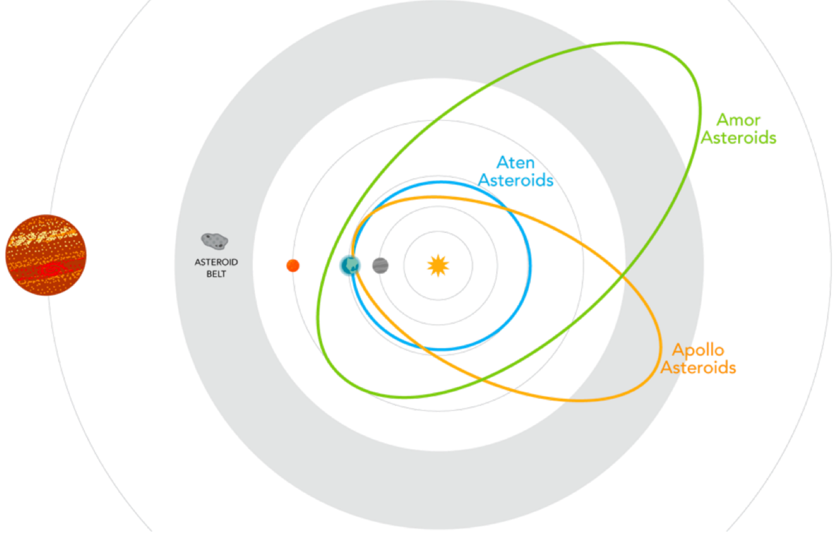
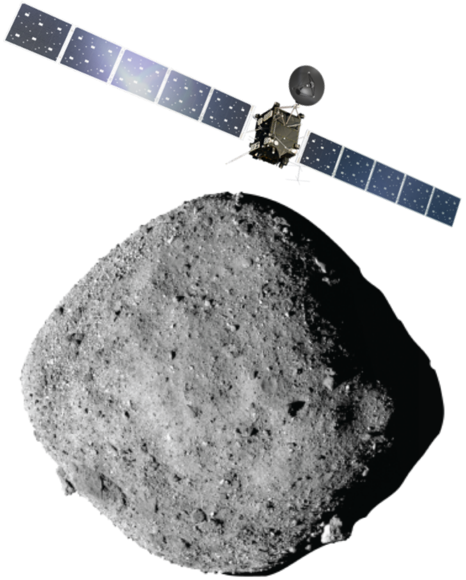
Small Bodies and Icy Moons of the Solar System

Alice Lucchetti, Luca Penasa, Costanza Rossi, Maurizio Pajola, Filippo Tusberti, Joel Beccarelli, Giovanni Munaretto, Patrizia Borin, Pamela Cambianica, Gabriele Cremonese.

Small Bodies

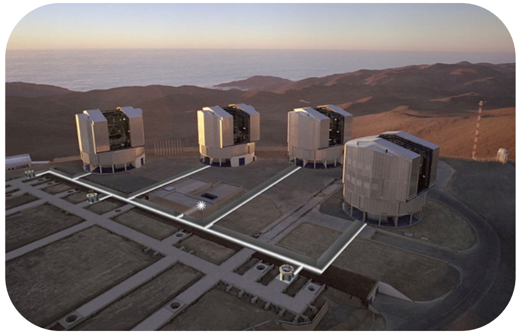
- ✓ **Asteroids and comets** are the remnants of the original **building blocks of our Solar System**.
- ✓ Help us better understand the **formation** of the Solar System over 4.5 billion years ago;
- ✓ Source of the **water and organic molecules** that may have made their way to Earth and other planetary bodies early in their histories;
- ✓ An uncontaminated **asteroid and/or comet sample** from a known source would enable precise analyses, revolutionizing our understanding of the early Solar System, and cannot be duplicated by spacecraft-based instruments or by studying meteorites.
- ✓ The understanding of **NEAs** is important from both a scientific and **planetary defense** perspective.





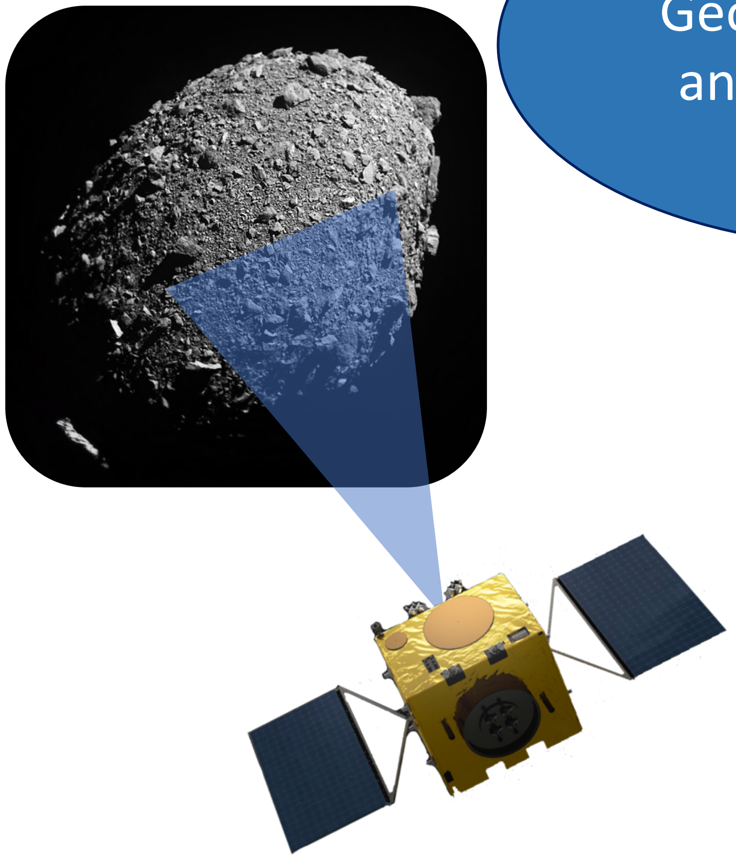
Remote sensing observations by spacecraft

Ground based observations



Joint observations of interplanetary targets by both spacecraft and Earth-based instruments have provided and continue to promise an enriched level of science products emerging from the investigation.

