Morphological and compositional analysis of boulders distributions on comet 67P/Churyumov-Gerasimenko

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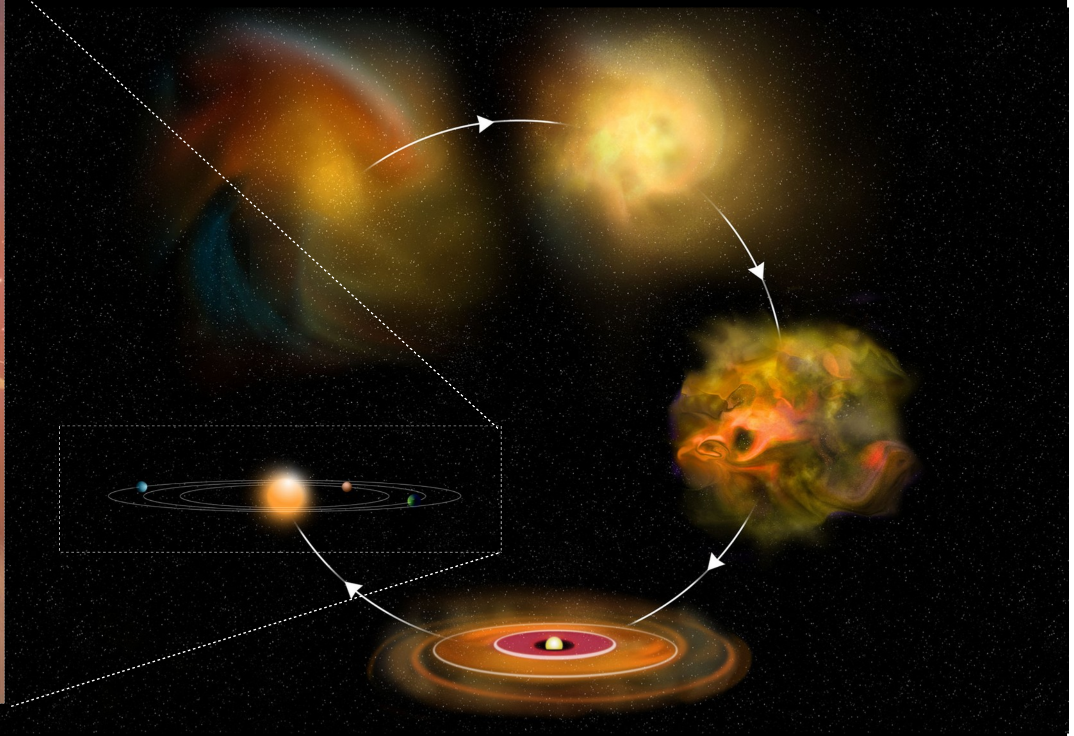
Admission to the final exam
13 September 2019
Centro di Ateneo di Studi e Attività Spaziali "Giuseppe Colombo"- **CISAS**

Outline

- ✓ Overview
  - Origin of Comets
  - The Rosetta Mission
  - Comet 67P/Churyumov-Gerasimenko
- ✓ Fragmentation and Fractals. The case of isolated boulder fields on comet 67P
- ✓ Time Evolution of Dust in the Hapi Region
- ✓ Thermal and Stress Analysis in Boulders of Comet 67P
- ✓ Conclusions
- ✓ Future Works
- ✓ List of Publications

Overview - Origin of Comets

Why are comets and asteroids so important for the understanding of the Solar System formation?



Comets and asteroids are leftovers of the Solar System formation

Overview - The Rosetta Mission

2 March 2004
Launch

10-years journey towards comet 67P

2867 Steins (2008)
21 Lutetia (2010)

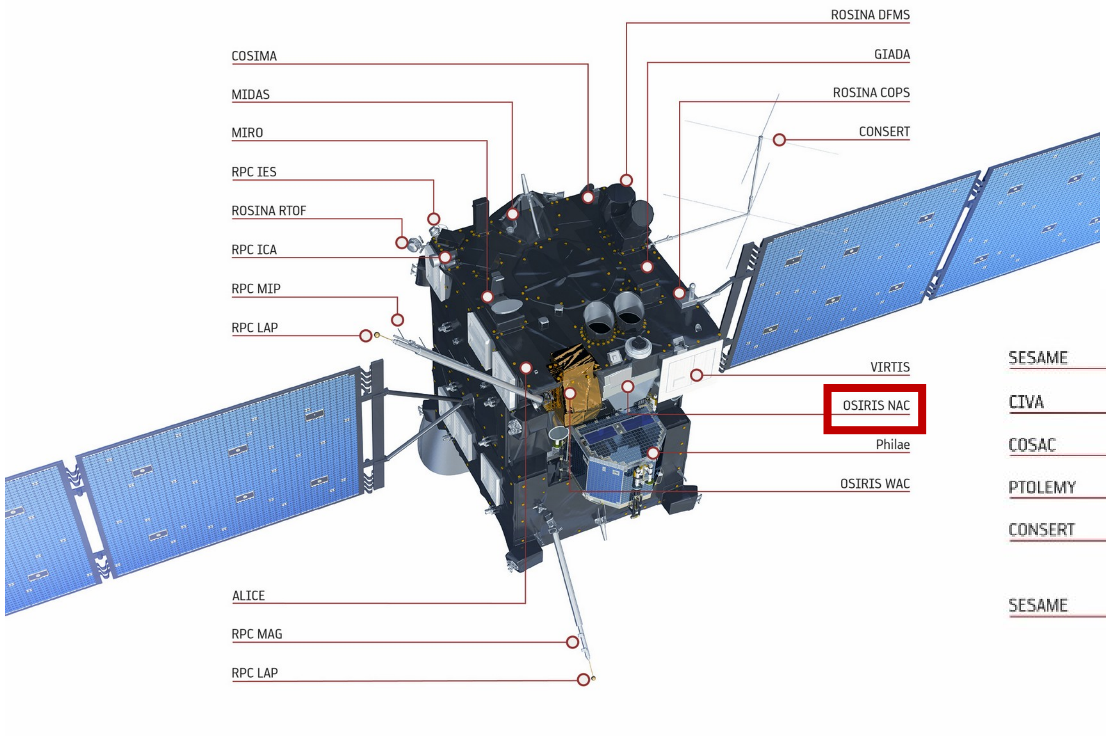
June 2011
Hybernation mode

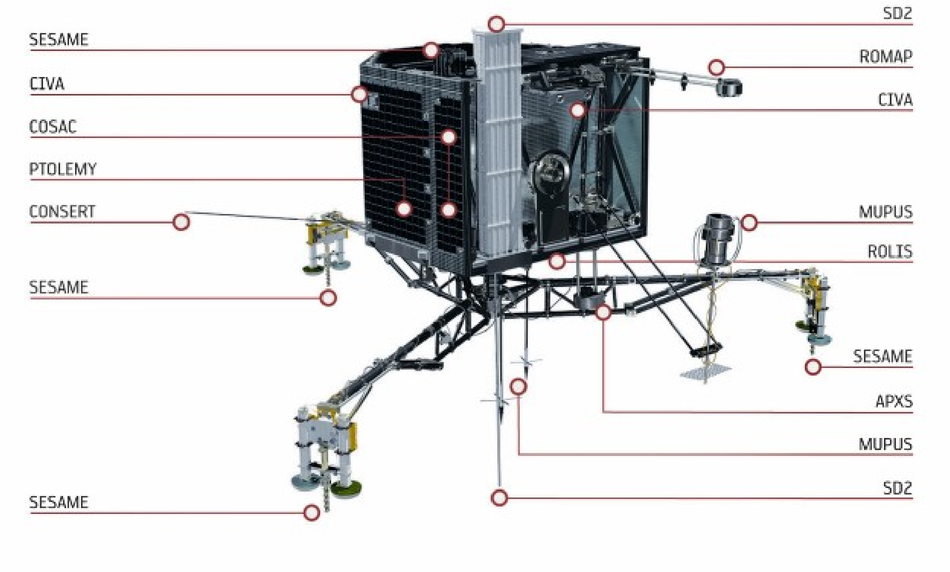
6 August 2014
Arrival of comet

12 November 2014
Philae landing

30 September 2016
End of the mission

The first mission designed to orbit and land on a comet



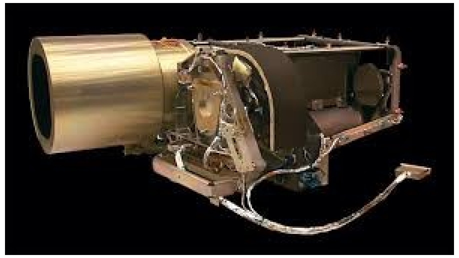


Overview - OSIRIS

Optical, Spectroscopic and Infrared Remote Imaging System
(**OSIRIS**)

