Formation of 67P

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Overview

- Discuss a number of formation and processing scenarios
- Provide my view on what steps we need to take concerning numerical computer simulations, laboratory work, Rosetta instrument data analysis, and future comet spacecraft missions (including CAESAR) to advance our understanding of comet nucleus formation
- Focus on *physical* processes as opposed to *chemistry*

Would we recognize it if we saw it?

Formation

Hierarchical agglomeration

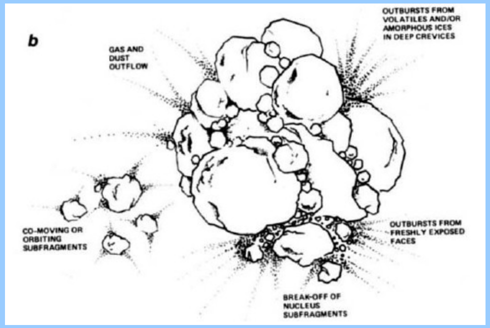


Image credit: Weissman (1986, *Nature* **320**, 242)

Gravitational collapse of pebble swarm formed by streaming instability

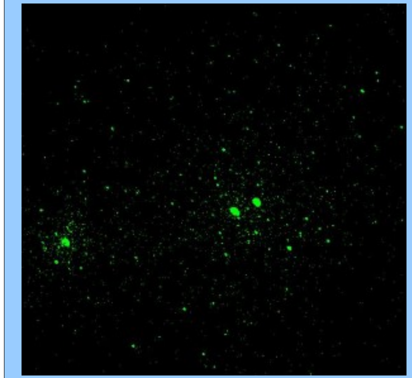


Image credit: Nesvorny *et al.* (2010, *Astron. J.* **140**, 785)

Catastrophic collision: collisional rubble-pile

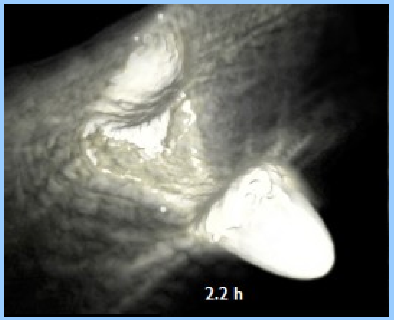


Image credit: Jutzi & Benz (2016, *Astron. Astrophys.* , **597**, A62)

Secondary processing

Tidal disruption & reassembly

Image credit: NASA, ESA, H. Weaver, E. Smith (STScI)

Nucleus splitting & fragmentation

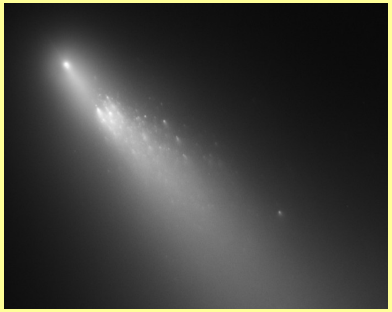


Image credit: NASA, ESA, H. Weaver (JHU / APL), M. Mutchler, Z. Levay (STScI)

Strong erosion due to sublimation

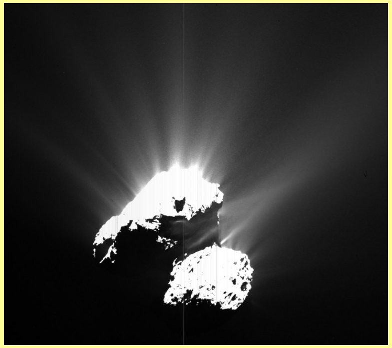


Image credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA

What we need: Testable Hypotheses

- *Quantitative* description of nuclei with specific formation and processing history
  - We need to know what to look for to design appropriate instruments with meaningful technical specifications

- Are all scenarios unique?
  - Can we tell the difference between gravitational reassembly following a catastrophic collisional disruption and tidal disruption?

Pebble swarm collapse

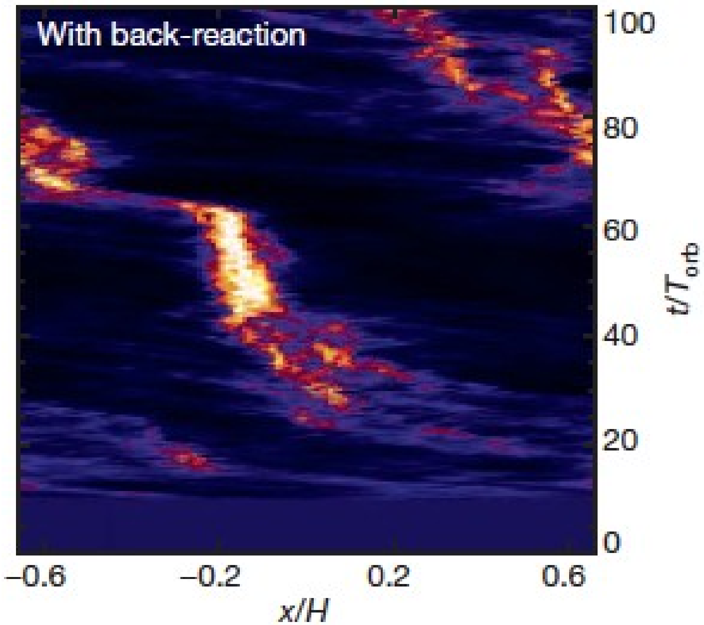


Image credit: Johansen *et al.* (2007, *Nature* **448**, 1022)

