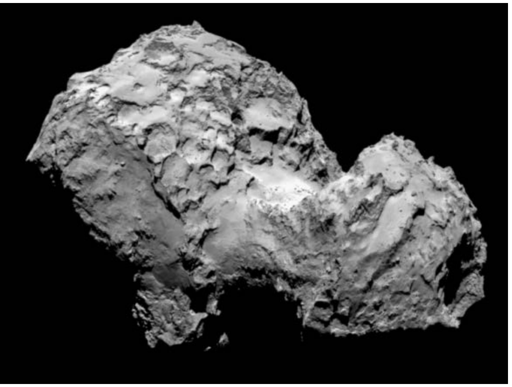
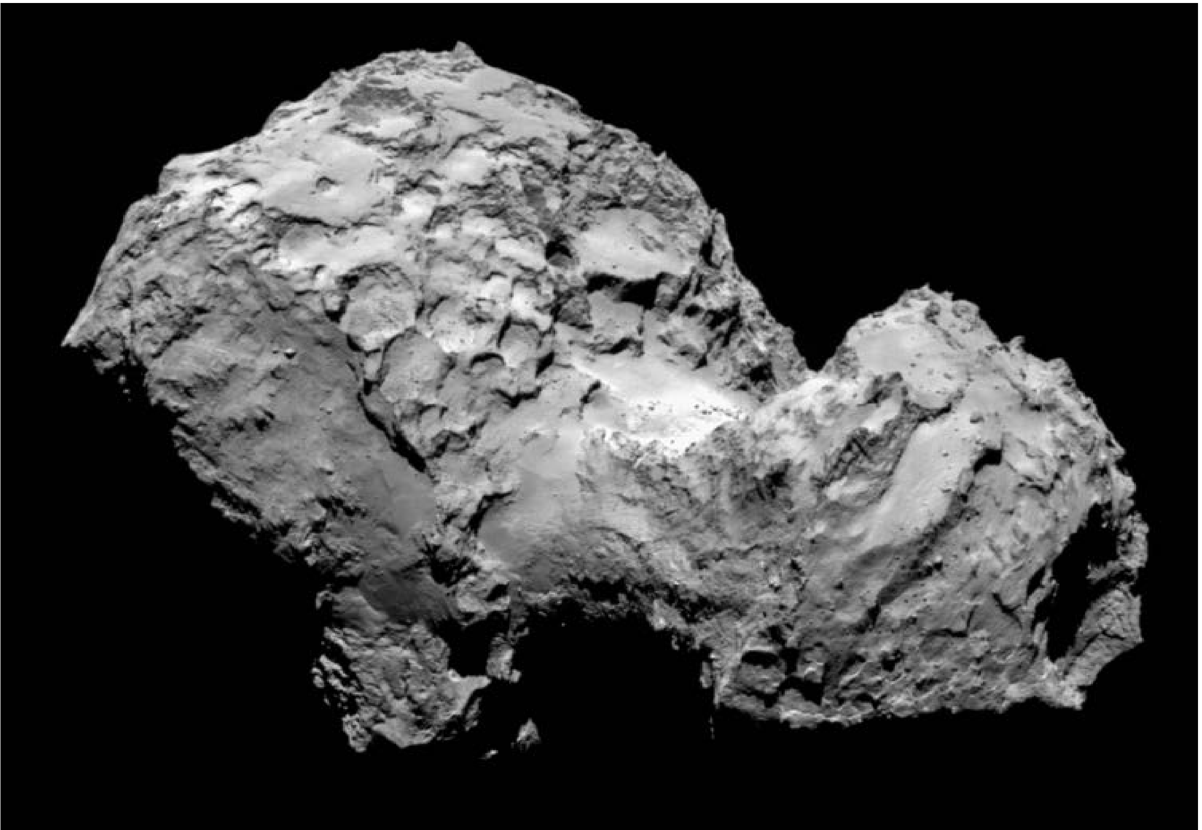
Cometary Science questions: Contribution from Rosetta so far

1. Are comets unchanged from the protoplanetary disk or collisional products from the Kuiper belt?
2. Origin of water on Earth
3. Origin of organic material/ building blocks of life on Earth
4. Structure of the cometary nucleus
5. Cometary activity



Were comets formed in the protoplanetary disk or are they the product of collisions in the Kuiper belt?

- ❑ Main “observable” difference is the impact/collision velocity
    - Heating, evaporation, compaction may be expected
- ❑ No collisional evolution would require modification of theories of solar system evolution



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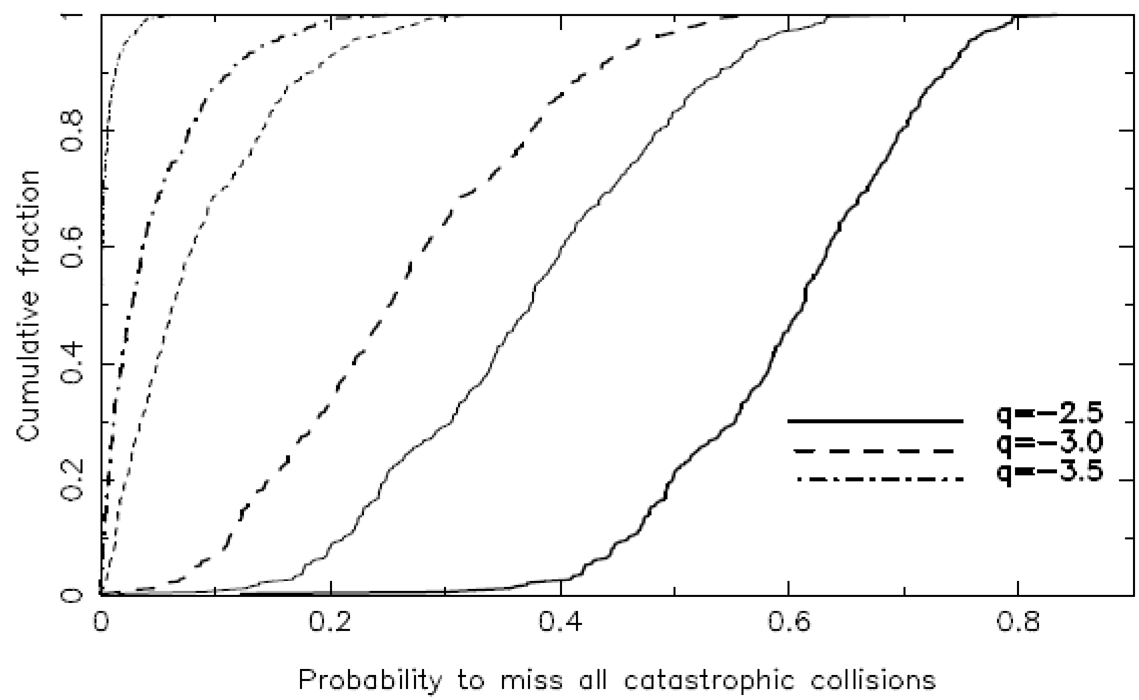
Collisions after formation are expected

- Many comets are likely to be disrupted after the formation
- In particular, many collisions modifying the shape are expected to happen
- Or are the number of small bodies overestimated in current models?
    - ❑ Would require a very steep size distribution in 100m – 1 km size range

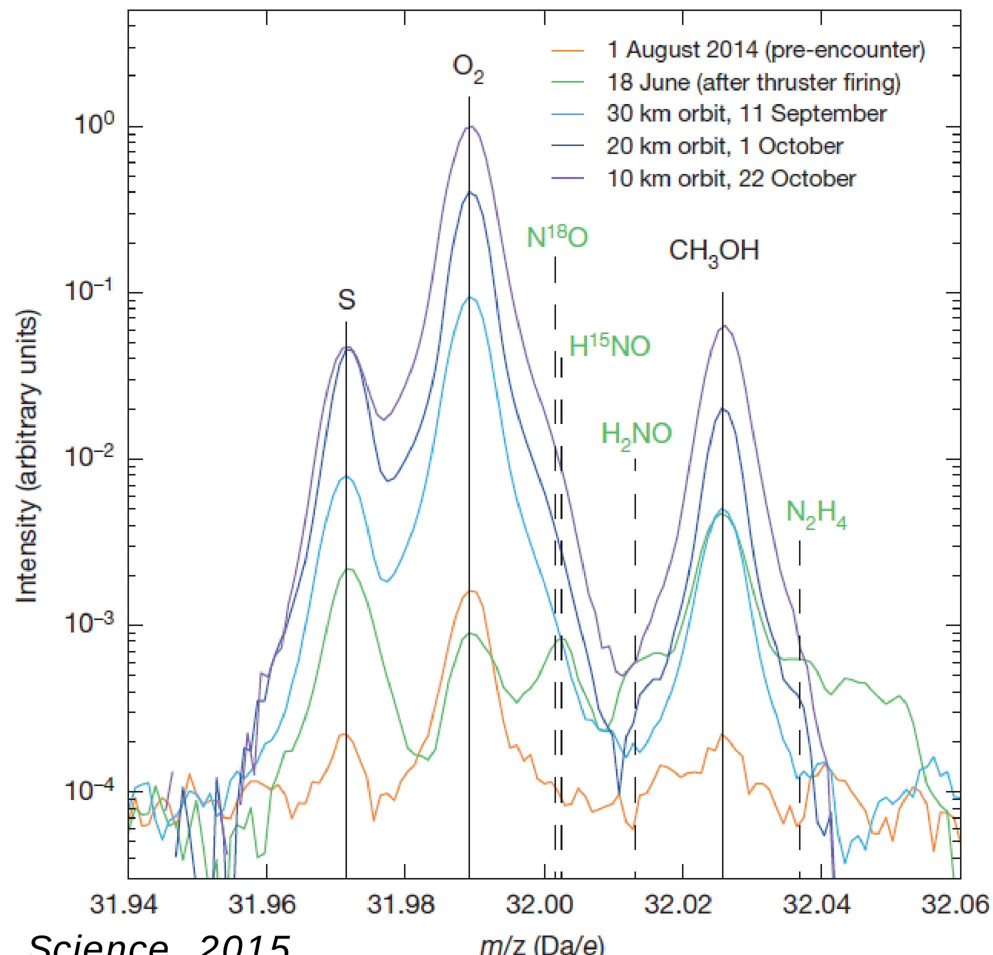


Source: Morbidelli and Rickman 2015

Effects of a high (one or few km / s) velocity collision in the Kuiper belt

- Evaporation of supervolatiles?
  - ❑ CO well known in comets
  - ❑ N_2, noble gases and O_2 detected by Rosetta
- Would those supervolatiles survive collision and reaccumulation?
  - ❑ This is currently being modelled and controversial

ROSINA detection of abundant O_2

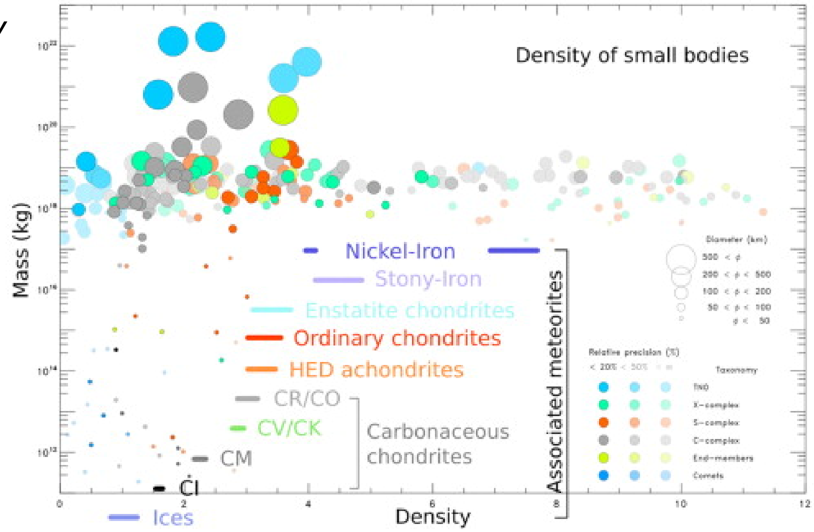


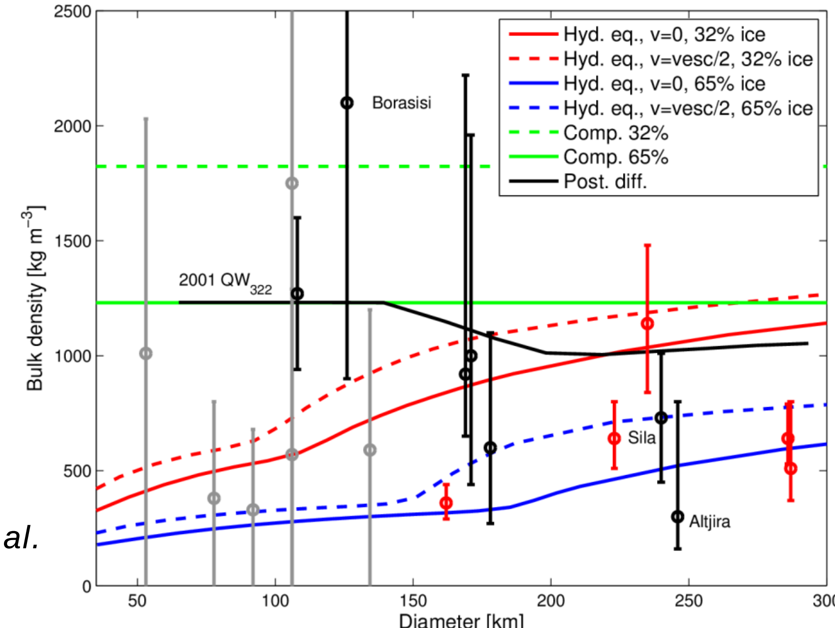
Bieler et al., Science, 2015

Can bodies maintain their low density in high-velocity collisions?

