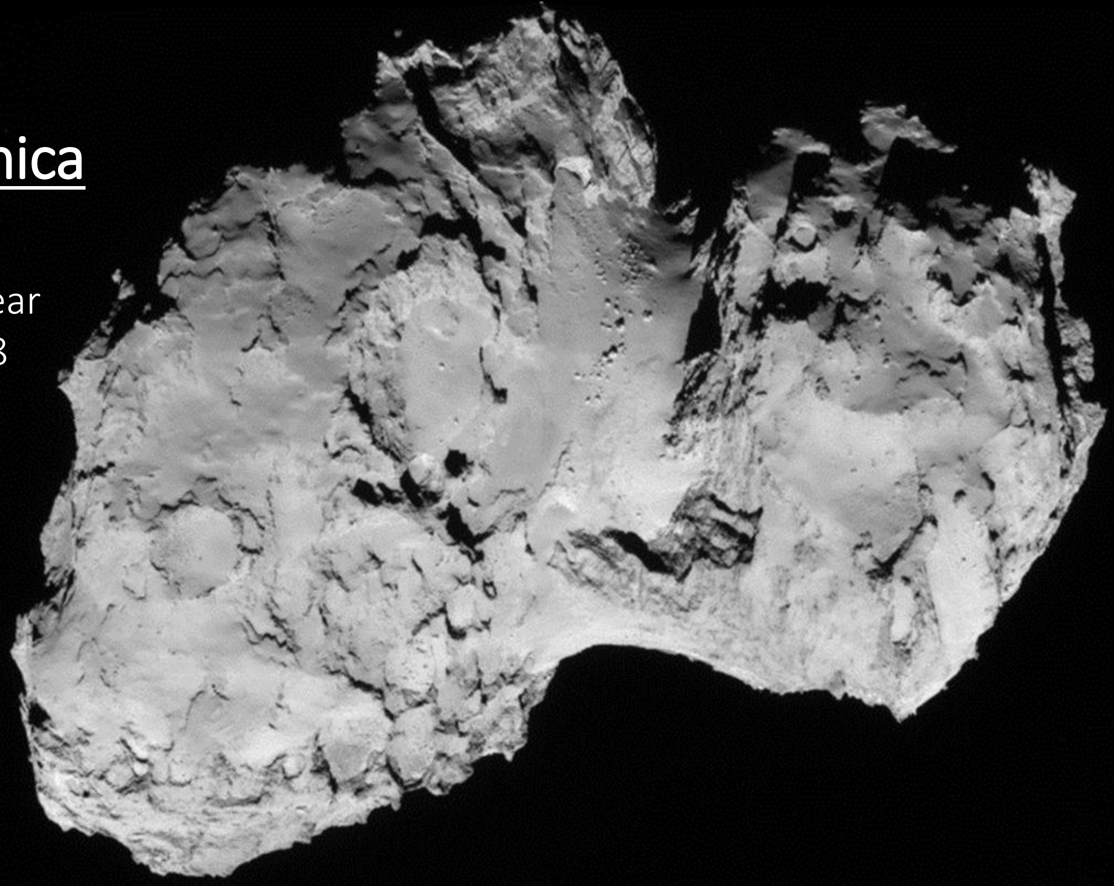
Morphological and compositional analysis of boulder distribution on comet 67P/Churyumov-Gerasimenko

PhD student

Pamela Cambianica

Admission to Third Year
13 September 2018

Supervisor: **Giampiero Naletto**
Co-supervisor: **Gabriele Cremonese**

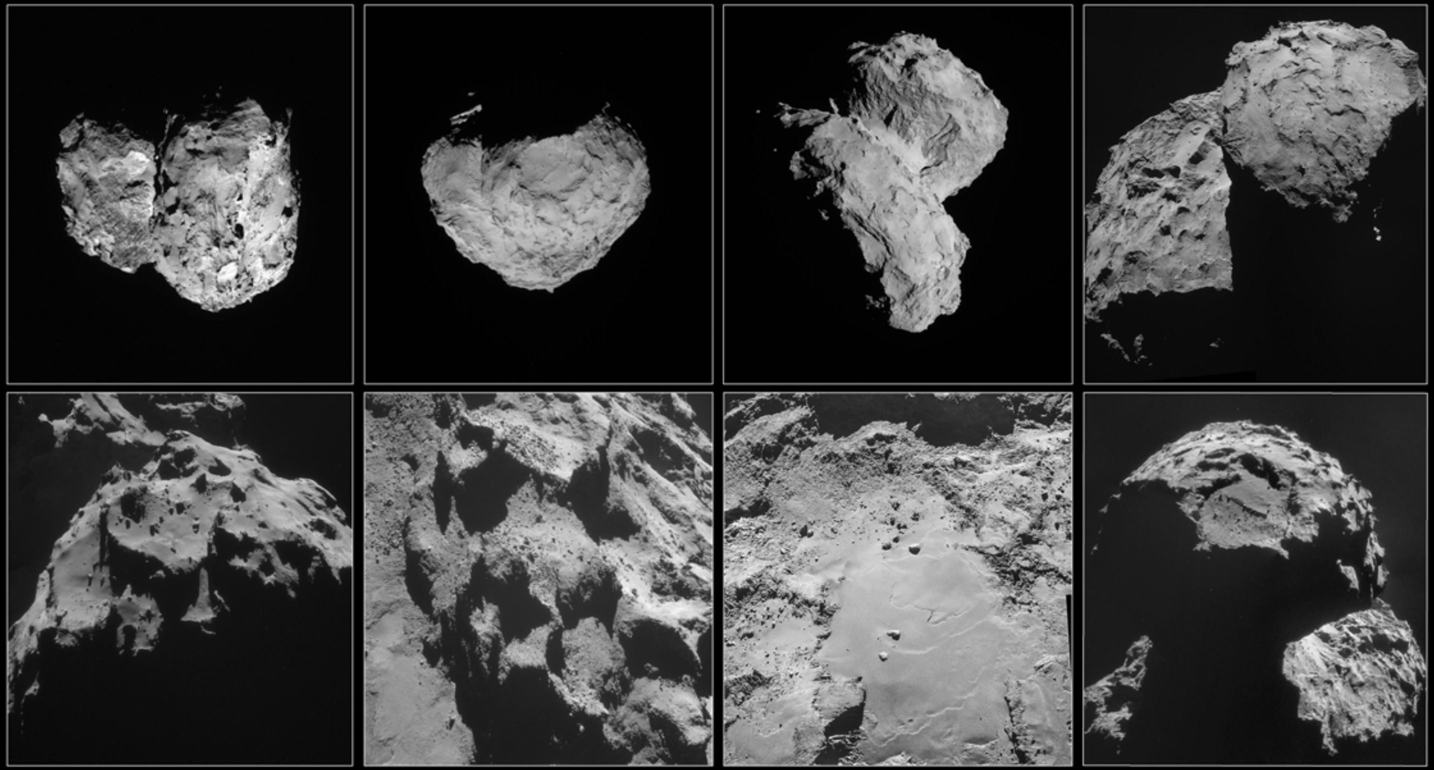


Morphological and compositional analysis of boulder distribution on comet 67P/C-G

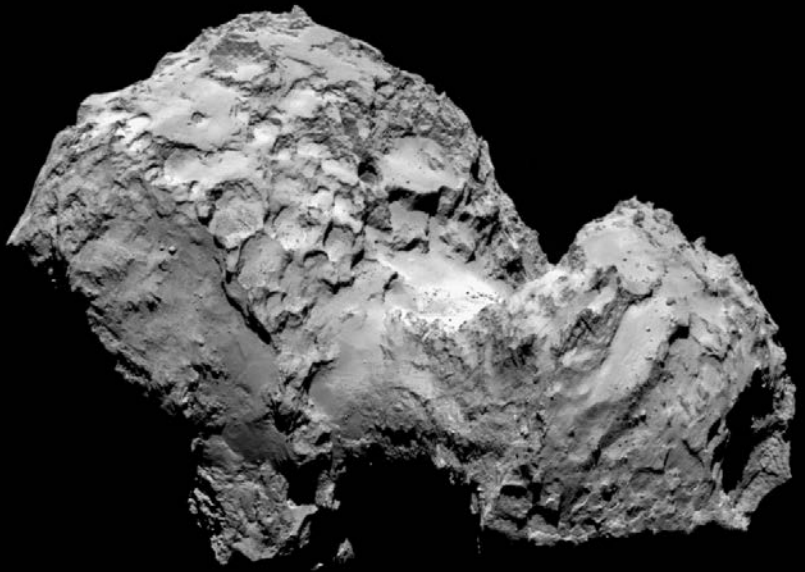
Credits: ESA

Aims:

- To define a method to analyze in a quantitative manner populations of boulders



Morphological and compositional analysis of boulder distribution on comet 67P/C-G



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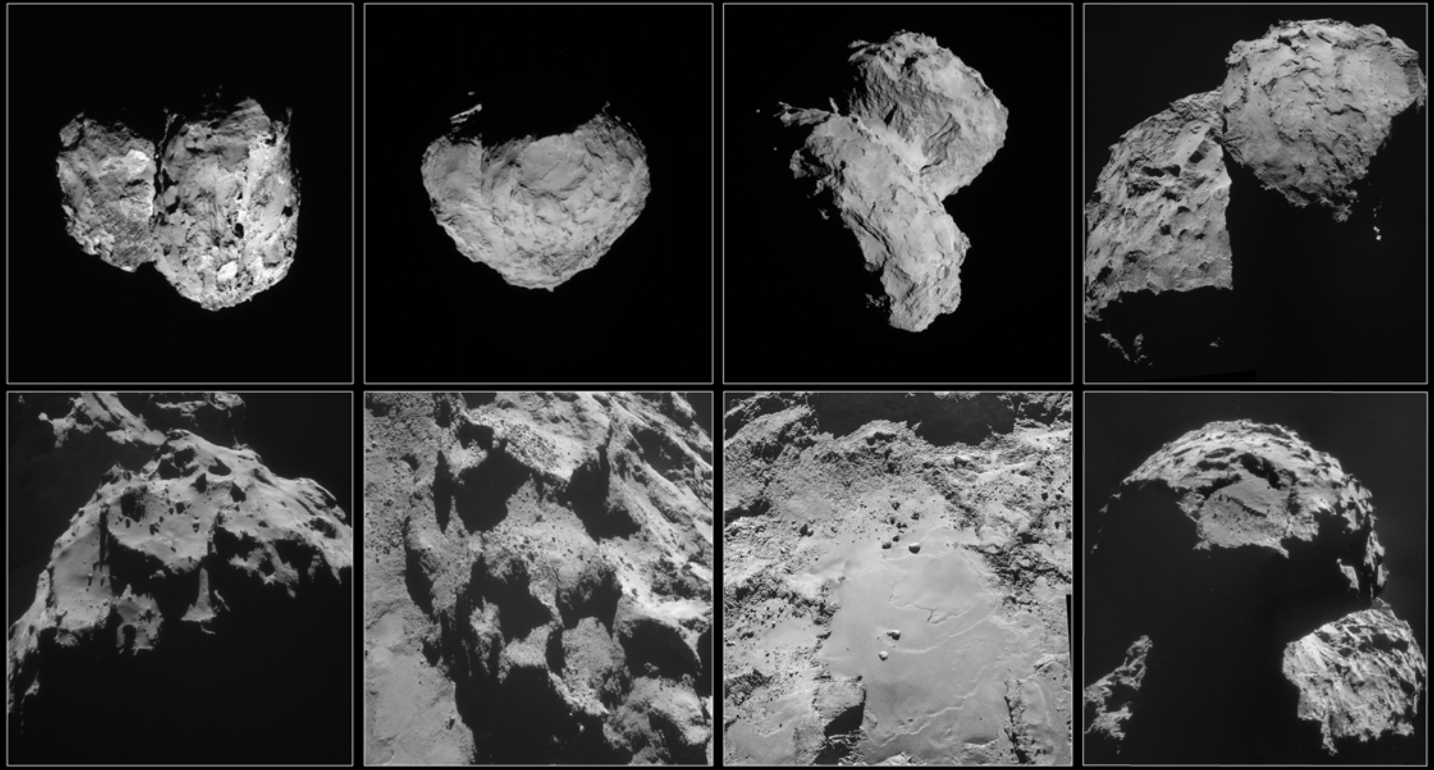
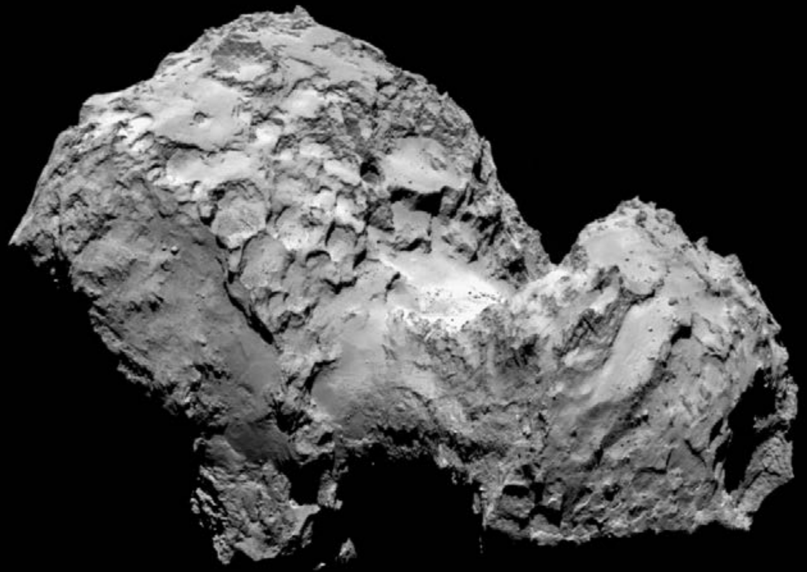
- To link the method with others described in literature



Morphological and compositional analysis of boulder distribution on comet 67P/C-G



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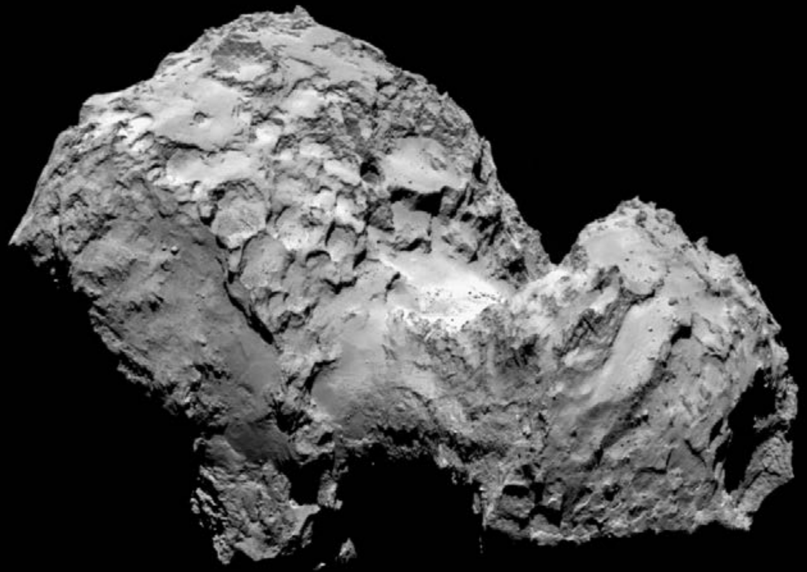
Aims:

- To define a method to analyze in a quantitative manner populations of boulders
- To link the method with others described in literature
- To define possible processes responsible for the boulder fragmentation through OSIRIS image analysis

NAC_2016-07-09T11.25.15.786Z_ID30_1397549000_F41

Morphological and compositional analysis of boulder distribution on comet 67P/C-G



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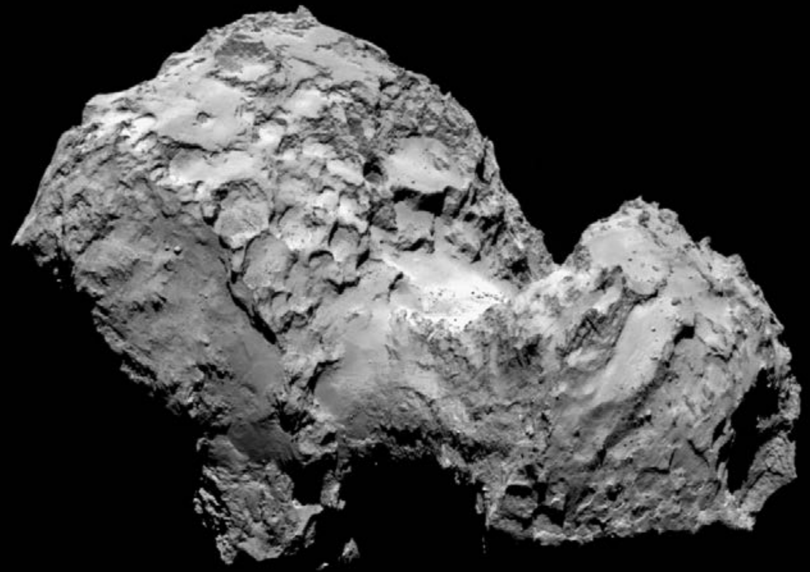
- To understand the rule of thermal stress and fatigue in terms of propagation of cracks and fragmentation

Morphological and compositional analysis of boulder distribution on comet 67P/C-G