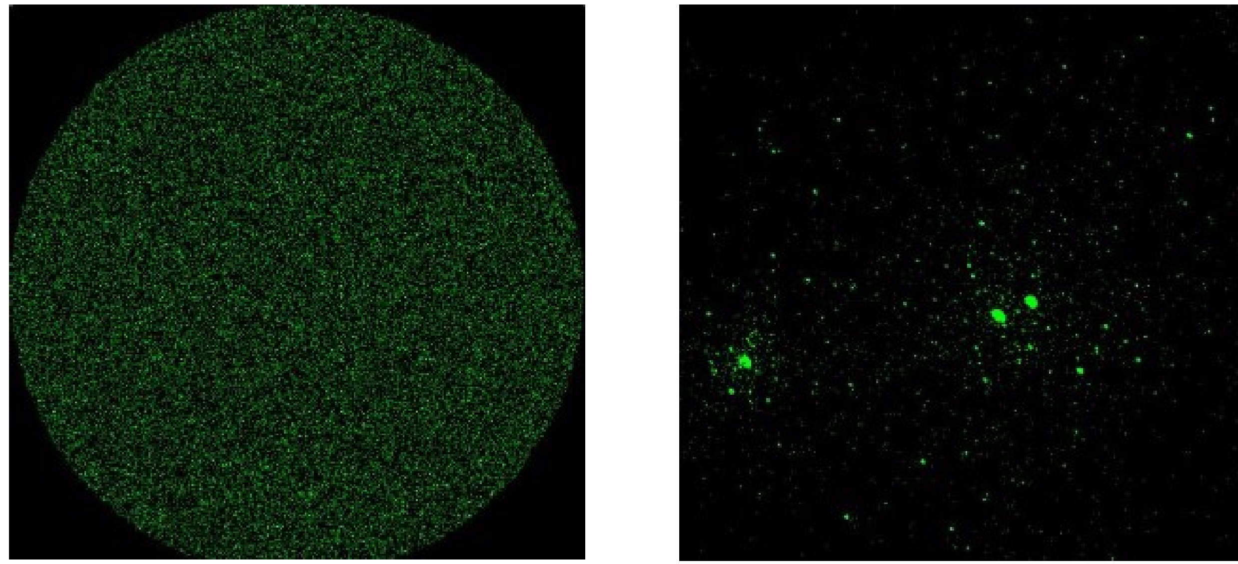


Image credit: Nesvorny *et al.* (2010, *Astron. J.* **140**, 785)

- Paradigm of planetesimal growth since 2005 (e.g. Johansen *et al.* 2007, *Nature* **448**, 1022)
- Undoubtedly active: dynamically cold classical TNOs *ultrawide binaries of similar size & color*
- Bodies in D≥100km class, separated by 10^3 to 10^5 km

- Mechanism efficient at D ≈ 1km? At 100 km free fall time-scale 25 yr, at 1km several 10^3 yr
- Time of formation?
  - Very early: potential ^{26}Al problem: (66652) Borasisi ρ=2100±1200 kg m^{-3}; 2001 QW_{322} ρ=1600±1400 kg m^{-3}
  - Very late: pebble size ≈ skin depth; at 23 AU T≈80 K, loss of CO, CO_2 (large body at T≈55K). Also, radial drift peaks at ~cm size at 30 AU (compare “1 meter drift barrier” at 1 AU)

Pebble swarm collapse: what we need (I)

- The highest-resolution "pencil code" simulations thus far (512^3 cells, $1.5 \cdot 10^8$ superparticles; Johansen *et al.* 2015, *Sci. Adv.* **1**, 1500109) form pebble swarms that would collapse to D≈60 km bodies. *Need to be pushed to D≈1-10km to predict <u>size distribution</u>, internal velocity fields (incl. <u>angular momentum</u>)*

- N-body simulations of swarm collapse radially resolved for the first time (Wahlberg Jansson & Johansen 2017, *MNRAS* **469**, S149) but lacks rotation. *Couple with angular momentum above to predict <u>porosity profile</u> and properties of potential <u>layering (e.g., thickness)</u>, and <u>component separation.</u>*

- Tidal evolution of ~1 km bodies separated by 10-1000 km. *What is the predicted frequency of contact binaries?*

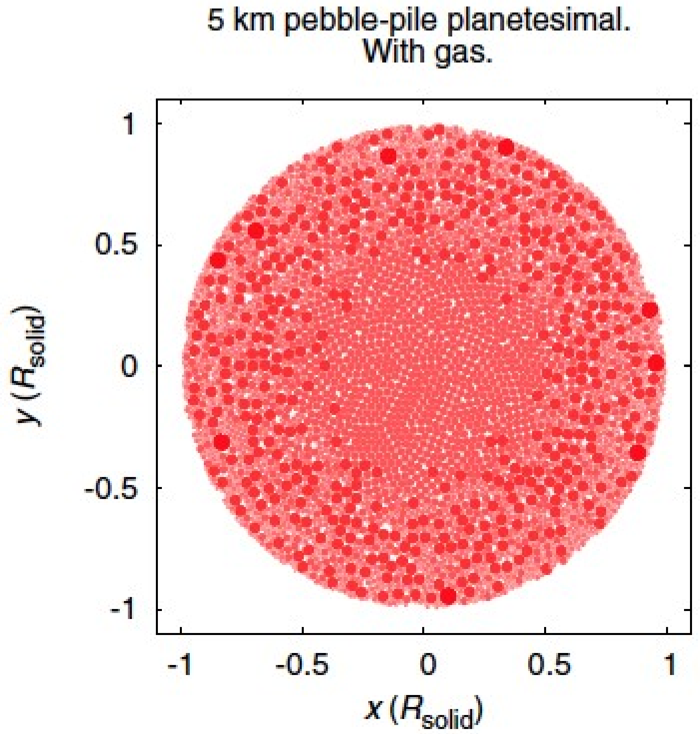


Image credit: Wahlberg Jansson & Johansen (2017, *MNRAS* **469**, S149)

Pebble swarm collapse: what we need (II)

- Pebbles can hardly survive on the surface (compaction during consolidation; fracturing; coverage by fallback; “breccia formation”)
  - Philae images, coma dust instruments, CAESAR reveal important information about *processed* material, not primordial pebbles
- Access to the interior, sensitivity to mm-cm scale structures
  - Collapsed cliffs, accessing ~10 m depth – MIRO (λ=0.53-1.59cm) NASA RDAP investigation funded (Davidsson)
  - Lander with Ground-Penetrating Radar
- CONSERT: continued efforts to understand porosity vs. depth
- OSIRIS: continued efforts to characterize layering (dimensions, albedo, color)
- CAESAR: what’s the story on ^{26}Al?