Wide Angle Camera

Narrow Angle Camera

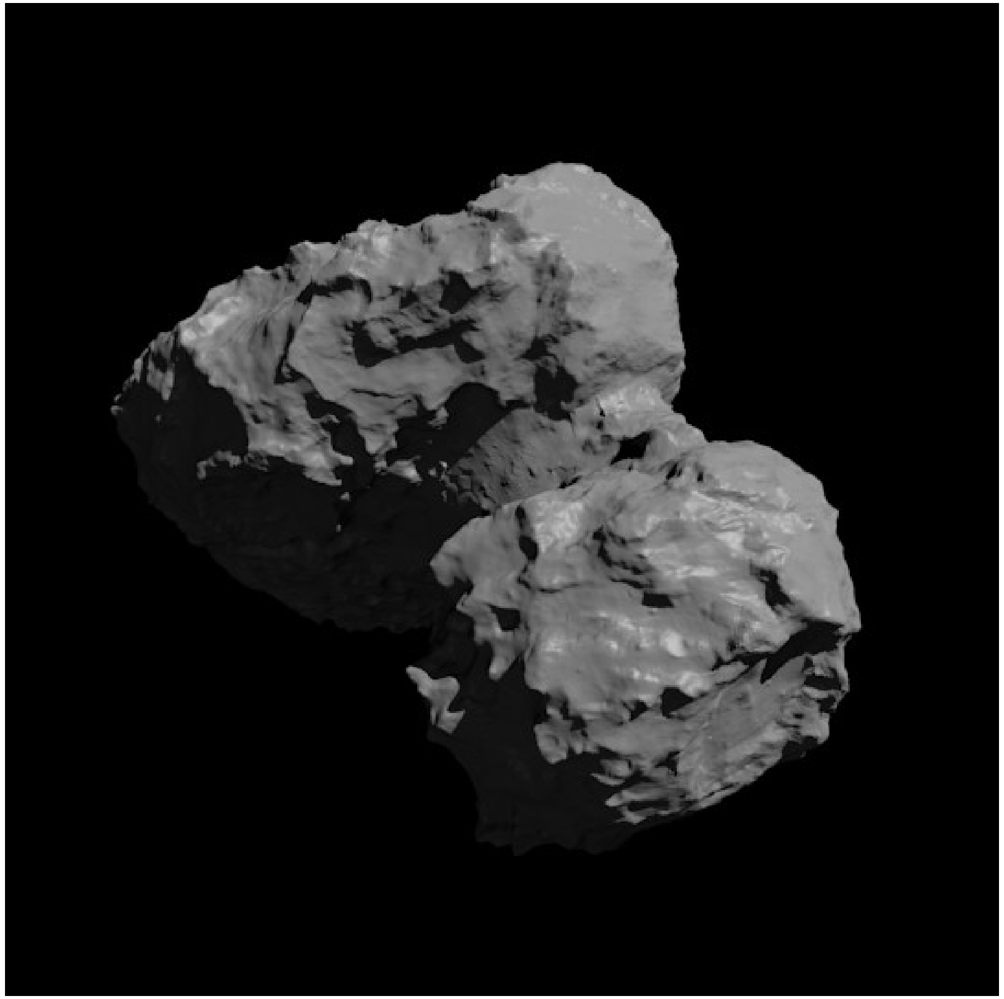


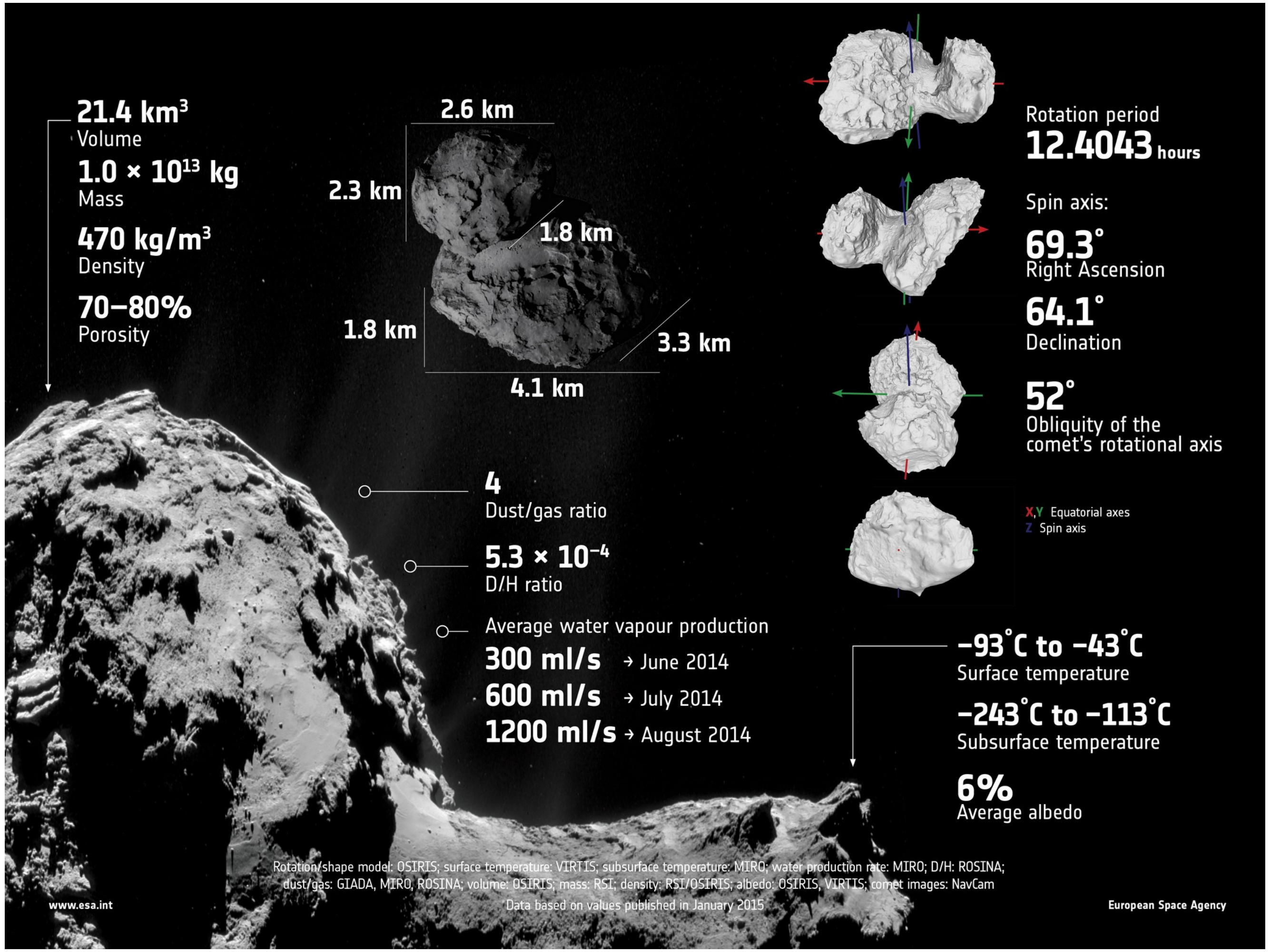
	NAC	WAC
Optical design	3-mirror off-axis	2-mirror off-axis
Angular resolution [µrad px−1]	18.6	101
Focal length [mm]	717.4	140 (sag)/131 (tan)
Mass [kg]	13.2	9.48
Field of view [°]	2.20 − 2.22	11.35 − 12.11
F-number	8	5.6
Spatial scale from 100 km [m px−1]	1.86	10.1
Typical filter bandpass [nm]	40	5
Wavelength range [nm]	250 − 1000	240 − 720
Number of filters	12	14

Mission

To image the comet's nucleus and its gas and dust coma

Overview - Comet 67P/Churyumov-Gerasimenko





Overview - Comet 67P/Churyumov-Gerasimenko

Huge variety of terrains

- Smooth
- Hummocky
- Partially or entirely covered by dust

Morphological dicothomy

Huge variety of landforms and features

- Smooth flat planes
- Vertical cliffs
- Talus aprons
- Pits
- Boulders

Objectives

Boulders

Opportunity to study the physical properties and the evolution of the comet

Imprints of geological and erosional processes that affected the surface

To study phenomena responsible for the **fragmentation** of the surface

Thermal stress weathering
Gravitational phenomena
Activity

Fragmentation and Fractals. The case of isolated boulder fields on comet 67P

Fragmentation and Fractals. The case of isolated boulder fields on comet 67P

Astronomy & Astrophysics manuscript no. 34775
June 25, 2019

Quantitative analysis of isolated boulder fields on comet 67P/Churyumov-Gerasimenko

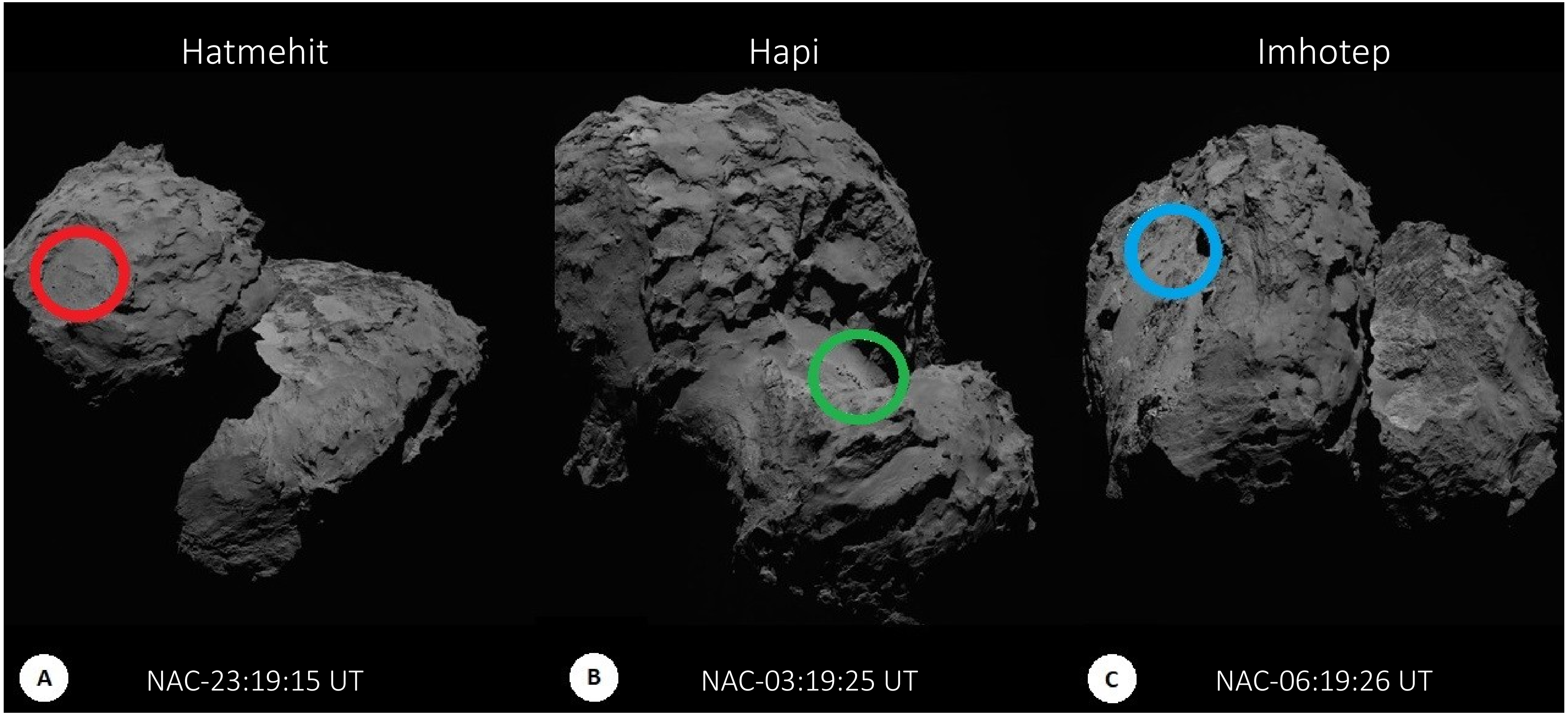
P. Cambianica[1], G. Cremonese[2], G. Naletto[1,5,6], A. Lucchetti[2], M. Pajola[2], L. Penasa[1], E. Simioni[2], M. Massironi[4,1], S. Ferrari[1], D. Bodewits[14], F. La Forgia[3], H. Sierks[7], P. L. Lamy[8], R. Rodrigo[9,10], D. Koschny[11], B. Davidsson[12], M. A. Barucci[13], J.-L. Bertaux[8], I. Bertini[3], V. Da Deppo[6], S. Debei[15], M. De Cecco[16], J. Deller[7], S. Fornasier[13], M. Fulle[17], P. J. Gutiérrez[18], C. Güttler[7], W.-H. Ip[20,21], H. U. Keller[22,19], L. M. Lara[19], M. Lazzarin[3], Z.-Y. Lin[20], J. J. López-Moreno[18], F. Marzari[5], S. Mottola[19], X. Shi[7], F. Scholten[19], I. Toth[23], C. Tubiana[7], and J.-B. Vincent[19]

(Affiliations can be found after the references)

Received 4 December 2018 / Accepted 7 June 2019

To characterize isolated boulder populations unrelated to specific niches or detachment scarps