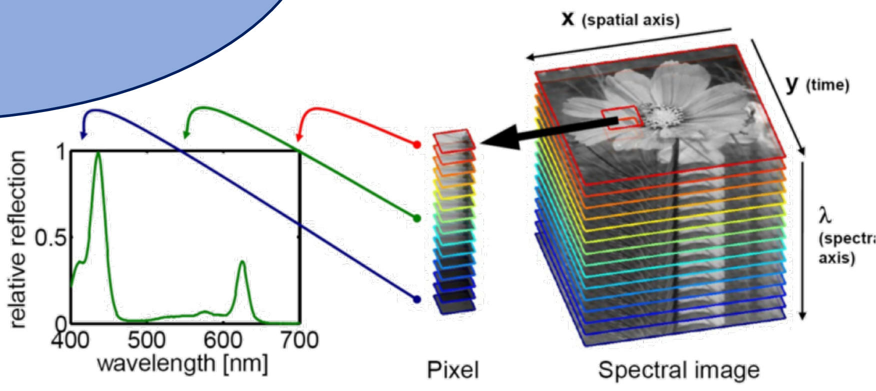
Small Bodies | Remote sensing data

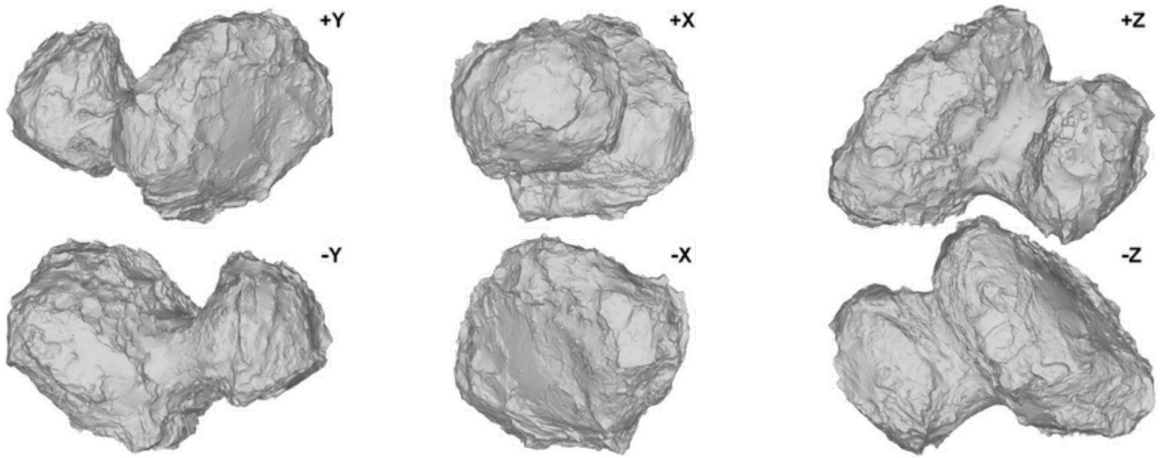


Geomorphological analysis (images)

Compositional analysis (spectra)

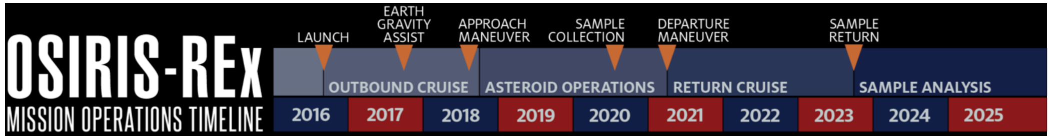
3D analysis (Digital Terrain Models)