Hierarchical agglomeration

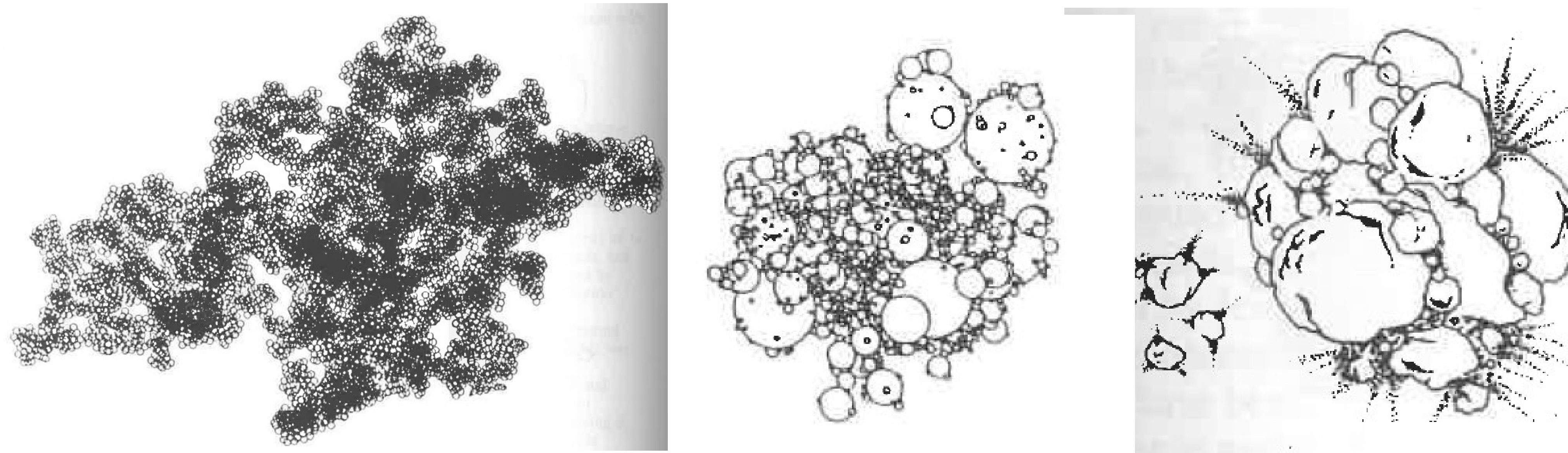
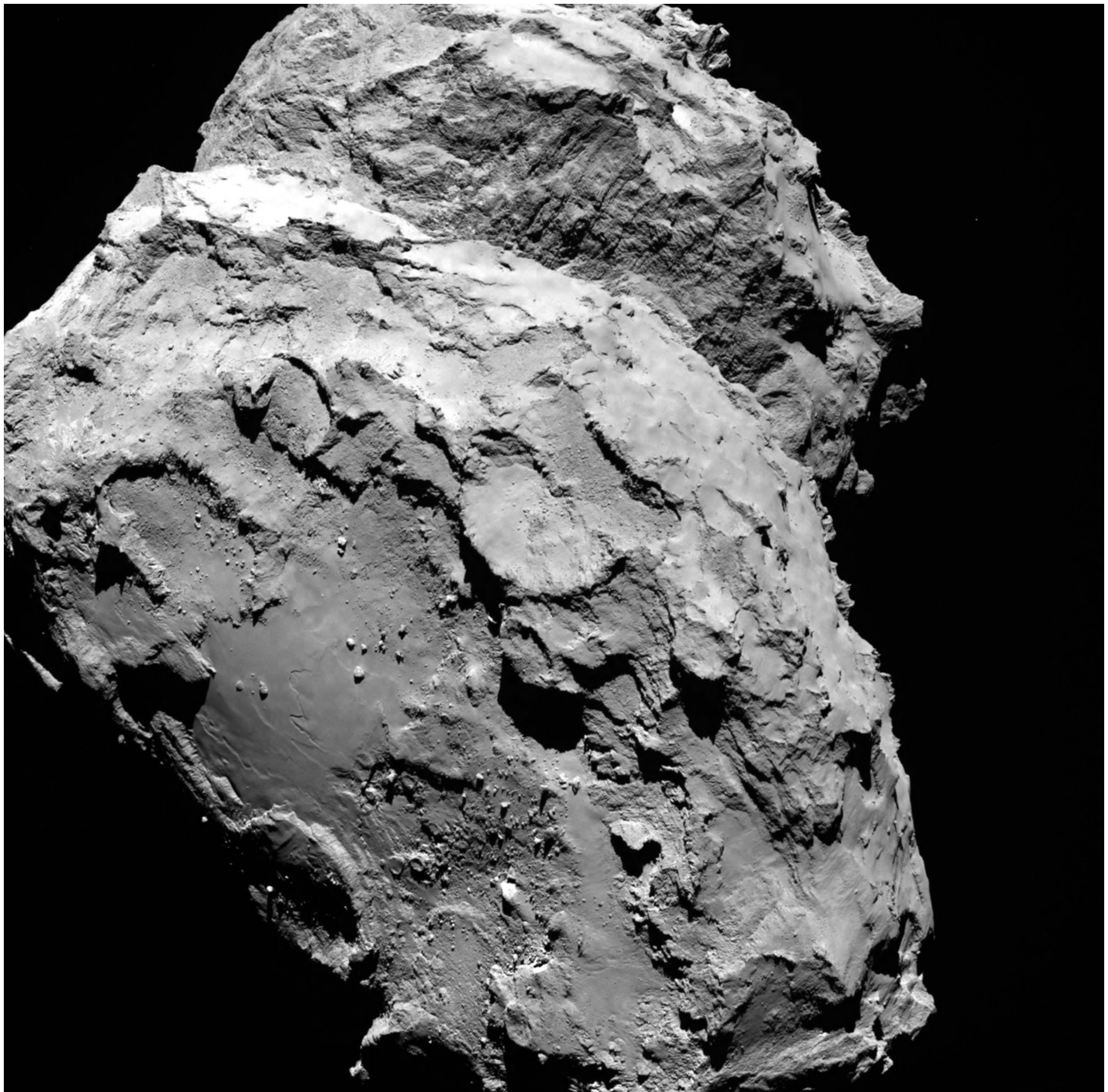


Image credit: Donn (1991, *Comets in the Post-Halley Era, Vol I,* Newburn *et al.* Eds.)

- Paradigm of planetesimal growth ~1975-2005 (e.g., Weidenschilling 1997, *Icarus* **127**, 290; Kenyon & Luu 1998, *Astrophys. J.* **115**, 2136; Windmark *et al.* 2012, *Astron. Astrophys.* **540**, A73)
- Undoubtedly active up to cm-dm size

- Growth beyond ~0.1 m seriously questioned (bouncing, fragmentation)
- Expectations of finding large (10-100 m) cavities not fulfilled (CONSERT, RSI)
- Expectations of finding clearly recognizable planetesimals not fulfilled
  - Interpretation of meter-sized “goosebumps” as building-blocks (Sierks *et al.* 2015, *Science* **347**, aaa1044; Davidsson *et al.* 2016, *Astron. Astrophys.* **592**, A63) is controversial

How should a cometesimal look like?