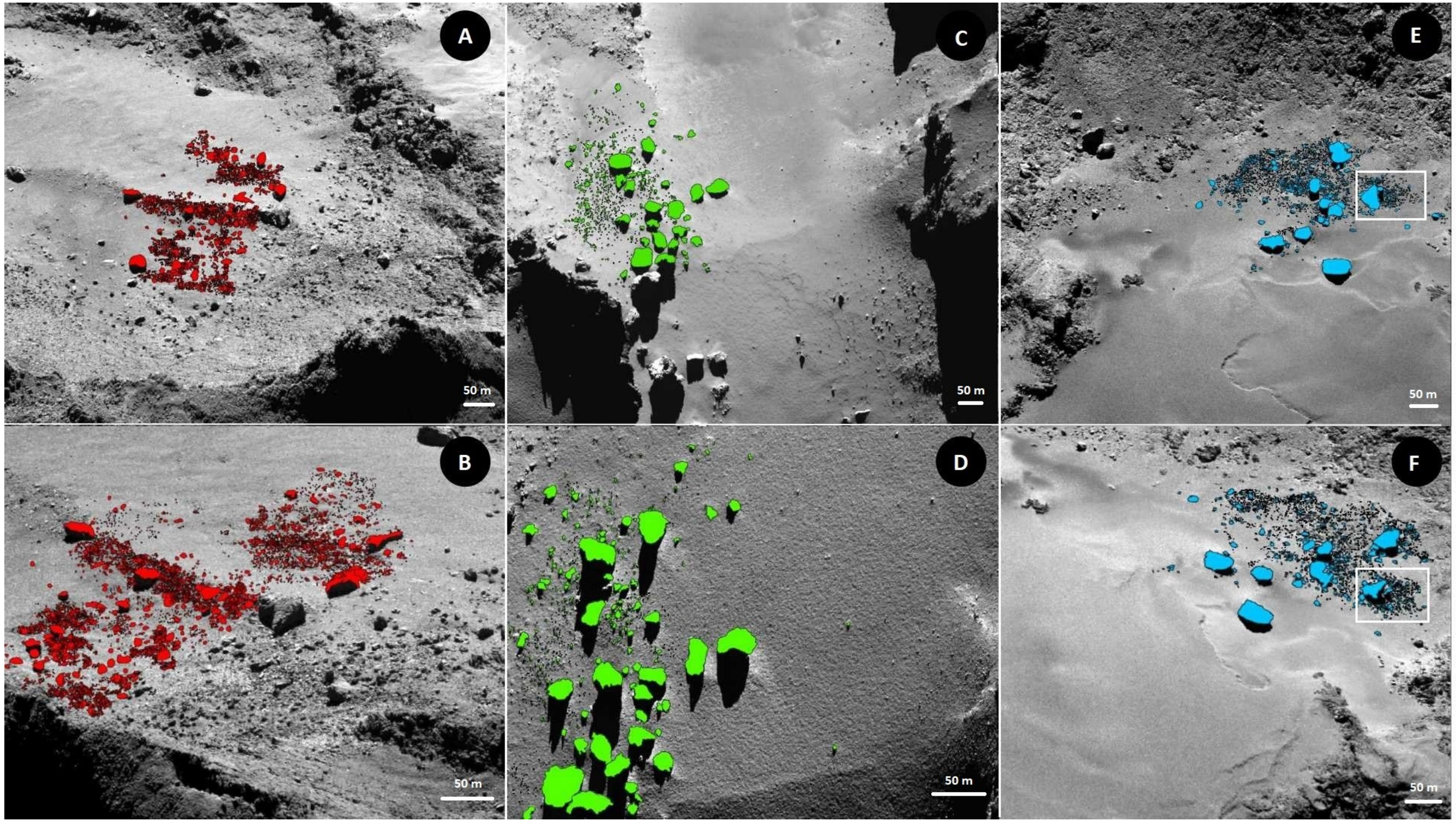
Data Selection



Data Selection

Pre-perihelion

Post-perihelion



Hatmehit | Hapi | Imhotep

11811 boulders

Size-frequency distribution

Cumulative fractional area

Fractal theory

Shape factors

Method

SIZE-FREQUENCY DISTRIBUTION

The SFD of rocks on surfaces can supply geological information related to the body's origin and evolution

$$N(\geq r)=kr^{-D}$$

-6.5 < D <-5
Collapses and pit formation
-4.5 < D <-3.5
Gravitational events
due to thermal fragmentation
-2.0 < D <-1.0
Gravitational events +
sublimation and in-situ
fragmentation

CUMULATIVE FRACTIONAL AREA

The CFA covered by rocks *vs* diameter curve is represented in a log-log plot.
Usually, the distribution is fitted by an exponential equation

$$F(\geq D)=ke^{-q(x)D}$$

F(D) is the CFA covered by rocks of diameter D or larger
k is the total area covered by all rocks
q(x) governs how abruptly the area covered by rocks decreases with increasing diameter

Method - Results

SIZE-FREQUENCY DISTRIBUTION

Region	D (..)
Hatmehit pre	-2.7
Hatmehit post	-2.8
Hapi pre	-1.7
Hapi post	-1.2
Imhotep pre	-2.4
Imhotep post	-2.4

-6.5 < D <-5
Collapses and pit formation
-4.5 < D <-3.5
Gravitational events
due to thermal fragmentation
-2.0 < D <-1.0
Gravitational events +
sublimation and in-situ
fragmentation

CUMULATIVE FRACTIONAL AREA

Region	Trend line	R^2
Hatmehit pre	$y=0.0632x^{-0.792}$	0.9942
Hatmehit post	$y=0.0594x^{-0.639}$	0.9875
Hapi pre	$y=0.0648\ x^{-0.179}$	0.9120
Hapi post	$y=0.0556x^{-0.150}$	0.8545
Imhotep pre	$y=0.0697\ x^{-0.364}$	0.9945
Imhotep post	$y=0.0548\ x^{-0.378}$	0.9910

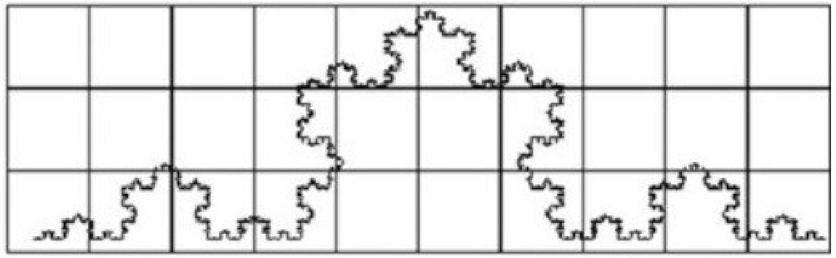
Fractal Theory - Boxcount

The size distribution of material expected from fractures and fragmentation would allow a fractal rule

(Mandelbrot, 1982)

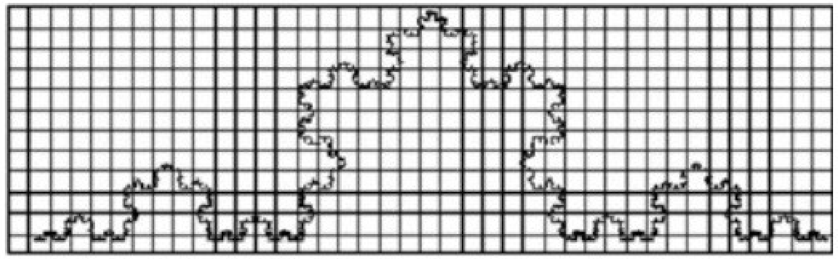
BOXCOUNT METHOD

Analysis of a complex 2D pattern by breaking an image into smaller pieces, and analyzing the pieces at each smaller scale



S=1/3

S=1/12



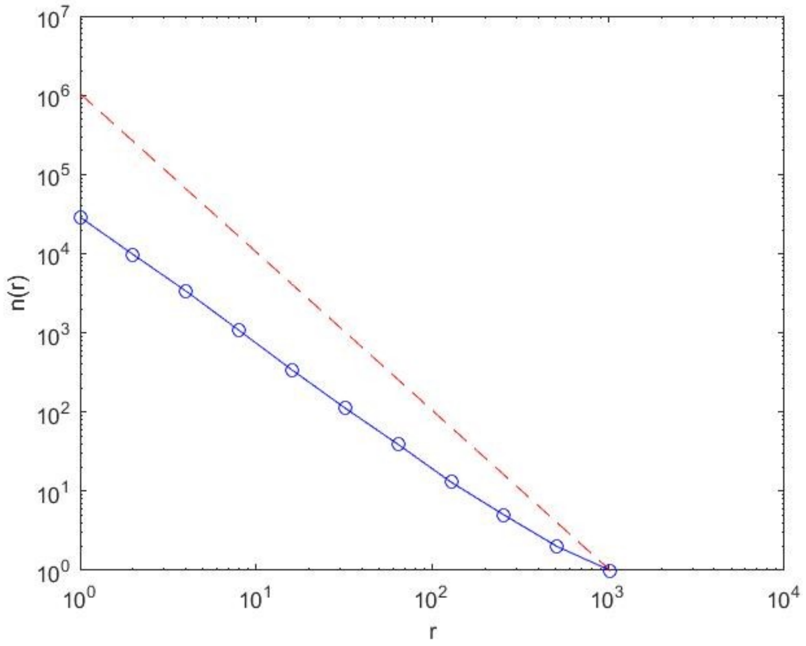
How many boxes are required to cover the image?

Calculation of the Minkowski-Bouligand dimension seeing how this number changes as the grid became finer

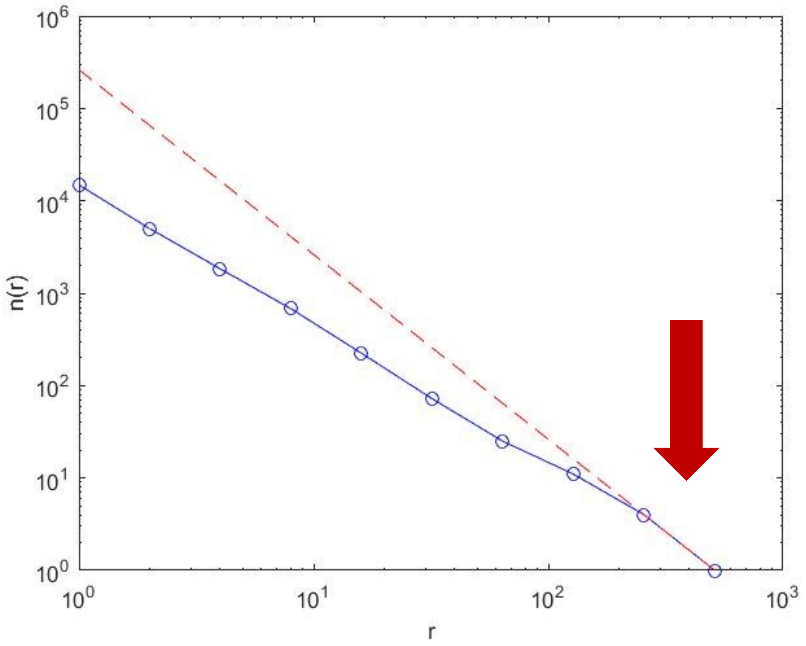
$$D_f = lim_{r \longrightarrow 0} \frac{log(N(r))}{log(1/r)}$$

Fractal Theory - Results

Imhotep pre-perihelion



Hapi pre-perihelion



n(r) = number of boxes needed to cover the set as a function of the size **r** of the boxes

Solid line = power-law $N(r)=N_o r^{-Df}$. It should appear if the set is fractal

Dotted line = it appears showing the scaling $N(r)=r^{-2}$ for comparison, expected for a space-filling 2D image

The discrepancy between the two curves indicates a possible fractal behavior of the image