- Density of comets is low ($C/G \sim 530\ kg/m^3$)
- Comparable to that of ~100 km TNOs
- Lower than that of large TNOs
- Can compression be avoided at fast impacts?
- Can all short-period comets origin from medium sized TNOs?

Carry

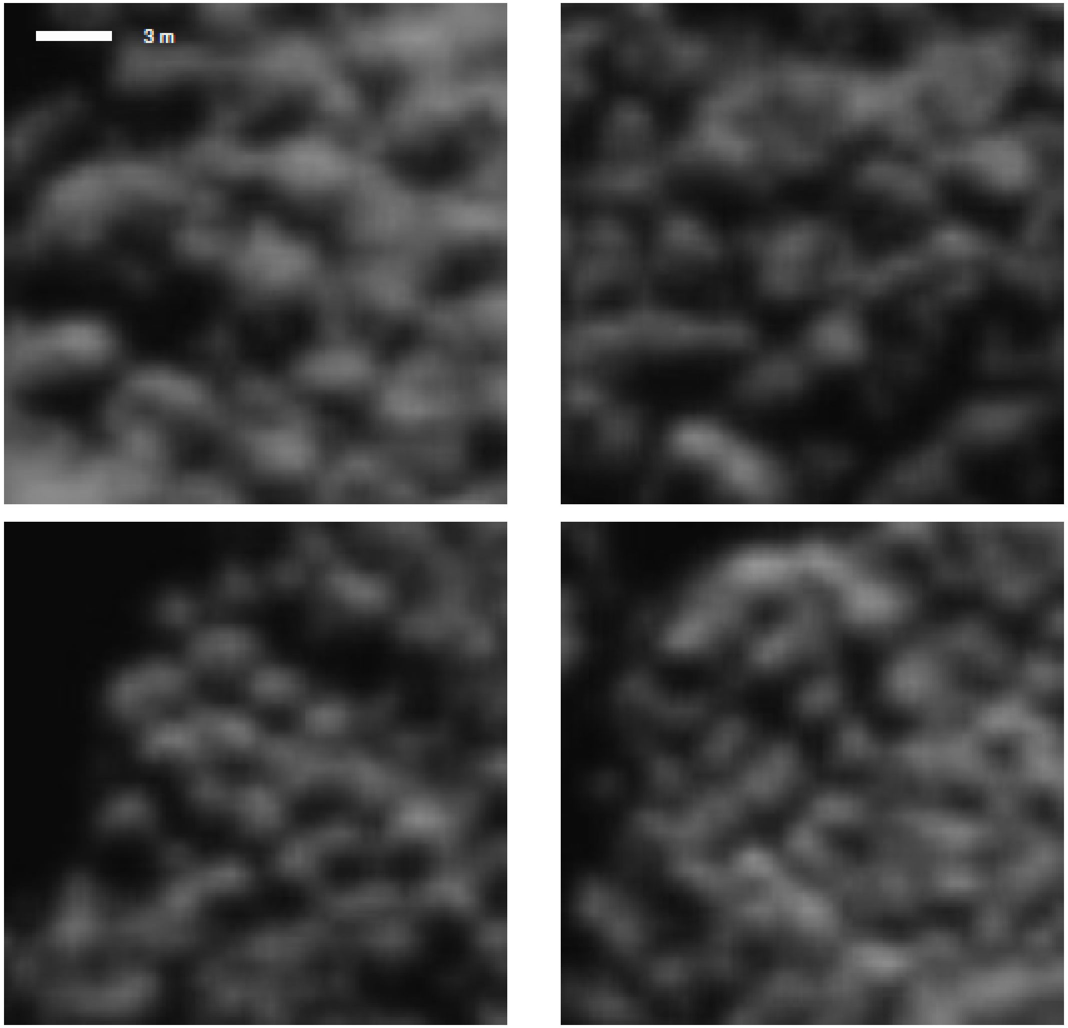




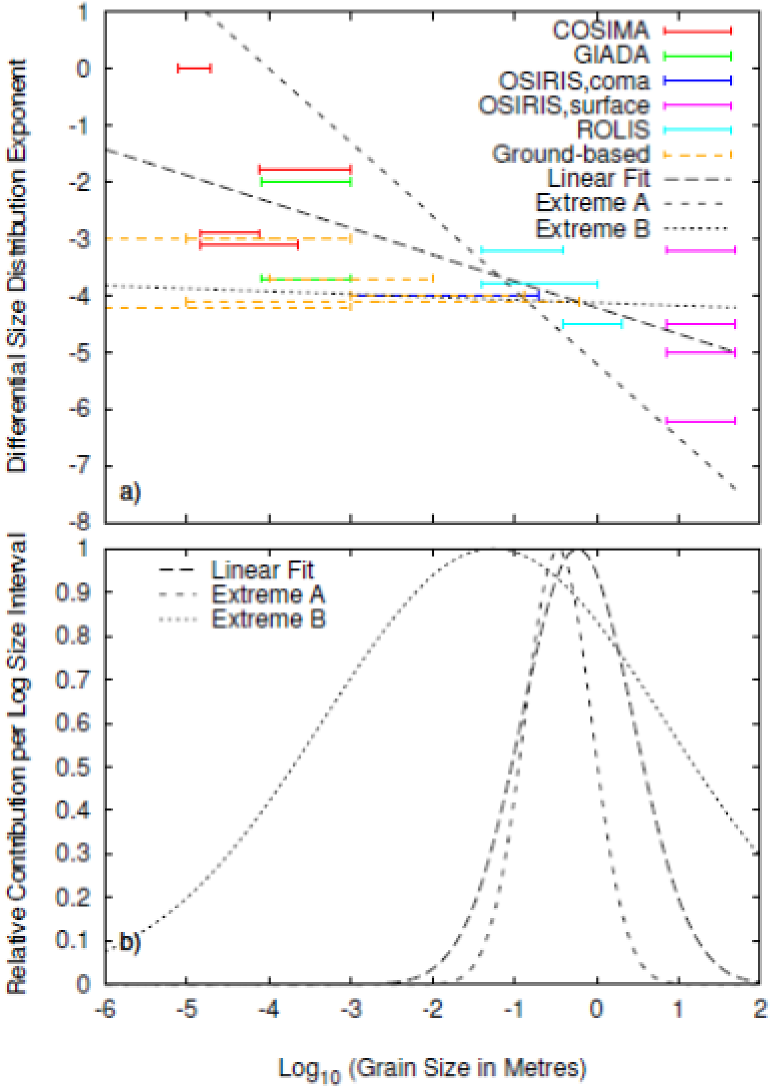
Davidsson et al.

Do we see fundamental building blocks?

meter-sized?

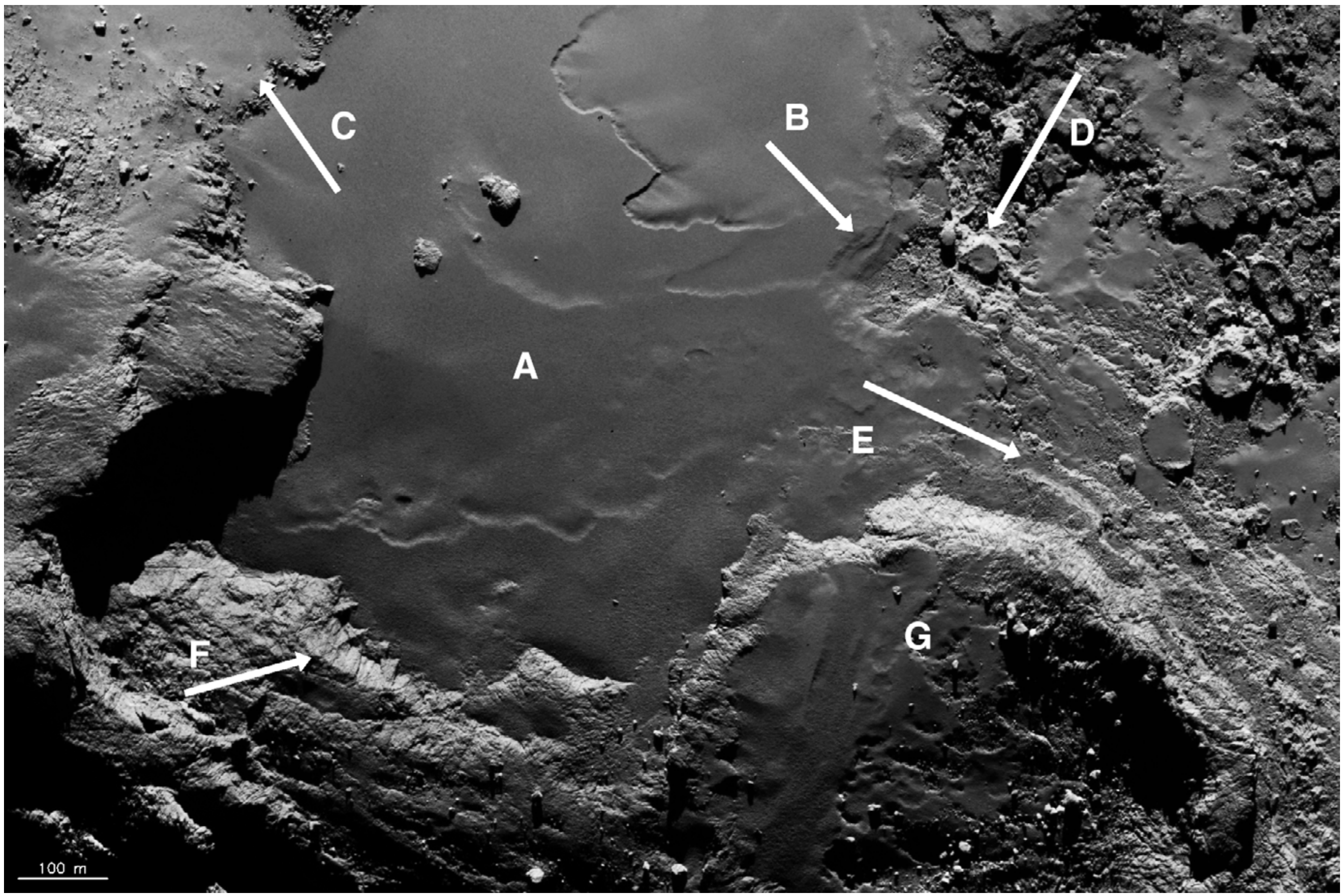


cm-sized ?



How can we distinguish between formation models?