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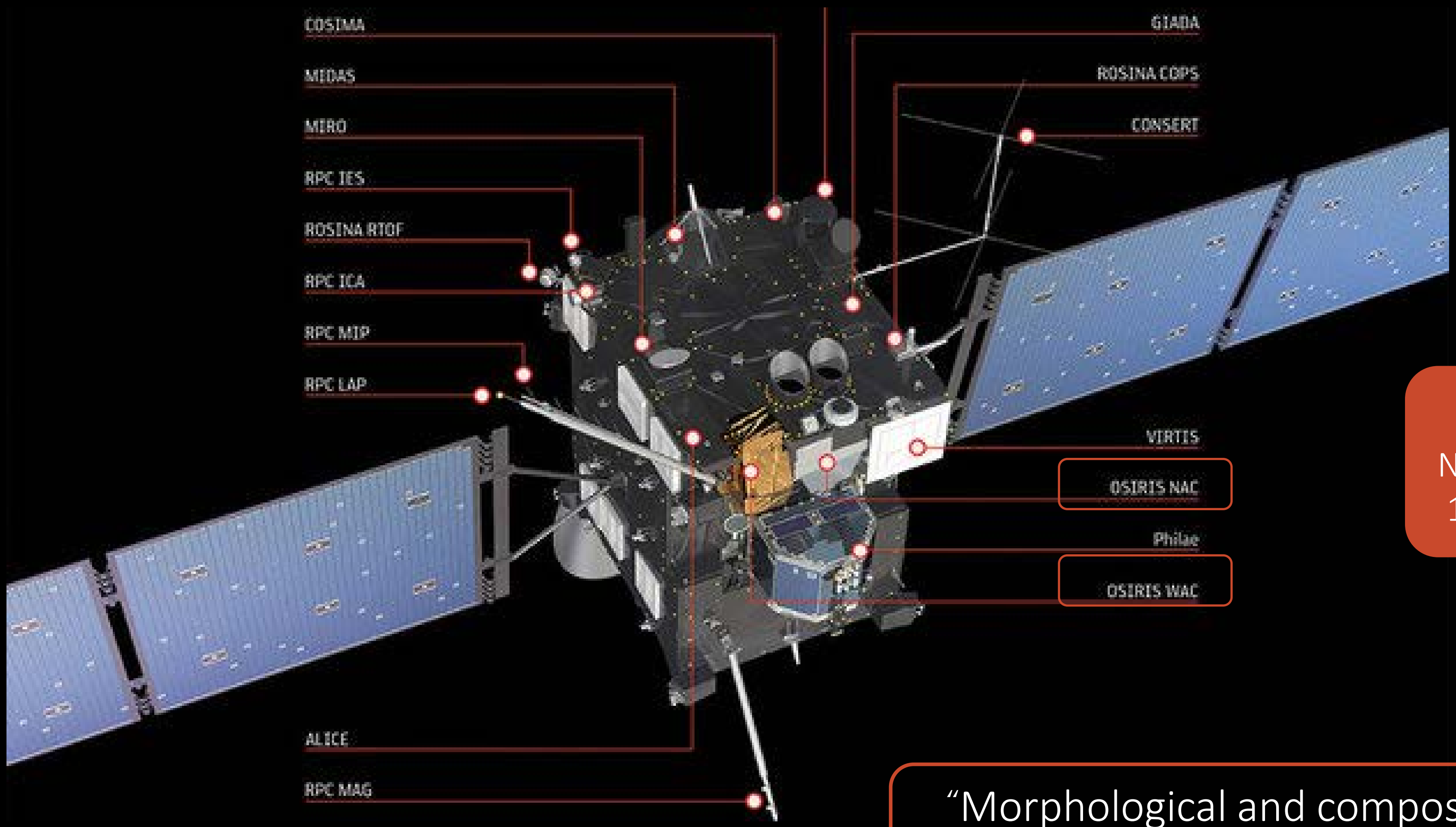
- To define possible processes responsible for the boulder fragmentation through OSIRIS image analysis
- To understand the rule of thermal stress and fatigue in terms of propagation of cracks and fragmentation
- To develope a fragmentation model able to explain the presence of some features, like boulders, on the surface of comet 67P/C-G

The Rosetta mission – OSIRIS instrument



Credits: ESA

Optical Spectroscopic Infrared Remote Imaging System (OSIRIS)
(Keller et al. 2007)

NAC
Narrow Angle Camera
1.86 m/px at 100 km

WAC
Wide Angle Camera
10.1 m/px at km

Nucleus

Coma

"Morphological and compositional analysis of boulder distribution on comet 67P/C-G"

Outline

Analysis of OSIRIS images

- Quantitative analysis of Imhotep, Hapi and Hatmehit boulder populations on comet 67P/Churyumov- Gerasimenko
- Measurements of erosion and dust deposits in the Hapi region

Thermal and stress analysis

- Thermal analysis of boulders of 67P/C-G comet
- Stress analysis of boulders of 67P/C-G comet

- Future works
- Personal training plan
- List of publications

Analysis of OSIRIS images

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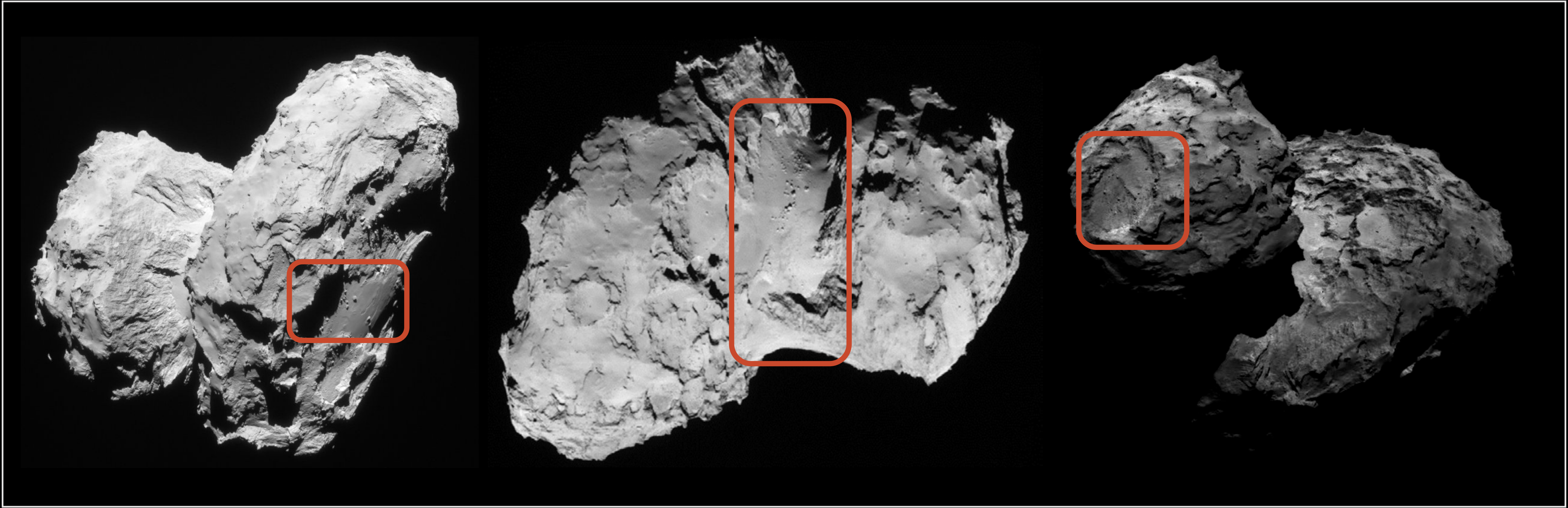
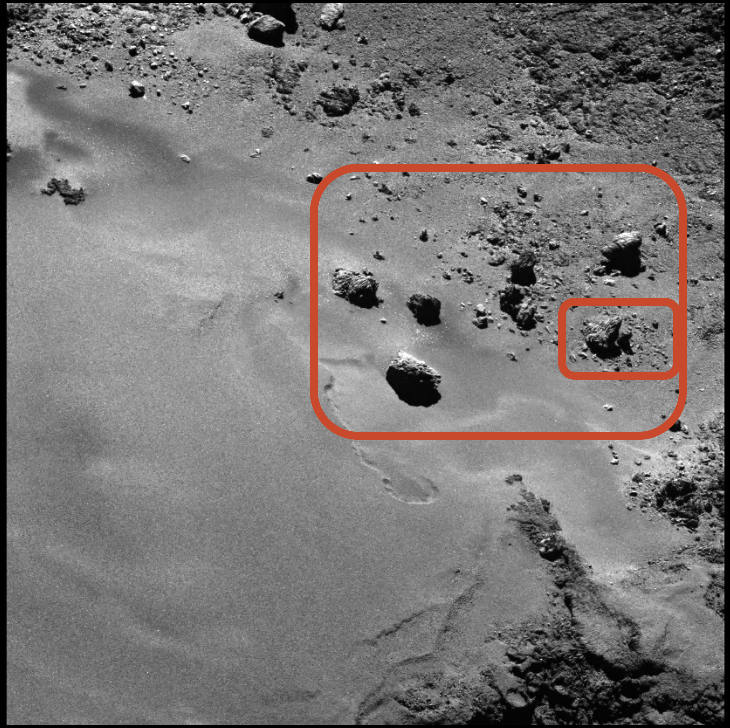
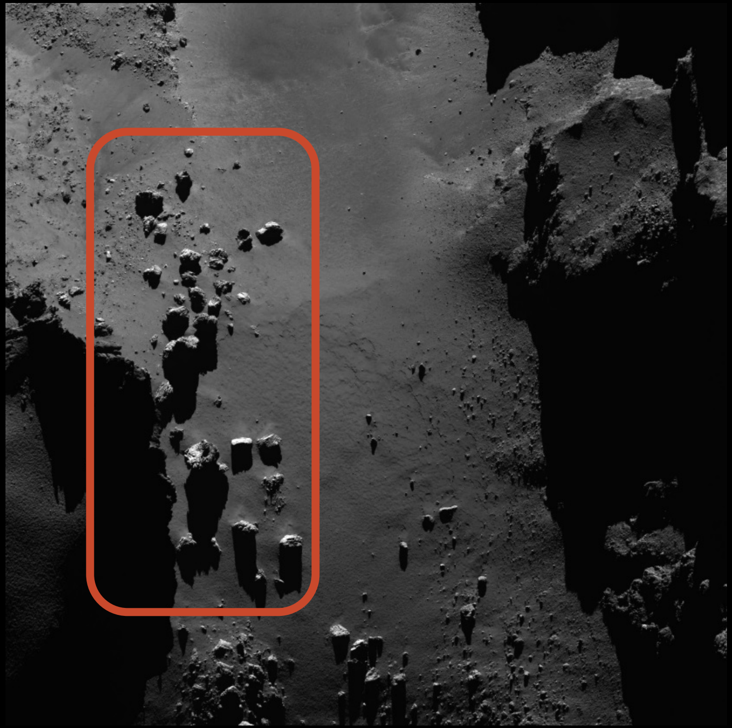
Selection of surface images – Pre and post-perihelion

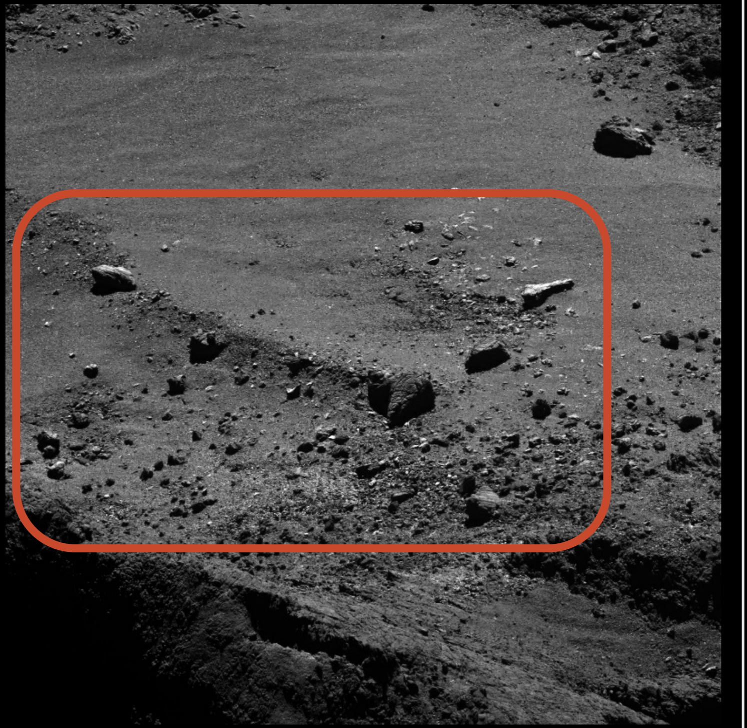


Imhotep	Hapi	Hatmehit
NAC_2014-09-29T13.29.30.598Z_ID30_1397549600_F22	NAC_2014-12-10T06.29.11.447Z_ID10_1397549002_F24	NAC_2014-12-12T17.42.03.690Z_ID30_1397549500_F24
NAC_2016-07-09T11.25.15.786Z_ID30_1397549000_F41	NAC_2016-07-20T08.02.48.392Z_ID30_1397549001_F22.	NAC_2016-07-23T17.54.43.732Z_ID30_1397549002_F41

Selection of surface images – Pre and post-perihelion







Imhotep	**Hapi**	**Hatmehit**
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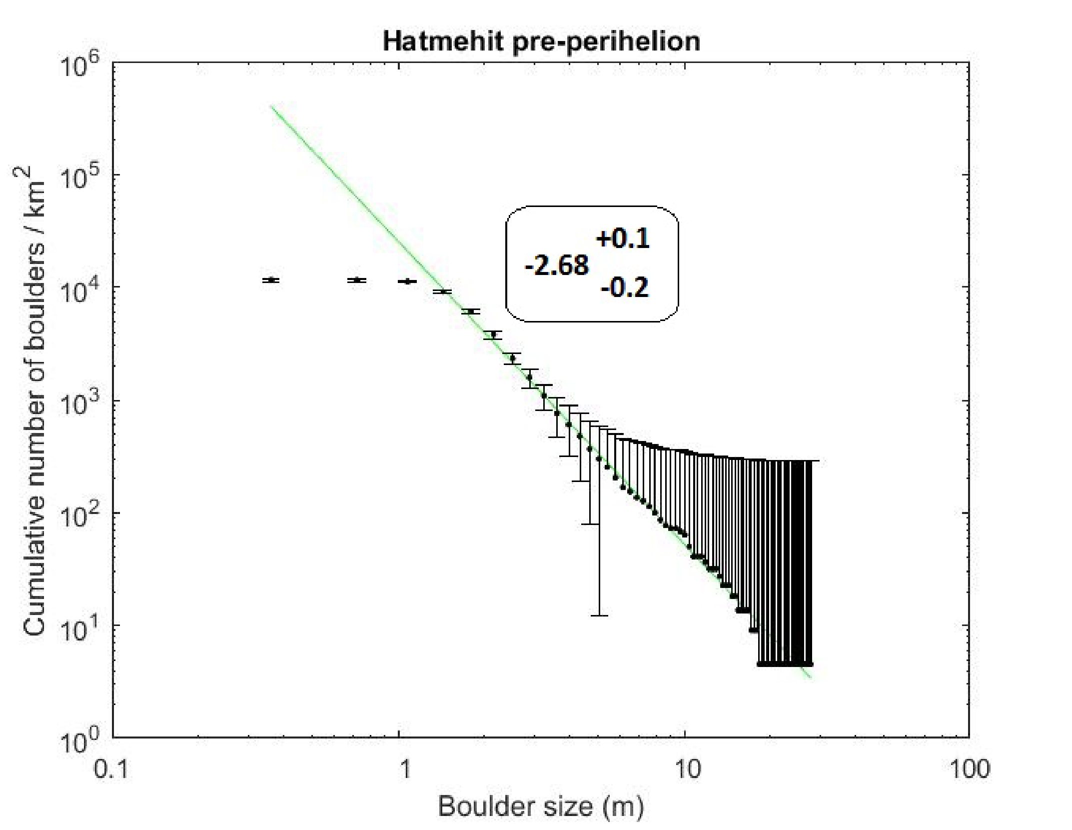
Cumulative size-frequency distribution

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



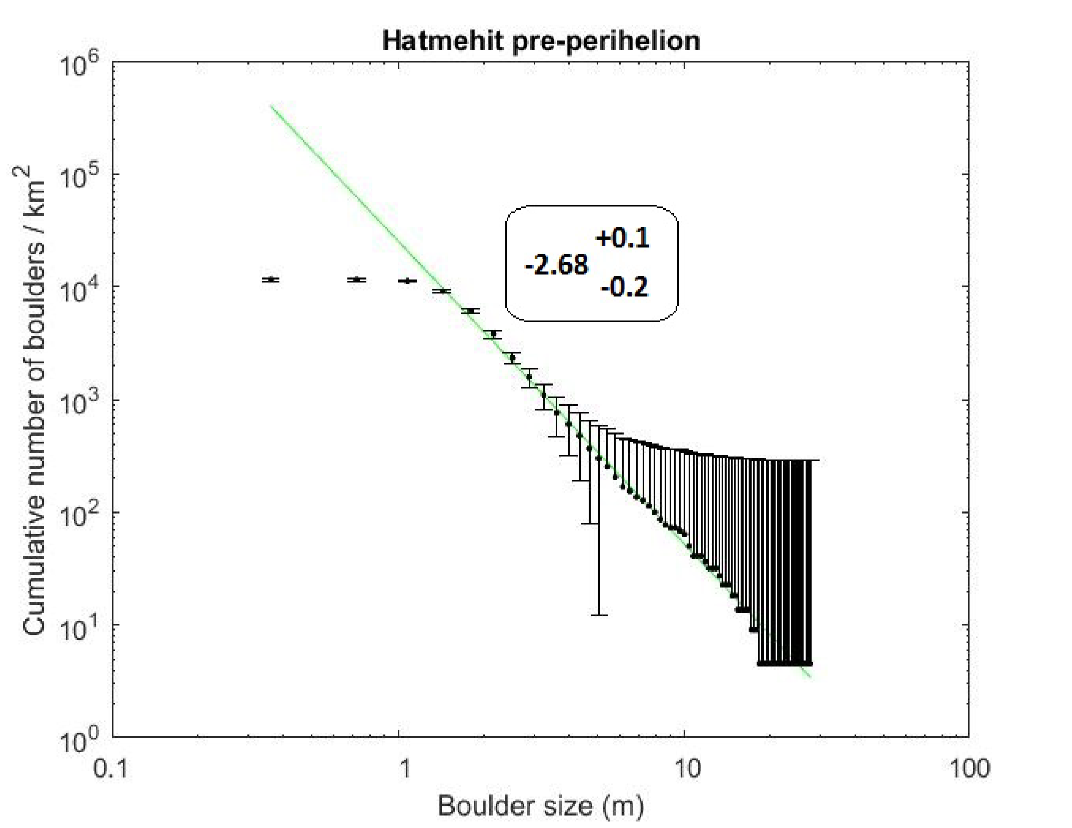
A power function can be used to fit data from every regions to represent the general form of rock size distribution

$$N(\geq a) = ka^{-D}$$

Cumulative size-frequency distribution – Fractal theory

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

Empirical data have suggested that the size distribution of material expected from fractures and fragmentation would allow a fractal rule



$$N\left(\frac{1}{b_i}\right) = k\left(\frac{1}{b_i}\right)^{-r}$$ (Mandelbrot, 1982)

$$N(\geq a) = ka^{-D}$$

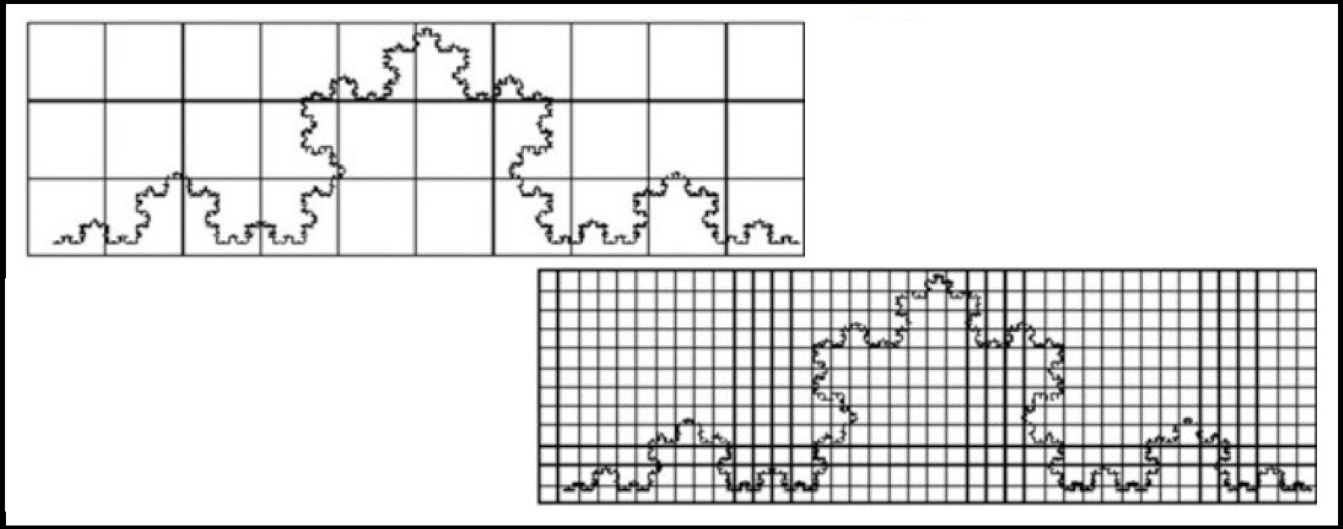
k number of initiators of unit length
b scaling factor > 1
r fractal dimension