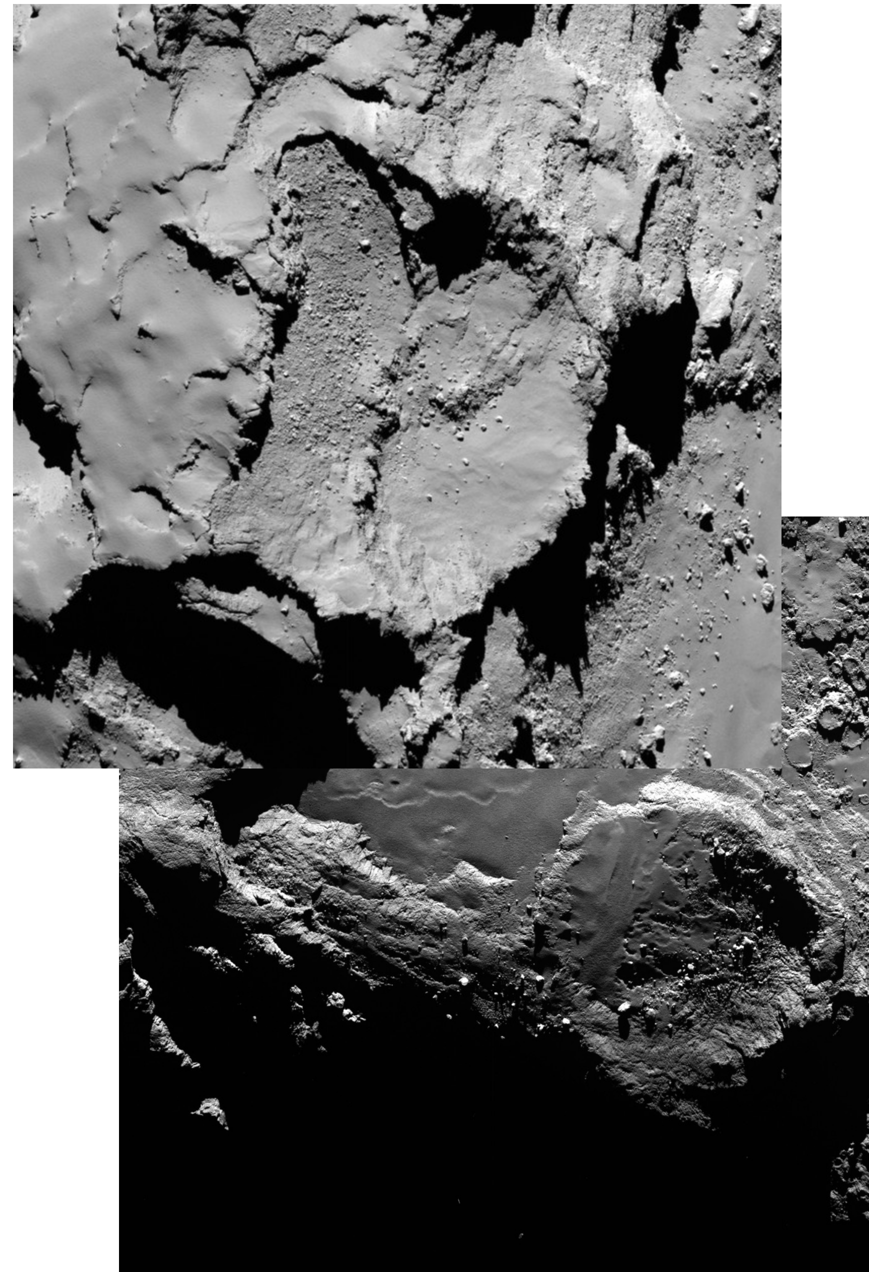
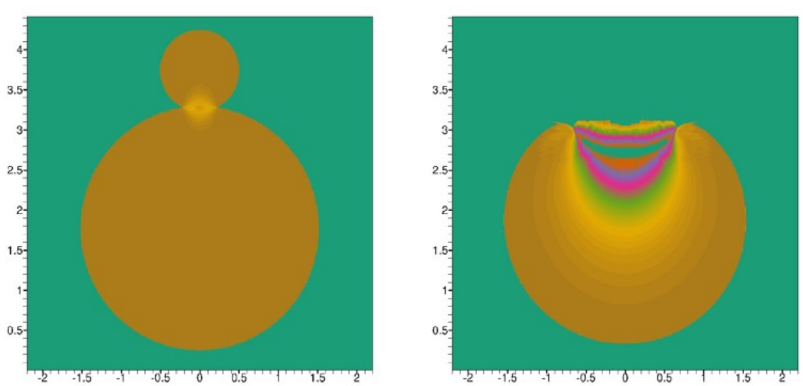


Image credit: ESA/Rosetta/MPS for OSIRIS Team
MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA

Hierarchical agglomeration: what we need (I)

- *Better understanding of dynamical friction and viscous stirring in gas disks to obtain <u>cometesimal collision velocities over time</u>*
- *Multiple mergers with SPH / HD to understand internal structure (<u>porosity profile, void spaces, layering</u>) hierarchically grown bodies*
- *Continued laboratory work on small and sticky monomers at cryogenic conditions to study <u>coagulation, fragmentation, bouncing</u>*



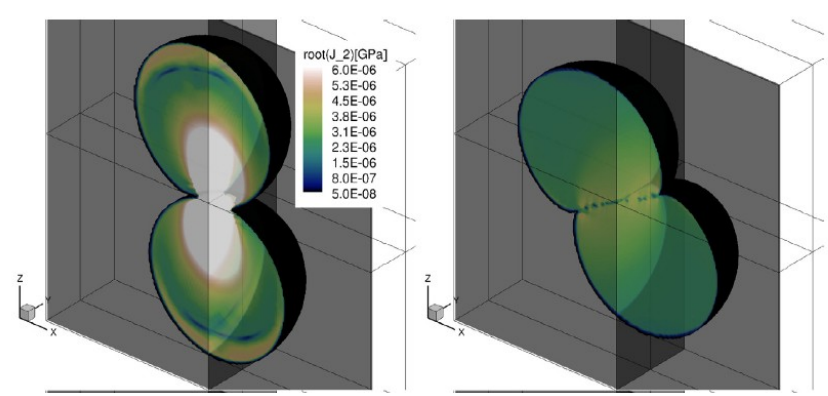


Image credit: de Niems *et al.* (2018, *Icarus* **301**, 196)

Hierarchical agglomeration: what we need (II)

- CONSERT: continue refinement of upper limit on size of heterogeneities; porosity gradient
- ROSINA: to what extent does the *lobes* differ in terms of chemical and isotopic composition?
- CAESAR: What is the size of *monomer* grains? Does organics and/or ice encapsulate silicate grains? What is the sticking properties of the organics?
- Continuation of CONSERT (e.g. CORE) for global characterization and population diversity
- Flyby of Centaurs to view shape prior to strong erosion