Analysis of “all” geomorphological features on the nucleus



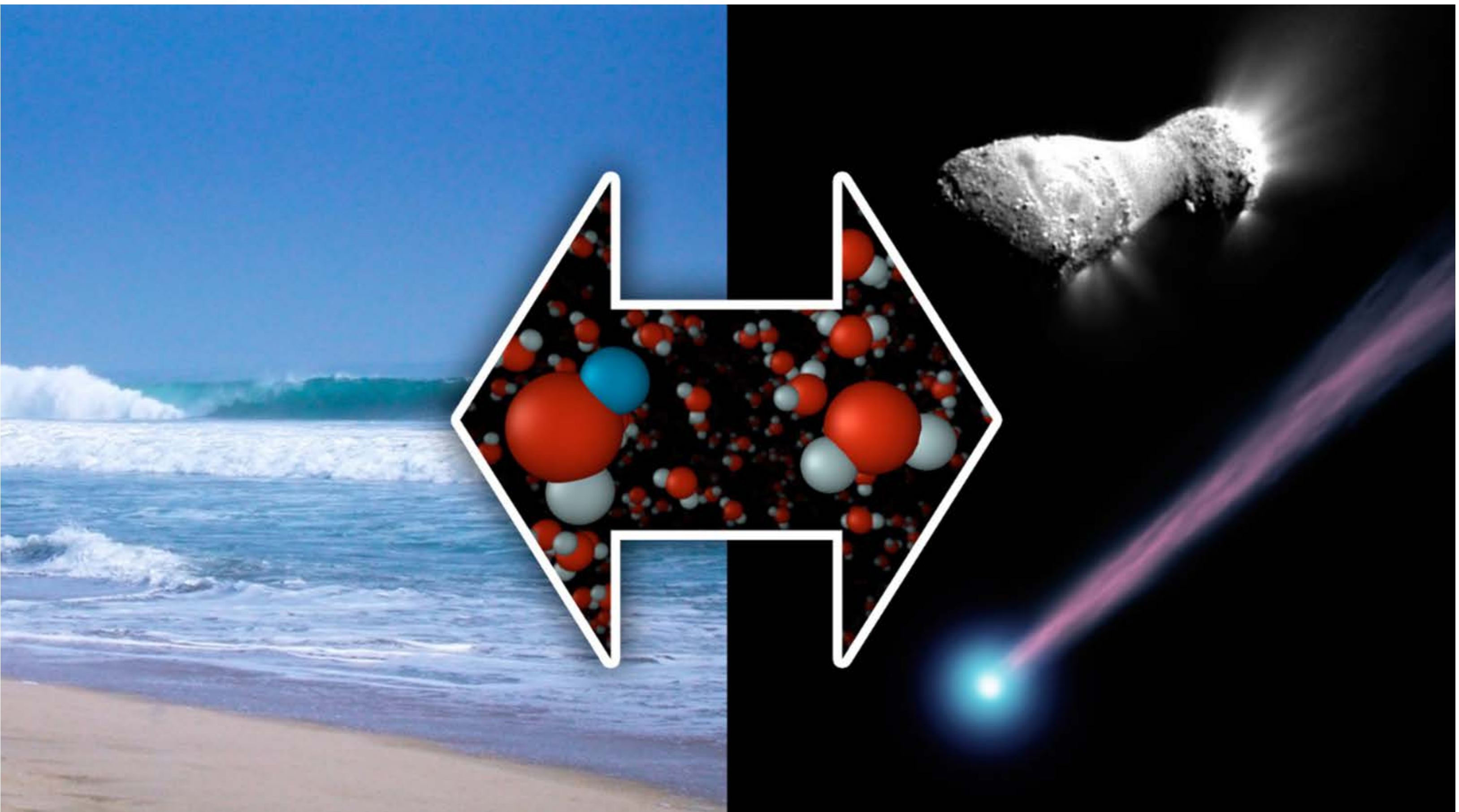
Just in one image:

Smooth terrain (A, C)
Layering (B,E)
Circular structures (D)
Fracturing (F)

Source: Thomas et al. 2015

Did comets bring water and organics to Earth?

- Earth did form inside the snowline
  - ❑ Where does the water come from?



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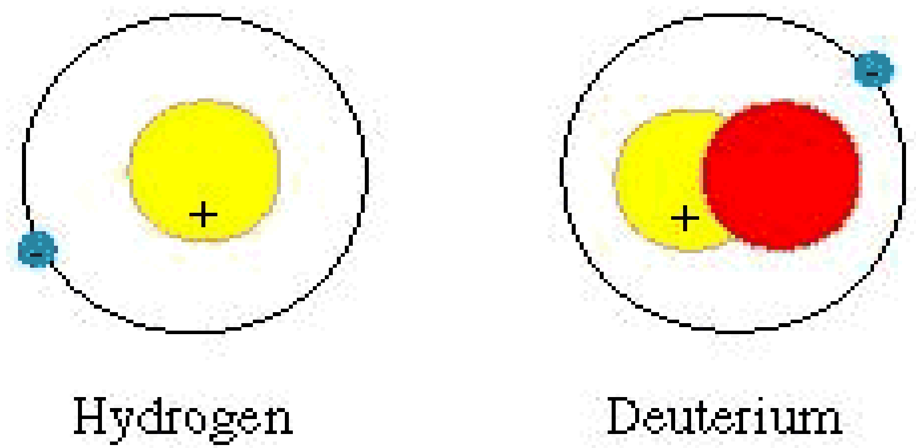
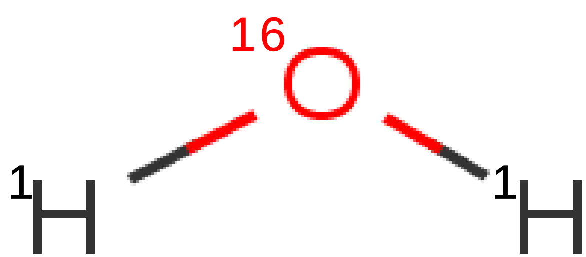
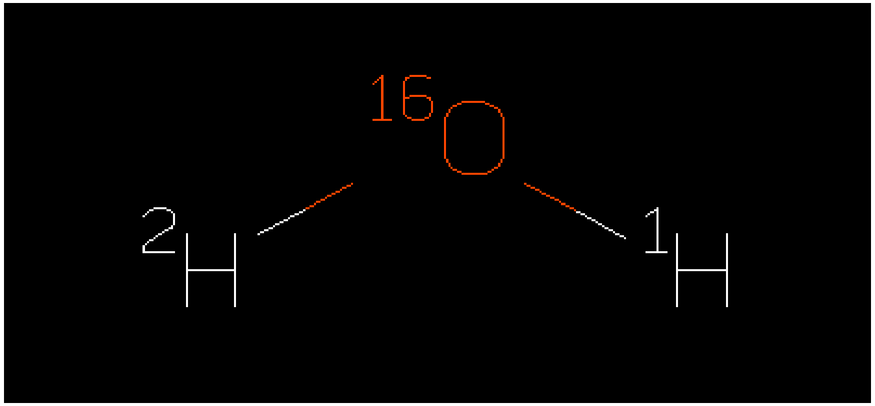
The D/H ratio in water

esa





H_2O



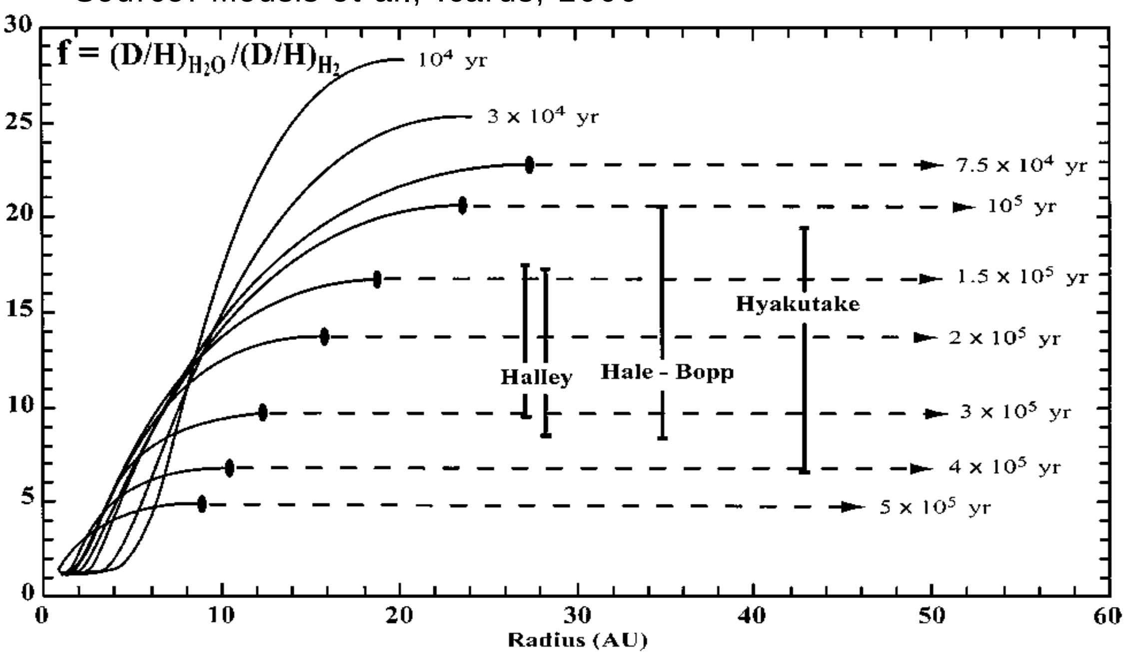
HDO

D/H in the solar system

- Hydrogen: Ratio HD/H_2 has not changed since the formation of the solar system
- Water: Ratio HDO/H_2O ha changed:

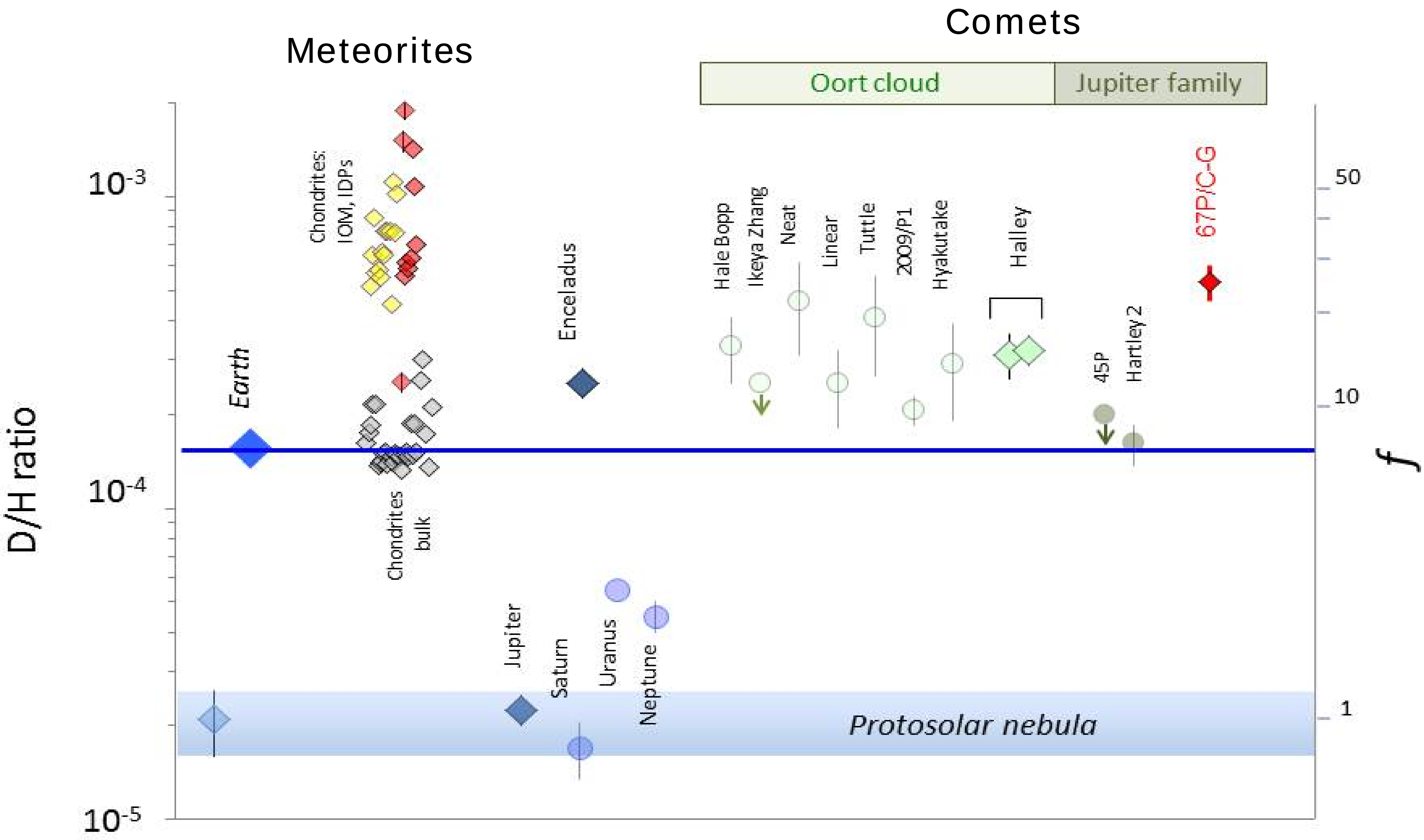
$$HD + H_2O \leftrightarrow H_2 + HDO$$

Source: Mousis et al., Icarus, 2000



Expectation:
Increase of HDO/H_2O with distance from the sun
=> Key point: Relative D/H ratio provides information about source regions