The SFD curve can be represented by a fractal theory, a power-law which appears as a straight line in a log-log plot

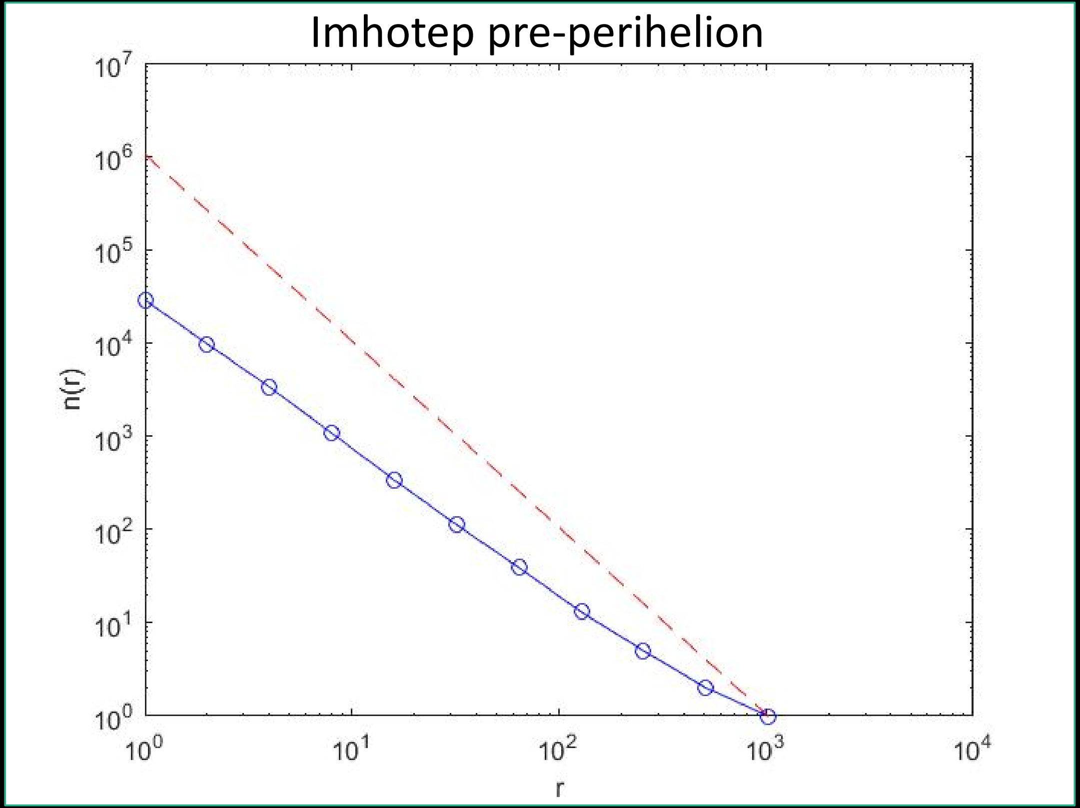
Fractal theory – BoxCount (1/2)

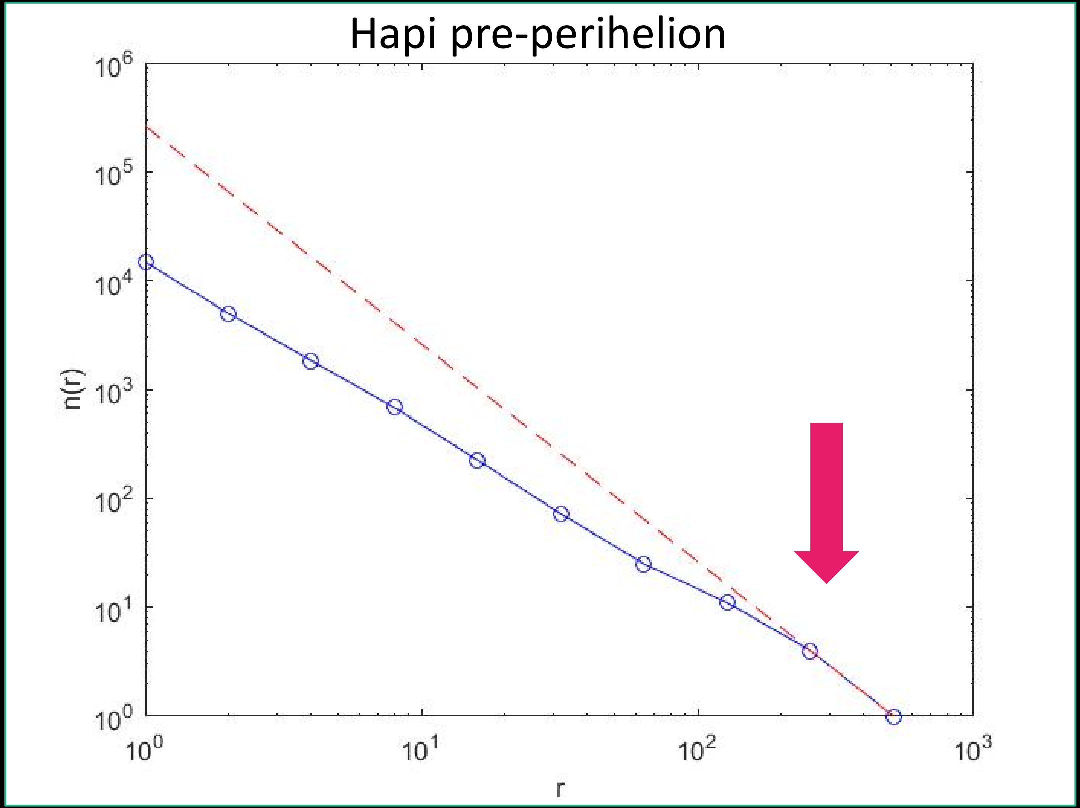
Analysis of a complex 2D pattern by breaking an image into smaller pieces, and analyzing the pieces at each smaller scale

- 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



Fractal theory – BoxCount (2/2)



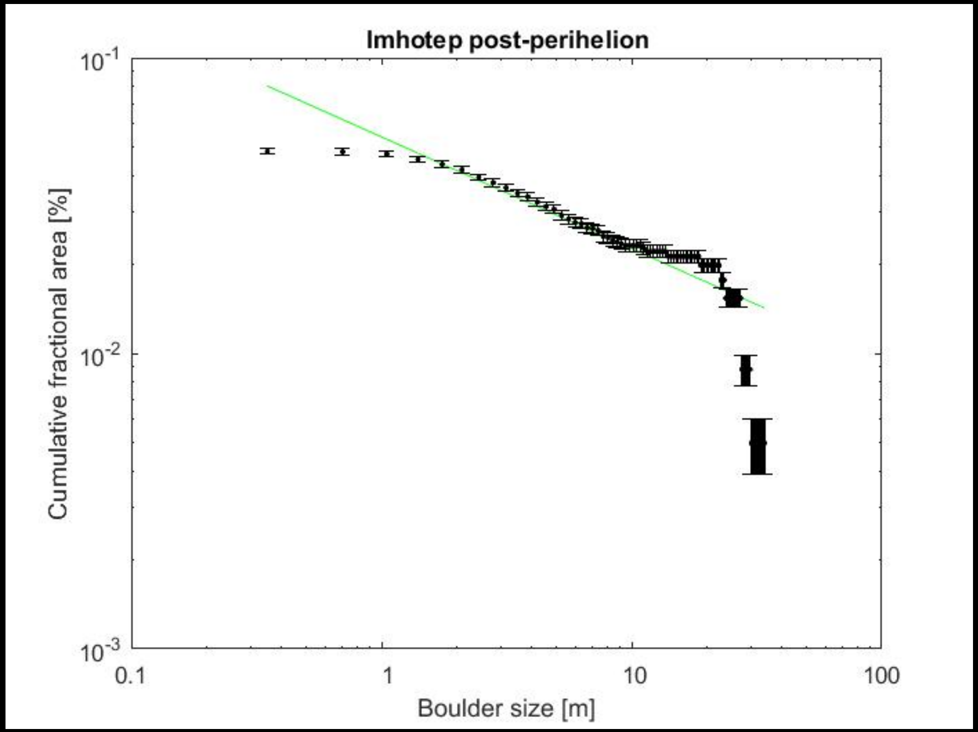


The discrepancy between the two curves indicates a possible fractal behavior of the image

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

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 or power-law equation



$$\boxed{F(\geq D) = Kx^{-q(D)}}$$

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

Boulders shape

The morphologies of rocks should provide records on rock surface processes if signature in their shape and surface texture can be identified and interpreted.

- Sphericity and elongation reflect the lithology of the mass itself
- Roundness describes transport or weathering history

The final shape is strongly influenced by the composition of particles

- Slate rocks tend to split into planar fragments
- Jointed rocks tend to split into cubic fragments
- Corners and edges are most vulnerable than faces

Shape factors

Dimensionless quantities calculated from measured dimension, such as diameter, area, perimeter, etc.
The factors are normalized, that is the values range from 0-1 where 1 represents an ideal case of maximum symmetry.

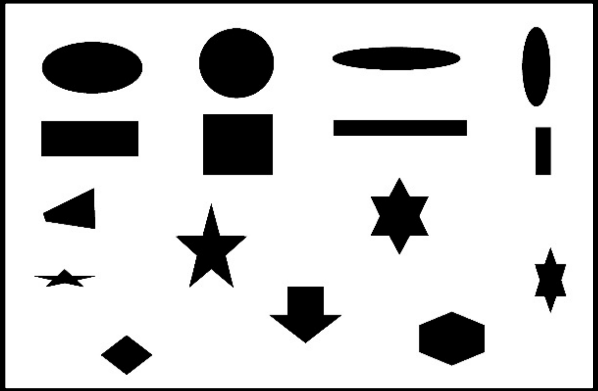
Aspect Ratio Circularity Roundness Compactness Elongation Solidity Convexity Feret's diameter

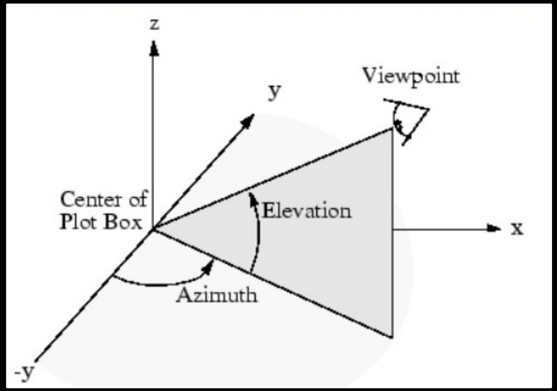
Boulders shape – Source of errors

- To classify each area in terms of shape factors
- To compare pre and post perihelion shape factors

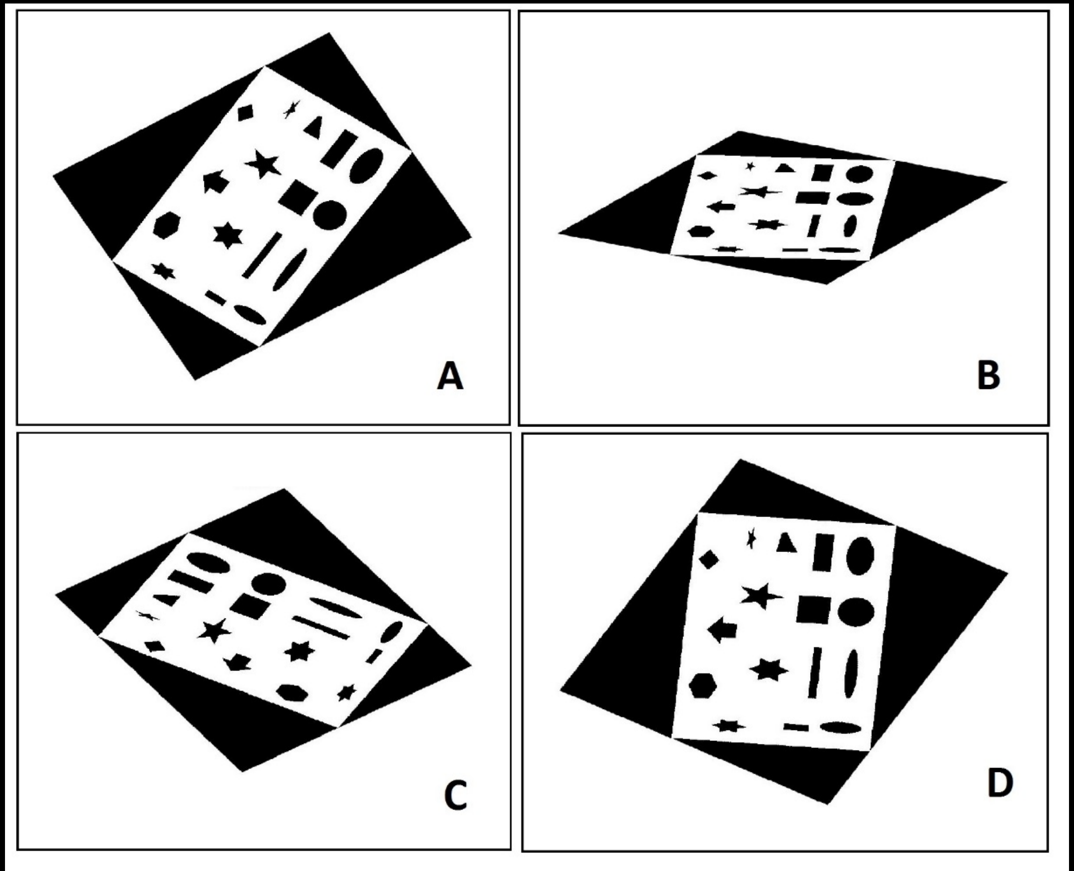
→ Elongation and azimuth

Synthetic image test





(A) Random
(B) azimuth = **120** elevation = **20**
(C) azimuth = **55** elevation = **40**
(D) azimuth = **120** elevation = **50**



Quantitative analysis of Imhotep, Hapi and Hatmehit boulder populations on comet 67P/Churyumov-Gerasimenko

P. Cambianica[1], G. Cremonese[2], G. Naletto[5,1,6], A. Lucchetti[2], M. Pajola[2], L. Penasa[1], E. Simioni[2], M. Massironi[4,1], S. Ferrari[1], F. LaForgia[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[14], I. Bertini[3], D. Bodewits[15], V. Da Deppo[6], S. Debei[16], M. De Cecco[17], J. Deller[7], S. Fornasier[13], M. Fulle[18], O. Groussin[19], P. J. Gutiérrez[20], C. Güttler[7], S. F. Hviid[21], W.-H. Ip[22,23], L. Jorda[19], H. U. Keller[24,21], J. Knollenberg[21], E. Kührt[21], M. Küppers[25], L. M. Lara[20], M. Lazzarin[3], J. J. López-Moreno[20], F. Marzari[5], X. Shi[7], N. Thomas[26,27], C. Tubiana[7], and J.-B. Vincent[21]

(Affiliations can be found after the references)

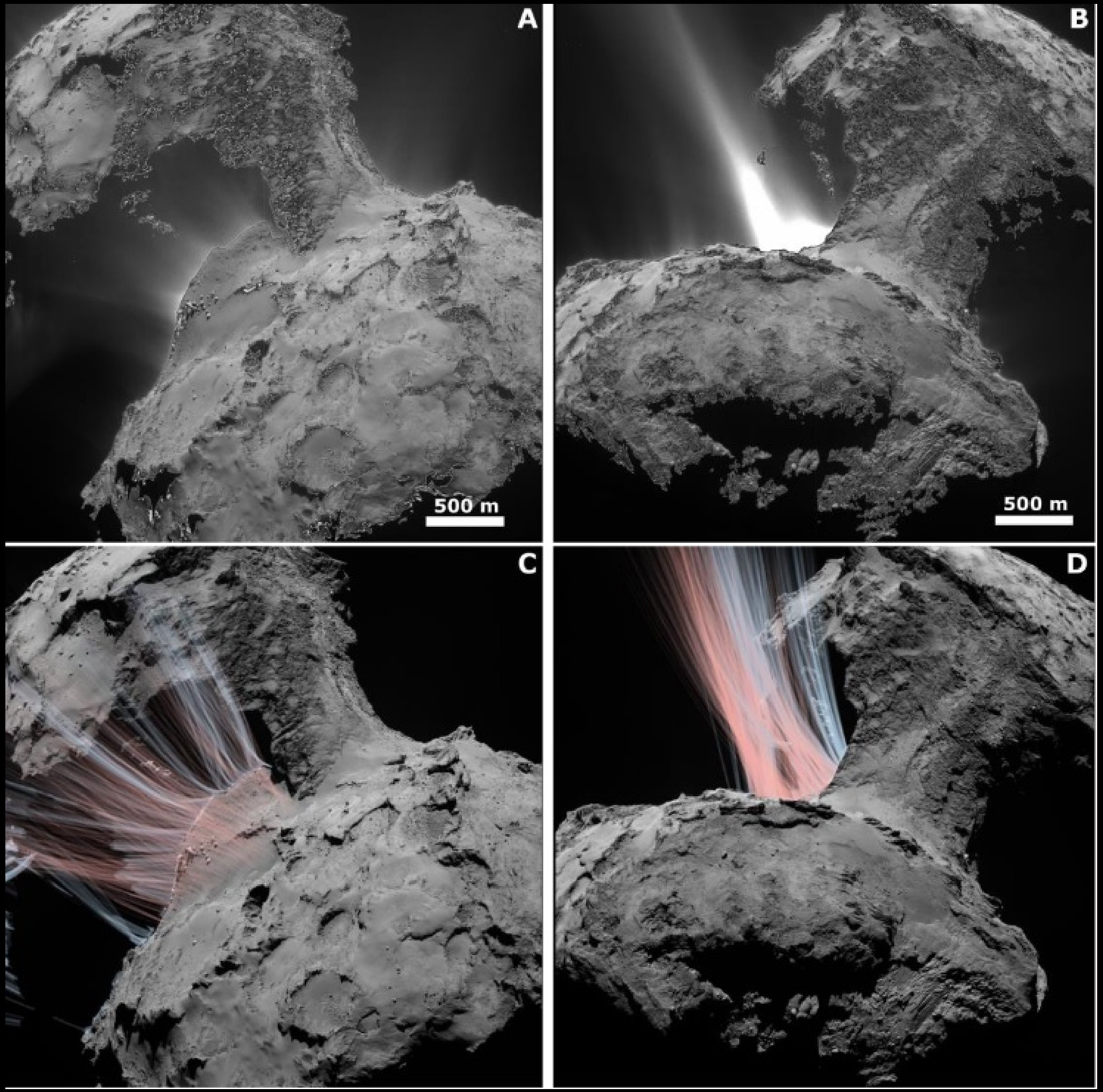
In preparation!