Collisional rubble pile

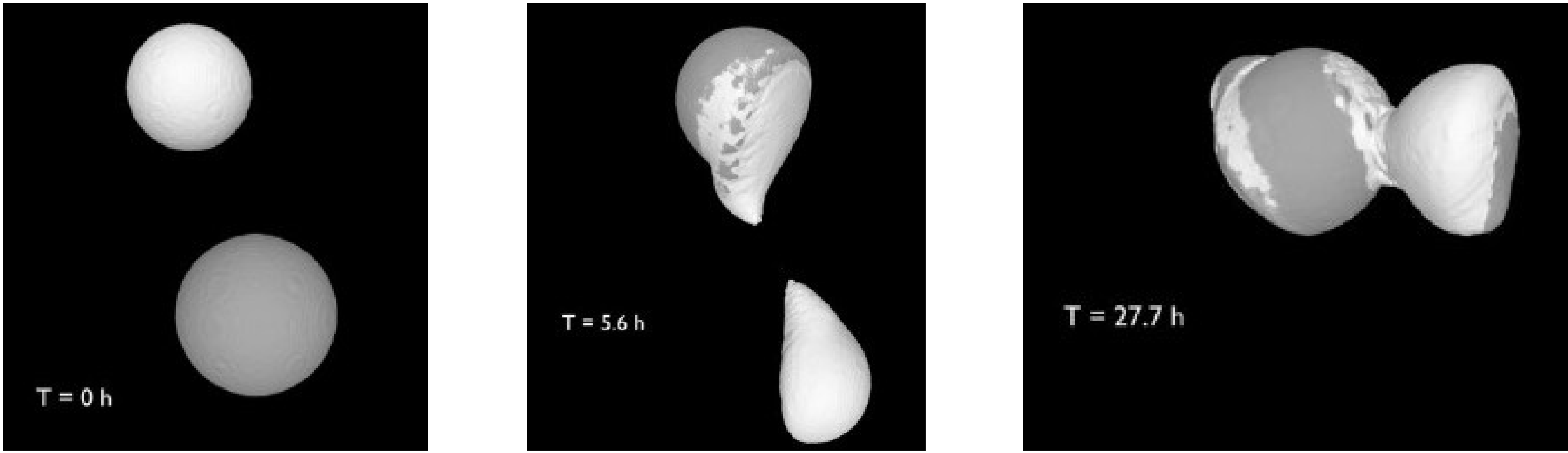


Image credit: Jutzi & Asphaug (2015, *Science* **348**, 1355)

- Standard model (Nice + Primordial Disk population from JFCs) predict 67P is a collisional rubble pile (Brasser & Morbidelli 2013, *Icarus* **225**, 40; Morbidelli & Rickman 2015, *Astron. Astrophys.* **583**, A43; Rickman *et al.* 2015, *Astron. Astrophys.* **583**, A44)
- SPH models of pre-67P parent yield daughter with bilobate shape, cool material, high porosity (Jutzi *et al.* 2017, *Astron. Astrophys.* **597**, A61; Jutzi & Benz 2017, *Astron. Astrophys.* **597**, A62)

- Standard model: collisional cascade starts at much larger sizes where heating and volatile loss are problematic

Collisional rubble pile: what we need (I)

- Model disruption and heating of *entire* collisional chain to obtain *temperatures of parents at all levels, size distribution and porosity of all escaping fragments*
- Couple collision models with thermophysical models including sublimation and gas diffusion to *evaluate level of supervolatile loss*
- SPH models currently use ~50 m resolution and assume 40% macroporosity during reassembly that balances compression of rubble. *Increase resolution and explicitly model reassembly to obtain predictions on void space distribution, porosity, properties of potential layering*
- Model tidal disruption and reassembly and *quantify differences and similarities with collisional rubble piles.*

Image credit: NASA, ESA, H. Weaver, E. Smith (STScI)