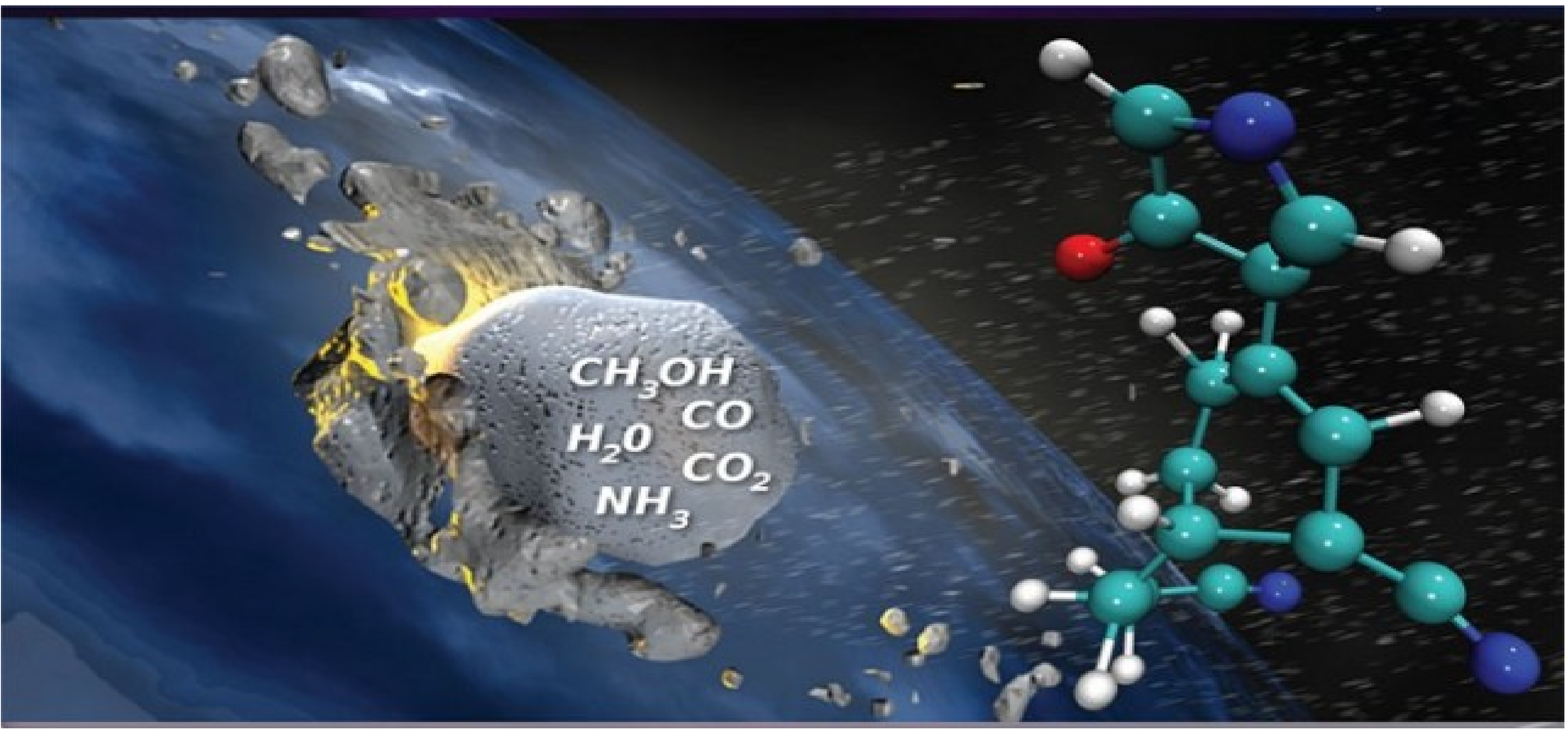
D / H in the solar system (observations)



D / H Conclusions

- Comets like 67P/C-G did not bring the oceans to Earth
- Asteroids are favoured by dynamical arguments as well
  - Comets may still play some role
- D/H varies largely between comets, including between Jupiter-family comets
  - Most straightforward explanation: Jupiter-family comets originate from different source regions

Did comets bring organic material to Earth (building blocks of life)?



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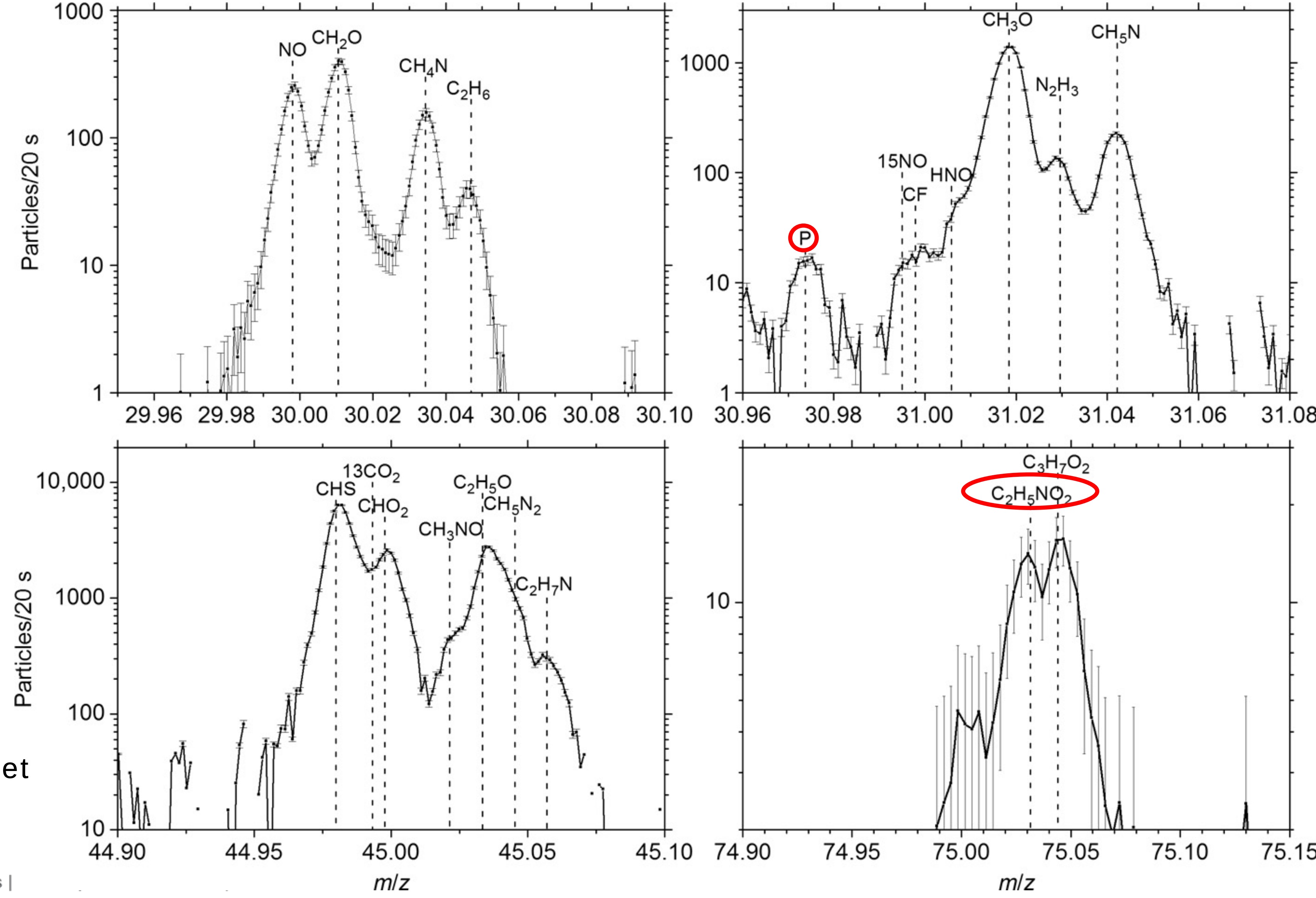
Complex organic molecules + others were found by Rosetta: Orbiter

$C_2H_5NO_2$ = Glycine (Amino Acid)

Phosphorus is an element important for life

Many organic molecules (not yet systematic analysed)

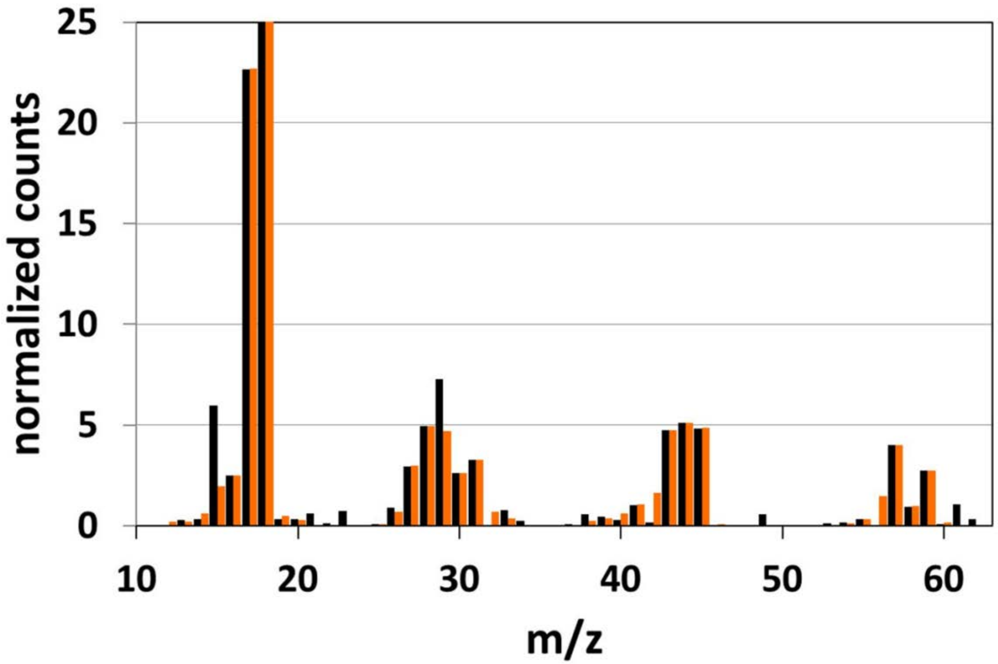


Altwegg et al.

Complex organics found on Rosetta lander (COSAC)

Table 1. The 16 molecules used to fit the COSAC mass spectrum.

Name	Formula	Molar mass (u)	MS fraction	Relative to water
Water	H_2O	18	80.92	100
Methane	CH_4	16	0.70	0.5
Methanenitrile (hydrogen cyanide)	HCN	27	1.06	0.9
Carbon monoxide	CO	28	1.09	1.2
Methylamine	CH_3NH_2	31	1.19	0.6
Ethanenitrile (acetonitrile)	CH_3CN	41	0.55	0.3
Isocyanic acid	HNCO	43	0.47	0.3
Ethanal (acetaldehyde)	CH_3CHO	44	1.01	0.5
Methanamide (formamide)	$HCONH_2$	45	3.73	1.8
Ethylamine	$C_2H_5NH_2$	45	0.72	0.3
Isocyanomethane (methyl isocyanate)	CH_3NCO	57	3.13	1.3
Propanone (acetone)	CH_3COCH_3	58	1.02	0.3
Propanal (propionaldehyde)	C_2H_5CHO	58	0.44	0.1
Ethanamide (acetamide)	CH_3CONH_2	59	2.20	0.7
2-Hydroxyethanal (glycolaldehyde)	CH_2OHCHO	60	0.98	0.4
1,2-Ethanediol (ethylene glycol)	$CH_2(OH)CH_2(OH)$	62	0.79	0.2