Astronomy & Astrophysics

Analysis of OSIRIS images

- Quantitative analysis of Imhotep, Hapi and Hatmehit boulder populations on comet 67P/Churyumov- Gerasimenko
- Measurements of erosion and dust deposits in the Hapi region

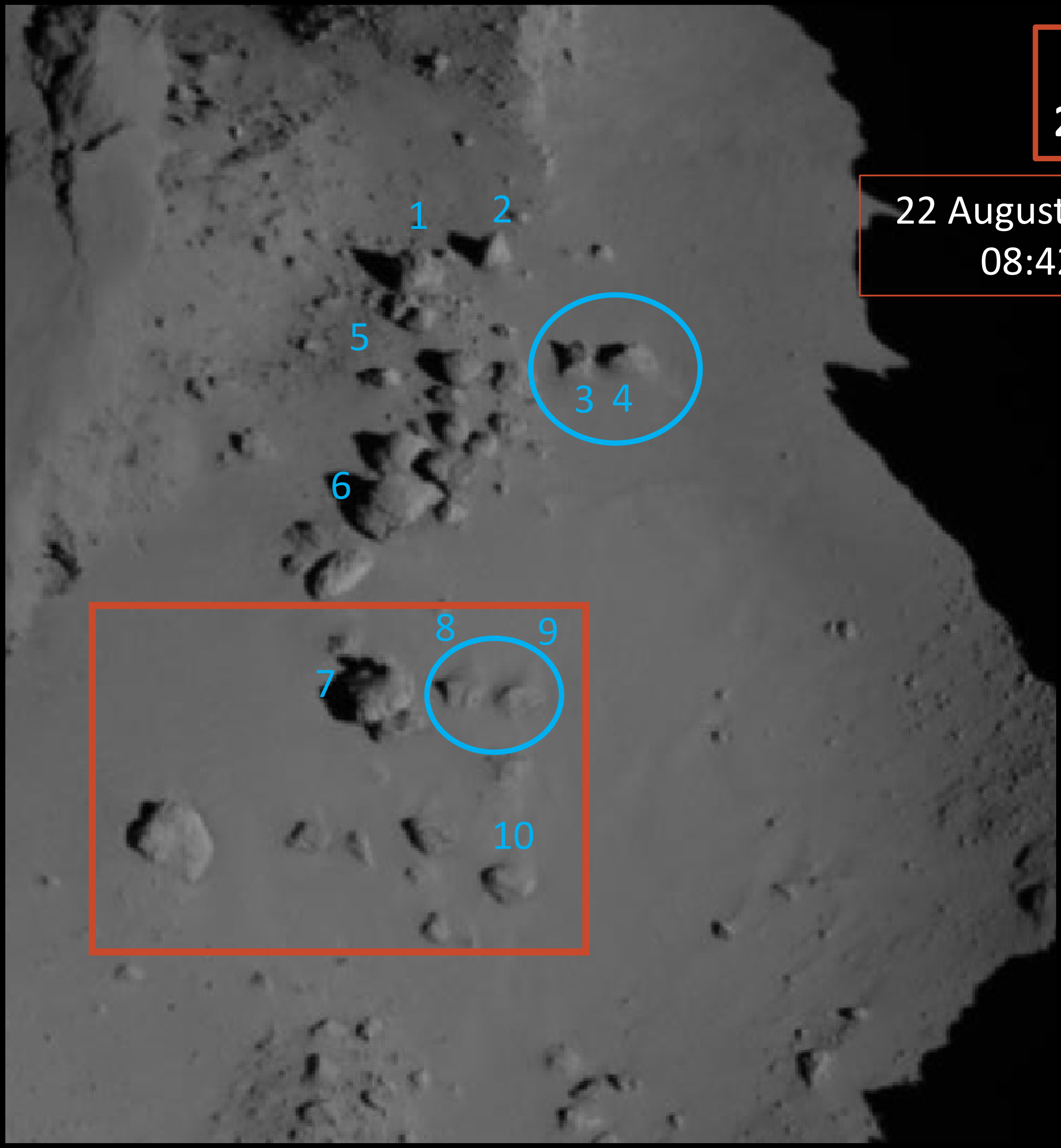
Measurements of erosion and dust deposits in the Hapi region



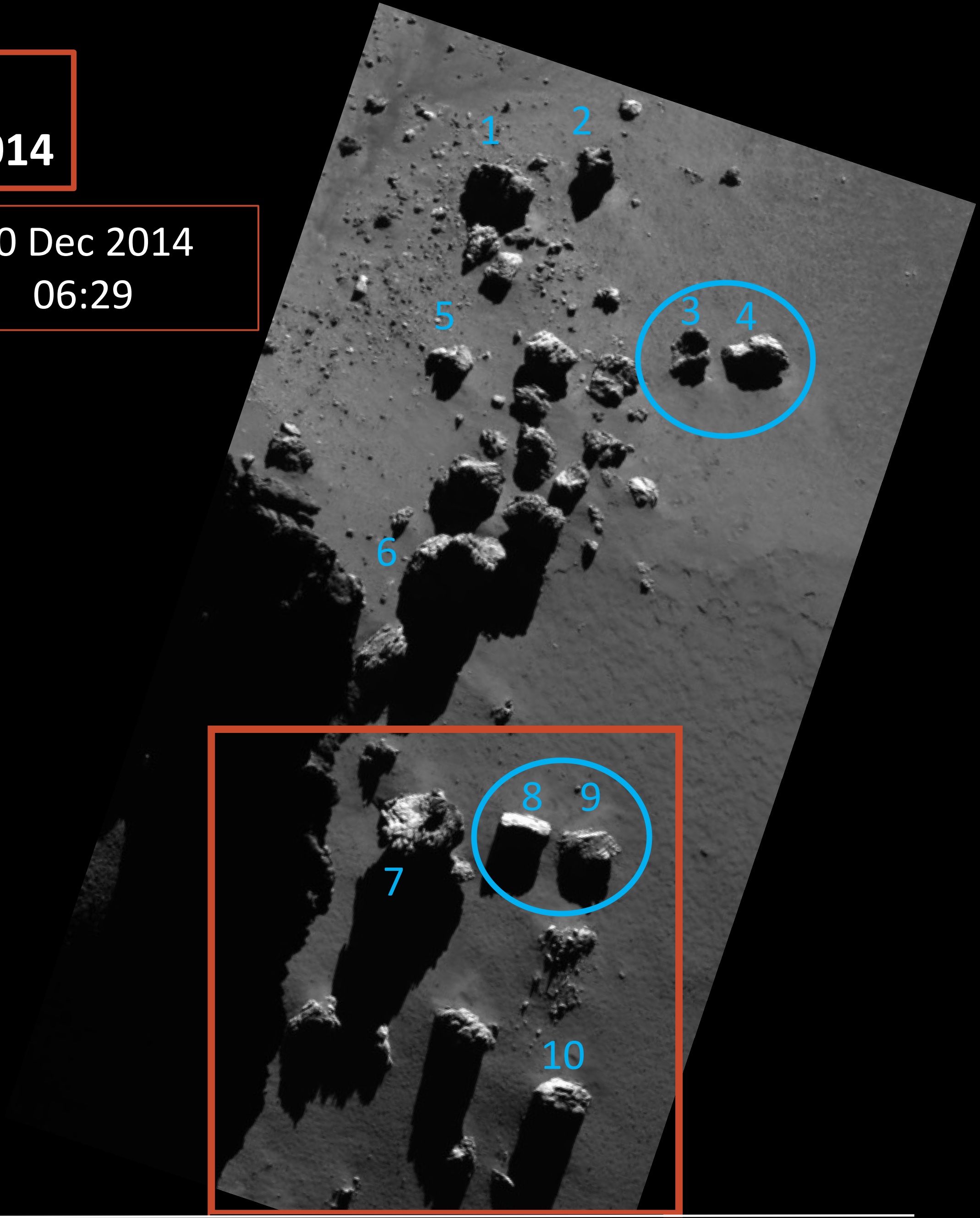
(Shi et al, 2018)

JETS
22 AUG 2014 and 14 MARCH 2015

Jet
22 August 2014



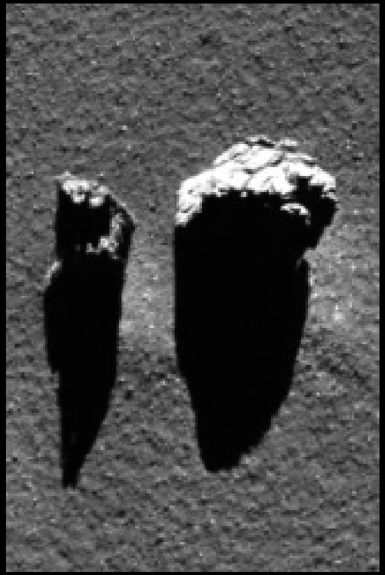
22 August 2014
08:42



10 Dec 2014
06:29

Dust cover or poor spatial resolution?

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



Boulder definition ⟹

SPICE KERNELS ⟹

MATLAB tool

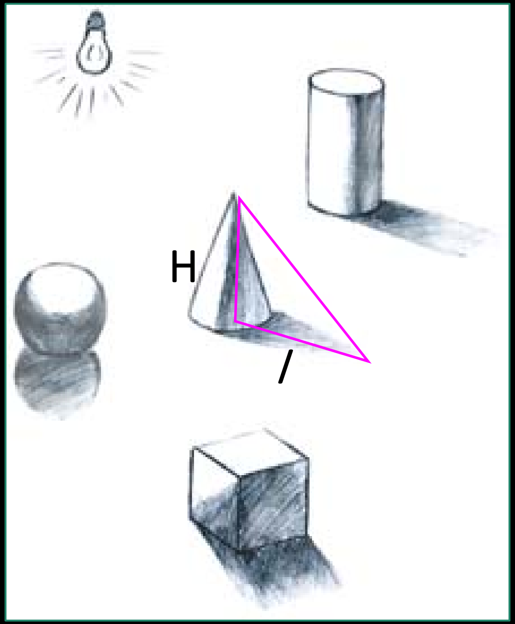
- Acquisition geometry
- Local surface
- Incidence angle

⇩

Height ⟹ Variation in height?

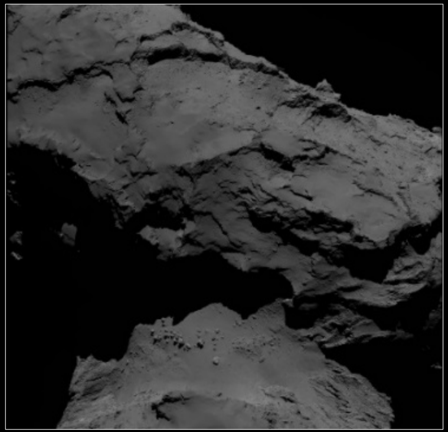
⇩

Measurements of erosion and deposit

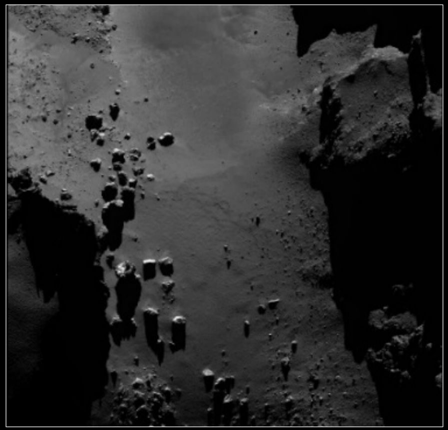


$$H = l\tan(\pi - i)$$

Data set



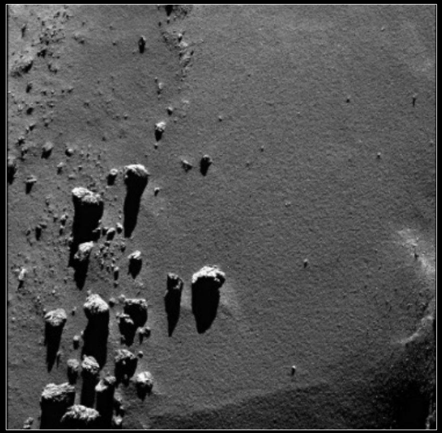
2014-08-21 19:42:54



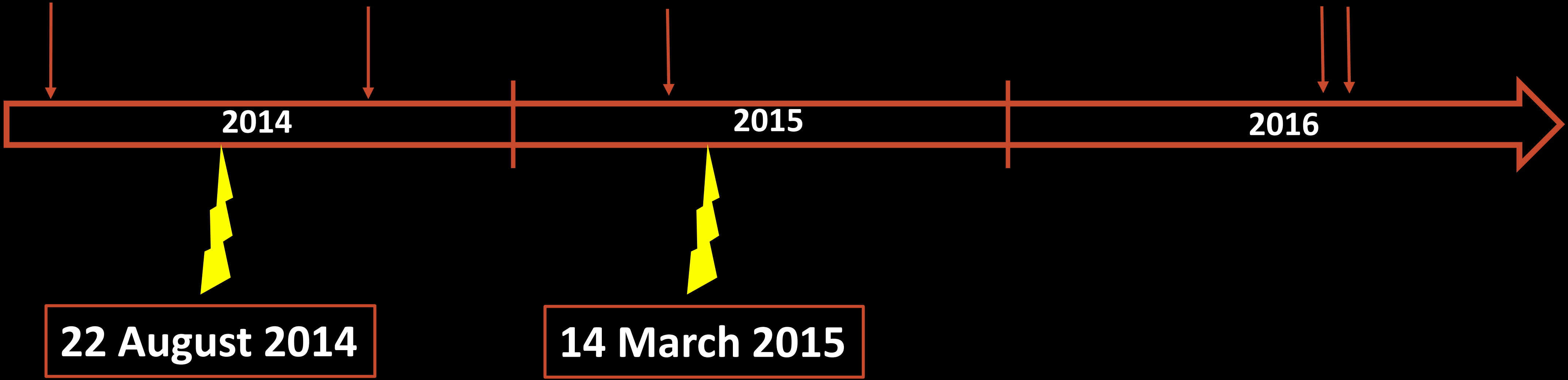
2014-12-10 06:29:11

2015-01-22 23:29:54

2016-06-19 11:09:40



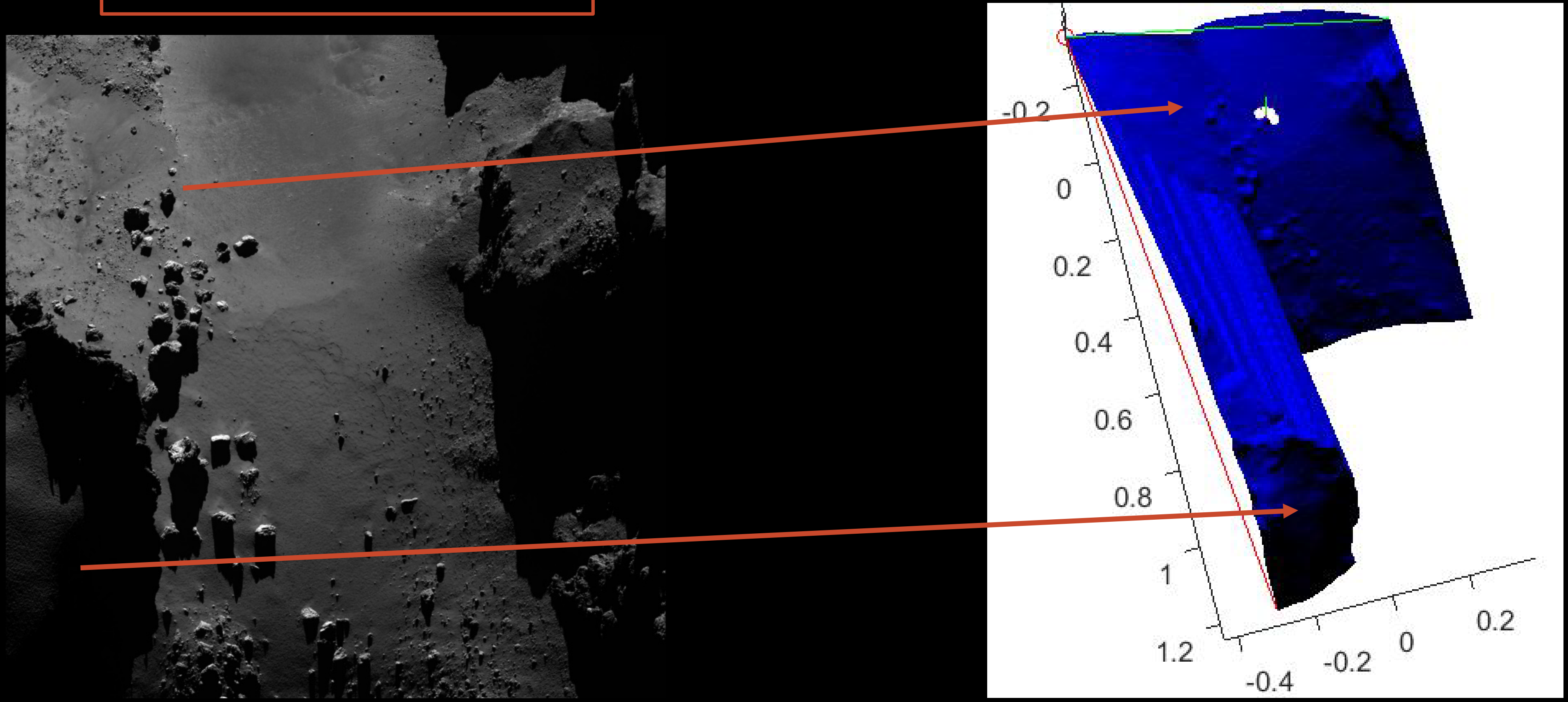
20-07-2016 08:02:36



Matlab tool – Selection of an epoch

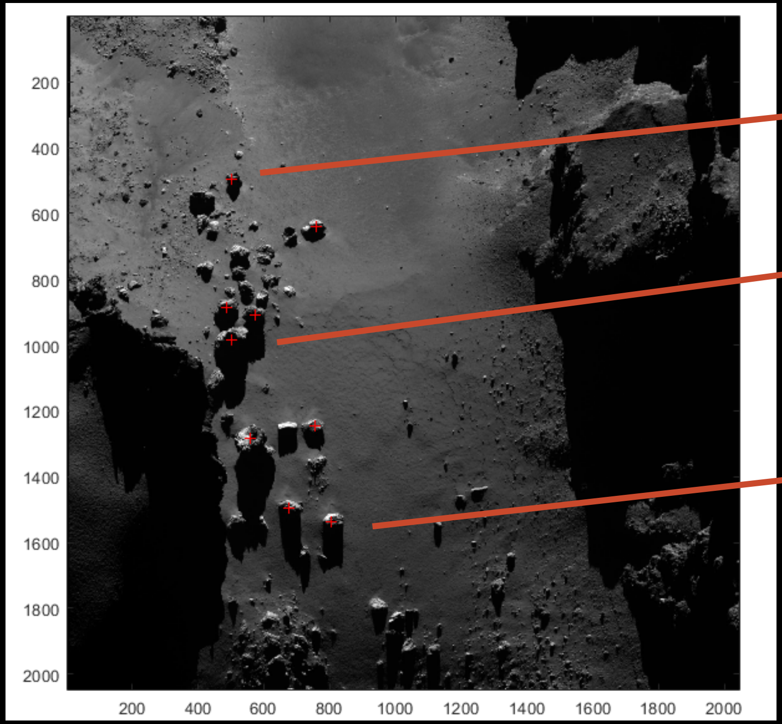
- We defined the boresight and the frame of instrument (NAC) by spice kernels
- We computed the boresight intercept of the projective ray of each pixel on the body shape (M0004 Vertices) at specific epoch.