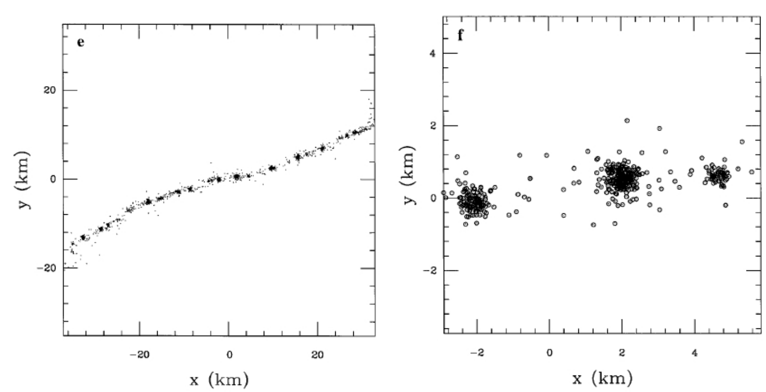


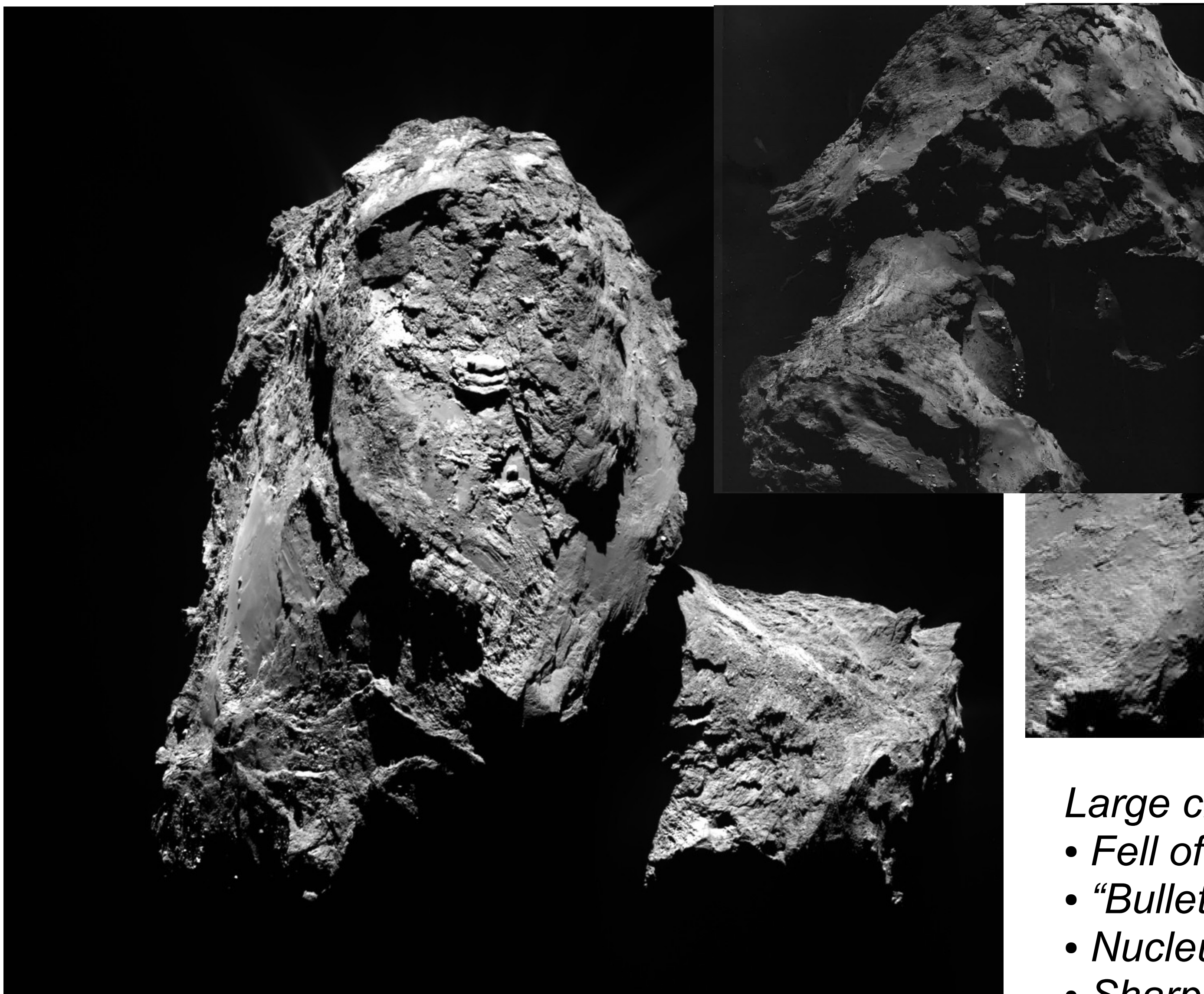
Image credit: Asphaug & Benz (1996, *Icarus* **121**, 225)

Collisional rubble pile: what we need (II)

- CONSERT: continue refinement of upper limit on size of heterogeneities; porosity gradient
- Continuation of CONSERT (e.g. CORE) for global characterization and population diversity
- Flyby large Centaurs and infer Primordial Disk collisional environment from cratering record

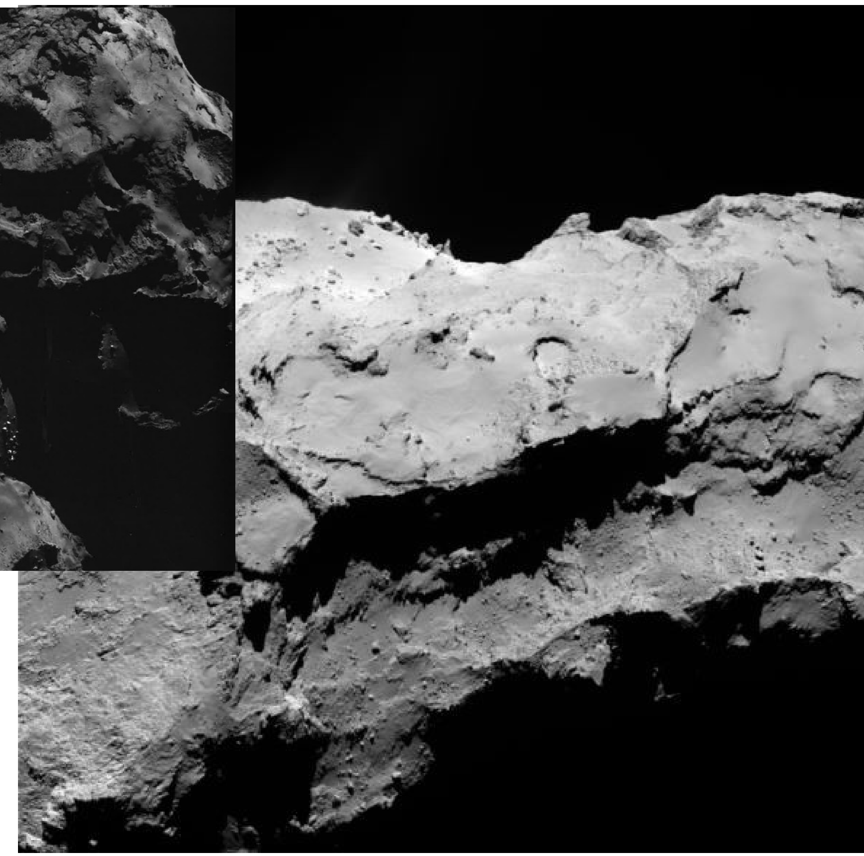
Gaping wounds: large sharp-edged depressions

Khonsu



Seth boundary with Anubis / Atum

Aten “torpedo hole”

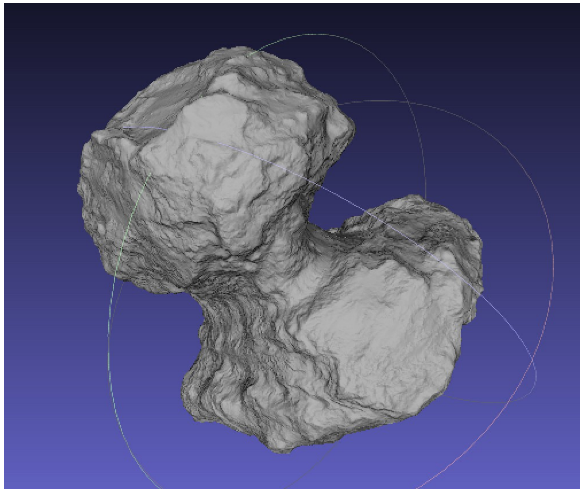


Large chunks have been removed:
- *Fell off when lobes merged?*
- *“Bullet wounds”?*
- *Nucleus splitting?*
- *Sharp edges: recent events?*

Image credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA

Erosion driven by sublimation

We need to understand the long-term and large-scale effects of sublimation, fragmentation, and splitting: it masks everything else