Boulders Shape

Morphologies of rocks → Records on rock surface processes →

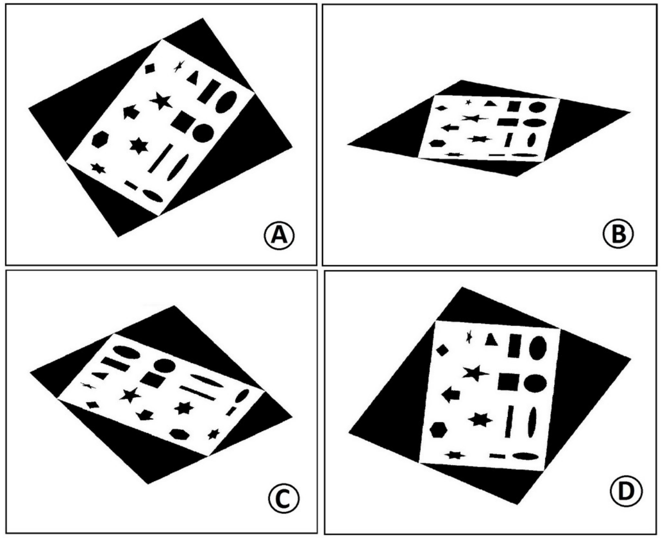
- Lithology of the mass
- Transport mechanisms
- Weathering history

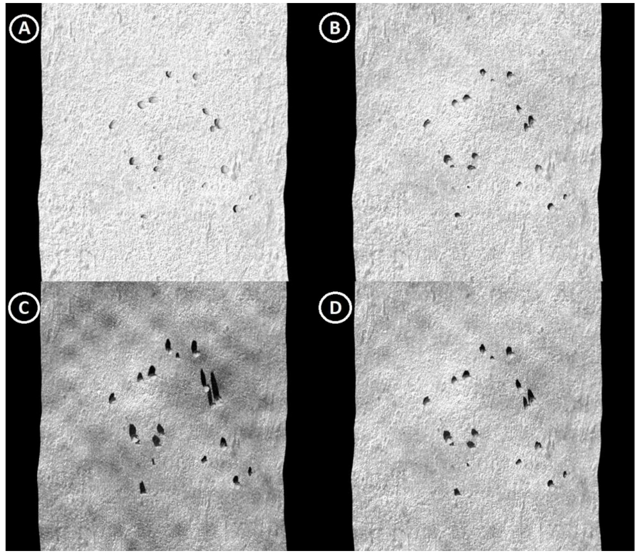
Shape factors

Dimensionless quantities calculated from measured dimension, such as diameter, area, perimeter, etc.

Aspect Ratio | Circularity | Roundness | Compactness | Elongation | Solidity | Complexity | Convexity | Feret's diameter

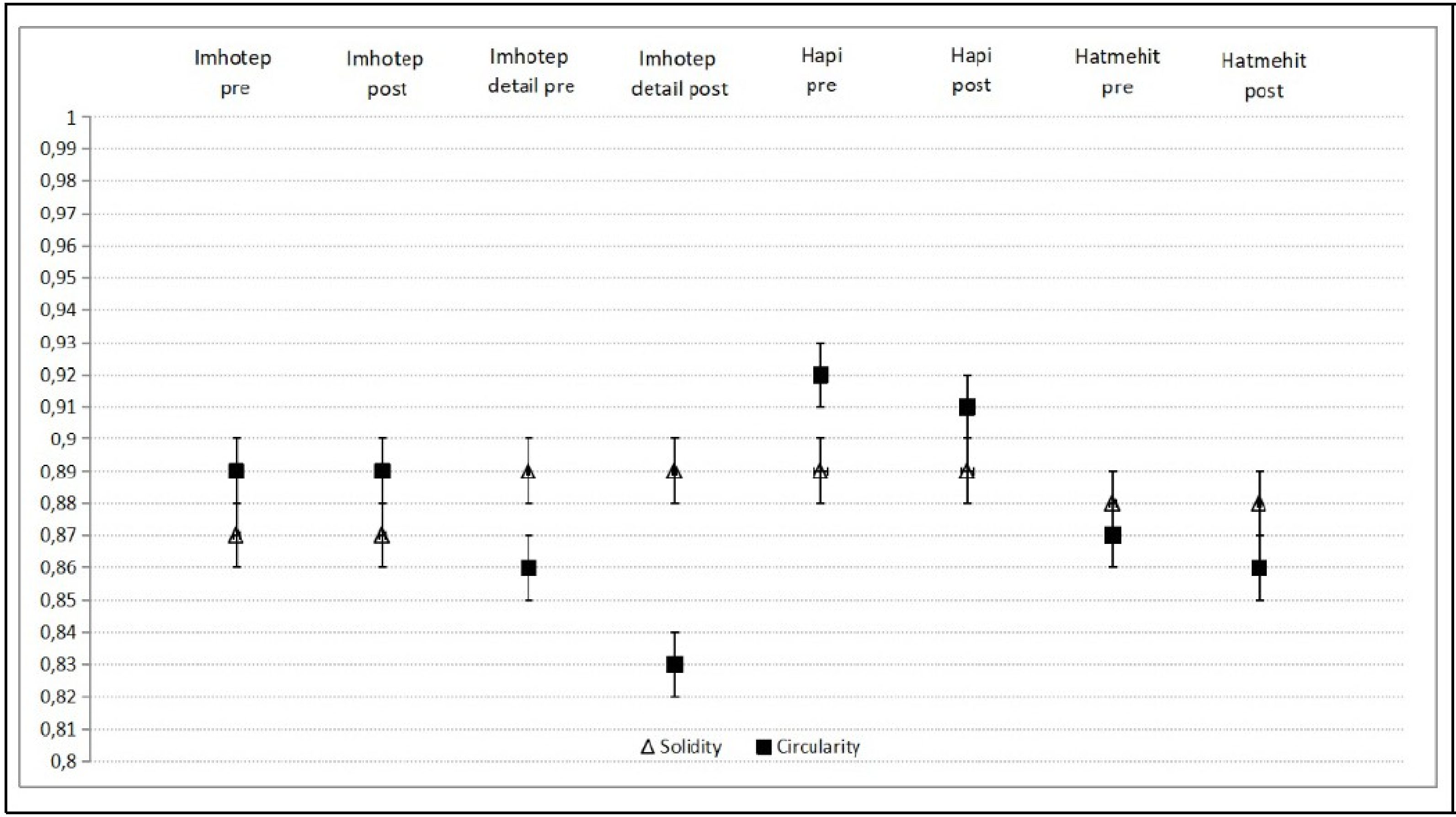
2D-test

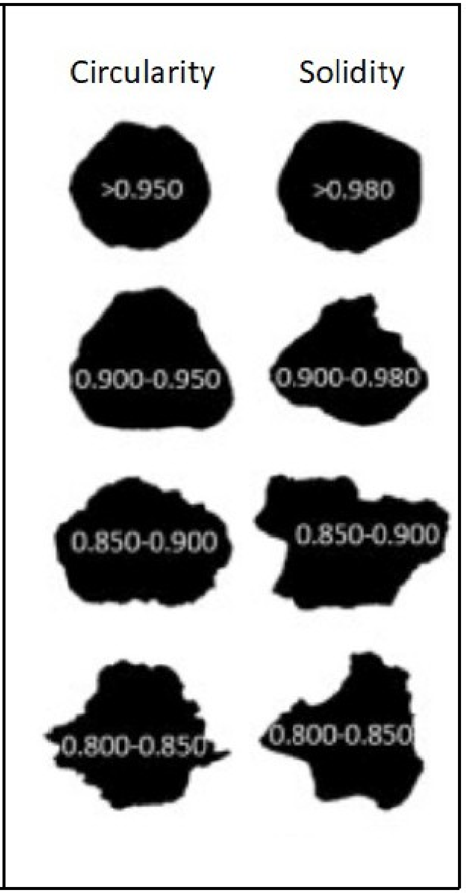




3D-test

Boulders Shape - Results





Conclusions

- We propose techniques to analyse populations of boulders
- No differences before and after the perihelion
- Anomalies

❖ The heat flux density received during the perihelion passage is not enough to change the examined populations

❖ There could have been changes, but the erosion was uniform and the shape parameters can only distinguish differential erosion.

Hapi area

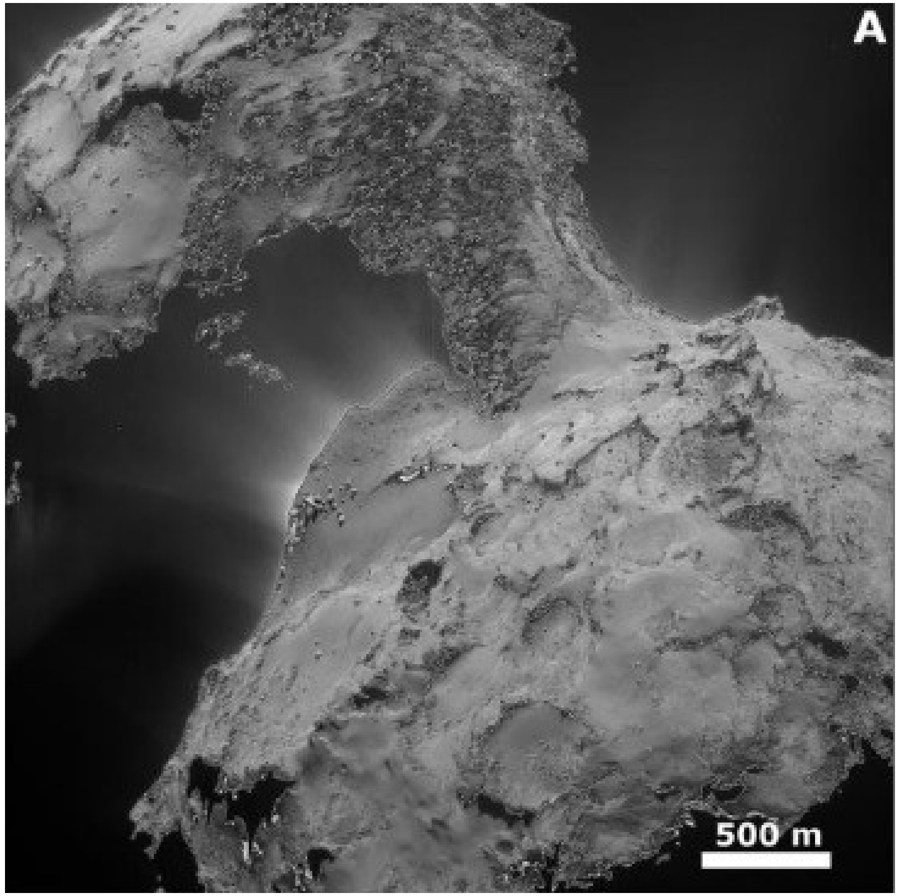
Boulders are collapsed during gravitational events and their fragmentation in-situ is controlled by thermal fatigue

These boulders would represent the tops of outcrops, immersed in a deposit of back fall material several tens of meters thick

(Keller et al. 2017)