10 December 2014 06:29:11

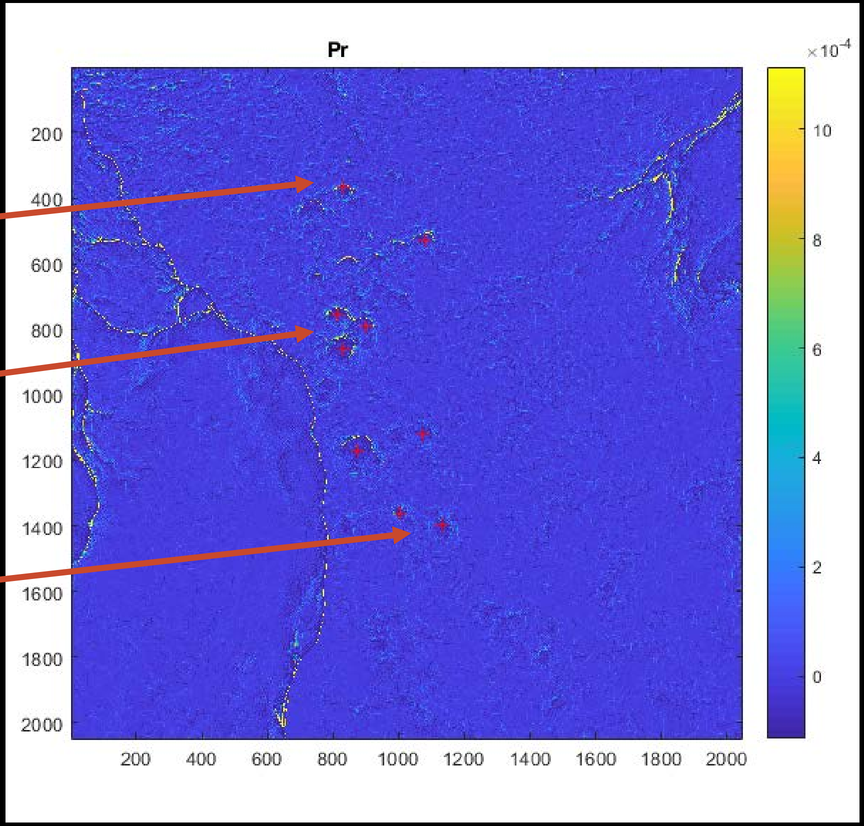


Matlab tool – Image alignment

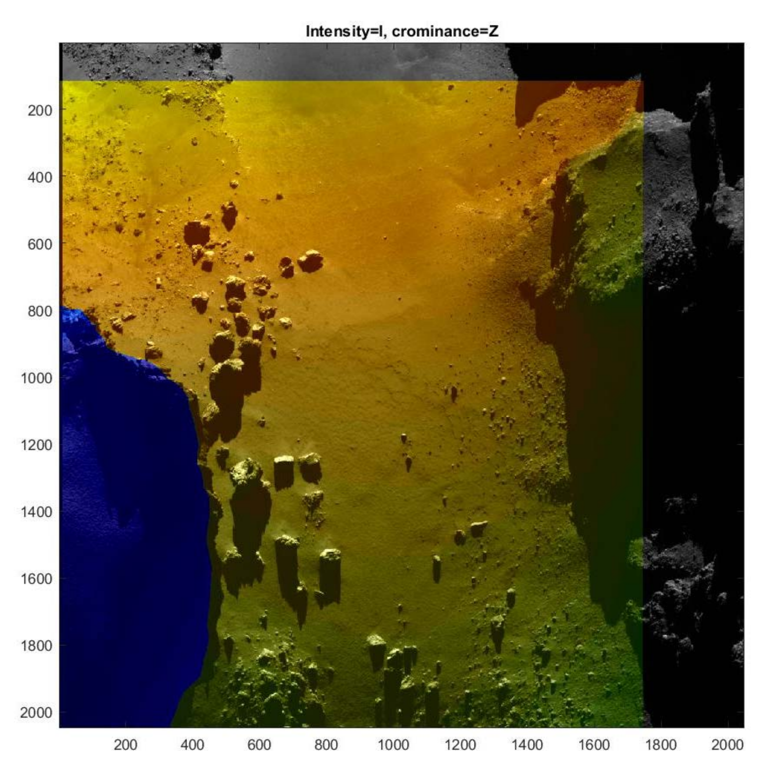
- Define transformation (Bundle Adjustment) between the 3D model and the pinhole camera model (it describes the mathematical relationship between the coordinates of a point in three-dimensional space and its projection onto the image plane of an *ideal* pinhole camera).
- We applied a Laplacian filter to the height model in the camera frame to fixed tie points. The Laplacian of an image highlights regions of rapid intensity change and is therefore often used for edge detection.



NAC image (I)



Laplacian filter (H)

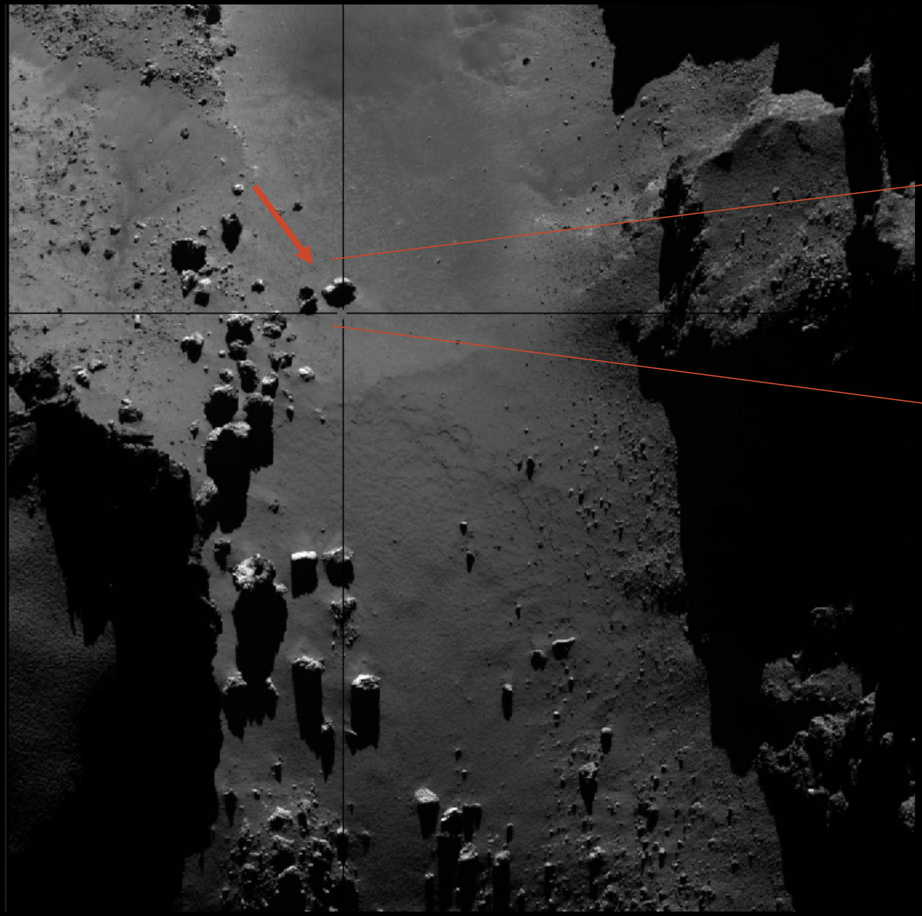


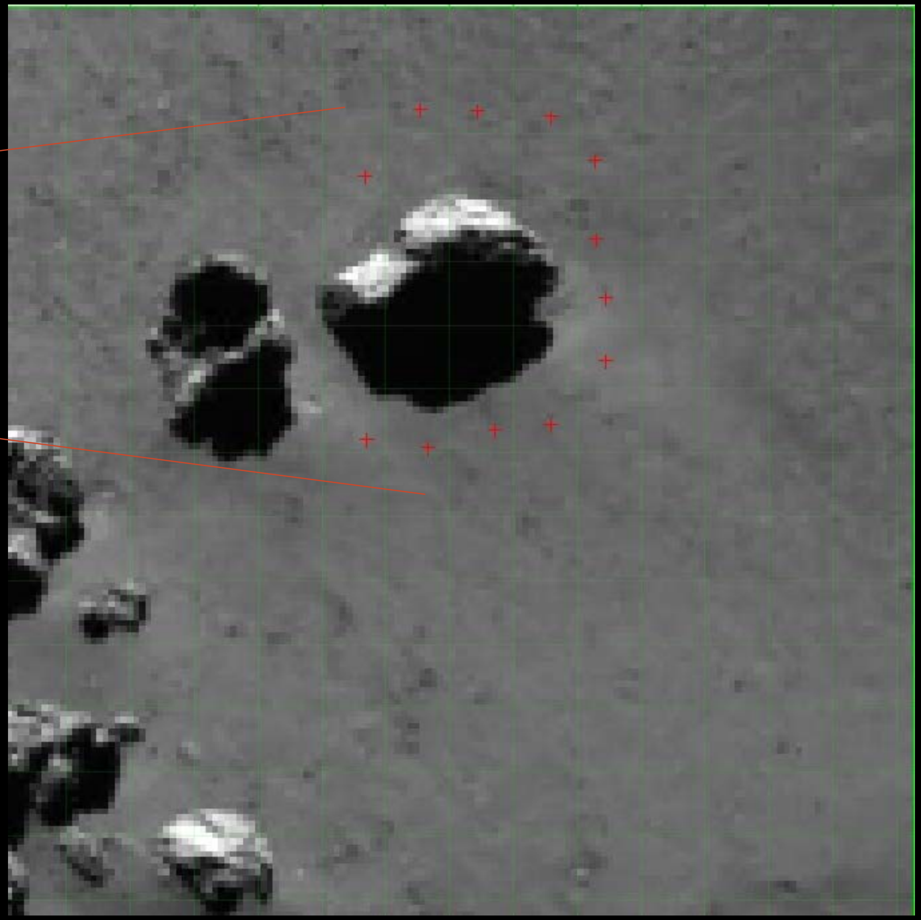
Aligned (H-I)

Matlab tool – Local surface definition

Define surfaces around the boulders to define the mean surface reference system on which calculate the incidence angle

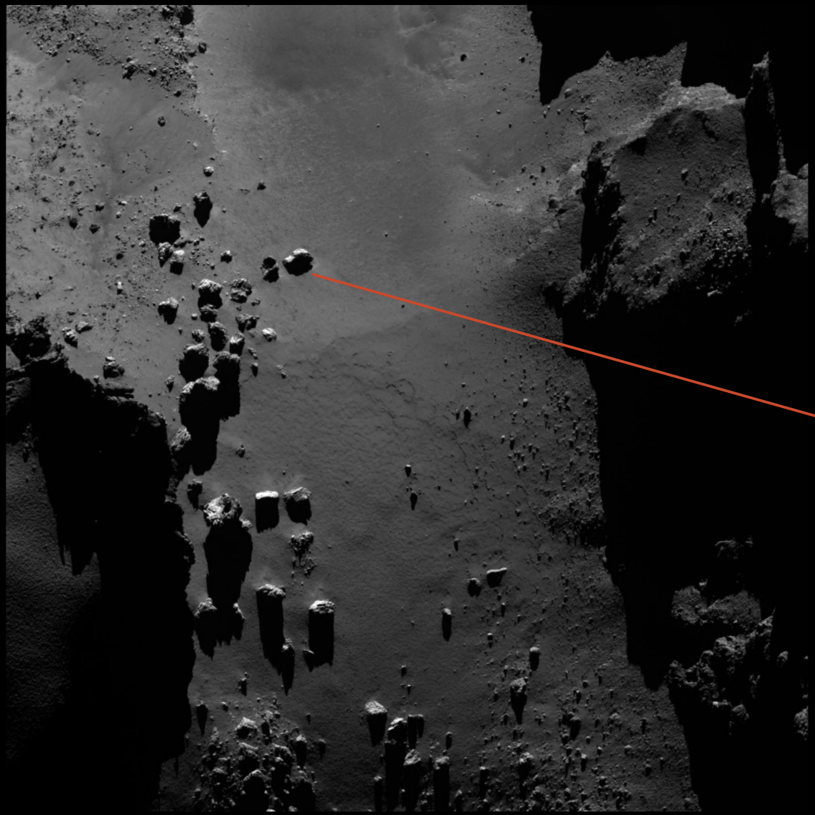
- To avoid the local granularity of the mesh
- To mediate the surface irregularities

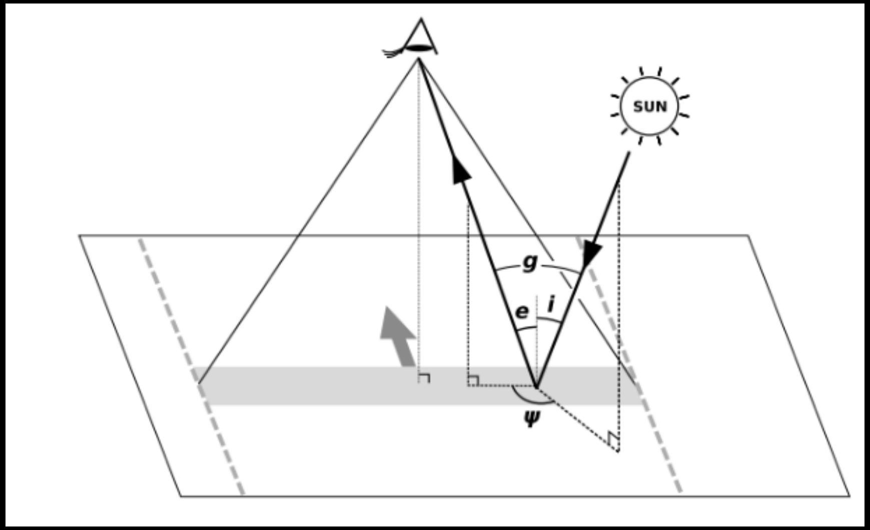




Matlab tool – Incidence and emission angles

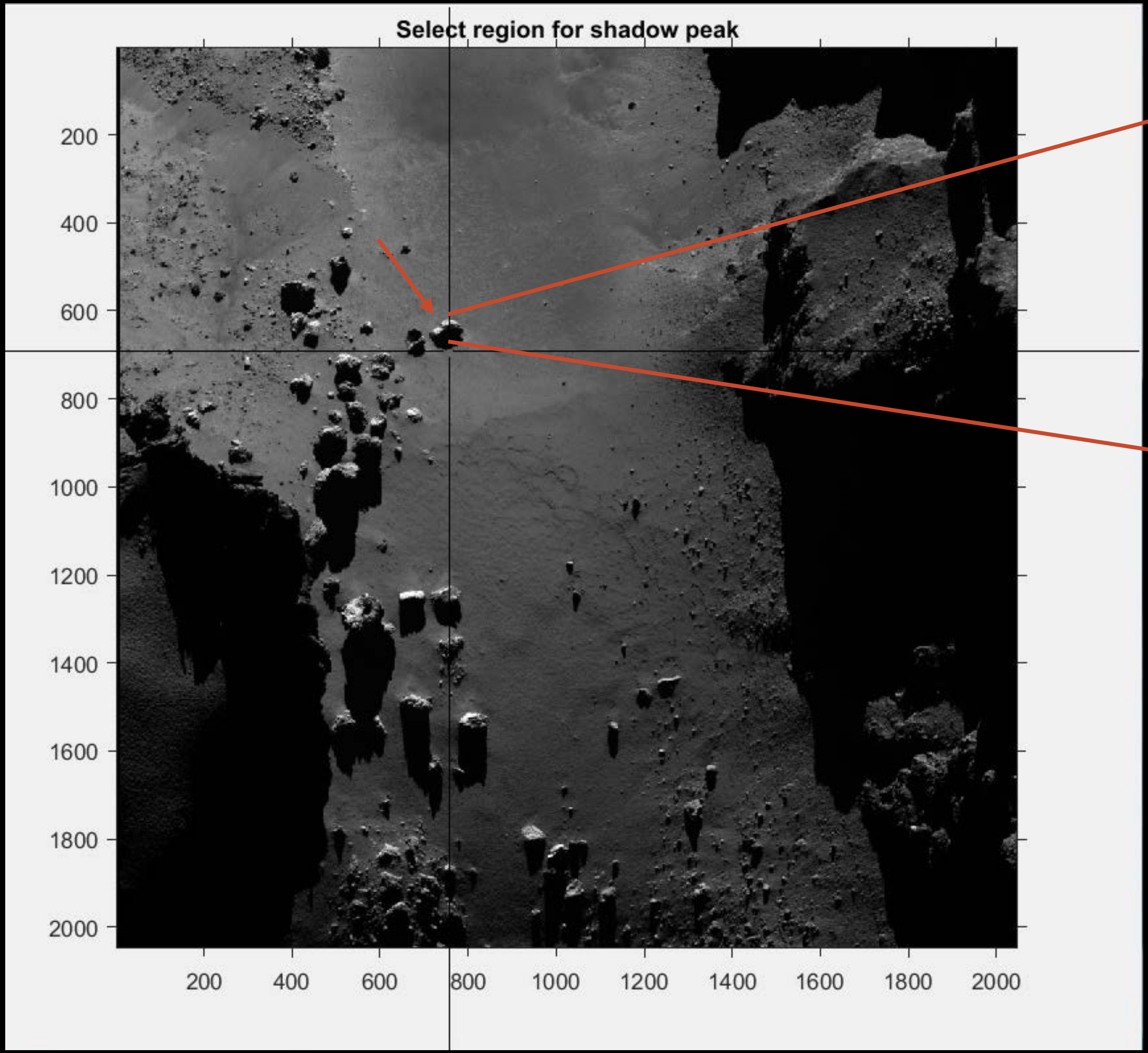
Incidence and emission angles are measured on the local surface avoiding the local granularity of the mesh.