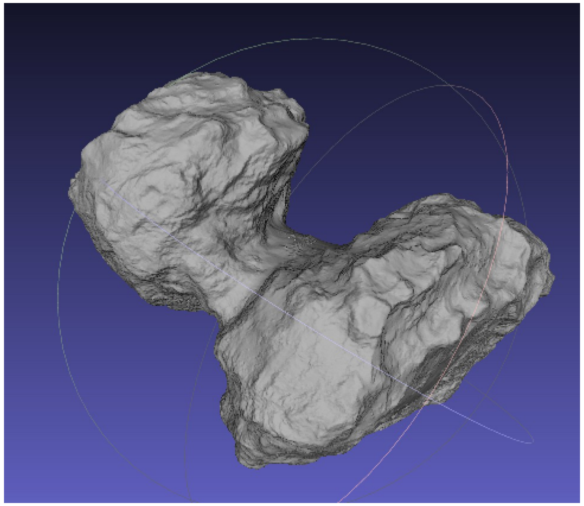
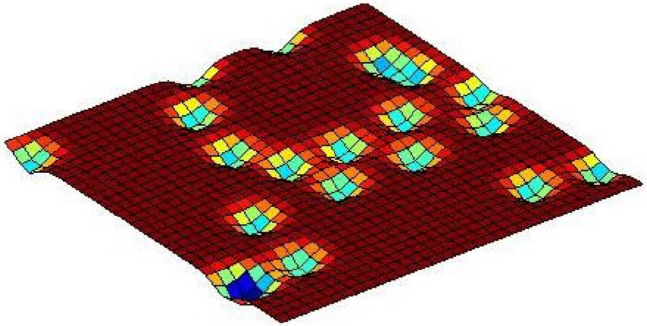
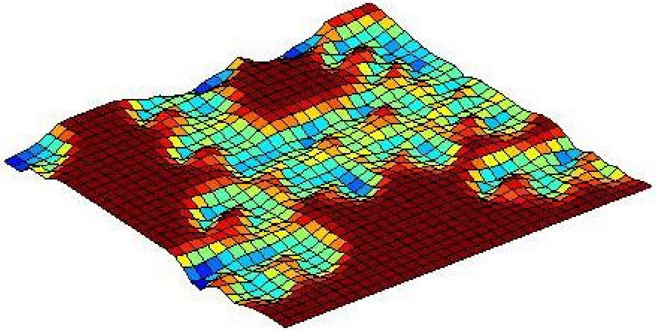


Image credit: Meshlab, Davidsson





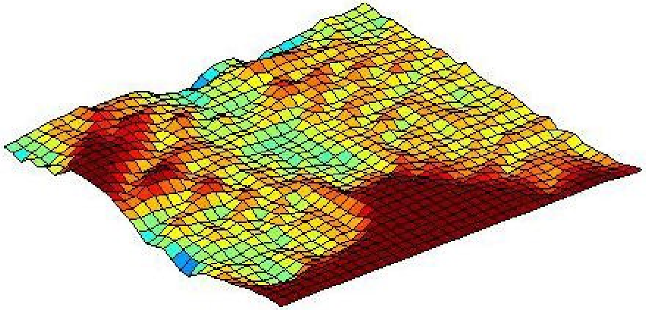


Image credit: Davidsson

Image credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA

The longterm effect of sublimation appears to be flattening of terrain

Erosion driven by sublimation

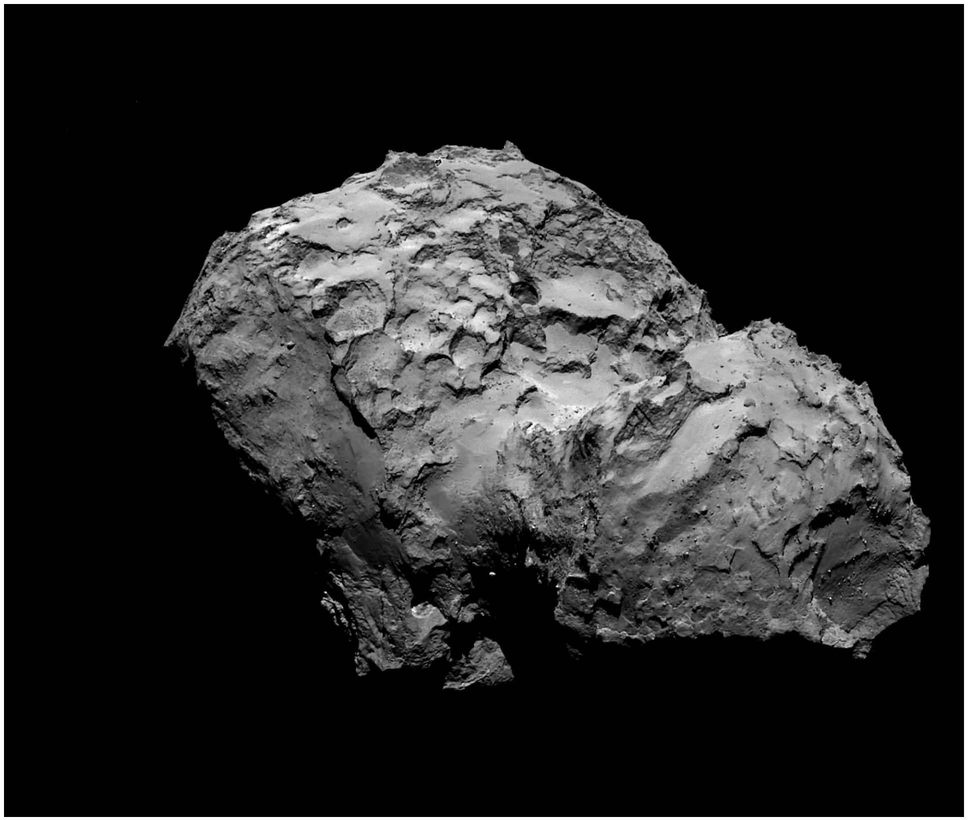


Image credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA

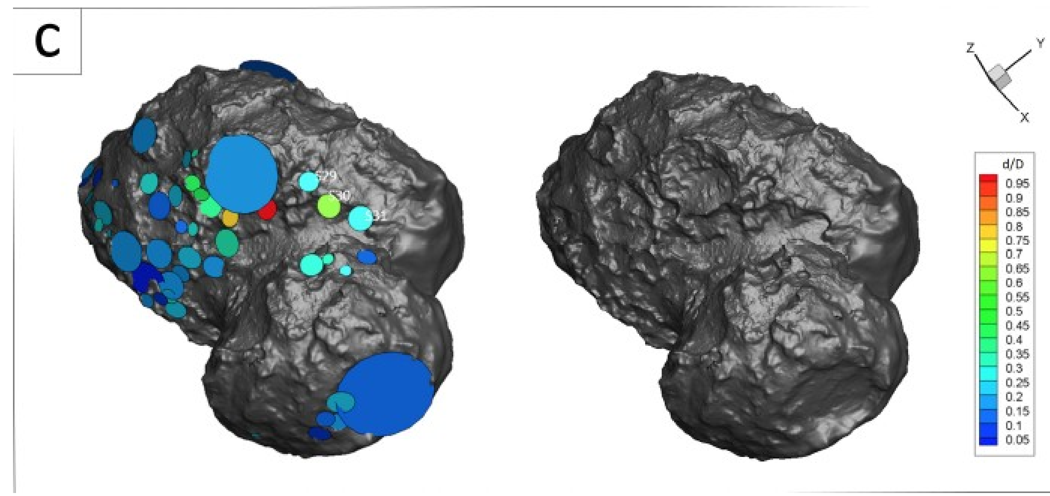


Image credit: Ip *et al.* (2016, *Astron. Astrophys.* **591**, A132)

If so, what is the significance of terraces and circular depressions?