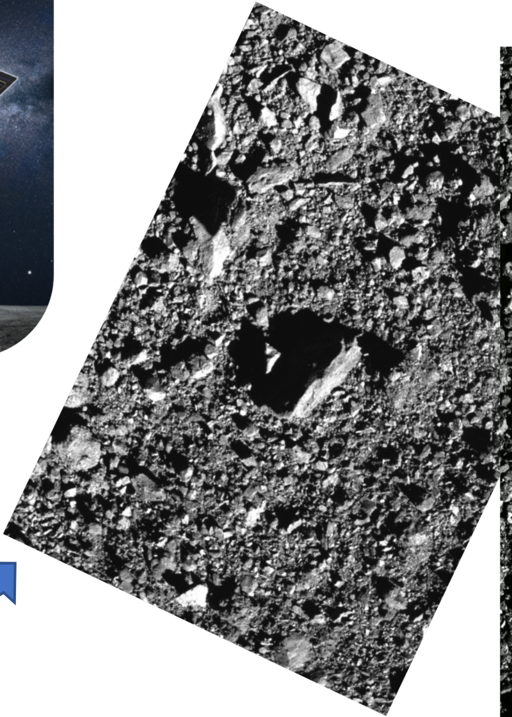


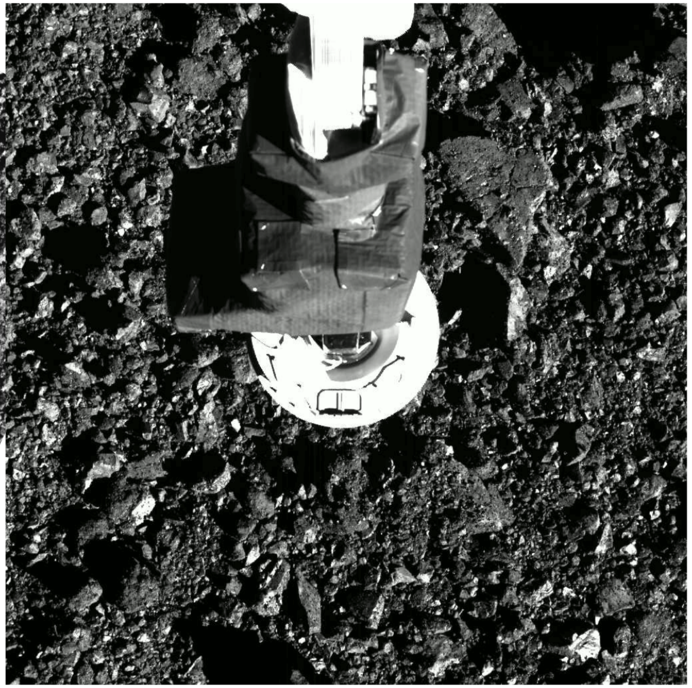


(101955) Bennu – NASA/OSIRIS-REx

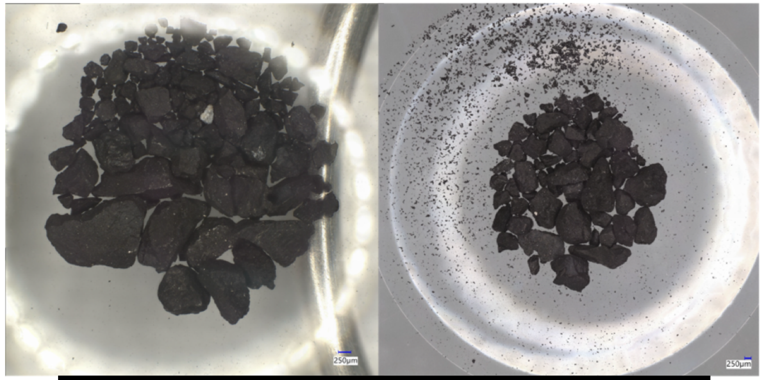
The **OSIRIS-REx mission** is the first U.S. mission to carry samples from an asteroid back to Earth and the largest sample returned from space since the Apollo era.