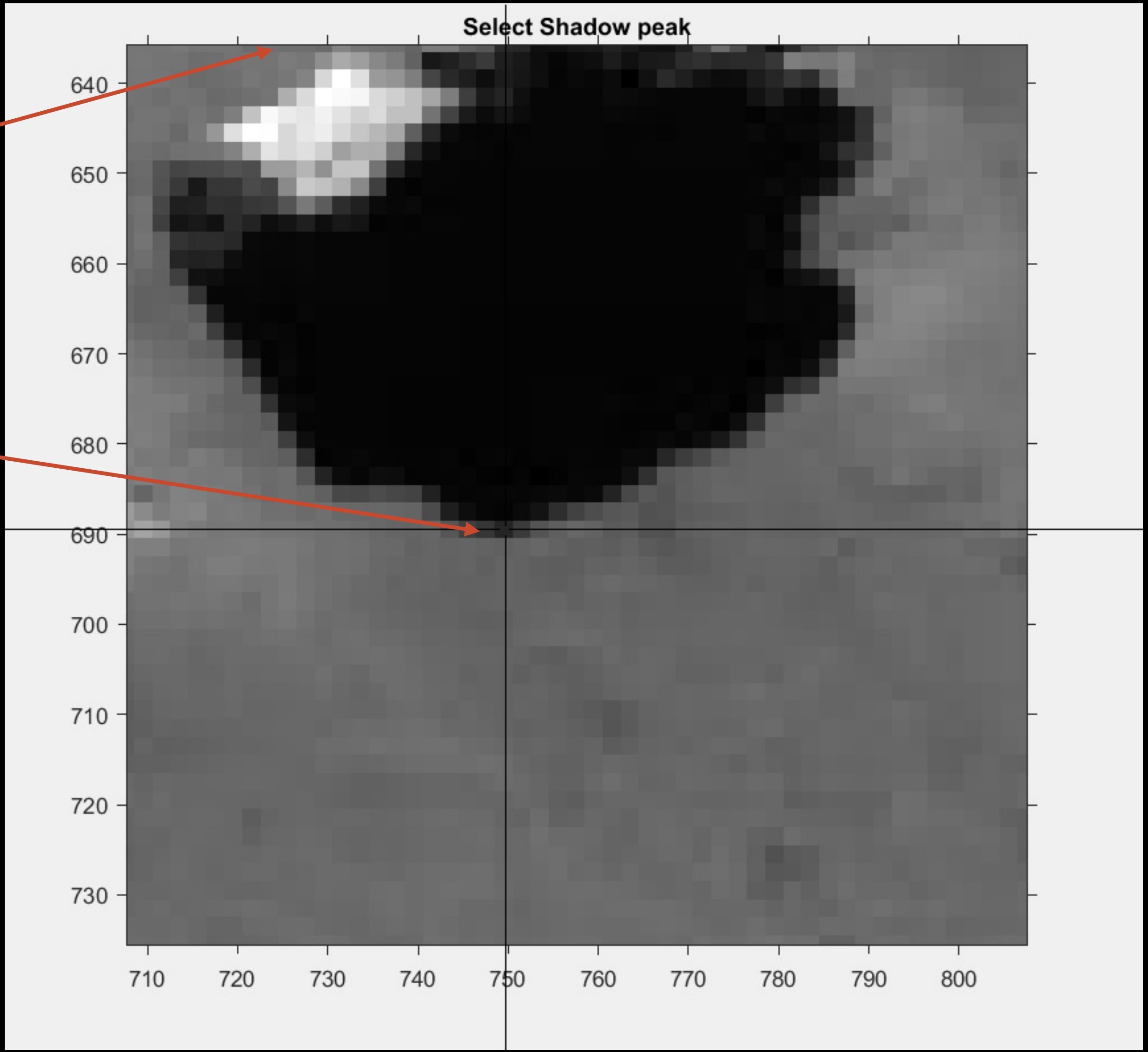




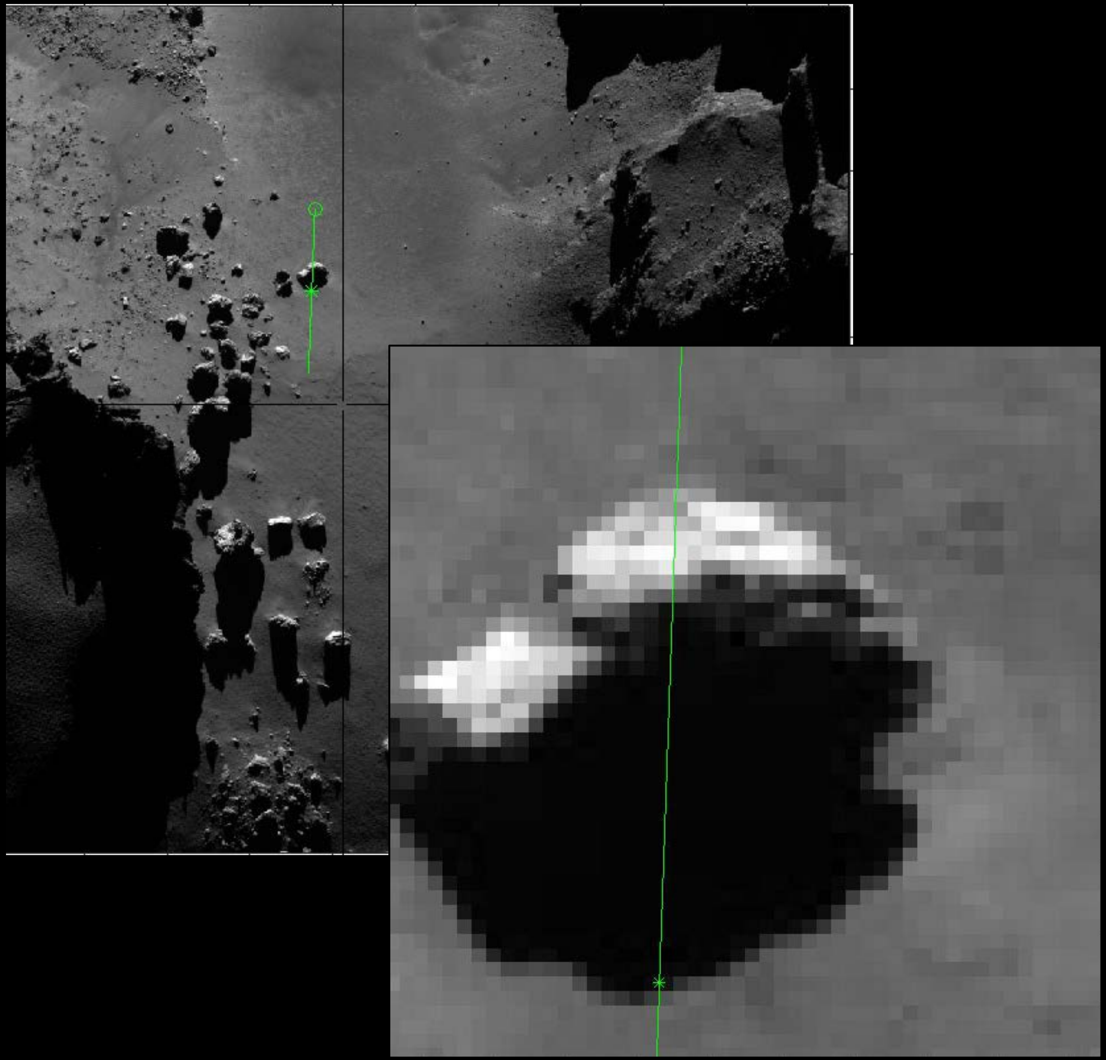
Range from spacecraft to intercept point (km): 20.365
Intercept solar incidence angle (deg): 50.644176
Intercept emission angle (deg): 41.261912

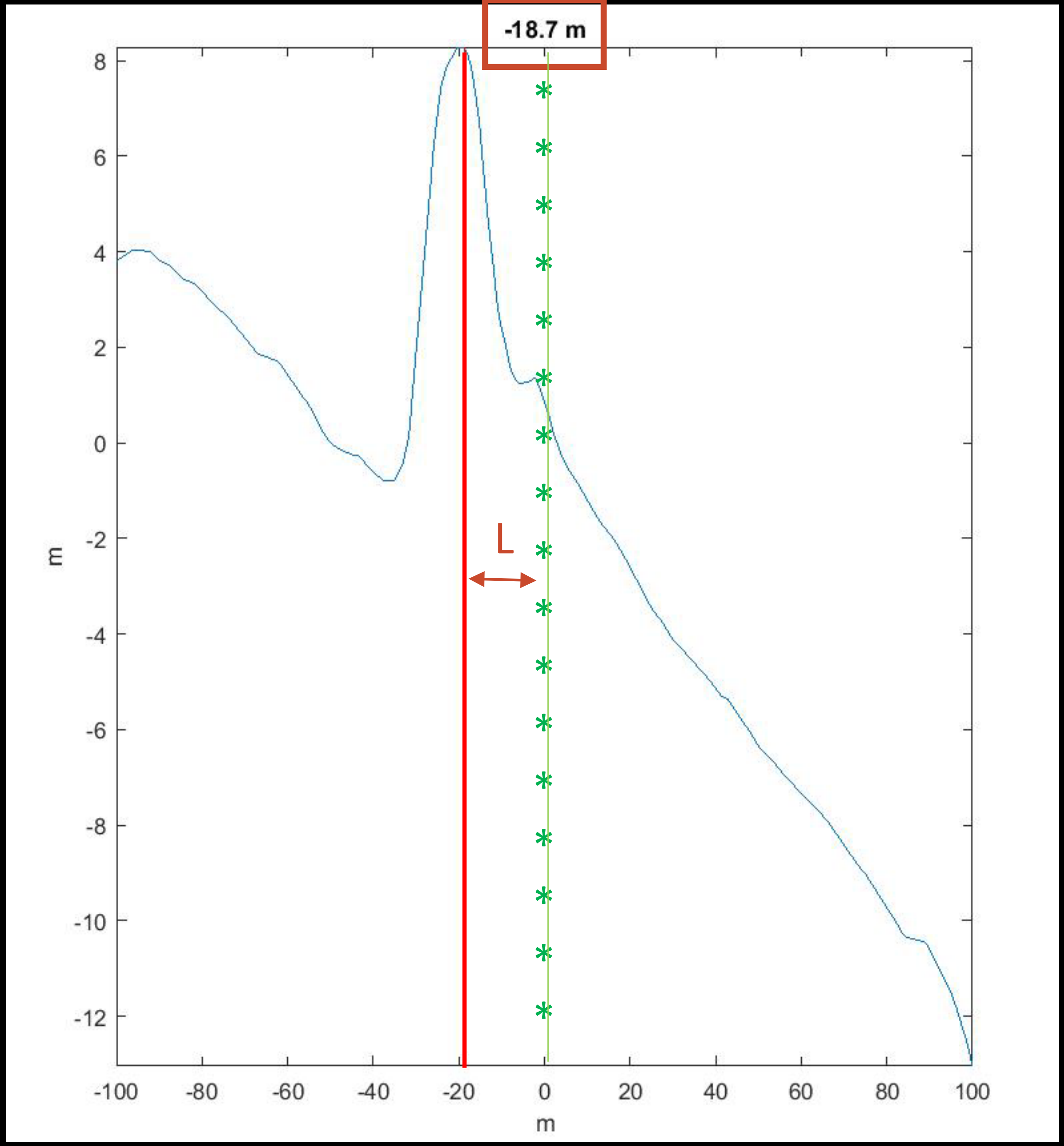
Matlab tool – Selection of shadow's peak





Matlab tool – Shadow's direction and length measurment





Preliminary results

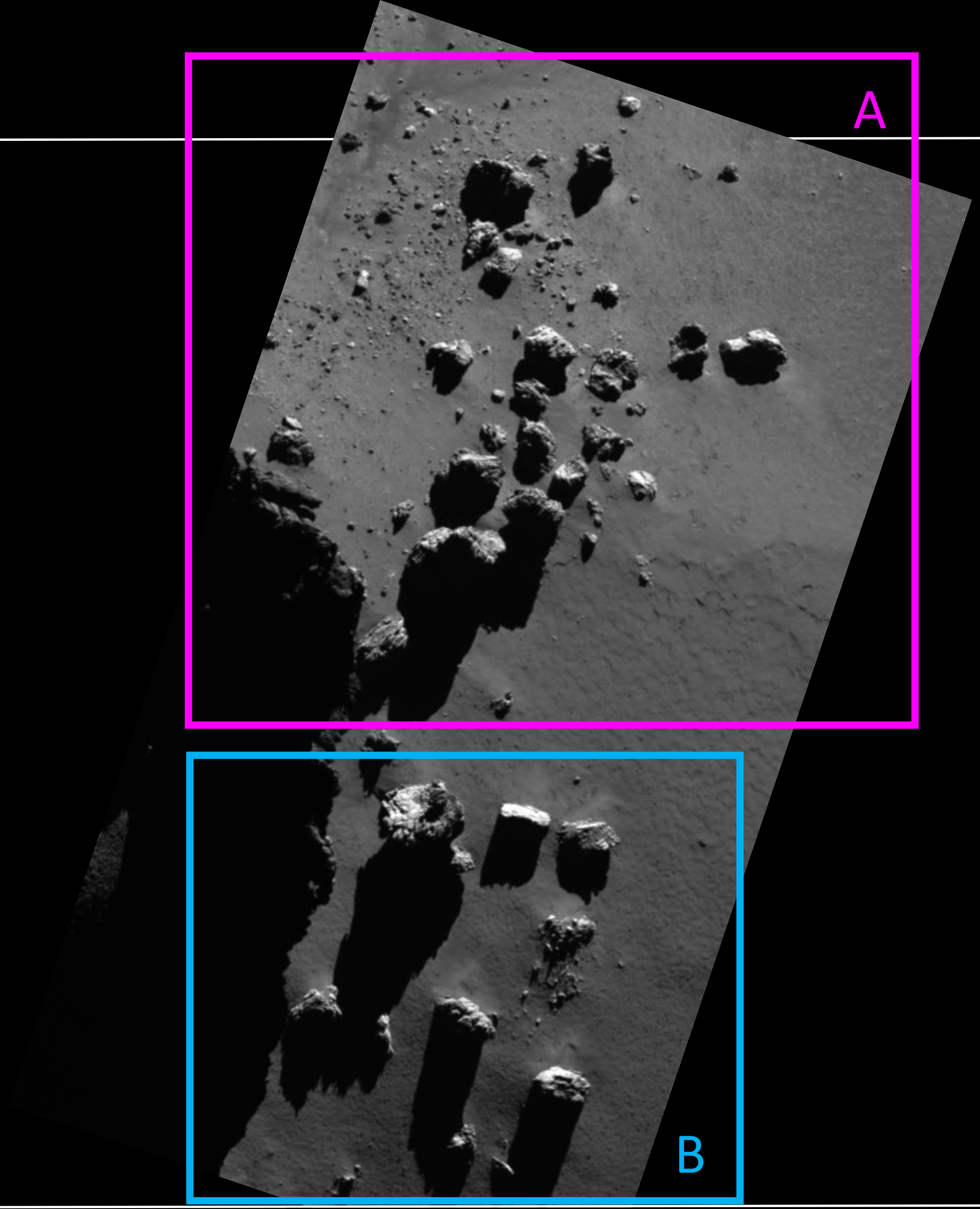
- Tool capable of measuring heights of a target on 2-d images
- Estimate of the deposit thickness within the considered region

Assumption

We assume a variation not considering the erosion and activity of the boulder itself

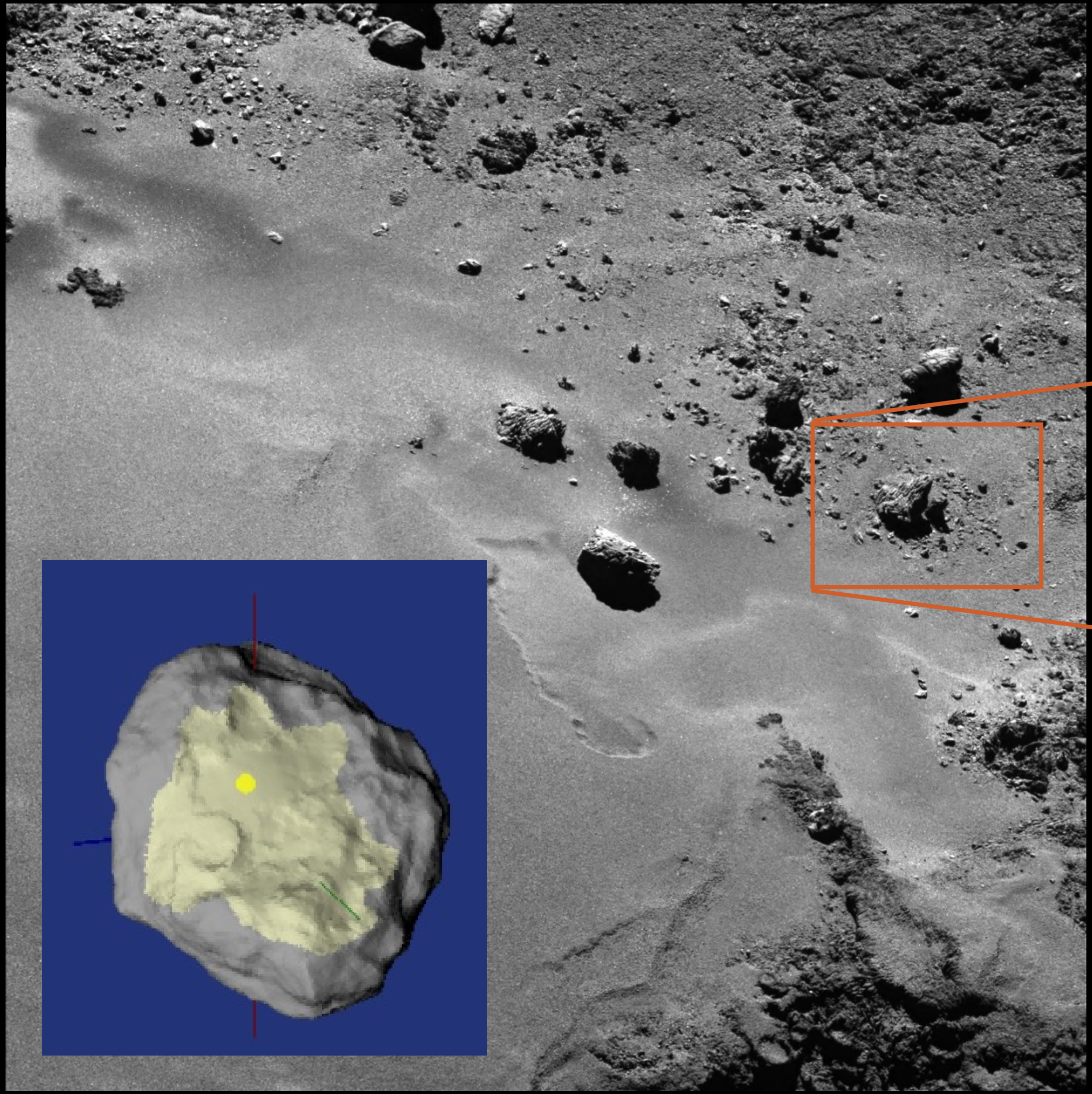
⇩

Fragmentation model



Thermal and stress analysis

Thermal analysis of boulders on comet 67P/C-G



NAC_2016-07-09T11.25.15.786Z_ID30_1397549000_F41

How was the boulder fragmented?