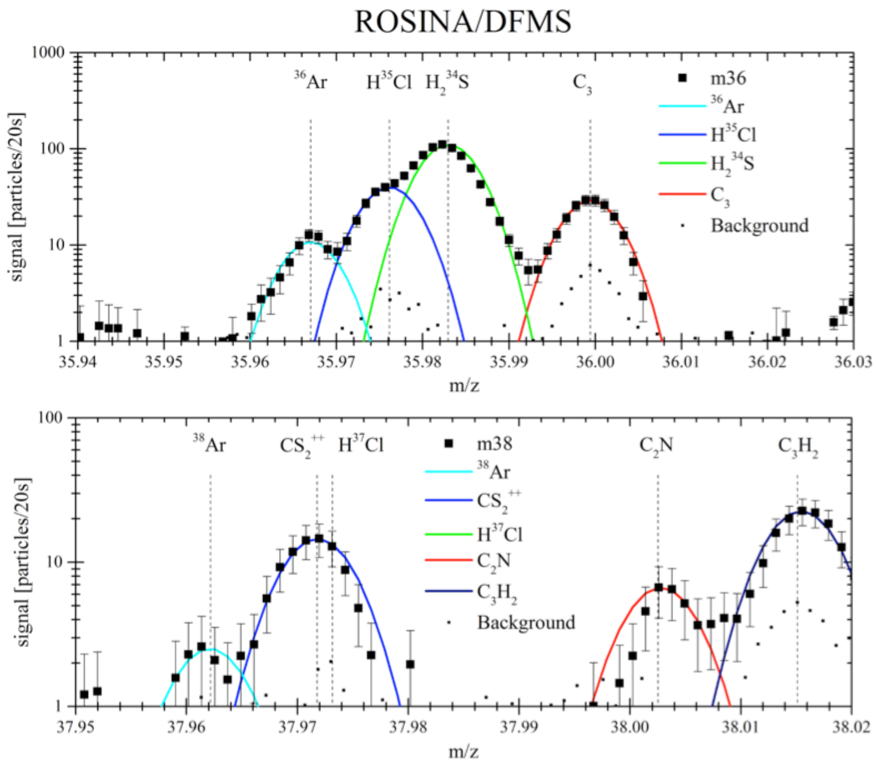


Evidence for complex organics was found in dust collected in the coma as well

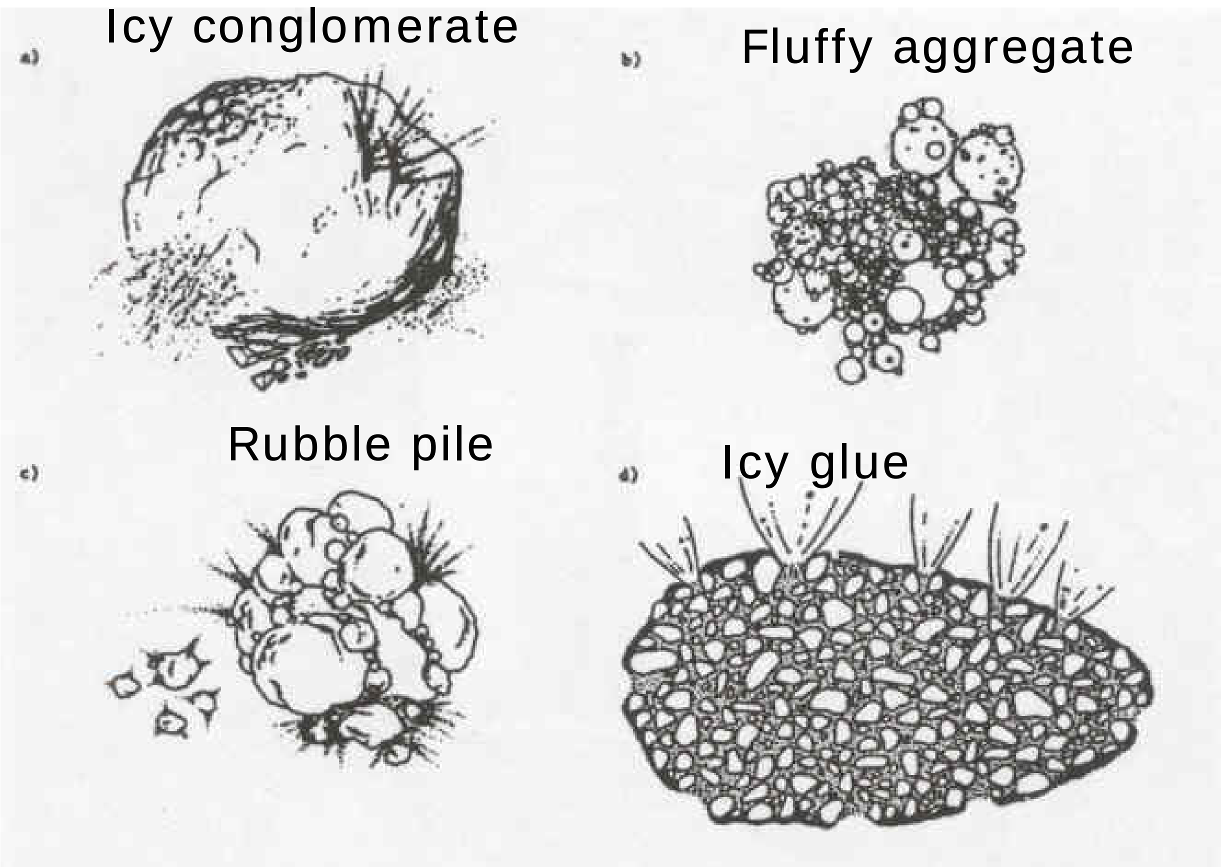
Conclusions (so far): Cometary contribution to early Earth

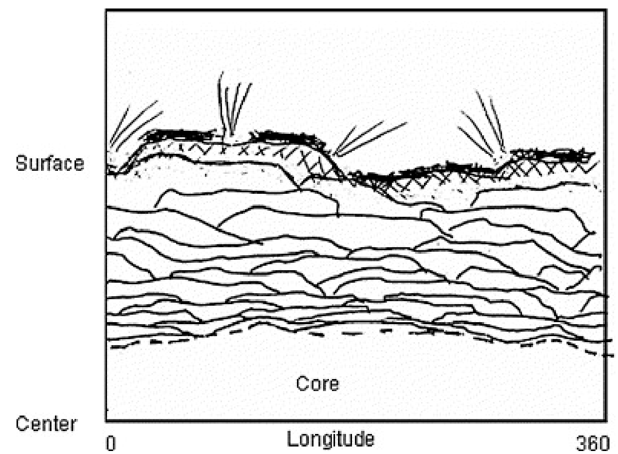
- Cometary contribution to H_2O, C, N negligible
- Cometary contribution may be significant for noble gases, complex organics
- Simplest amino acid (Glycine) may have been contributed
  - Other amino acids not detected so far
  - Probably not present on comets as they may require liquid water to form

Detection of Argon



What is the structure of the nucleus?

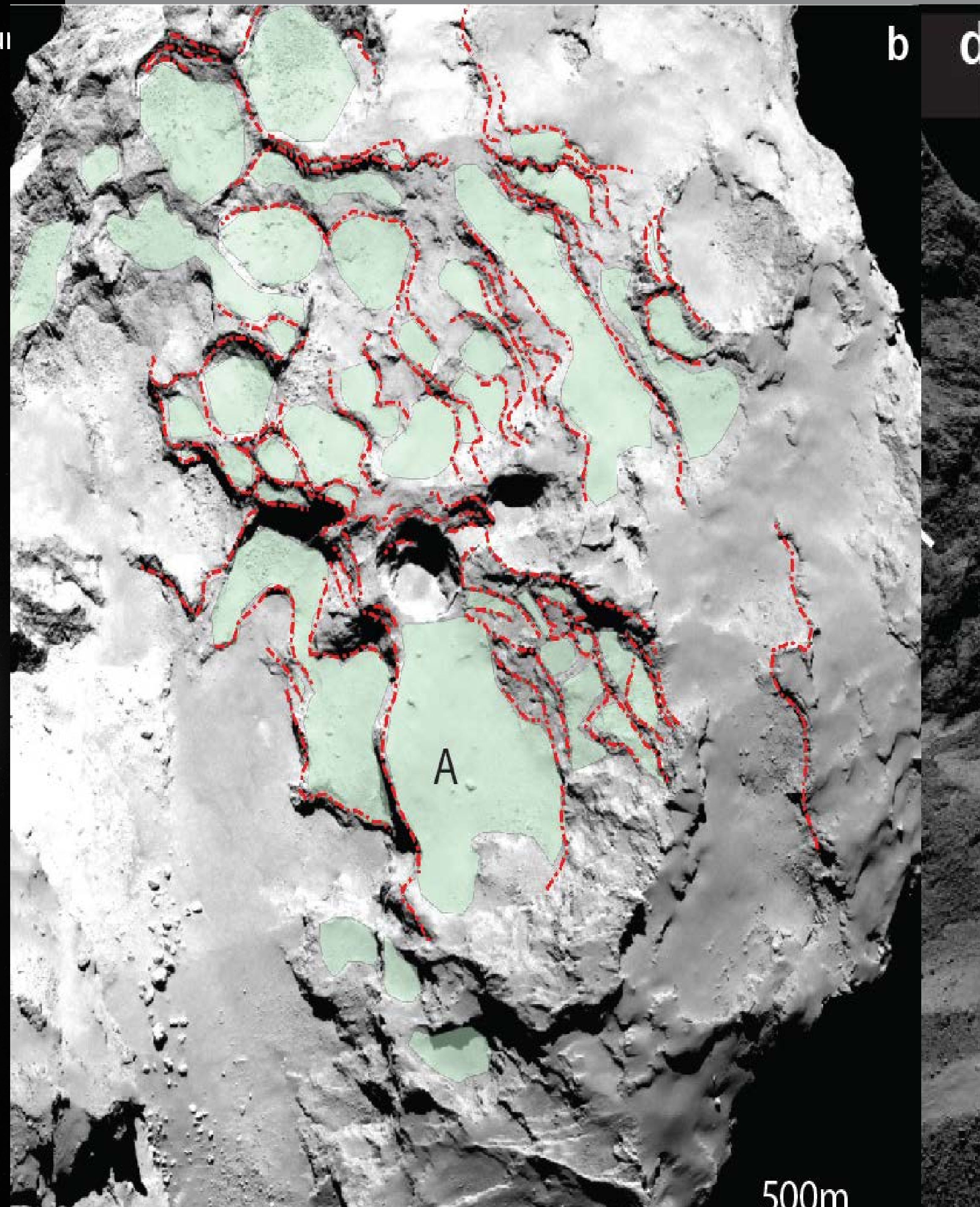




Credit: Belton et al.

Credit: Donn et al., Weissman

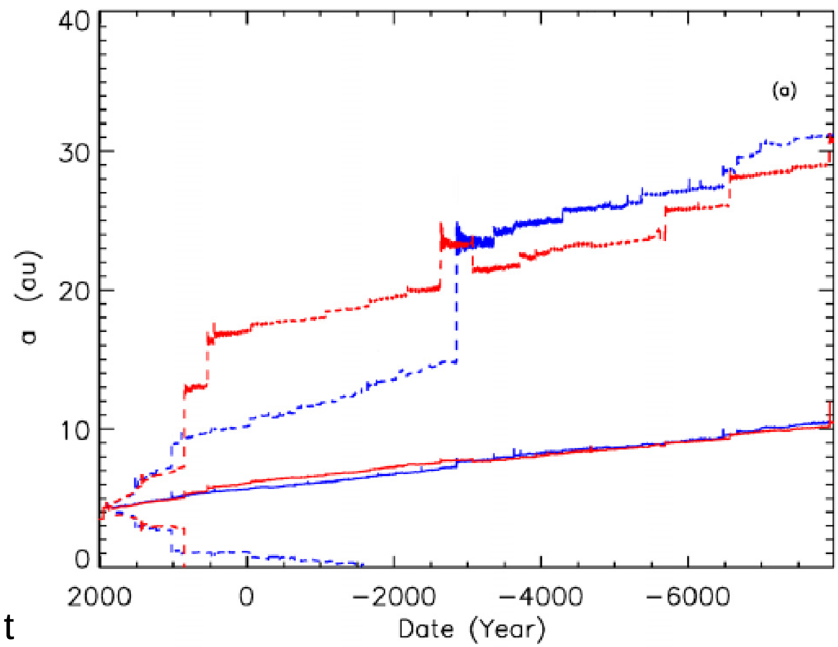
Massironi et al. 2015, Natur



Layers

- Layers were found, but are they primordial or erosional?
- No layering visible in colours
- Modelling required to determine if comet spent enough time close to the sun to acquire its current structure through erosion
  - This is statistical
  - Stability of rotation axis

    and argument of perihelion?



Source: Maquet

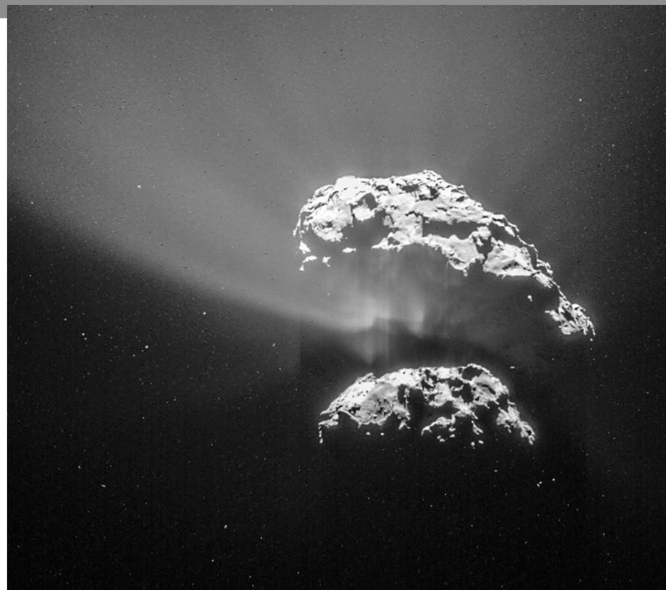
Homogeneity of nucleus

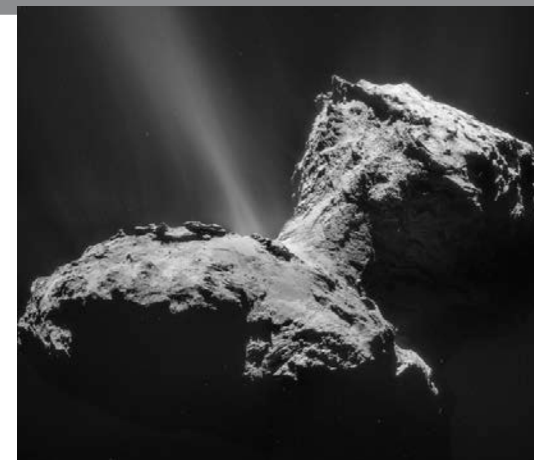
- CONSERT measurements of small lobe show no strong inhomogeinities on 10m scale
  - This may argue for small constituents of the nucleus but is not fully conclusive
- Indication for some global inhomogeneity from Radio science and shape and dynamic modelling
  - Slide density contrast between big lobe and small lobe
  - A few meters shift between centre of mass and centre of figure