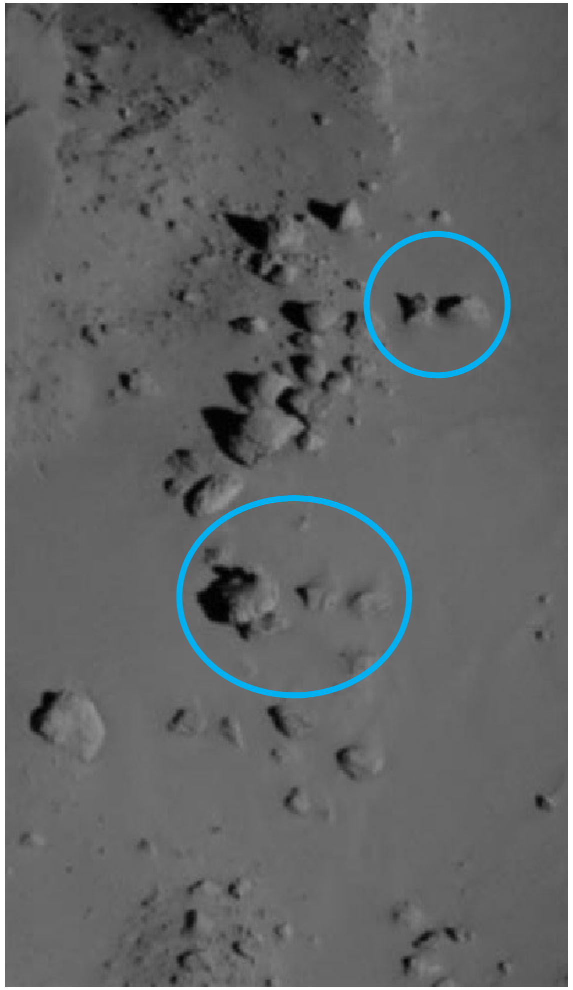
Time Evolution of Dust in the Hapi Region

Time Evolution of Dust in the Hapi Region

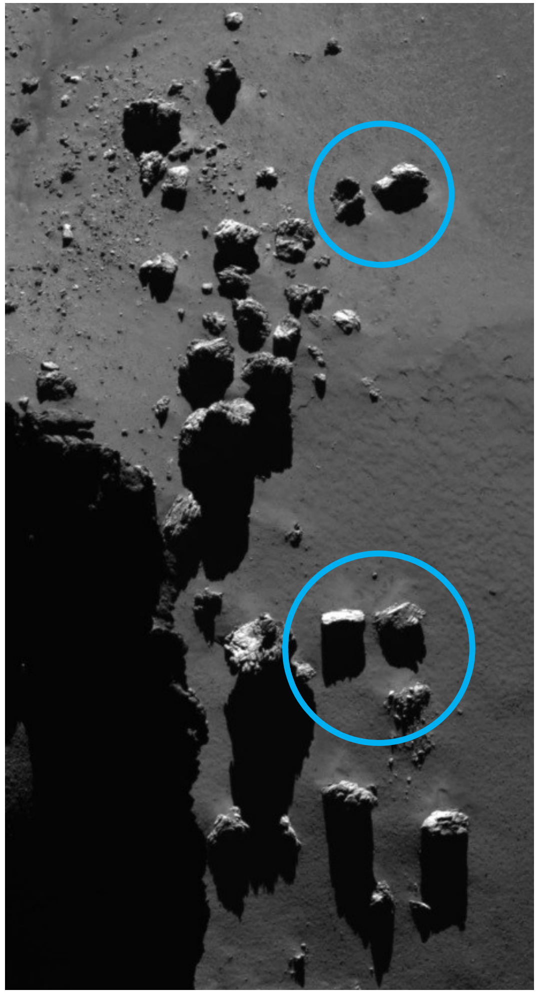


(Shi et al. 2018)

JETS
22 August 2014 and 14 March 2015

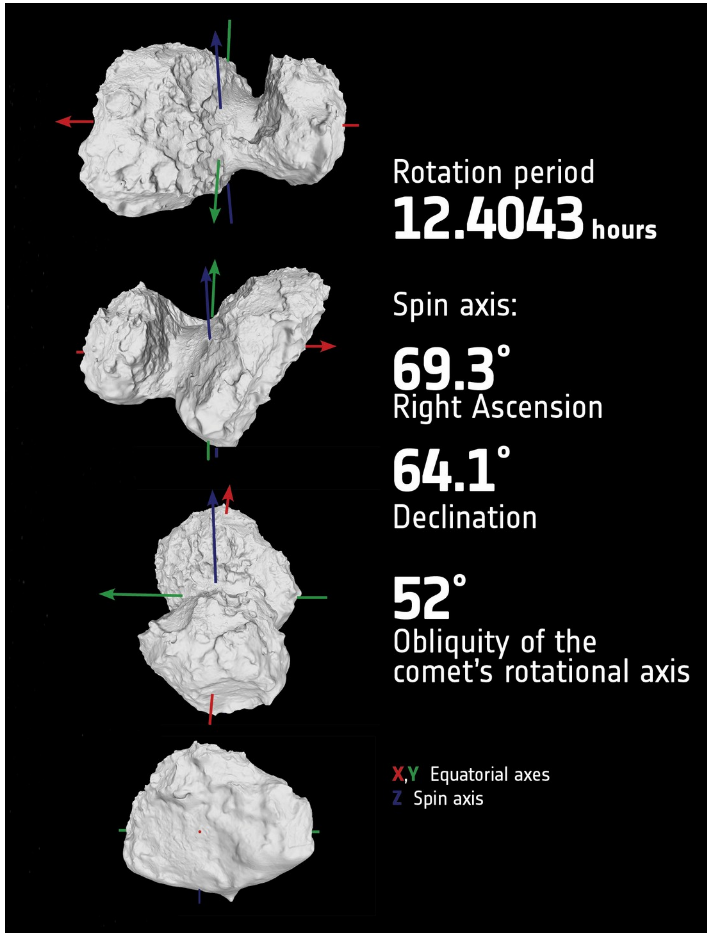


22 August 2014 08:42



10 Dec 2014 06:29

Mass Transfer

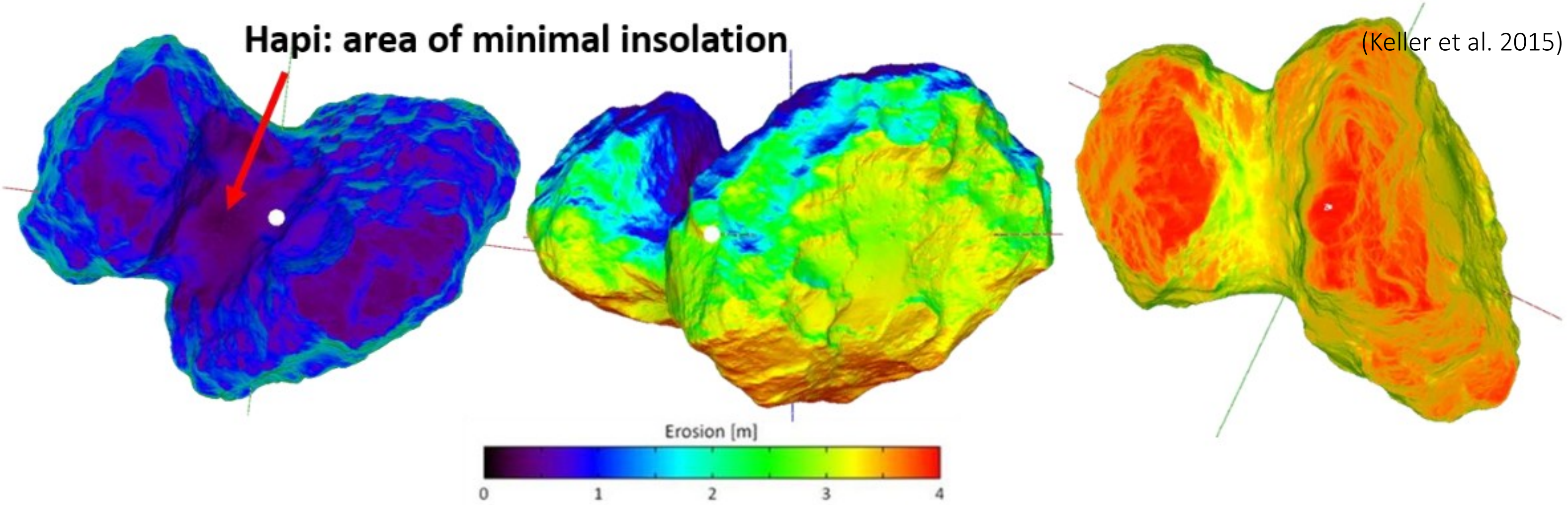


Comet 67P experiences strong seasons, resulting in significant differences in insolation between the northern and southern hemispheres. This strong dichotomy is reflected in the morphology between the two hemispheres.

Northern regions	Southern regions
Minimal amount of insolation and erosion	Southern summer = perihelion Strong insolation Strong erosion
FULLY COVERED OF DUST	CONSOLIDATED AND COARSE TERRAINS

Mass Transfer

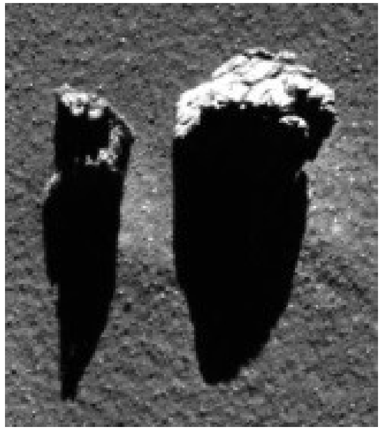
The dust cover in the northern regions can be the result of transport mechanisms of particles from the southern hemisphere during the southern summer.

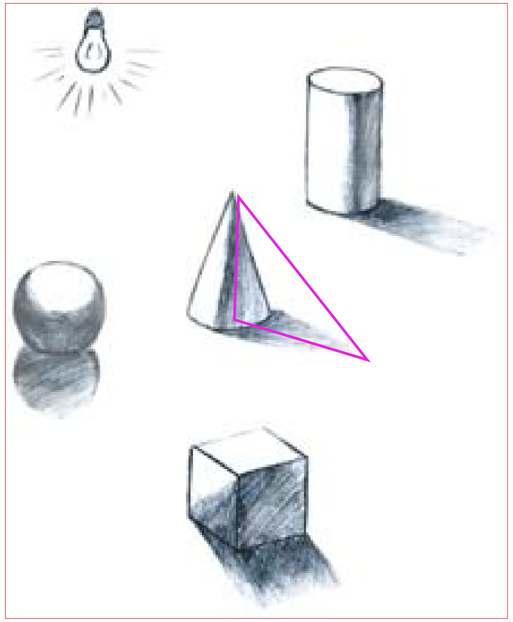


The erosion of the southern hemisphere, the subsequent transport of material, and then its fallout on the nucleus, are fundamental to investigate the pristine water ice abundance comet 67P, assuming that 67P's ice content is representative of the average value of all comets.