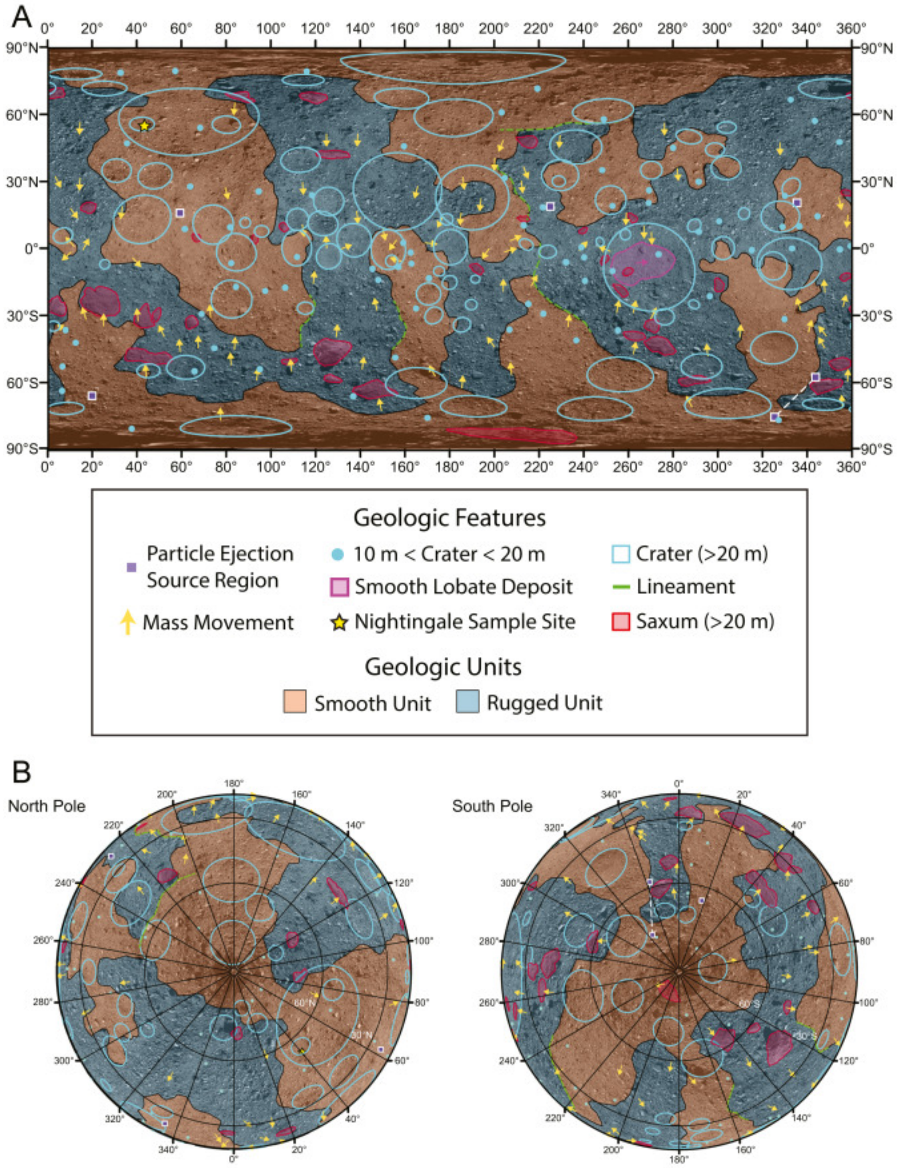


20 Oct 2020



Sept 2023

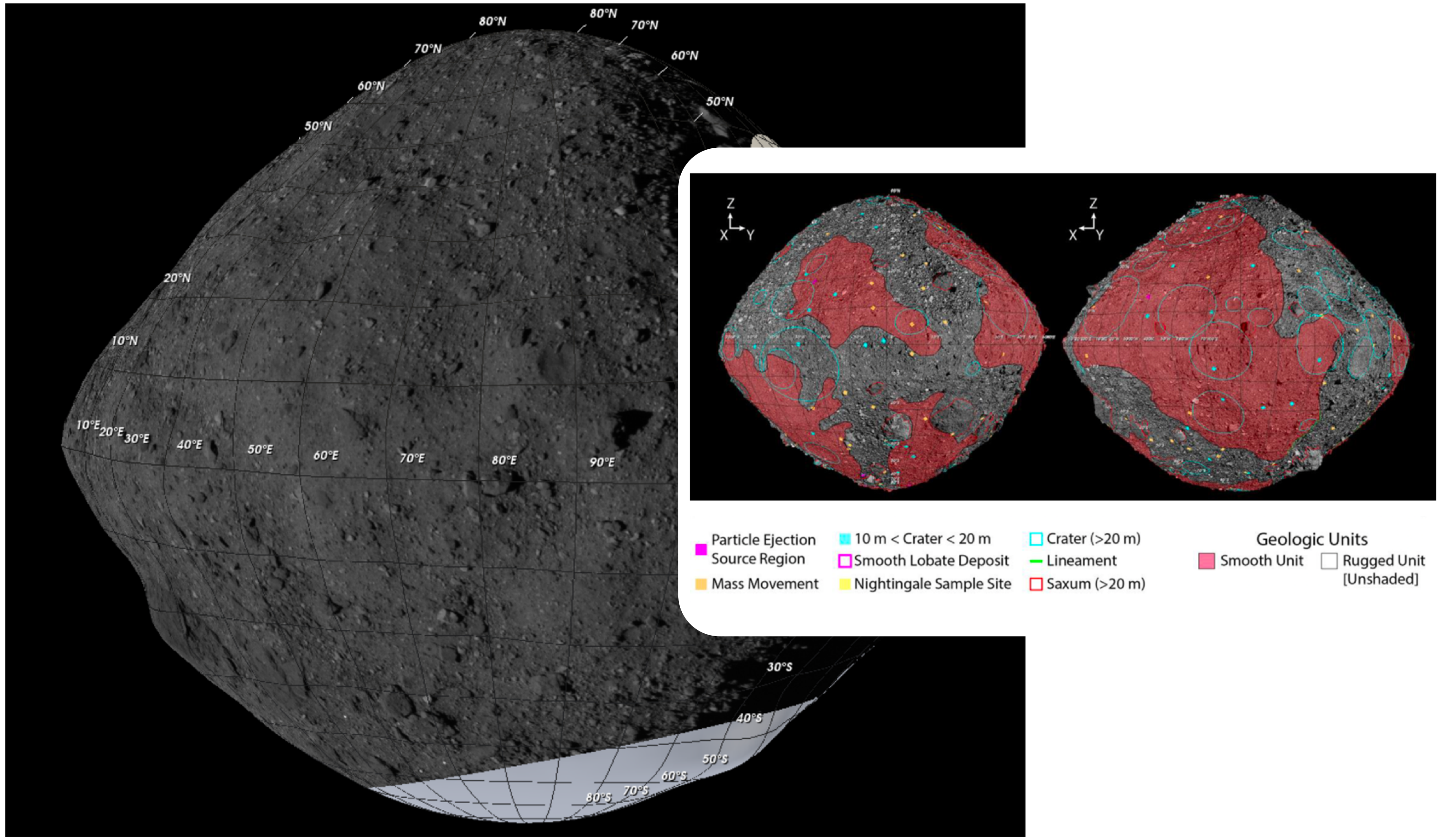
(101955) Bennu – NASA/OSIRIS-REx



Jawin et al., (2022)

Geological maps → discriminate between different geological units, textures and features.

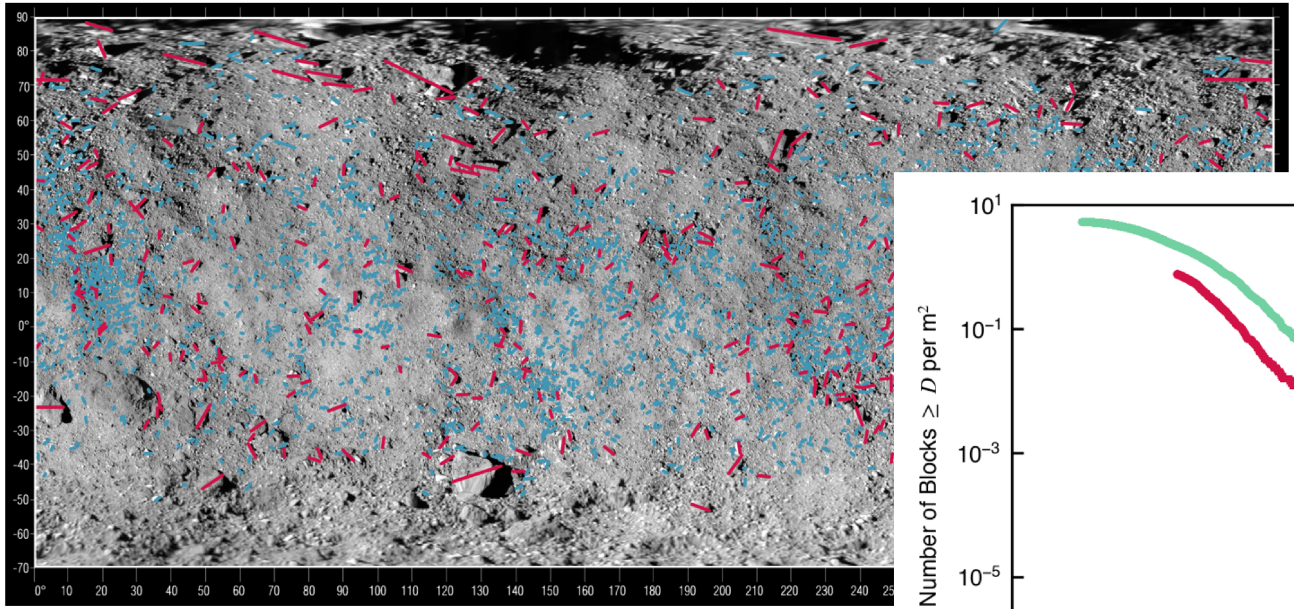
✓ Geological maps are fundamental in order to assess scientific goals for mission planning, not only for planetary surface exploration missions, including robotic landers/rovers and crewed missions but also for ISRU and safety.