- Evidences fo thermal fragmentation
- Far from landslides and niches

Good candidate for thermal cracking

Thermal analysis of boulders on comet 67P/C-G - Aim

Perform theoretical studies of transient temperature and thermal stress on boulder of comet 67P

COMSOL *Multiphysics Modeling Software –Finite Element Method* (FEM)

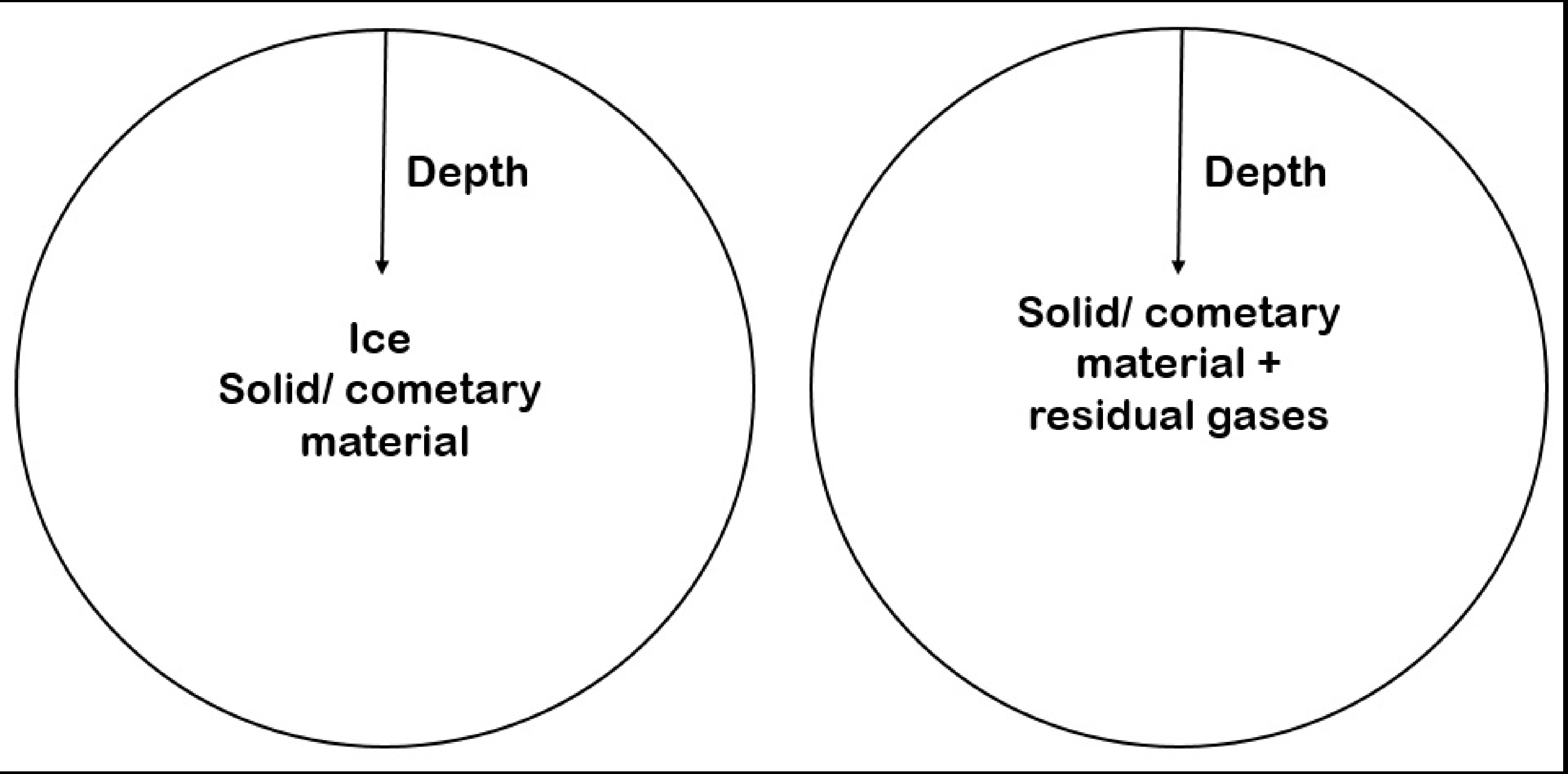
Thermal analysis of boulders on comet 67P/C-G - FEM

Perform theoretical studies of transient temperature and thermal stress on boulder of comet 67P

COMSOL *Multiphysics Modeling Software –Finite Element Method* (FEM)

Geometry and mesh

Geometry and mesh (1/3) - Geometry



Model 1

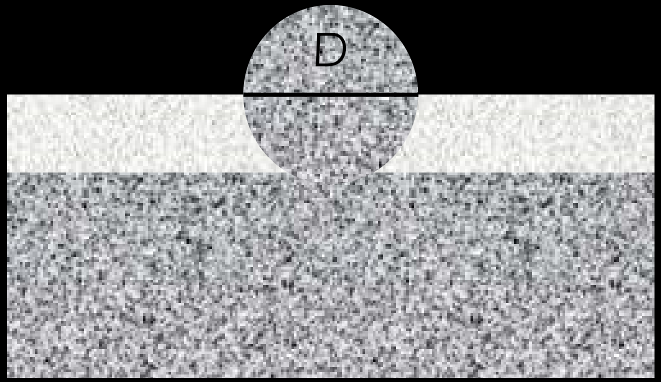
Model 2

Geometry and mesh (2/3) - Approximations

1° approximation
Shape of boulder: sphere

2° approximation
½ D just to compare results

3° approximation
No single point of contact

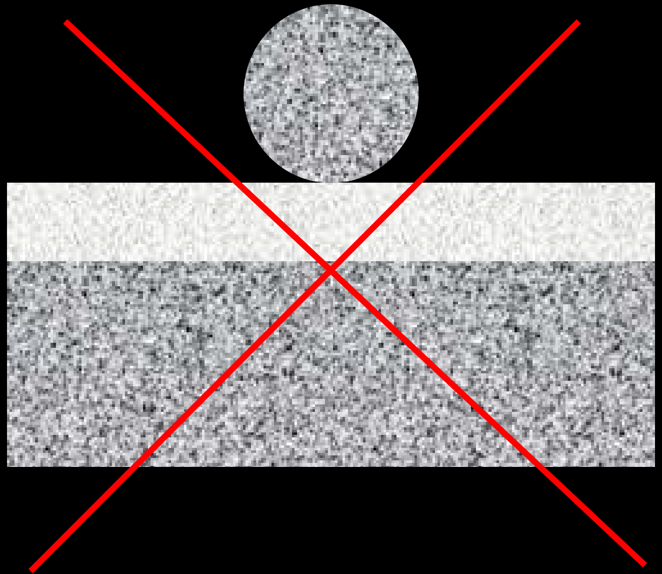


½ D

$^1/_3$ D

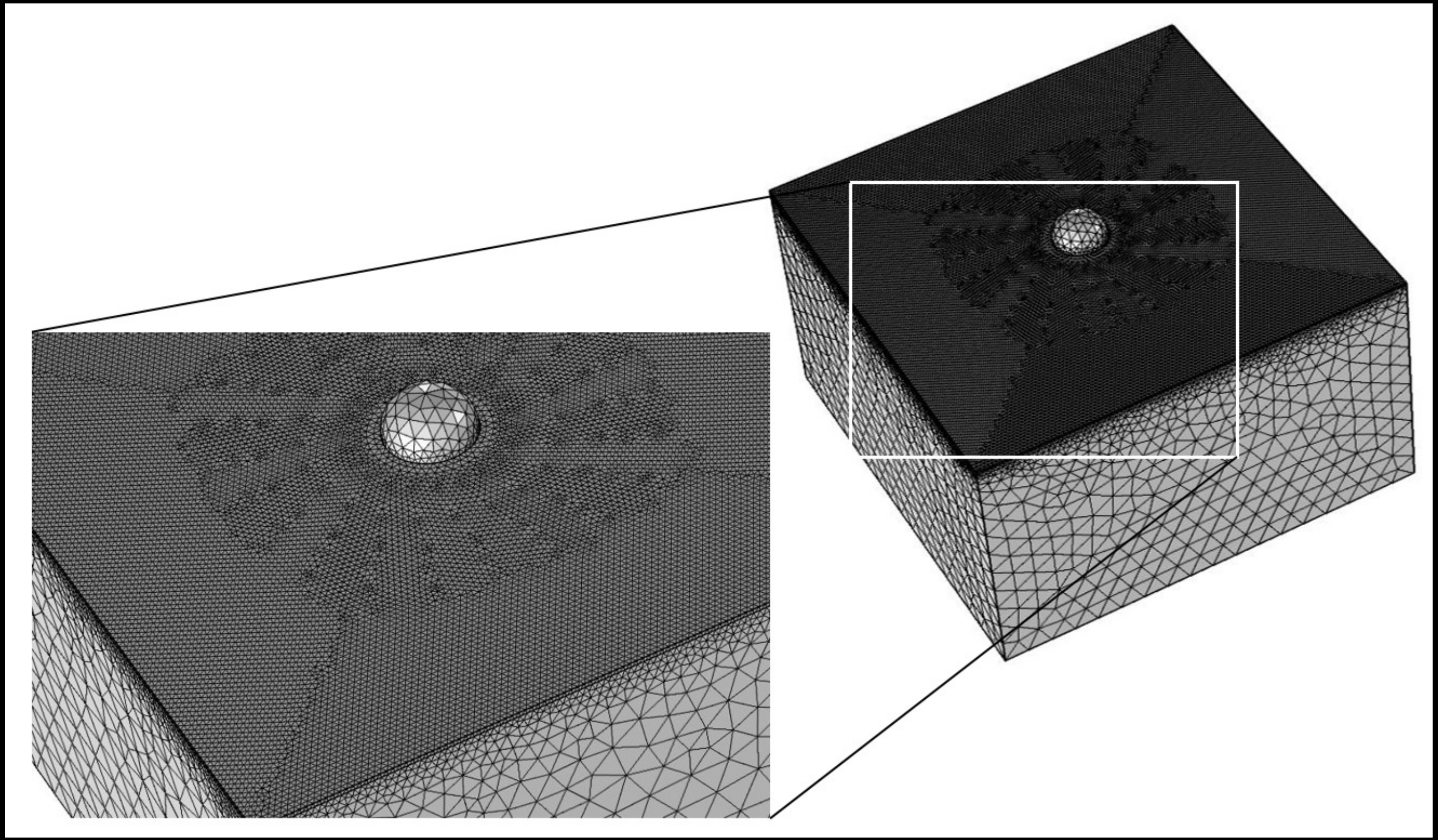
....

$^1/_{20}$ D



Geometry and mesh (3/3) - Mesh

Sphere diameter (D): 40 m
(Cambianica et al., in prep.)
Regolith depth: 0.1<m<2.0
(Mottola et al., 2015)
Block size: 2D x 2D x 2D
(Molaro et al., 2015)



Mesh:
Tetrahedral elements
Controlled by physics + manually adjustment

Thermal analysis of boulders on comet 67P/C-G - FEM

Perform theoretical studies of transient temperature and thermal stress on boulder of comet 67P

COMSOL *Multiphysics Modeling Software –Finite Element Method* (FEM)

- Geometry and mesh
- Material selection and properties

Material selection (1/8) - VIRTIS

VIRTIS

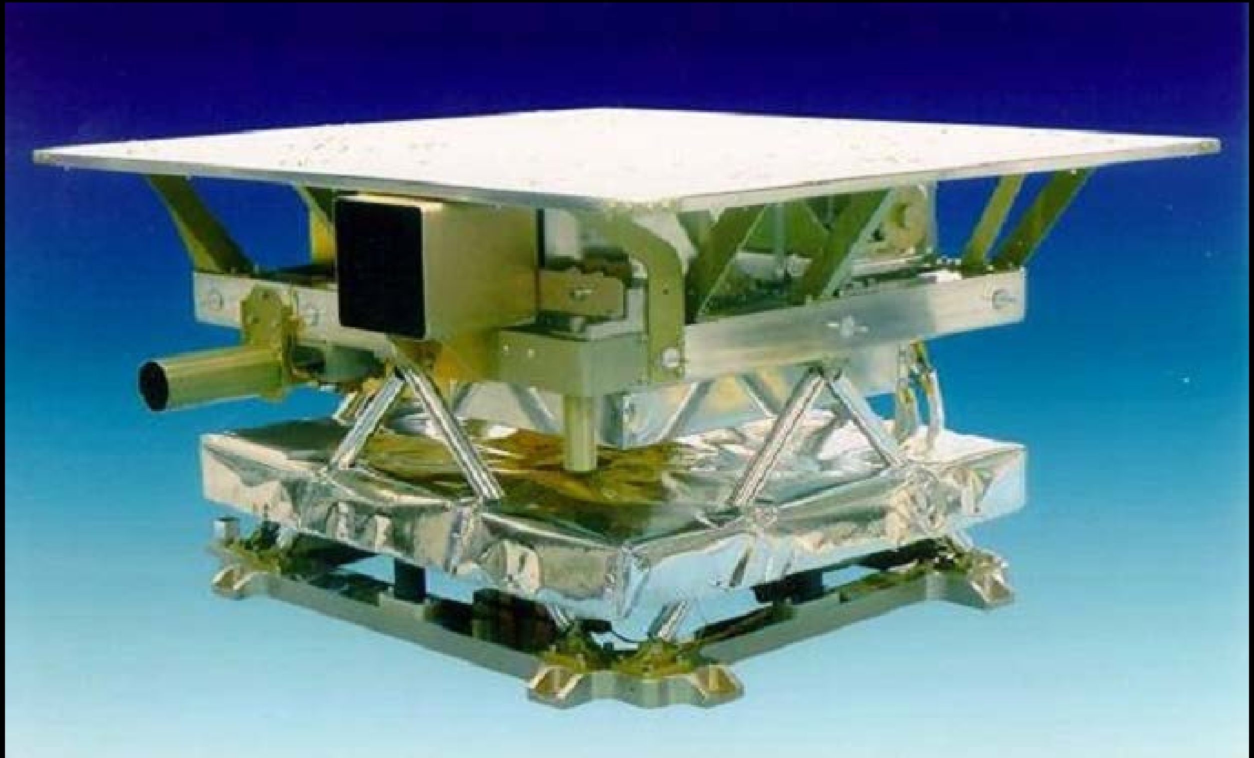
Visible InfraRed Thermal Imaging Spectrometer

(Capaccioni et al., 2015)

67P composition

(Quirico et al., 2015)

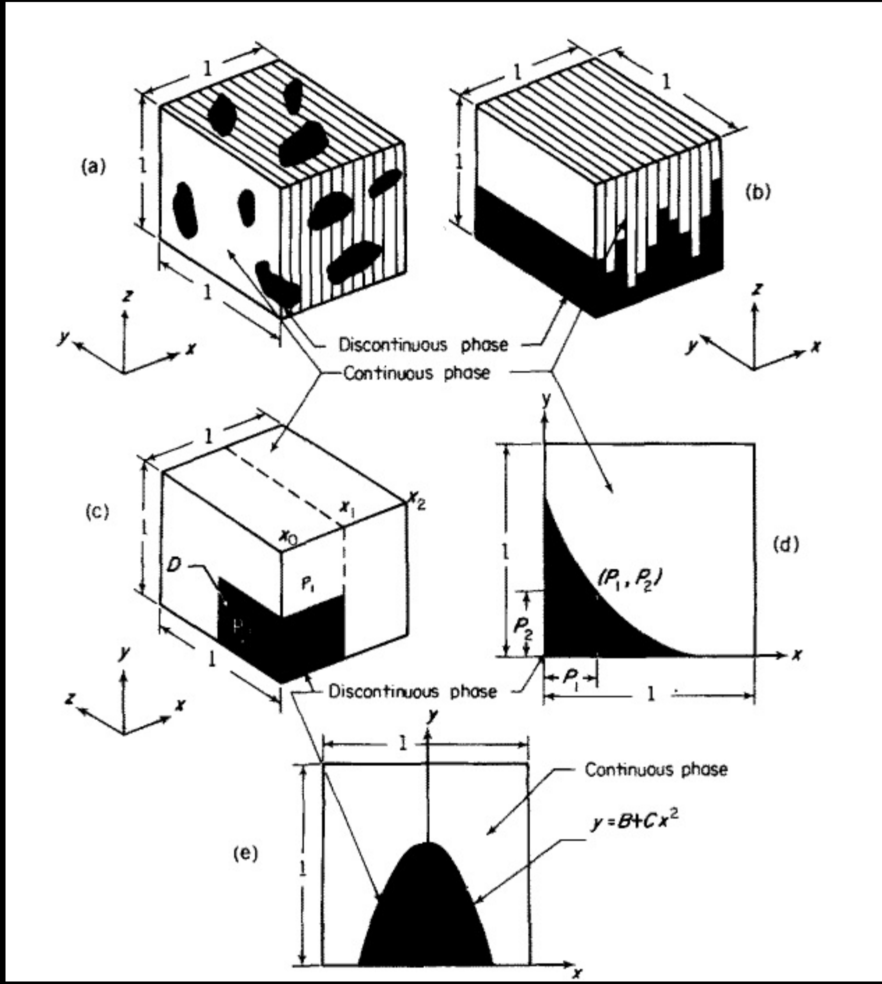
- CH chemical groups
- OH chemical groups
- Refractory material
- Polyaromatic organics solid
- Sulfides
- Fe-Ni alloys