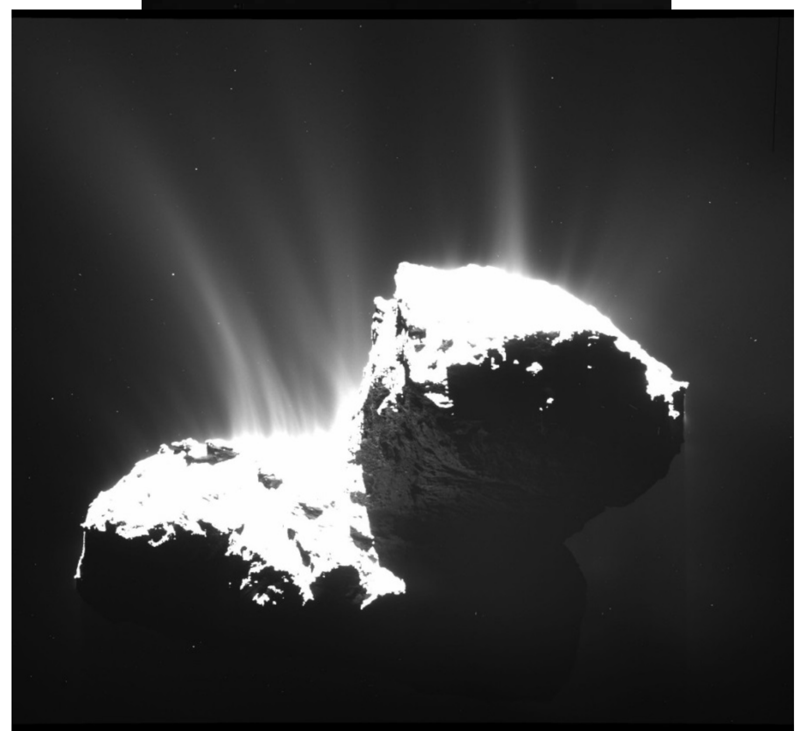
Nucleus structure: Current status

- Dust/ice ratio ~4-5 speaks against original icy snowball model
  - But homogeneous icy dustball is an option
- Overall homogeneity may be evidence for small building blocks
  - But not fully conclusive
- **Distinction between primordial surface features and evolutionary features is needed to make progress**

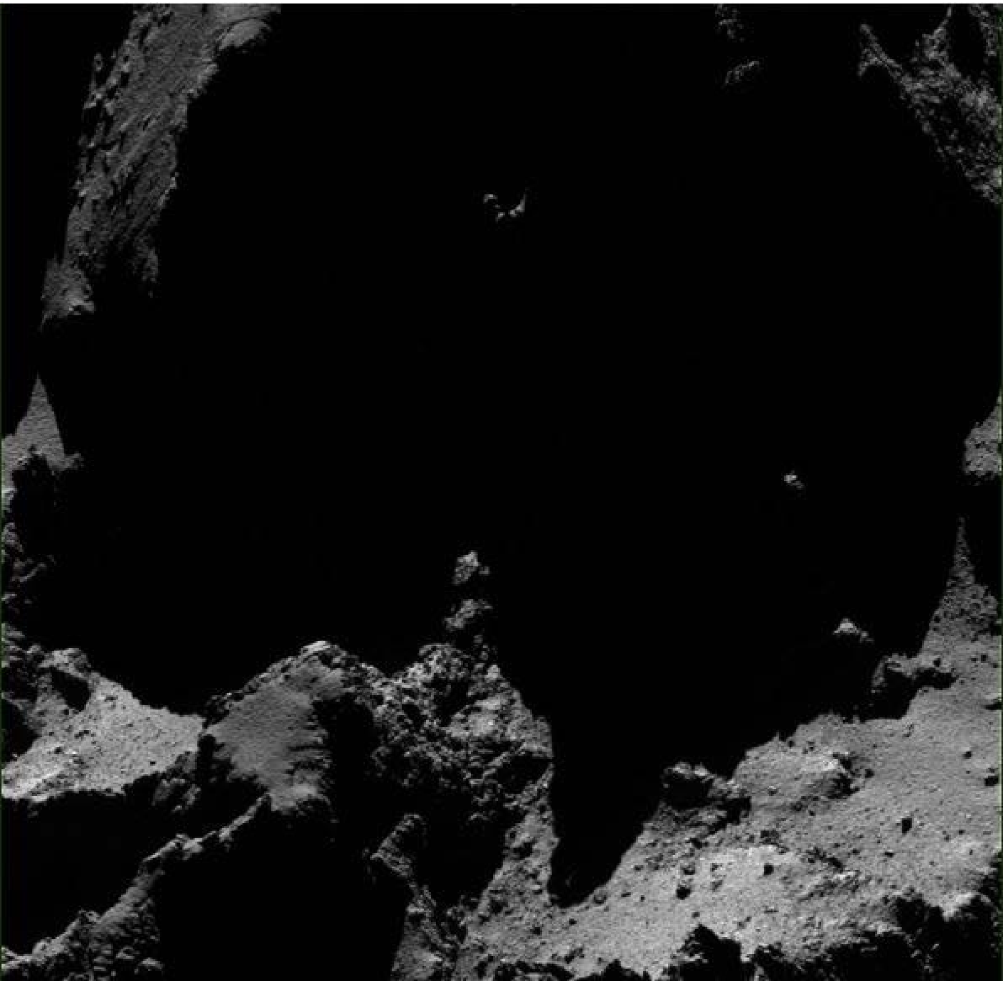
How does cometary activity work?