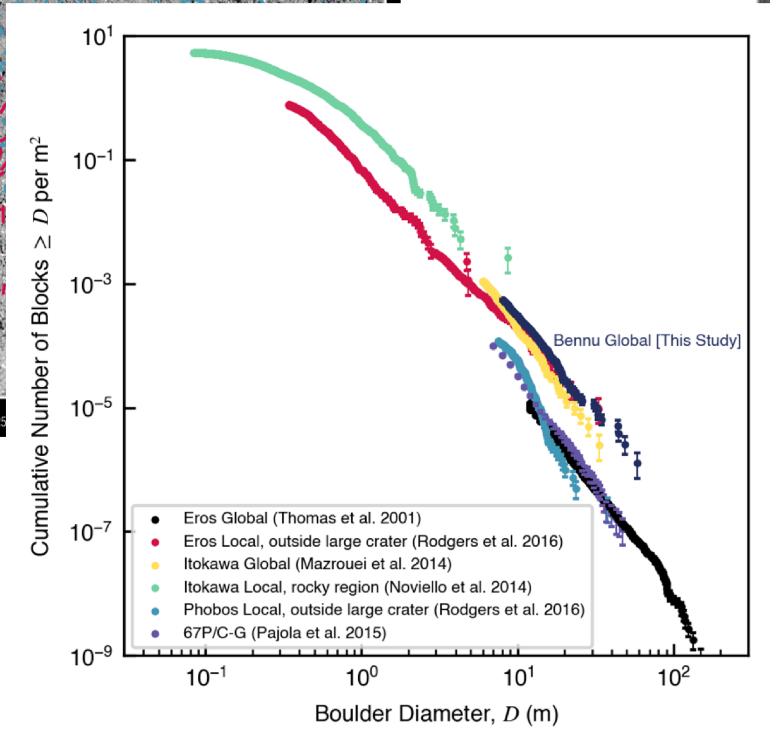
(101955) Bennu – NASA/OSIRIS-REx

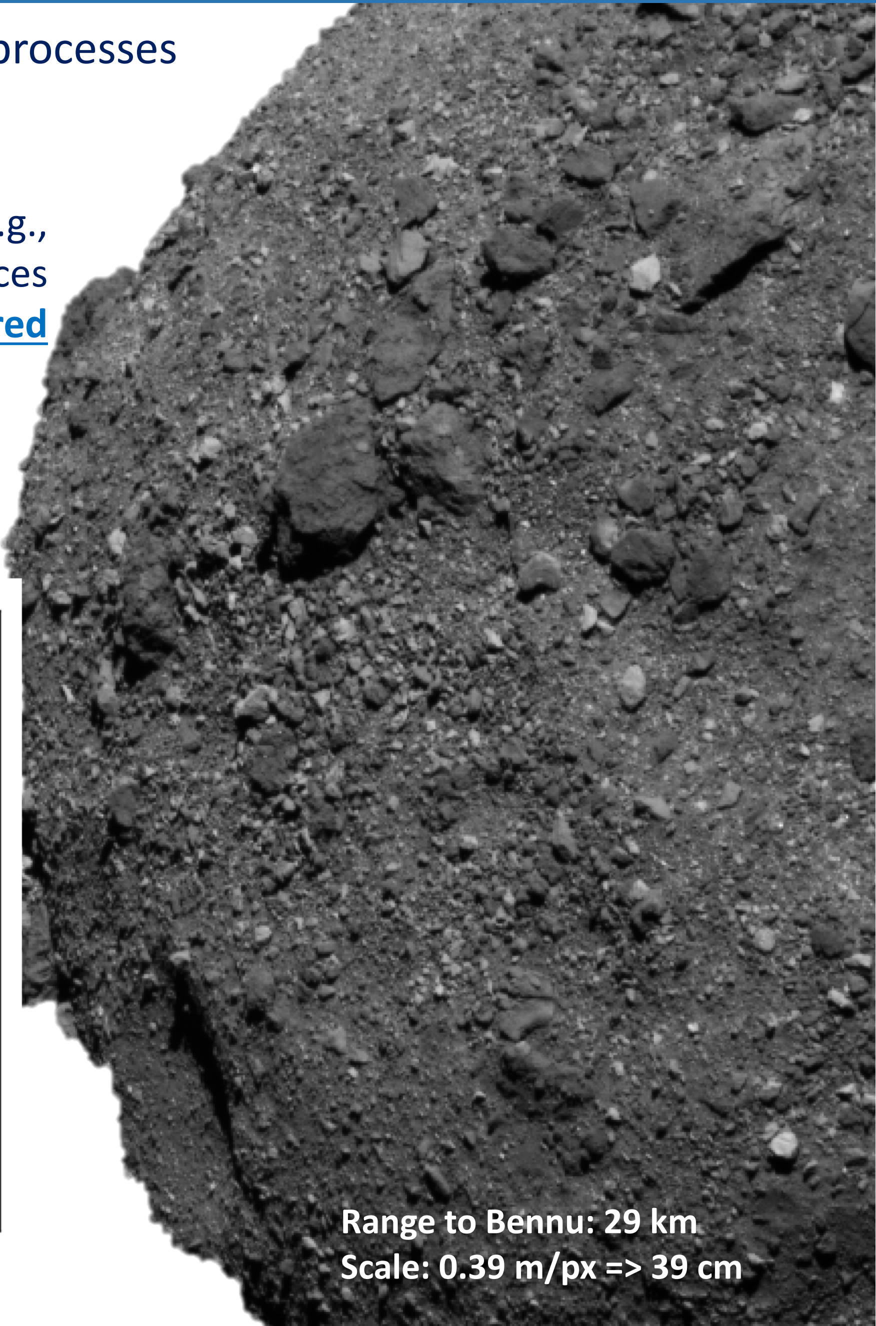
Boulder analysis → size-frequency distribution (SFD) to investigate a wide range of processes that occurred or are still occurring on a planetary/minor body surface.