Consolidated material

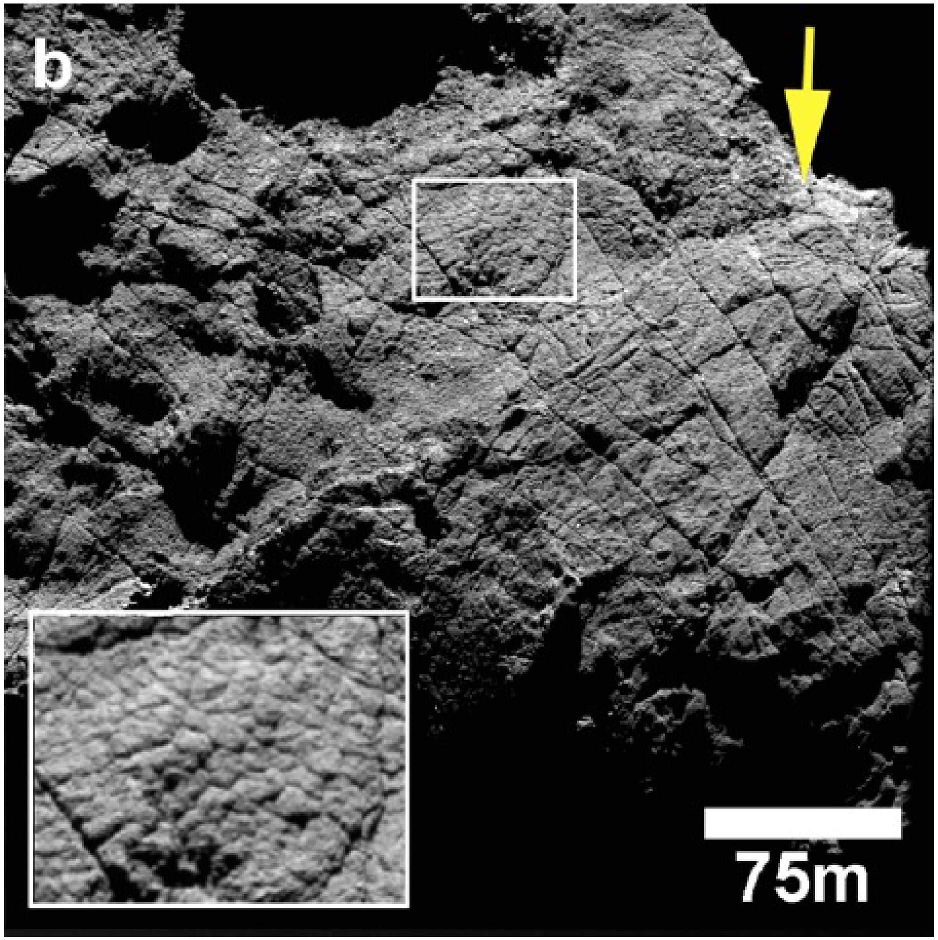


Image credit: El-Maarry *et al.* (2015, *Geophys. Res. Lett.* **42**, 5170)

- Density from radar (surface) and non-gravitational forces (bulk): Davidsson *et al.* (2009, *Icarus* **201**, 335) suggest *near-surface layer of consolidated materia*l
- SESAME, CONSERT, radar: 40-55% porosity in top meter, 75-85% at depth (Lethuillier *et al.* 2015, *Astron. Astrophys.* **591**, A32)
- Consolidated material cracks, some pieces transported from south to northern smooth terrains (Keller *et al.* 2017, *MNRAS* **469**, S357)
- Coma dust porosity, size-distribution unrelated to internal properties

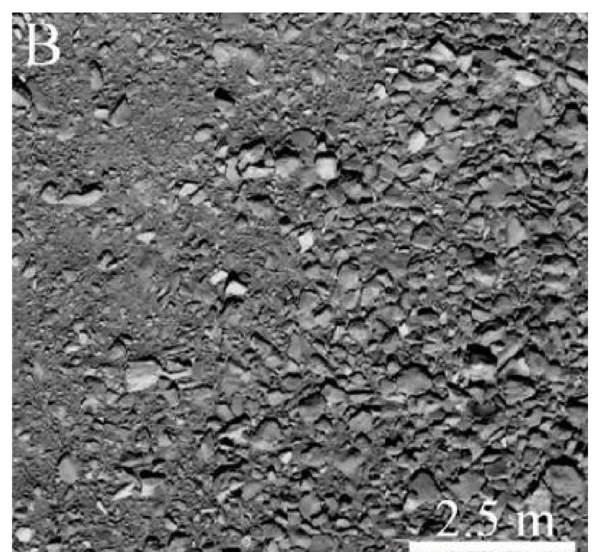


Image credit: Pajola *et al.* (2017, *MNRAS.* **469**, S636)

Solar processing: what we need

- Large sharp-edged depressions
  - Splitting: coupled thermophysical (crystallization, supervolatile gas pressure) and structural (SPH) models, including centrifugal forces
  - *Quantitative predictions on <u>shape and depth of depressions</u>*
- Consolidation and fracturing
  - MIRO: how does consolidated material *<u>differ</u>* from freshly exposed material at collapsed cliffs? (RDAP, Davidsson)
  - Laboratory experiments: *<u>why and how</u>* does comet material consolidate? What *<u>properties</u>* are needed to develop cracks?
  - CAESAR: tensile, compressional, shear strength, microstructure (organic sinter necks?) of chunks
- Sublimation and erosion
  - How does sublimation modify comet landscapes? What differences among layers are needed to create terraces?

Conclusions

- We need to figure out how different formation and processing scenarios differ *quantitatively*
- Rosetta data analysis is ongoing and will bring more answers
- We need to be specific (develop testable hypotheses) on how CAESAR and future comet missions may help us solve the origins issue