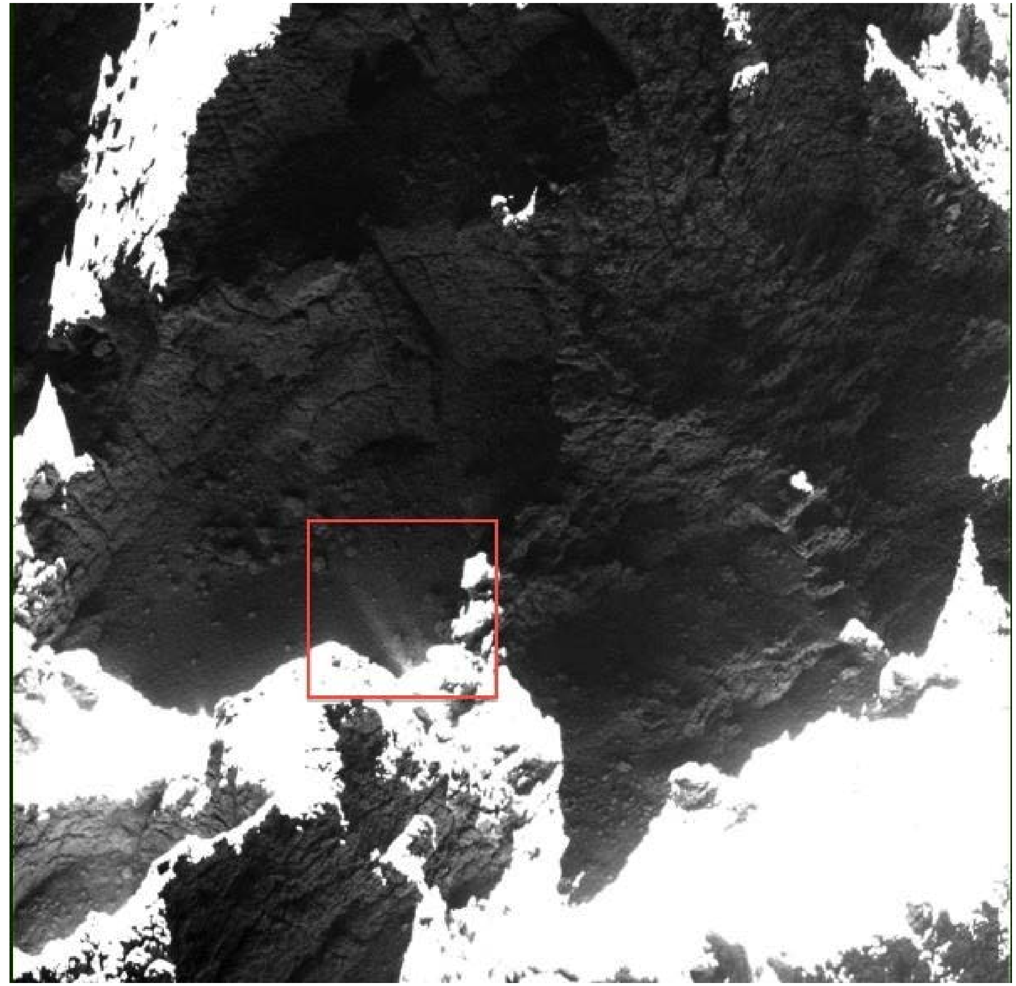




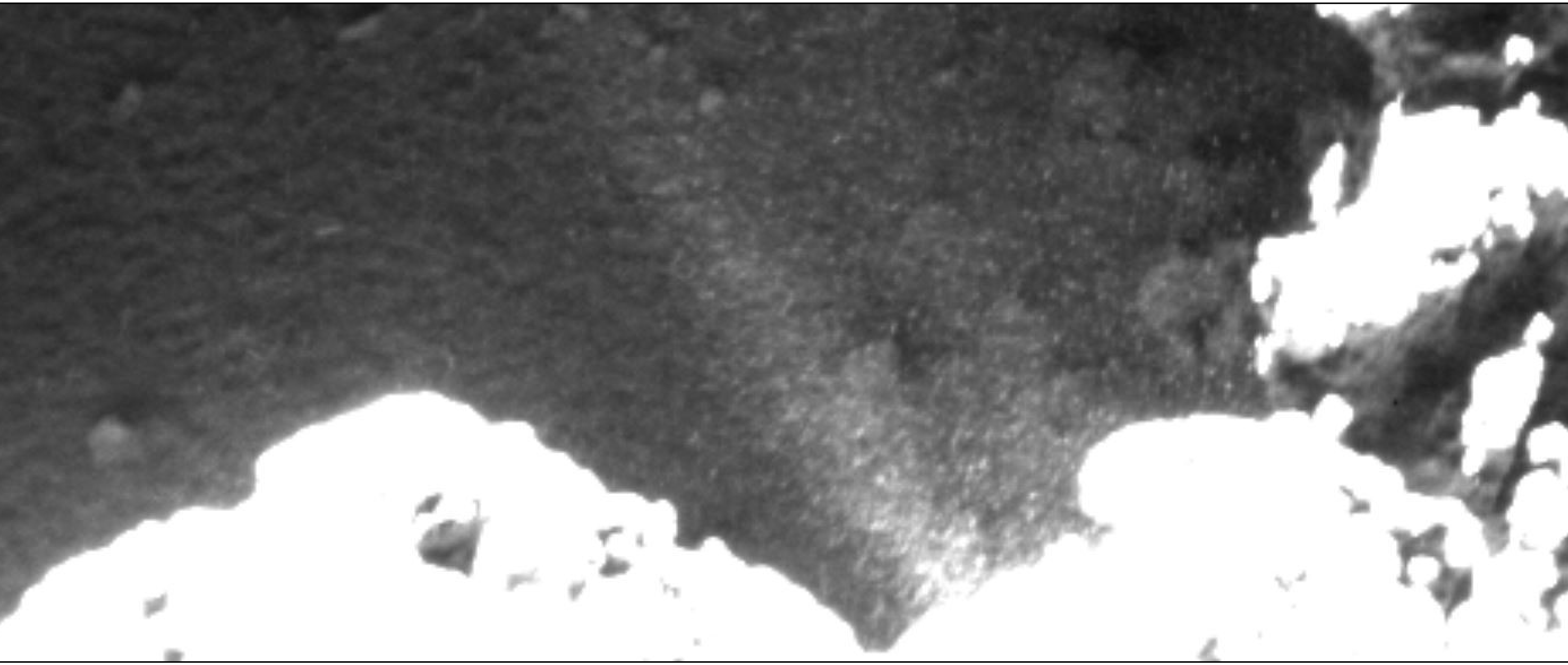


Large Particles: context



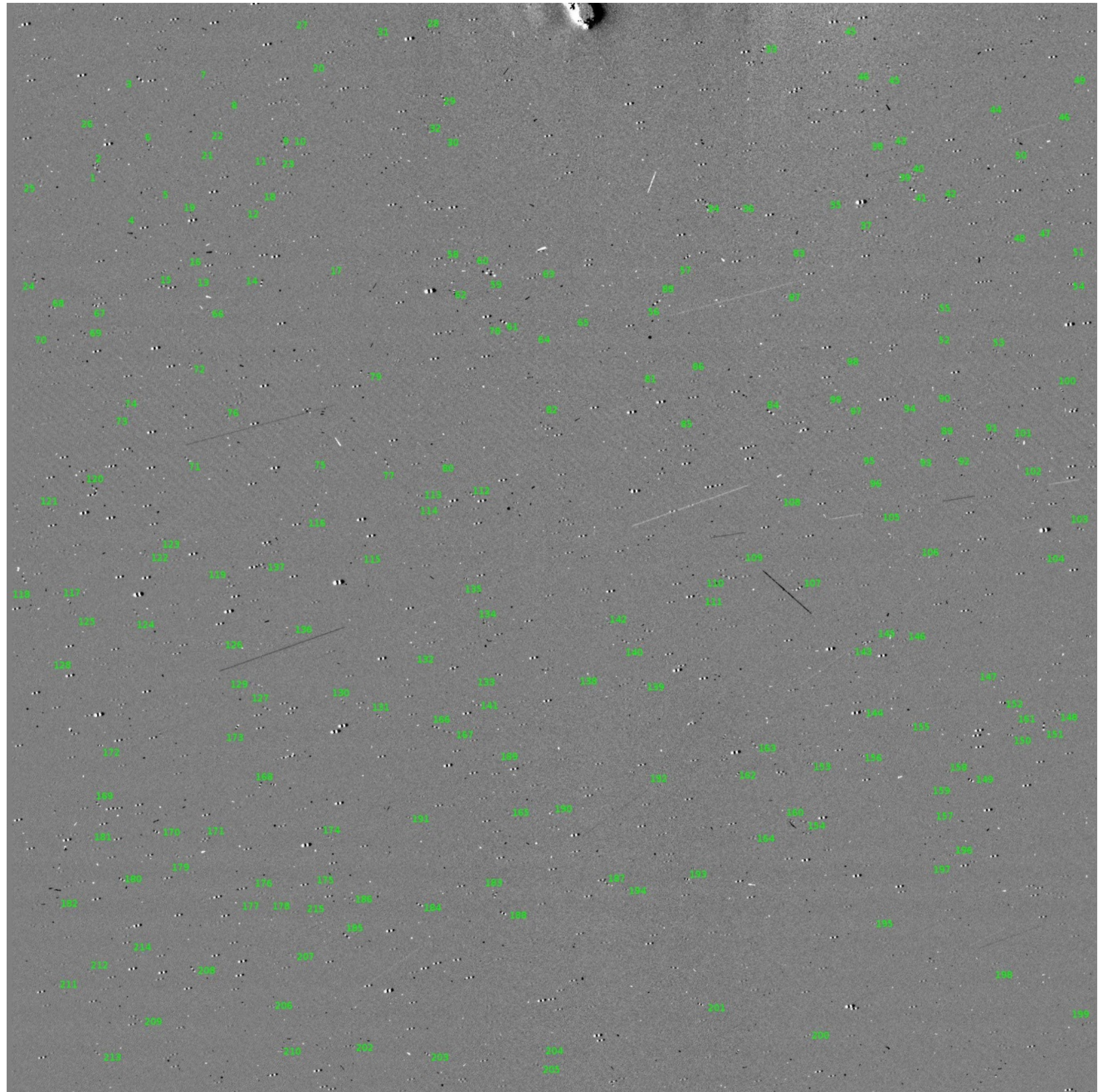


Large particles

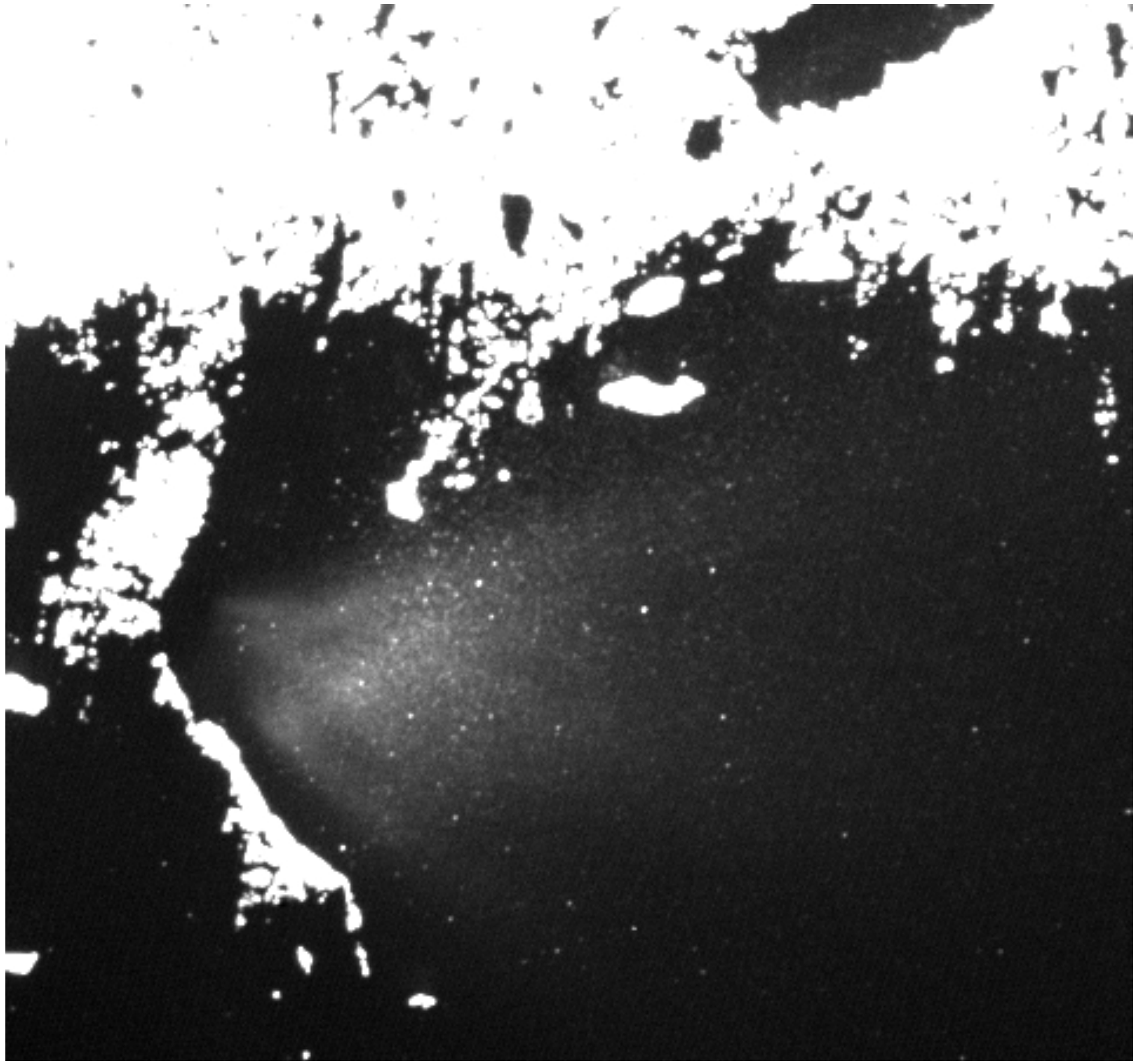


Large individual particles in the coma of the comet

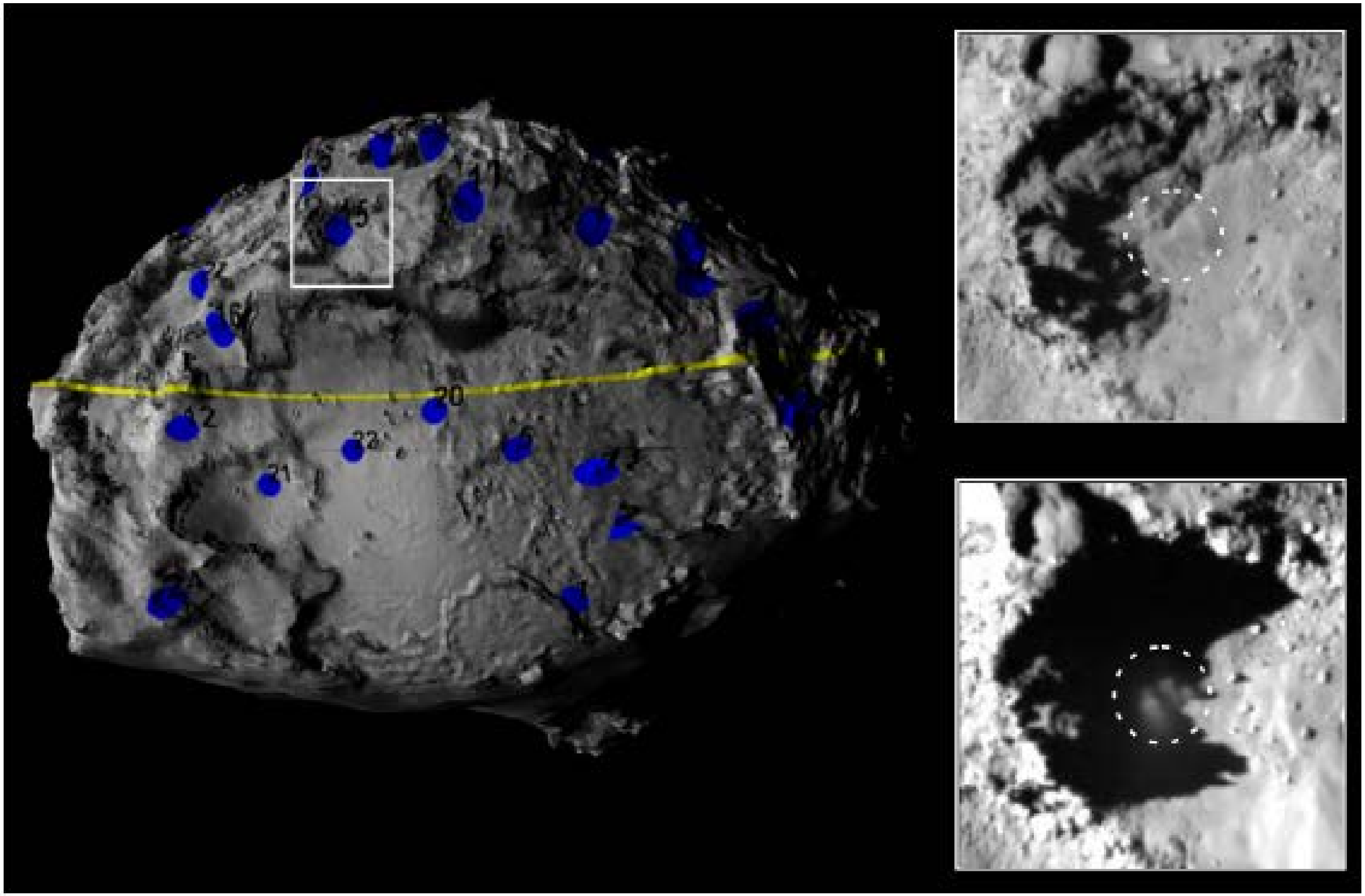
- Many individual particles found on images of the coma
  - Must be large particles
- That was the reason for the star tracker issues on Rosetta!