With the exception of planets like Mars, where erosive and depositional phenomena (e.g., Christensen, 1986) generate or degrade boulders, or on active/sublimating cometary surfaces where cliff collapses (Pajola et al., 2017a) occur forming taluses, **boulders are mainly considered the result of impact processes (Melosh, 1989).**



DellaGiustina al., (2019)

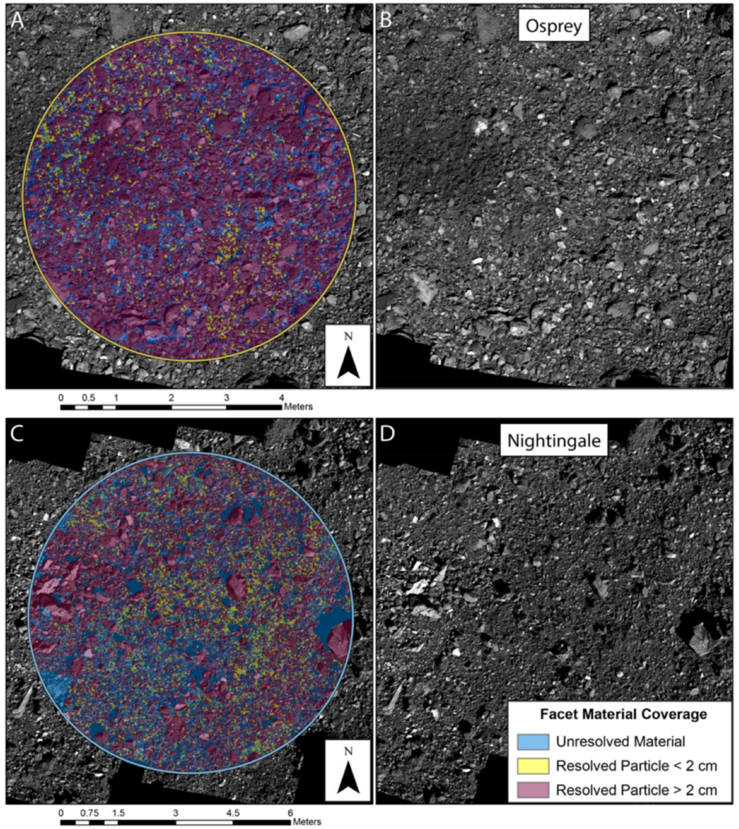




(101955) Bennu – NASA/OSIRIS-REx

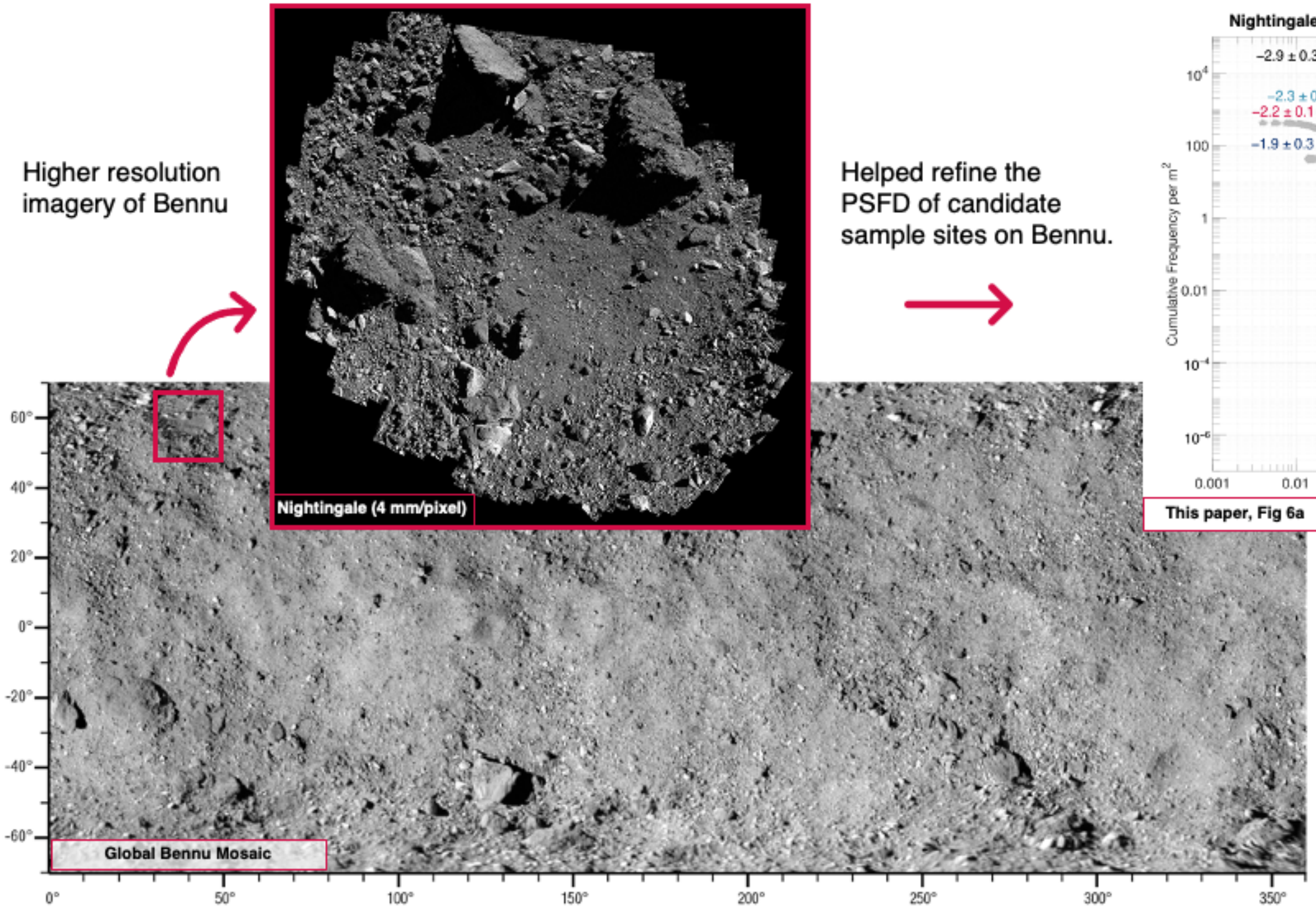
Sampling site selection

Geological maps, Boulders SFD, Slope maps, Thermal Inertia maps