Dust Erosion and Deposit

MATLAB Software



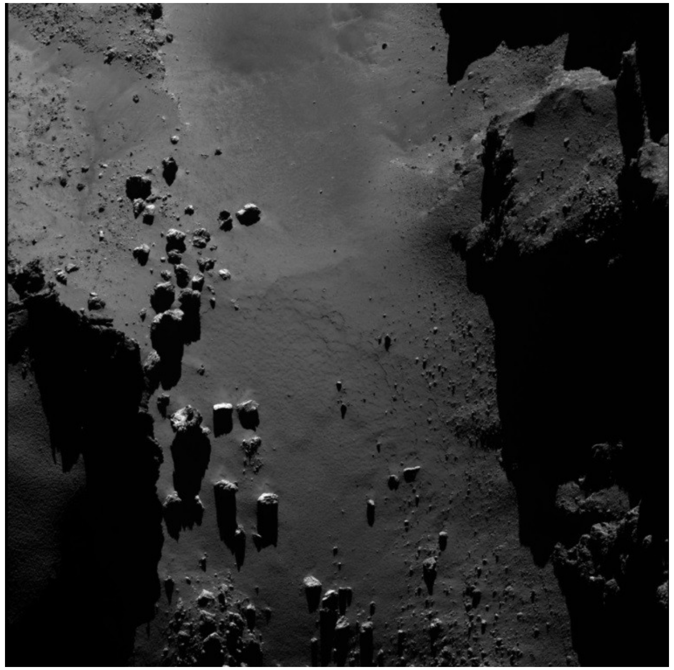


Height of boulders through the length of shadows can improve the knowledge of the erosion and deposit variation of the dust on the comet surface