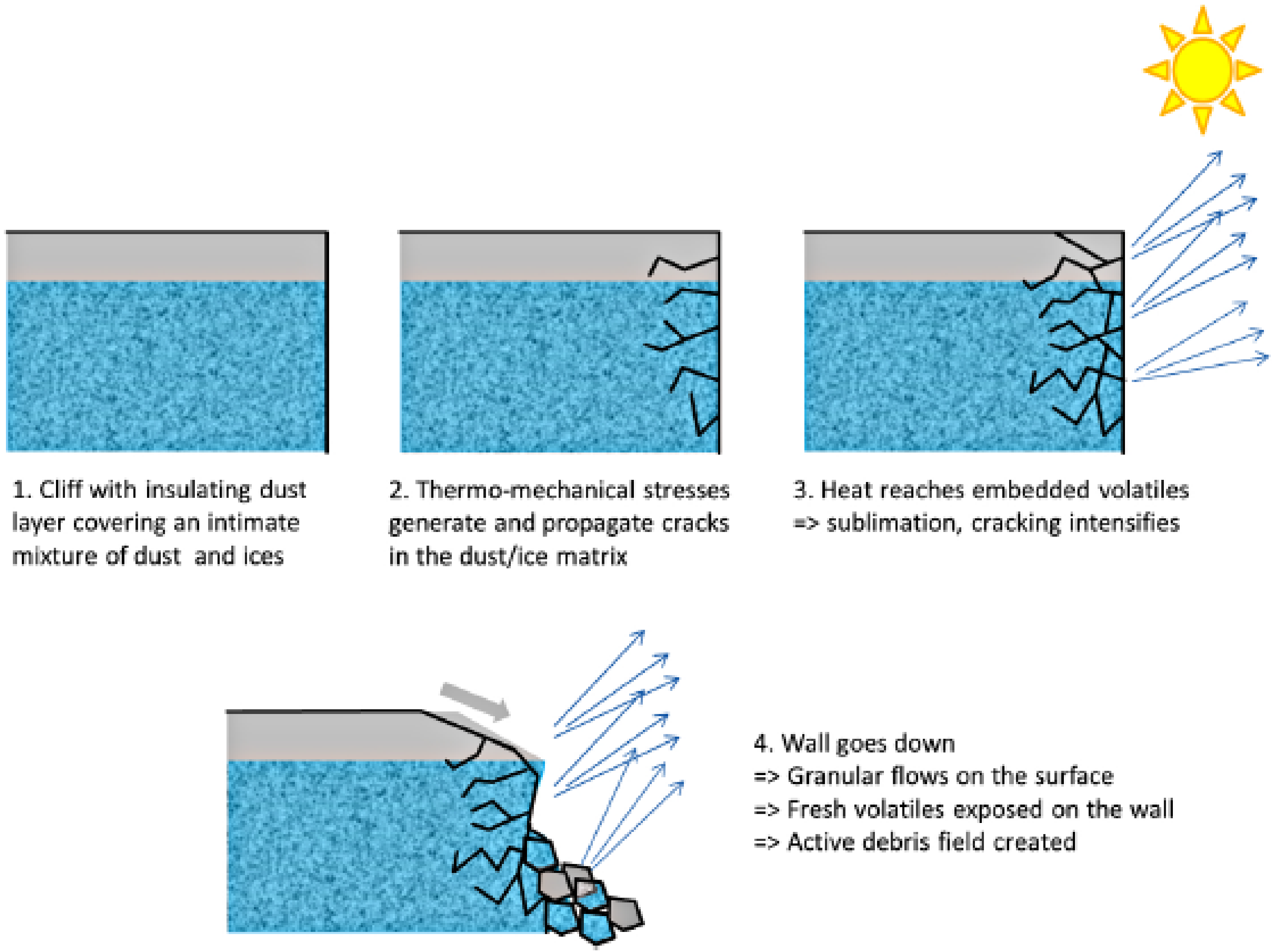
Activity from walls



Activity from walls

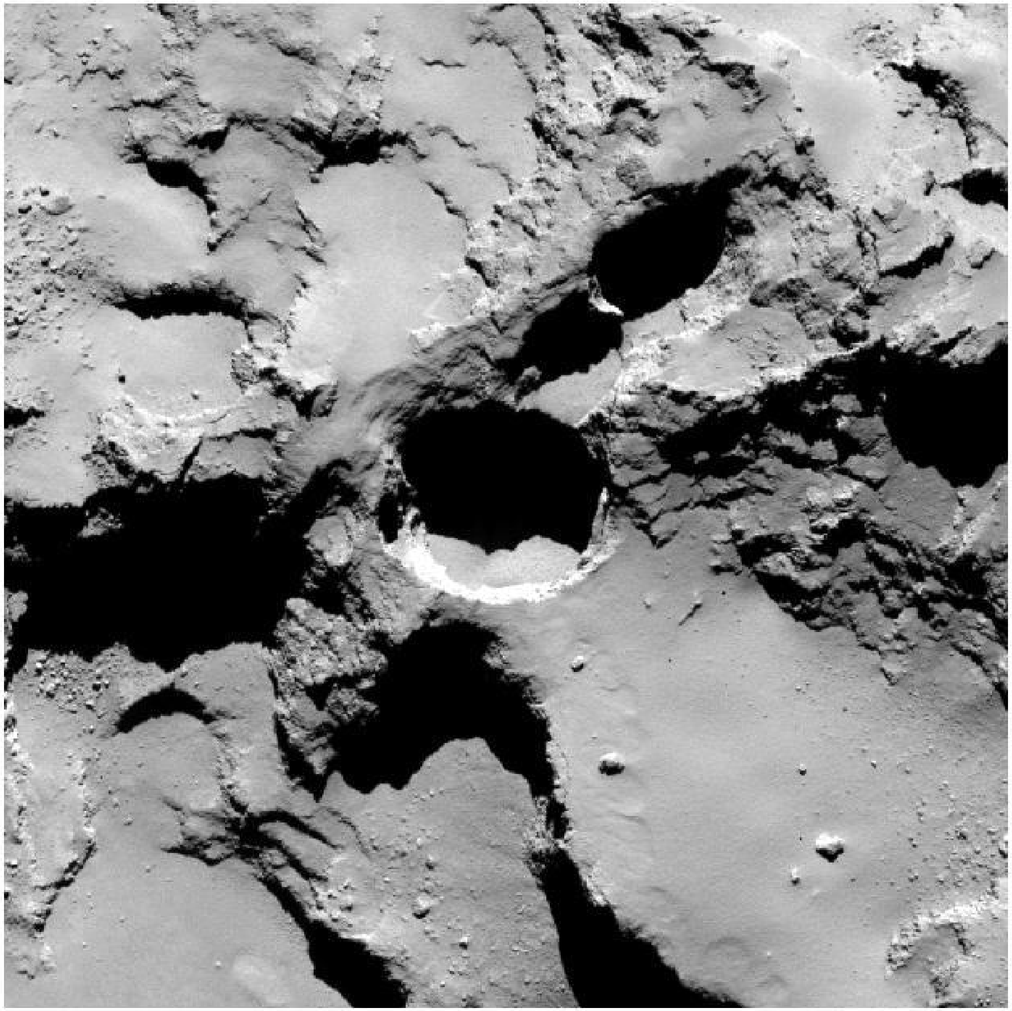


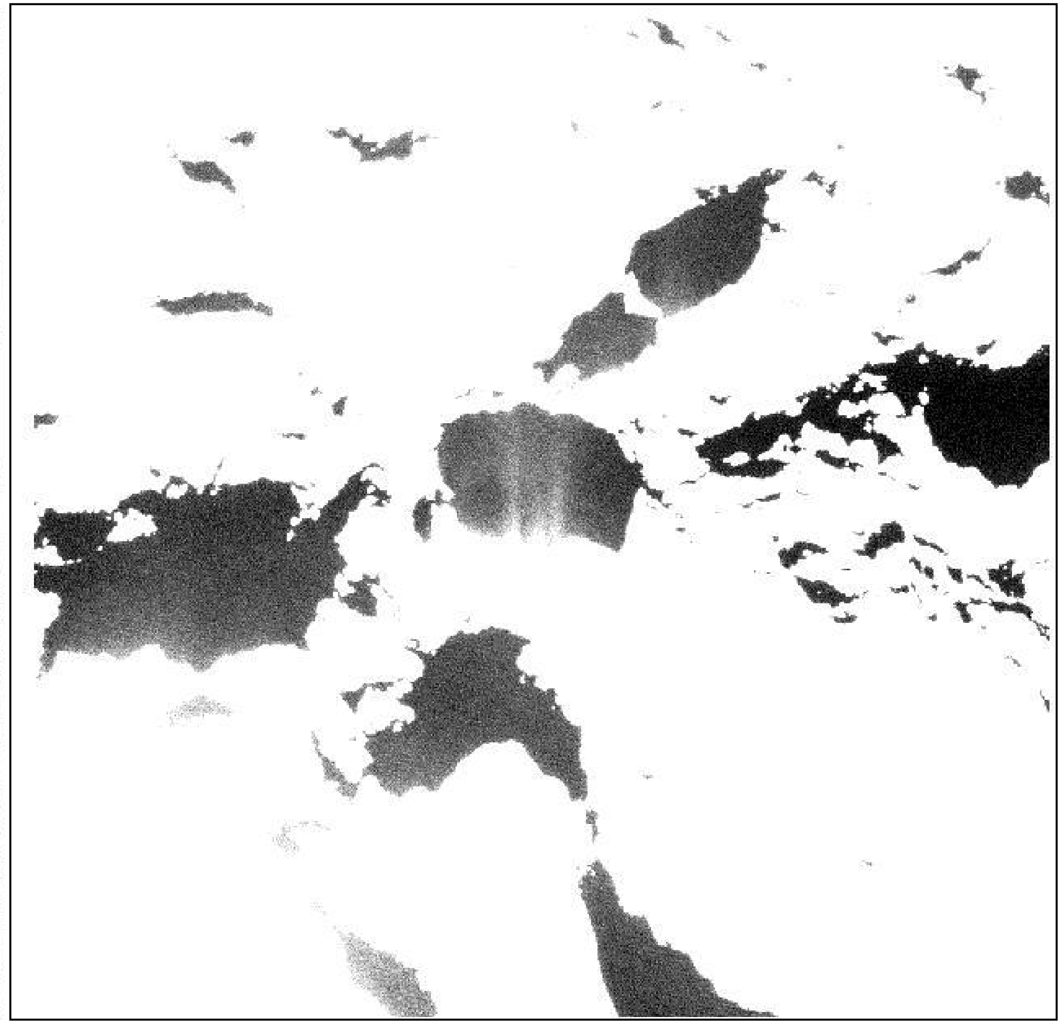
A new view at cometary activity



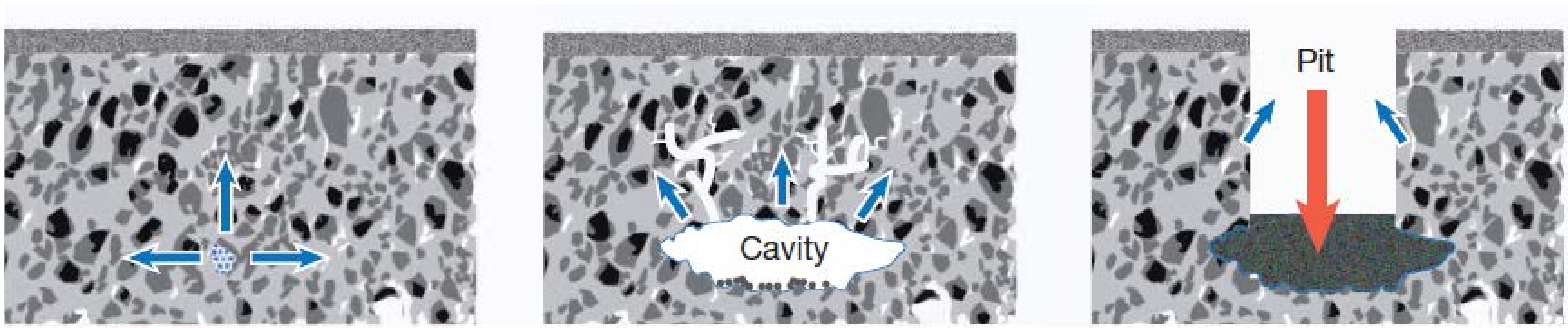
Vincent et al.

Activity from walls: Active pits



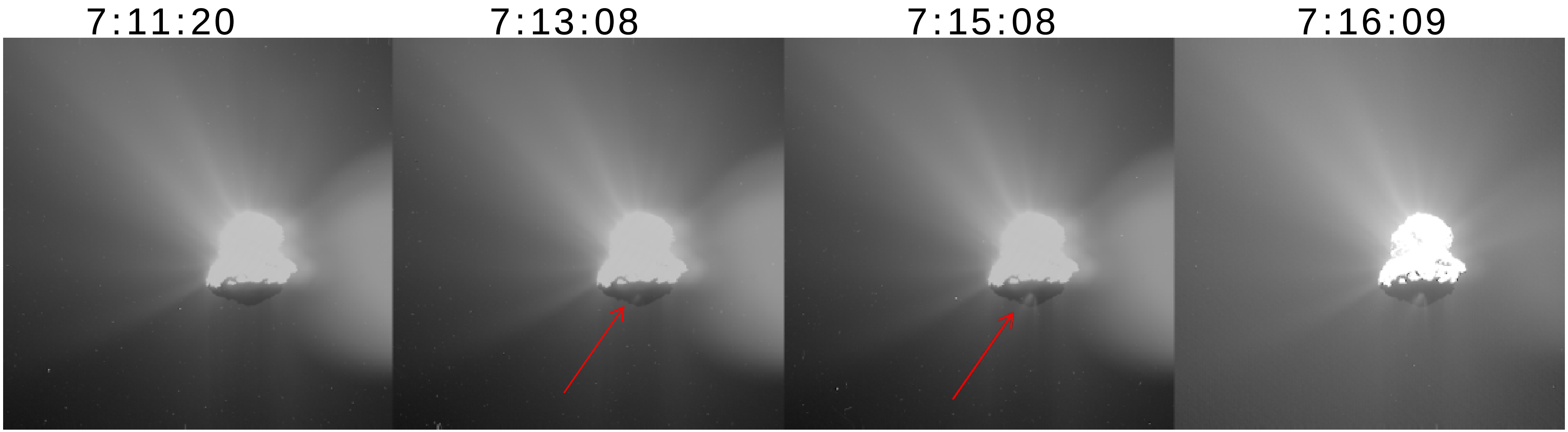


Active pits: sinkhole collapse as a possible explanation



Not all pits are active! Maybe explained if volatiles are gone from wall and bottom at some point….

Outbursts: Even on the nightside!



Crystallisation of amorphous ice?

Layer containing volatiles isolated from surface by low conductivity dust layer?

Status activity

- Interesting new ideas about onset and maintainance of activity from Rosetta data
  - More detailed modelling needed
  - Many data still to be analyzed
- Activity driven by large particles
- Activity is largely from walls
  - Caveat: Identification of source can be difficult
- Many new data on cometary outbursts
  - Mechanism(s) still unknown
  - Coordinated analysis of outburst data from different instruments just starting

Summary

- Origin of comets: The debate is ongoing
- Origin of water on Earth: Comets probably of minor importance
  - But diversity among Jupiter-family comets detected
- Origin of organics (and atmospheric noble gases): Comets may have played an important role
- Structure of cometary nucleus: Some hints, but question still open
- Activity: Many data, new ideas are coming up, to be looked at in more detail