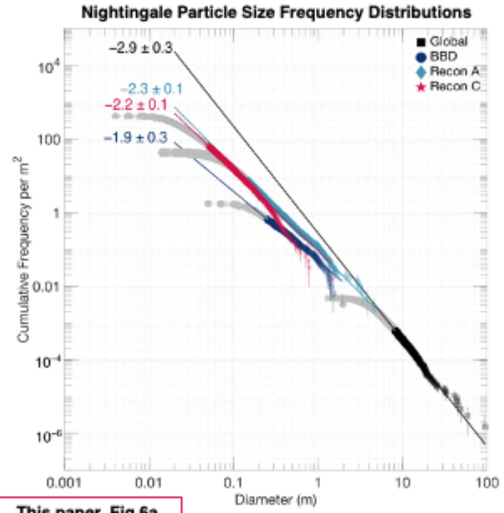
Walsh et al., (2021)

Higher resolution imagery of Bennu



Burke et al., (2021)

Helped refine the PSFD of candidate sample sites on Bennu.



This paper, Fig 6a

Which led to the selection of Nightingale crater as the prime candidate sample site.

On 20 October 2020, OSIRIS-REx successfully contacted the Nightingale sample site, gathering more than 60 grams of material.

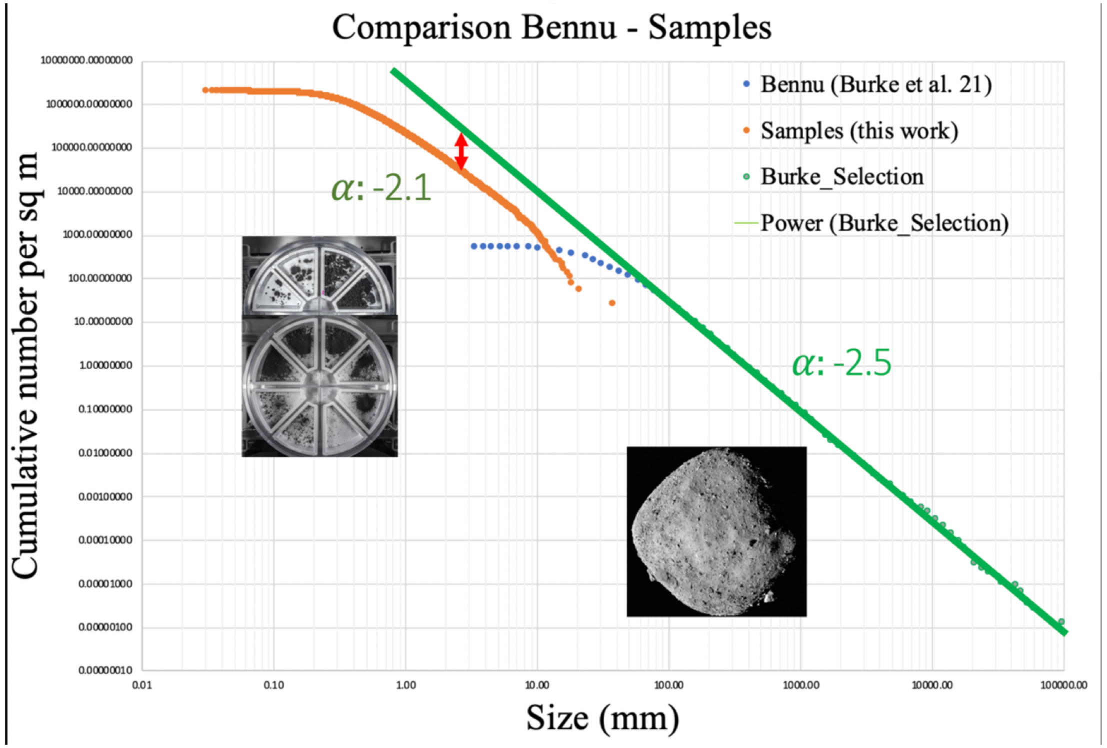
(101955) Bennu – NASA/OSIRIS-REx

Oct 2023 4 trays => 70.3 gr

Feb 2024 8 trays => 51.2 gr

Lauretta et al., (2024)