$$H = L \tan\left(\frac{\pi}{2} - i\right)$$

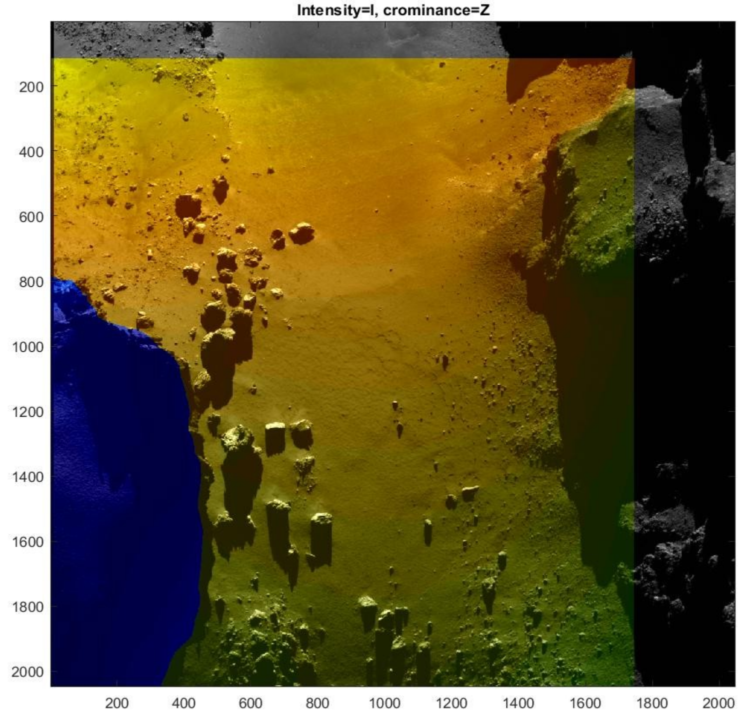
MATLAB Software

Selection of the image



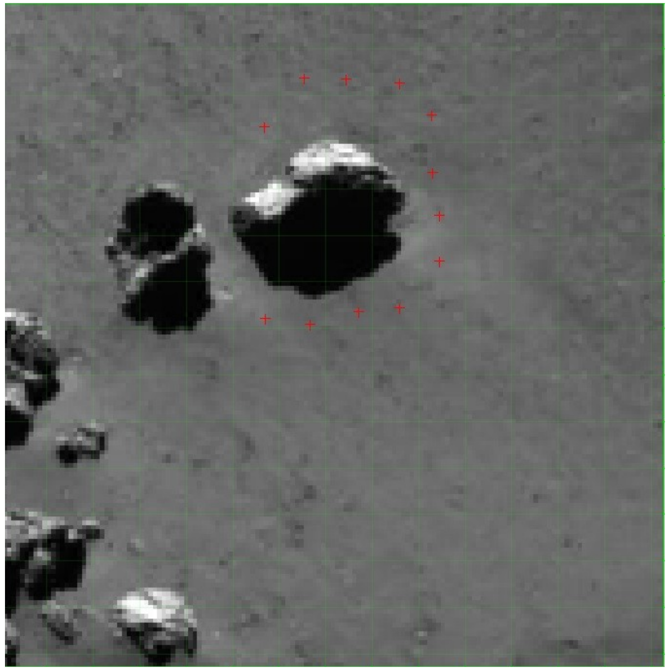
10 December 2014 06:29:11

Image alignment



To obtain the correct projection of the OSIRIS images on the 3D shape model

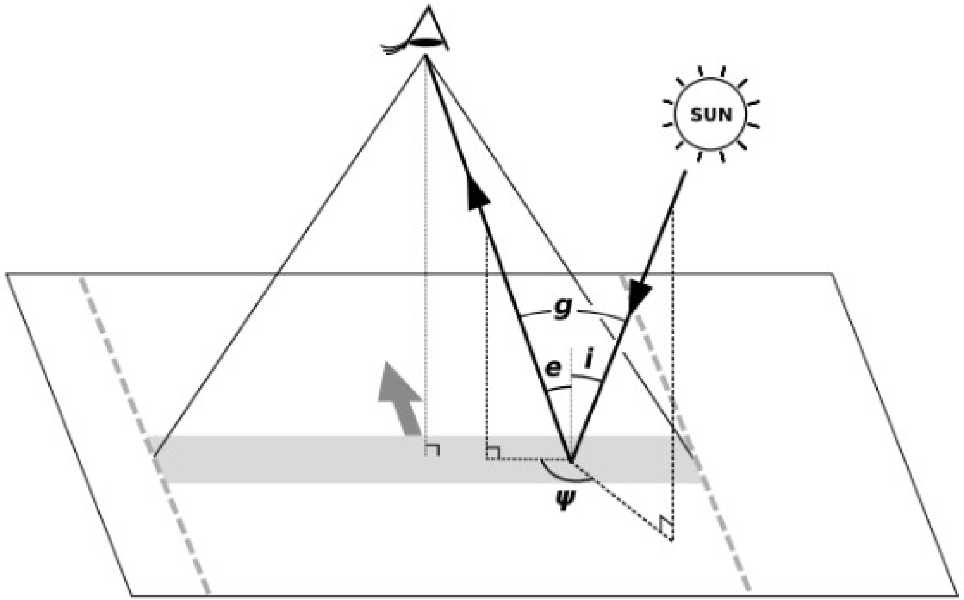
Local Surface Definition



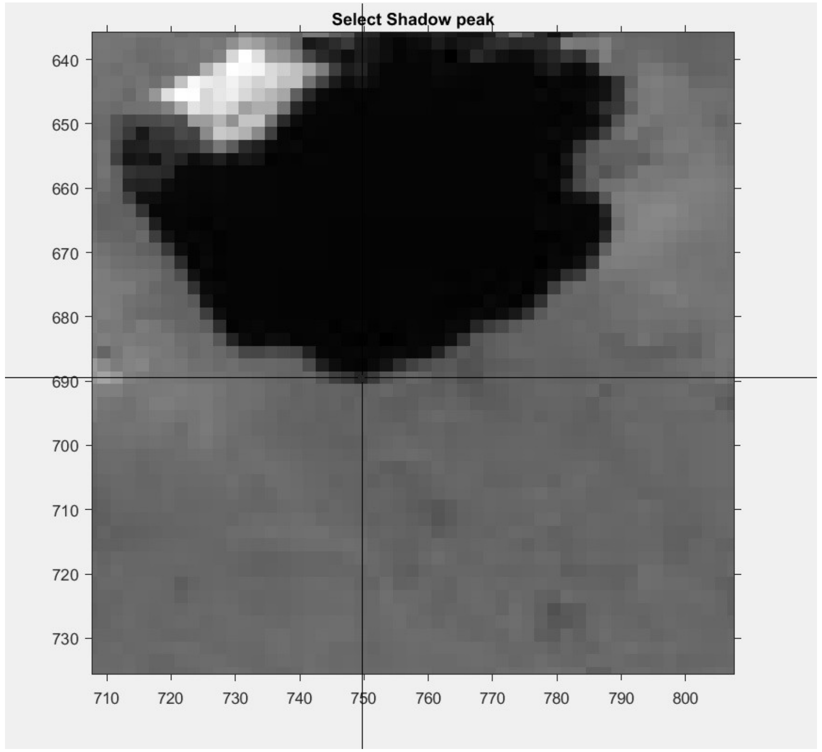
To avoid the local granularity

MATLAB Software

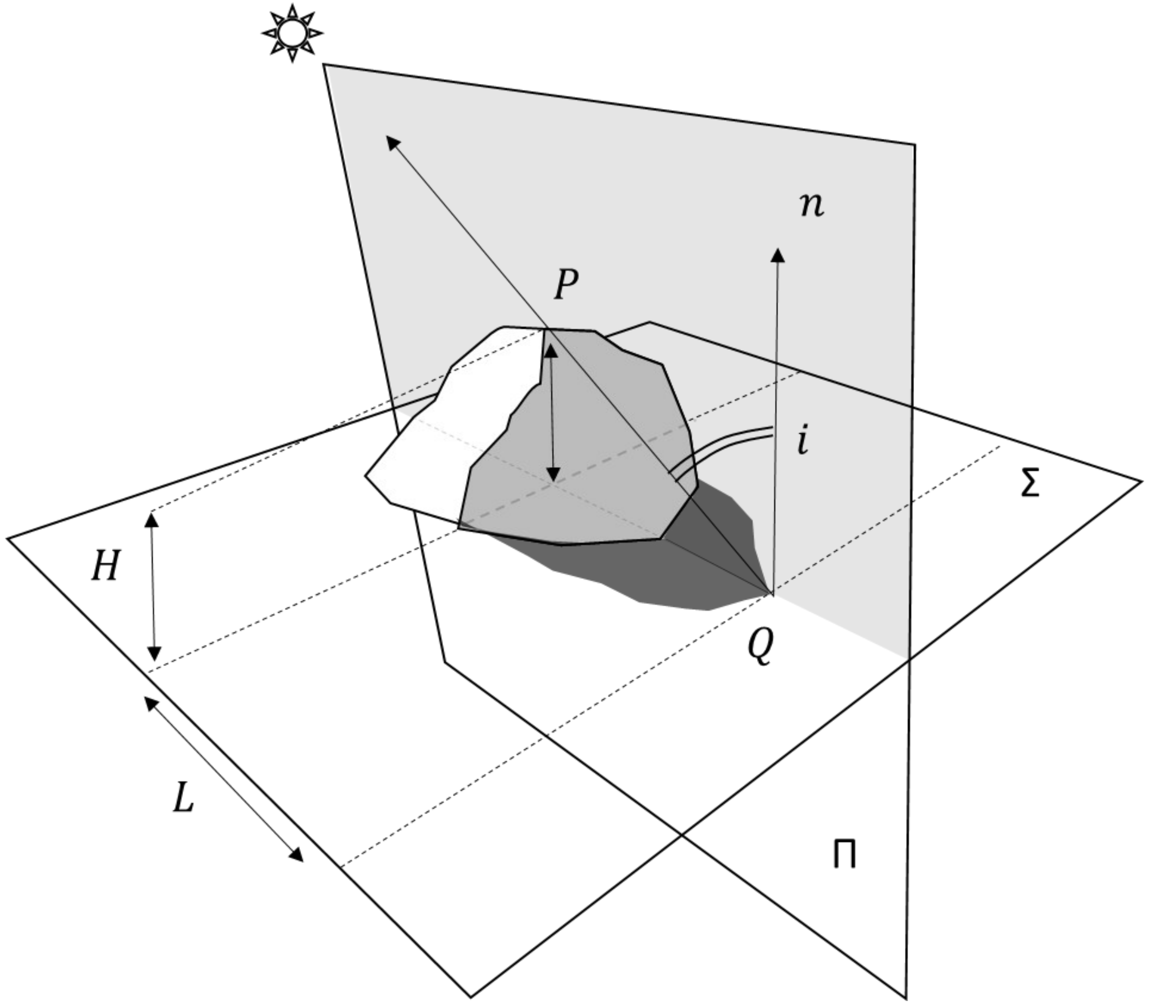
Incidence Angle

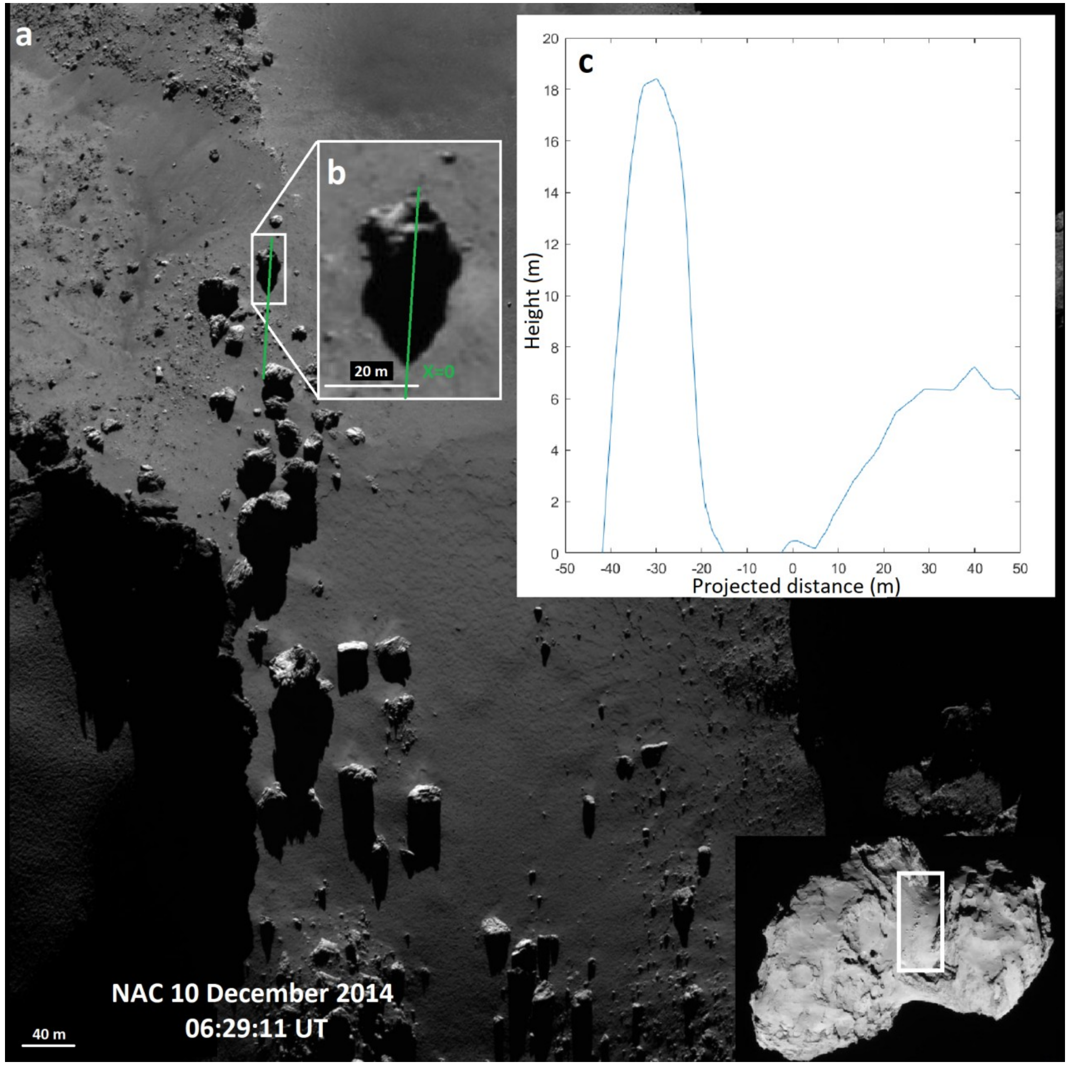


Peak of the Shadow



Output


n
P
i
Σ
H
Q
L
Π


a
b
c
20 m
X=0
Height (m)
Projected distance (m)
NAC 10 December 2014
06:29:11 UT
40 m

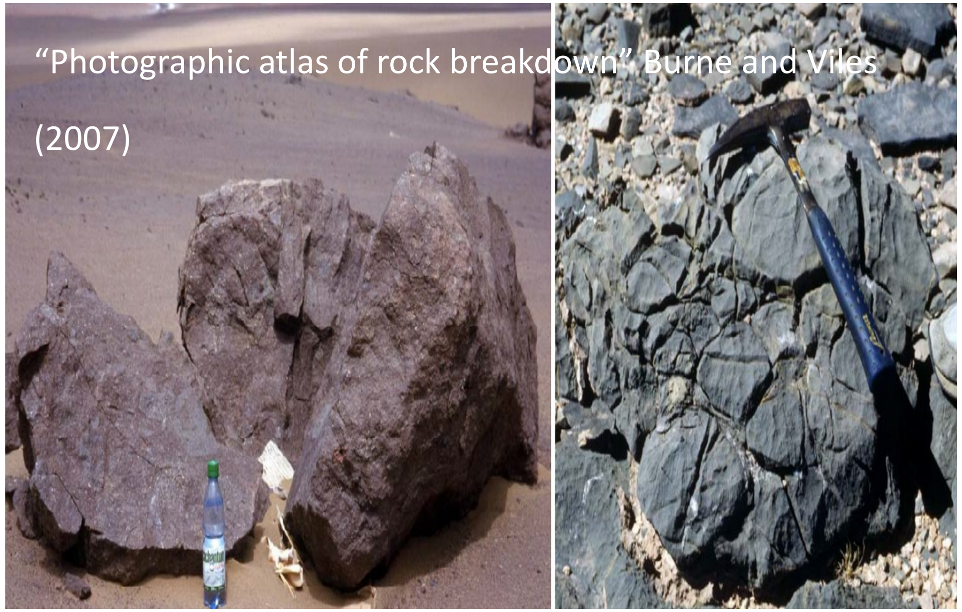
Thermal and Stress Analysis in Boulders of Comet 67P

Thermal Stress Weathering

“Rock breakdown due to the expansion and contraction of a rock induced by heating and/or cooling” (Lamp+2016)

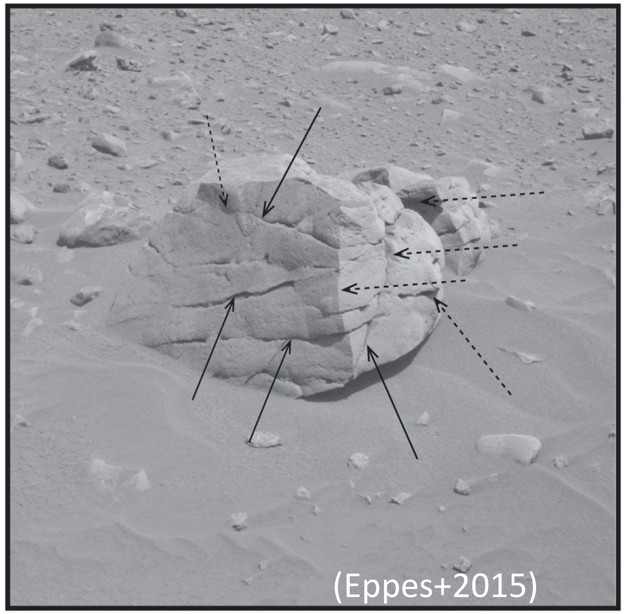
Thermal shock

Rapid failure in the material
as a result of a sudden ΔT


“Photographic atlas of rock breakdown” Burne and Viles (2007)

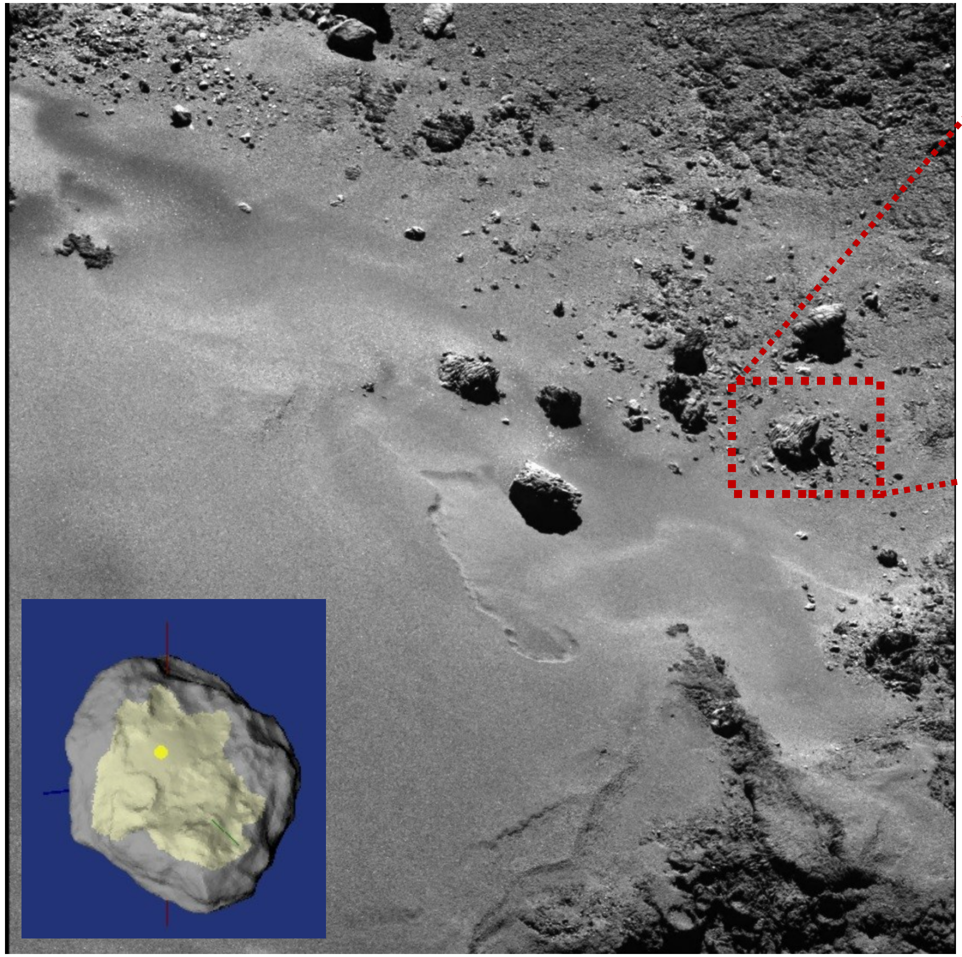
Thermal fatigue

Cyclic thermal expansion
and contraction of the material

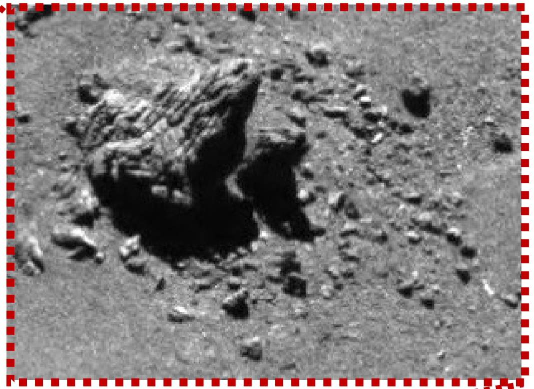

(Eppes+2015)

