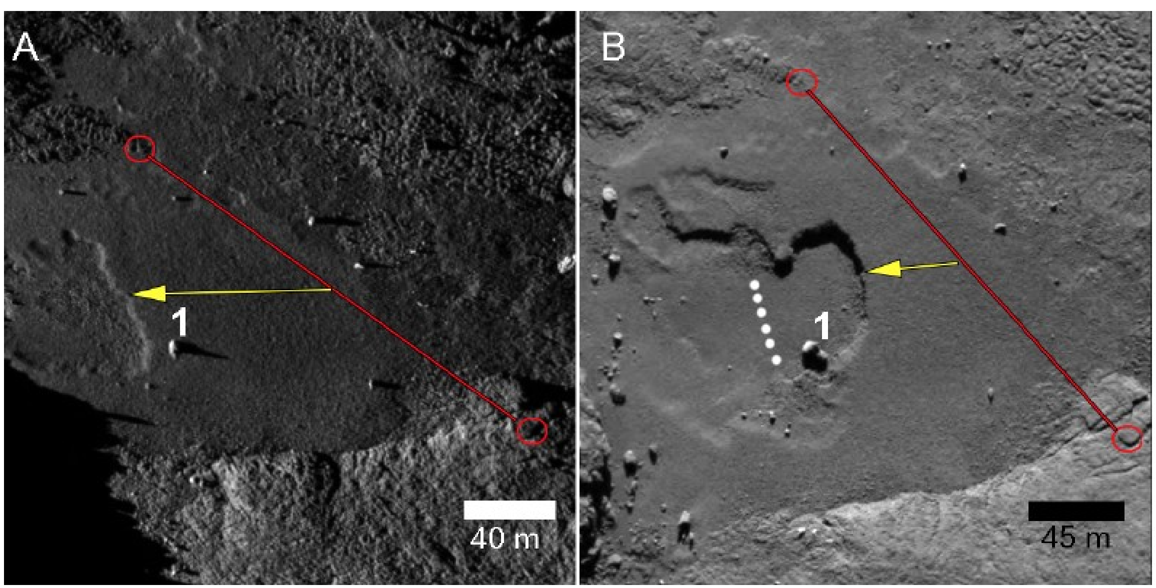


Image credits: Groussin *et al.* (2015, *A&A* **583**, A36)

Changes in smooth terrain: Hapi & Anubis



Hapi



Anubis

Image credits: El-Maarry *et al.* (2017, *Science* **355**, 1392)

Changes in smooth terrain: Hapi

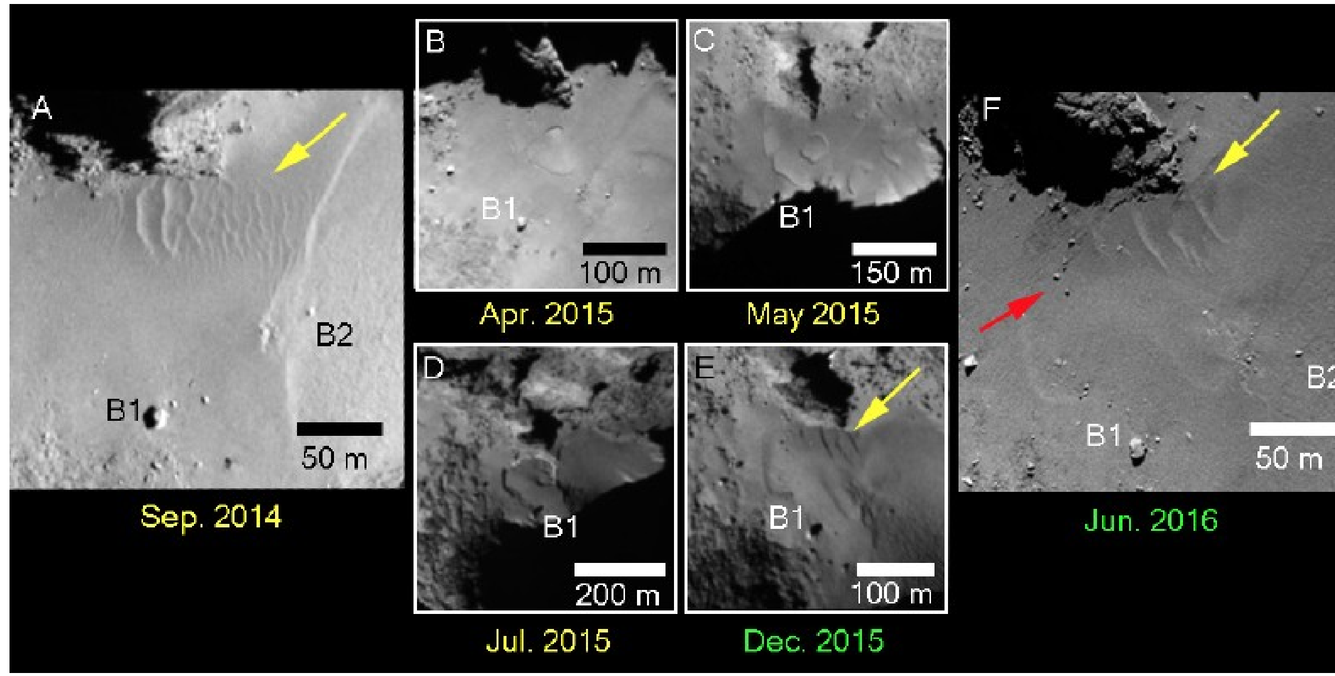


Image credits: El-Maarry *et al.* (2017, *Science* **355**, 1392)

Image credits: Thomas *et al.* (2015, *A&A* **583**, A17)

Summary

- Comet 67P/Churyumov-Gerasimenko is a geologically active object
- It formed as a very porous and weak object with low density and global-scale layering
- Solar heating has sculptured the nucleus in a manner regulated by the layering, giving rise to a system of terraces, cliffs, and pits
- Solar heating has “baked” the upper few meters and created consolidated terrain with a rock-like appearance
- Erosion of the consolidated terrain and coma fallback creates smooth deposits that changes significantly on short time scales
- Similar terrains are seen on other comet nuclei, suggesting these are common phenomena