Credits: INAF-IAPS

Material selection (3/8) – Thermal conductivity of mixtures

Cheng and Vachon model, 1968



Two-phase mixture

- $K_c > K_d$

$$R_e = \frac{2}{\sqrt{-C(K_d - K_c)[K_c + B(K_d - K_c)]}} \tan^{-1}\frac{B}{2}\sqrt{\frac{-C(K_d - K_c)}{K_c + B(K_d - K_c)}} + \frac{1-B}{K_c}$$

- $K_c < K_d$

$$R_e = \frac{1}{\sqrt{-C(K_d - K_c)[K_c + B(K_d - K_c)]}} \, ln \frac{\sqrt{K_c + B(K_d - K_c)} + \frac{B}{2}\sqrt{C(K_d - K_c)}}{\sqrt{K_c + B(K_d - K_c)} - \frac{B}{2}\sqrt{C(K_d - K_c)}} + \frac{1-B}{K_c}$$

$$B = \sqrt{3Pd/2}$$

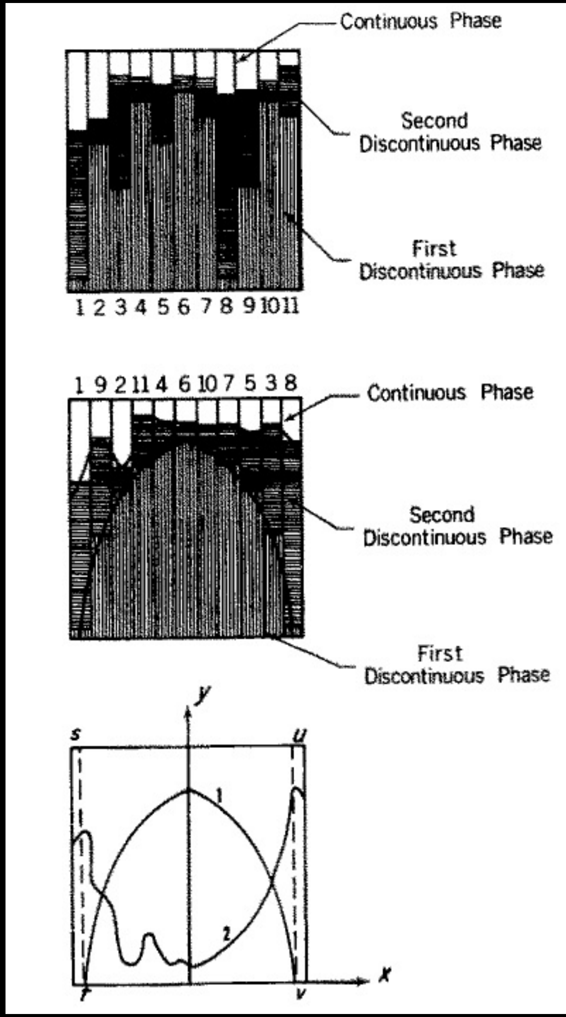
$$C = -4\sqrt{\left(\frac{2}{3}\right)Pd}$$

Pd
Phase volume fraction

Kd= thermal conductivity of the discontinuous phase
Kc= thermal conductivity of the continuous phase

Material selection (4/8) – Thermal conductivity of mixtures

Cheng and Vachon model, 1968



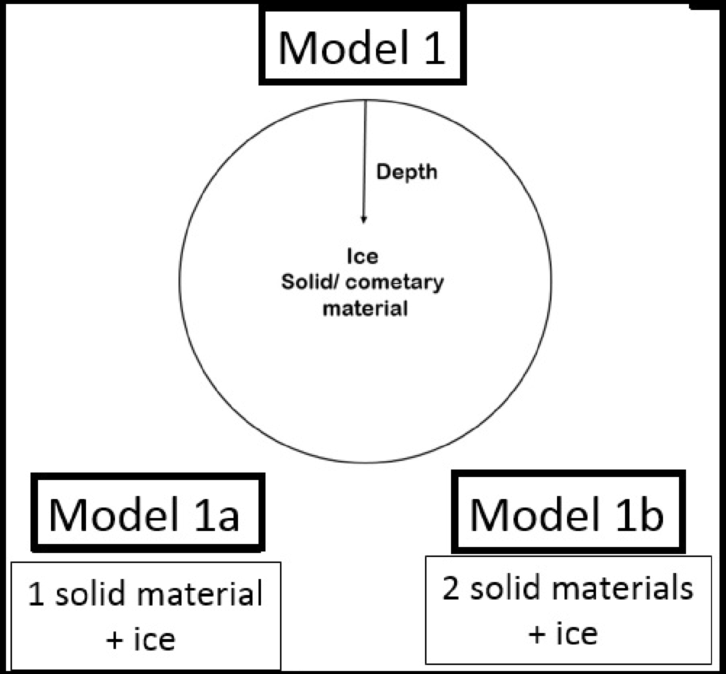
Three-phase mixture

$$R_e = \int \frac{dx}{K_c + (K_{d1} - K_c)y_1 + (K_{d2} - K_c)y_2}$$

- $\frac{Kd1}{Kc} > 100 \; and \; \frac{Kd2}{Kc} > 100$
- $\frac{Kd1}{Kc} > 100 \; and \; 10 < \frac{Kd2}{Kc} < 100$
- $10 < \frac{Kd1}{Kc} < 100 \; and \; 10 < \frac{Kd2}{Kc} < 100$
- $\frac{Kd1}{Kc} \sim 10 \; and \; \frac{Kd2}{Kc} \sim 10$
- $\frac{Kd1}{Kc} \sim 10 \; and \; \frac{Kd2}{Kc} \sim 1$
- $\frac{Kd1}{Kc} \sim 1 \; and \; \frac{Kd2}{Kc} \sim 1$
- $\frac{Kd1}{Kc} < 1 \; and \; or \; \frac{Kd2}{Kc} < 1$

Material selection (5/8) – Thermal conductivity – Model 1

Khader e Vachon model, 1973
Kumar et al. model, 1975



1a

Two-phase mixture

- $K_c > K_d$

$$R_e = \frac{2}{\sqrt{-C(K_d - K_c)[K_c + B(K_d - K_c)]}} \tan^{-1} \frac{B}{2} \sqrt{\frac{-C(K_d - K_c)}{K_c + B(K_d - K_c)}} + \frac{1 - B}{K_c}$$

- $K_c < K_d$

$$R_e = \frac{1}{\sqrt{-C(K_d - K_c)[K_c + B(K_d - K_c)]}} \ln \frac{\sqrt{K_c + B(K_d - K_c)} + \frac{B}{2}\sqrt{C(K_d - K_c)}}{\sqrt{K_c + B(K_d - K_c)} - \frac{B}{2}\sqrt{C(K_d - K_c)}} + \frac{1 - B}{K_c}$$

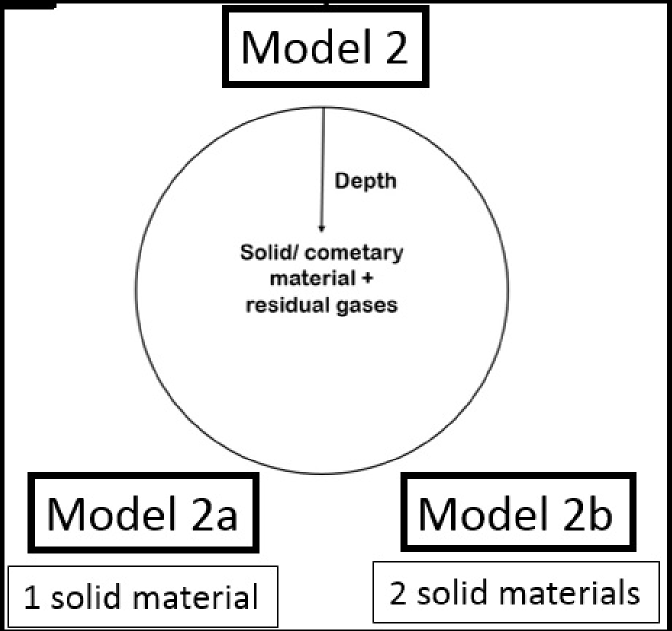
1b

Three-phase mixture

$$R_e = \int \frac{dx}{K_c + (K_{d1} - K_c)y_1 + (K_{d2} - K_c)y_2}$$

Material selection (7/8) – Thermal conductivity – Model 2

Khader e Vachon model, 1973
Kumar et al. model, 1975



2a

One-phase mixture

$$K_{eff} = \frac{3(1-P)(1-C_1^2 Z^{2/3})K_s}{(\pi/2)(\frac{3}{2C_1 Z^{1/3}} - 1) + (4 - 1.2C_1^2 Z^{2/3})}$$

$$C_1 = \frac{2g\rho\pi(1-\nu^2)^{1/3}}{16E(1-P_1)}$$

P = porosity
Z = depth
Ks= thermal conductivity of the solid material
ρ = density
g = gravitational constant
E = modulus of elasticity
ν = Poisson's ratio

2b

Two-phase mixture

- $K_c > K_d$

$$R_e = \frac{2}{\sqrt{-C(K_d-K_c)[K_c+B(K_d-K_c)]}} \tan^{-1}\frac{B}{2}\sqrt{\frac{-C(K_d-K_c)}{K_c+B(K_d-K_c)}} + \frac{1-B}{K_c}$$

- $K_c < K_d$

$$R_e = \frac{1}{\sqrt{-C(K_d-K_c)[K_c+B(K_d-K_c)]}} \ln\frac{\sqrt{K_c+B(K_d-K_c)} + \frac{B}{2}\sqrt{C(K_d-K_c)}}{\sqrt{K_c+B(K_d-K_c)} - \frac{B}{2}\sqrt{C(K_d-K_c)}} + \frac{1-B}{K_c}$$

K_{eff}

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Perform theoretical studies of transient temperature and thermal stress on boulder of comet 67P

COMSOL *Multiphysics Modeling Software –Finite Element Method* (FEM)

- Geometry and mesh
- Material selection and properties
- Physics, boundary conditions and heat source

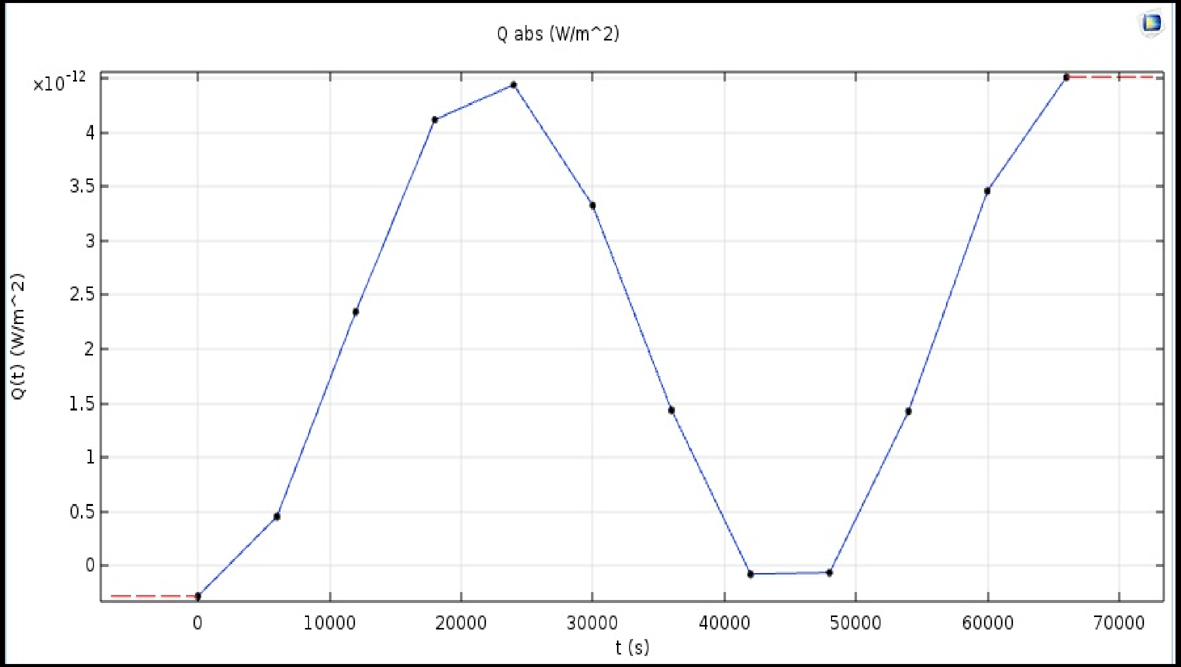
Physics, boundary conditions and heat source (1/3)

NAIF SPICE →

- Specific incidence angles at selected epoch and region (Imhotep in this case)
- X sun, Y sun, Z sun
- Comet 67P– Sun distance

$$Q_{abs} = (1 - A)\frac{S_0}{R^2}\cos(i)$$

A = albedo
S_0 = solar constant
R = comet 67P-Sun distance
i = incidence angle



Physics, boundary conditions and heat source (2/3)

NAIF SPICE →

- Specific incidence angles at selected epoch and region (Imhotep in this case)
- X sun, Y sun, Z sun
- Comet 67P– Sun distance

$$Q = (1 - A)\frac{S_0}{R^2}\cos(i)$$

A = albedo
S_0 = solar constant
R = comet 67P-Sun distance
i = incidence angle

Input parameters

COMSOL MULTIPHYSICS®

Physics, boundary conditions and heat source (3/3)

Heat transfer with surface-to-surface radiation

Model heat transfer by conduction, convection, and radiation

- Heat equation

$$\rho C_p \frac{\delta T}{\delta t} + \rho C_p \boldsymbol{u} \nabla T + \nabla \boldsymbol{q} = Q$$

- Fourier's law of heat conduction

$$\boldsymbol{q} = -k \nabla T$$

ρ = density [kg/m^3]
C_p = heat capacity at constant pressure [J/kgK]
K = solid thermal conductivity [W/mK]
u = velocity field if the parts of the model is moving
Q = heat source [W/m^3]

T_{abm} = 100 K
P_{amb} = 0 Pa

Solid Mechanics

Linear elastic material

$$\boxed{\nabla S + F_v = 0}$$

S = stress gradient
Fv = external force

Transient study

$$\frac{\partial T}{\partial t}$$

Future works

Measurements of erosion and dust deposits in the Hapi region

- Extend the statistics by analizing other images
- Discriminate between dust cover variation and boulder’s activity
- Apply this method to other regions and other objects
- Analyze possible volumetric variations of big boulders

Thermal and stress analysis

- Shape of boulder: different shapes, irregularities, edges, cavities
- Perform the analysis form different combinations of materials, geometry, etc…
- Correlate the Von Mises stress with the propagation of cracks

- Propagate cracks

Fragmentation model

Personal training plan and Gannt bar chart

	Expected ECTS	Attained ECTS
Interdisciplinary Module/Activity	19.2	19.2
Curriculum oriented activities	17.84	11.82
Other educational activities	4.8	4.8
TOT	**41.84**	**35.52**

LEVEL	ACTIVITY DESCRIPTION AND EVENTS	I YEAR	II YEAR	III YEAR
Event	Presentation for approval research			
WP100	**OSIRIS and the Rosetta Mission**			
WP110	**Study of the related literature**			
WP111	The ROSETTA mission			
WP112	The OSIRIS camera			
WP200	**Comets and the 67P/Churyumov-Gerasimenko comet**			
WP210	**Study of the related literature**			
WP211	Formation and evolution			
WP212	Geomorphology			
WP213	Thermodynamics			
WP300	**Image analysis**			
WP310	Study of the related literature			
WP320	OSIRIS archive and images			
WP330	Statistical analysis - size-frequency			
WP340	Fractal theory			
WP350	Shape factors			
WP360	Boulders and fragments shape			
Event	Admission to second year			
WP400	**Thermodynamic and sublimation**			
WP410	Study of the related literature			
WP420	Thermal model			
WP430	Thermo-mechanical processes			
WP440	Study of ices			
WP450	Sublimation model			
Event	Admission to third year			
WP500	**Modeling and use of MATLAB**			
WP600	**Finite Element Method**			
Event	Admission to final examination			
WP700	**Writing thesis and reports**			

Publications

Papers

- Quantitative analysis of Imhotep, Hapi and Hatmehit boulder populations on comet 67P/Churyumov- Gerasimenko
Cambianica, P. et al. (in prep)
- The backscattering enhancement of comet 67P/Churyumov-Gerasimenko dust coma as seen by OSIRIS onboard Rosetta"
Bertini, I. et al. 2018
- The big lobe of 67P/Churyumov-Gerasimenko comet: morphological and spectrophotometric evidences of layering as from OSIRIS data
Ferrasi, S. et al. 2018
- Multidisciplinary analysis of the Hapi region located on Comet 67P/Churyumov-Gerasimenko
Pajola, M. et al. 2018 (in press)

Abstracts, conference proceedings

- EPSC 2018 - Thermal analysis of boulders on the 67P/Churyumov-Gerasimenko comet
Cambianica, P. et al.
- SAIT 2018 - Quantitative analysis of Imhotep, Hapi and Hatmehit boulder populations on comet 67P/Churyumov- Gerasimenko
Cambianica, P. et al.
- EPSC 2018 - Geomorphological units of Khepry and Imhotep regions of comet 67P/Churyumov-Gerasimenko
Ferrari, S. et al.
- EPSC 2018 - 3DPD application to the first CaSSIS DTMs
Simioni, E. et al.

Credits: ESA

Thanks for the attention

Pamela Cambianica
PhD Candidate @ CISAS
pamela.cambianica@inaf.it