Data Selection

Imhotep



NAC_2016-07-09T11.25.15.786Z_ID30_1397549000_F41

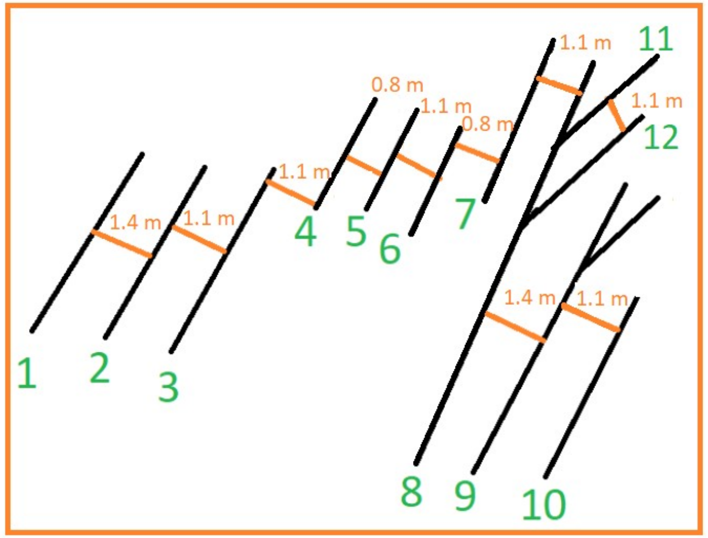


1+ 350 fragments
Spatial scale: 0.28 m/px
Diameters: 0.3- 8.3 m
Power-law: -2.7 +0.1/-0.2
Average: 1.4 m

(Cambianica et al., 2019)

Average spacing: 0.98 m
Length: 3.8 < m < 26.6
Preferred cracks orientation

- Non-random
- Strong north-south orientation



Workflow

Boundary conditions

Solar irradiance (W/ m^2)

(Keller+2015)

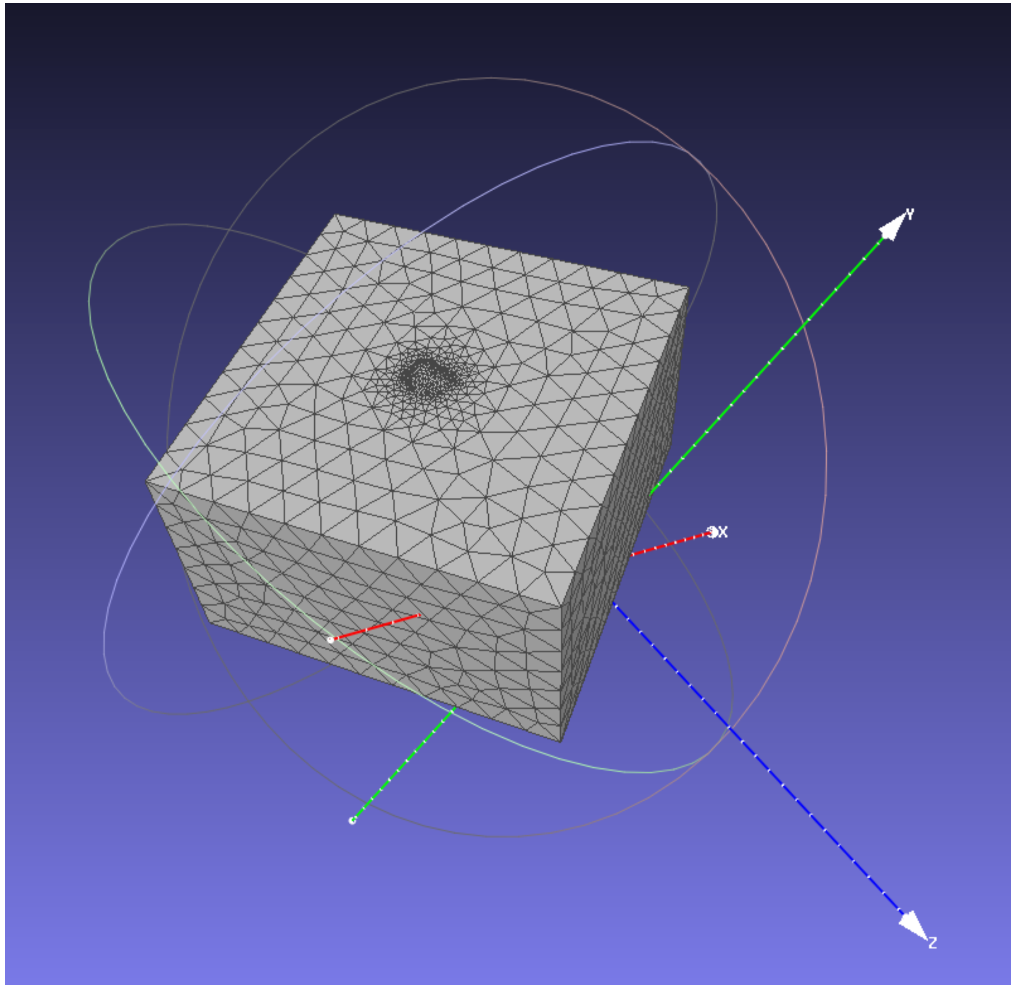
COMSOL MULTIPHYSICS®

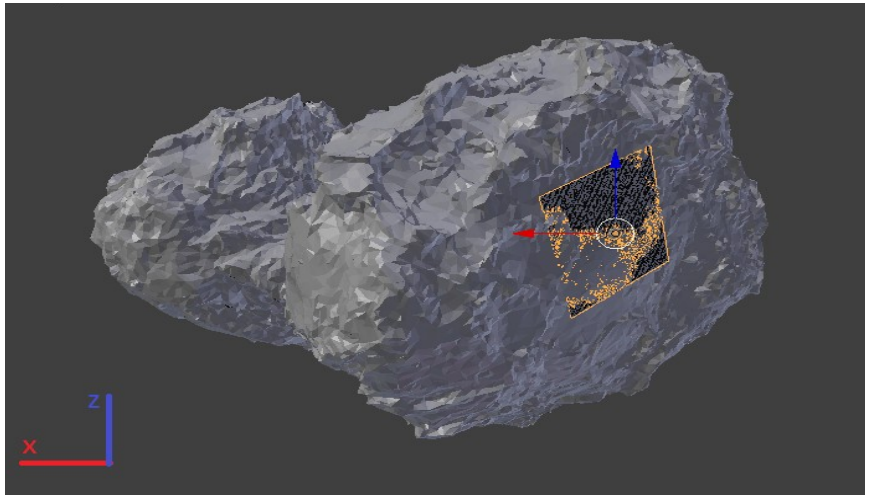
FEM Software

- ✓ Temperature variation within a boulder
- ✓ Maximum tensile stress (MPa)

Whether the modeled maximum tensile thermal stresses are sufficient to cause crack propagation

Geometry and Mesh





- Geodesic polihedron (40 m size boulder)
- Cubic volume (1 km x 1 km x 1 km)
- z-axis // rotating axis of the comet
- Two different meshes
- Thermal contact
- Controlled by the physics

Material Selection

<u>Nucleus</u>

organic components + minerals + water ice

- COOH- and OH groups
- polycyclic aromatic hydrocarbons
- refractory macromolecular material (CH_2 and CH_3)

(Filacchione+ 2019)

⇩

Carbon

Graphite

⇩

Thermal inertia **10-50 K m^{-2} s$^{-0.5}$**

(Gulkis+ 2015)

Conclusions

Method to analyze isolated boulder fields on comet 67P/Churyumov-Gerasimenko

New tool to measure and monitor the erosion and fallout on comet 67P/Churyumov-Gerasimenko

Thermomecanical model to simulate thermal stresses of boulders on comet 67P/Churyumov-Gerasimenko

Shape factors

Pristine 67P's ice content

Sunrise ans sunset are responsible for thermal fragmentation

Future Works

Global map of dust erosion/accretion- Application of the method in other regions

Thermomechanical model

We will model temperature and stresses including a regolith layer with variable thickness to understand the rule of this layer in terms of thermal conduction and cracks propagation

We will apply the Cheng and Vachon theory (1968) to calculate the thermal conductivity of two- and three-phase solid heterogeneous mixtures.

We will perform the simulation over the entire orbit of the comet to include in our study the thermal fatigue, and to determine the number of orbits necessary for the fragmentation of the surface.

List of Publications

First-authored peer reviewed papers

"Quantitative analysis of isolated boulders fields on comet 67P/Churyumov-Gerasimenko", *A&A* Rosetta 2 special issue, June 2019

"Comets and carbonaceous chondrites share a similar water content", *Science Advances*, Submitted

Co-authored peer reviewed papers

"The rocky-like behavior of cometary landslides in 67P/Churyumov-Gerasimenko", Lucchetti A. et al. 2019, JGR, Submitted

"Spectrophotometric variegation of the layering in comet 67P/Churyumov-Gerasimenko as seen by OSIRIS", Tognon G., et al. 2019, A&A, Rosetta 2 Special Issue

"Multidisciplinary analysis of the Hapi region located on Comet 67P/Churyumov-Gerasimenko", Pajola, M. et al. 2019, Volume 485, Issue 2, p.2139-2154

"The backscattering ratio of comet 67P/Churyumov-Gerasimenko dust coma as seen by OSIRIS onboard Rosetta", Bertini I. et al. 2019, *MNRAS*, Volume 482, Issue 3, p.2924-2933

"The big lobe of 67P/Churyumov-Gerasimenko comet: morphological and spectrophotometric evidences of layering as from OSIRIS data**"** , Ferrari, S. et al. 2018, *MNRAS*, Volume 479, Issue 2, p.1555-1568

List of Publications

Conferences

-
"Bouncing boulders on comet 67P", Vincent J-B et al. 2019, EPSC/DPS
"Sample return from a relic ocean world: The CALATHUS mission to Occator Crater, Ceres", IPPW 2019
"Geomorphological units of Khepry and Imhotep regions of comet 67P/Churyumov-Gerasimenko", Ferrari S. et al. 2018, EPSC
"3DPD application to the first CaSSIS DTMs", Simioni, E. et al. 2018, EPSC
"Thermal analysis of boulders on comet 67P/Churyumov-Gerasimenko", Cambianica et al. 2018, EPSC
"Quantitative analysis of Imhotep, Hapi and Hatmehit boulder populations on comet 67P/Churyumov-Gerasimenko", Cambianica et al. 2019, Congresso Nazionale di Scienze Planetarie
"Fragmentation processes on the 67P/Churyumov-Gerasimenko surface from the OSIRIS images" Cambianica et al. 2016, From Giotto to Rosetta

Thanks for the attention

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