Sample Pebbles SFD

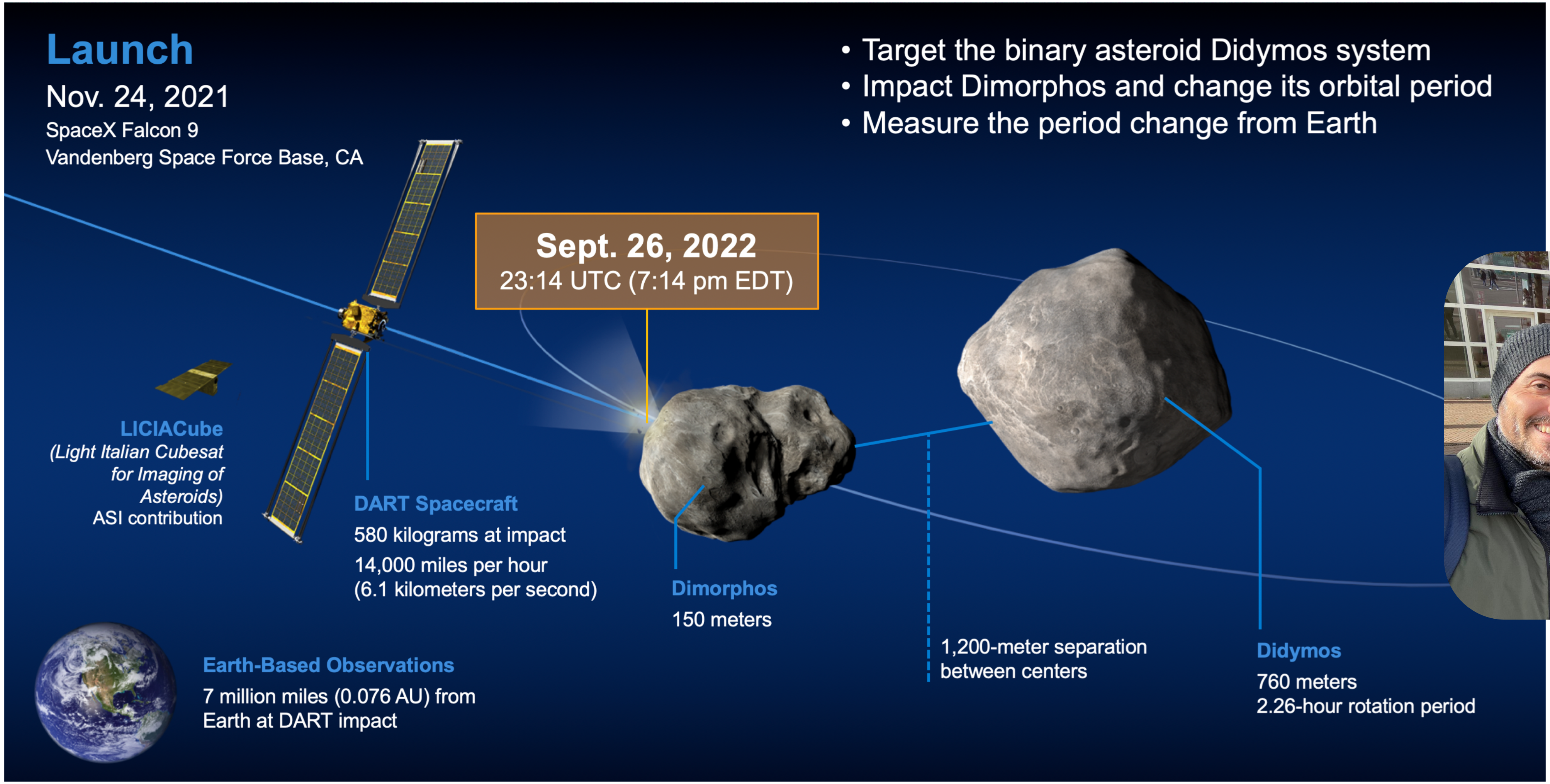


- ✓ Evaluate which is the best fitting curve/s at specific size-ranges (power-law? Weibull?) => **implications for formation and degradation processes;**
- ✓ **Comparison** between laboratory samples and Bennu boulder-pebble SFD => any changes? Why? Biases?

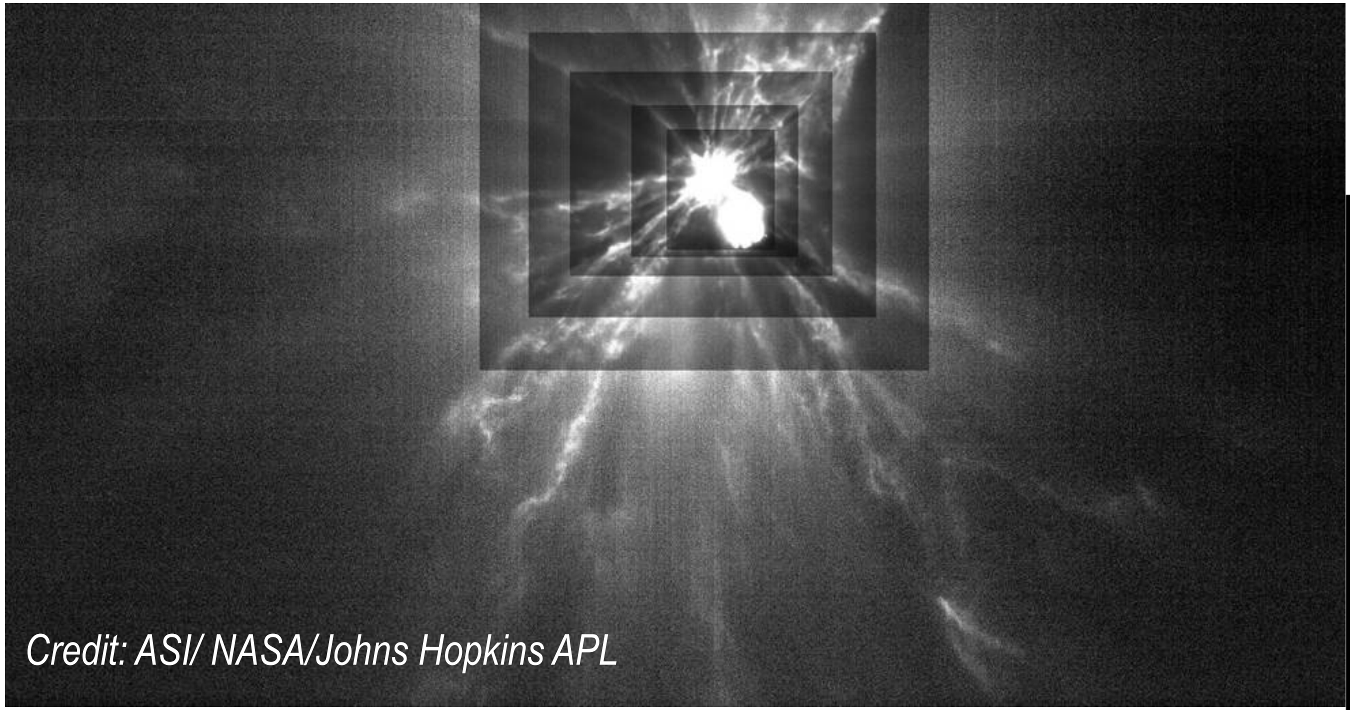
Didymos-Dimorphos – NASA/DART-ASI/LICIACube

DART: Double Asteroid Redirection Test

The First Planetary Defense Test Mission



Didymos-Dimorphos – NASA/DART-ASI/LICIACube

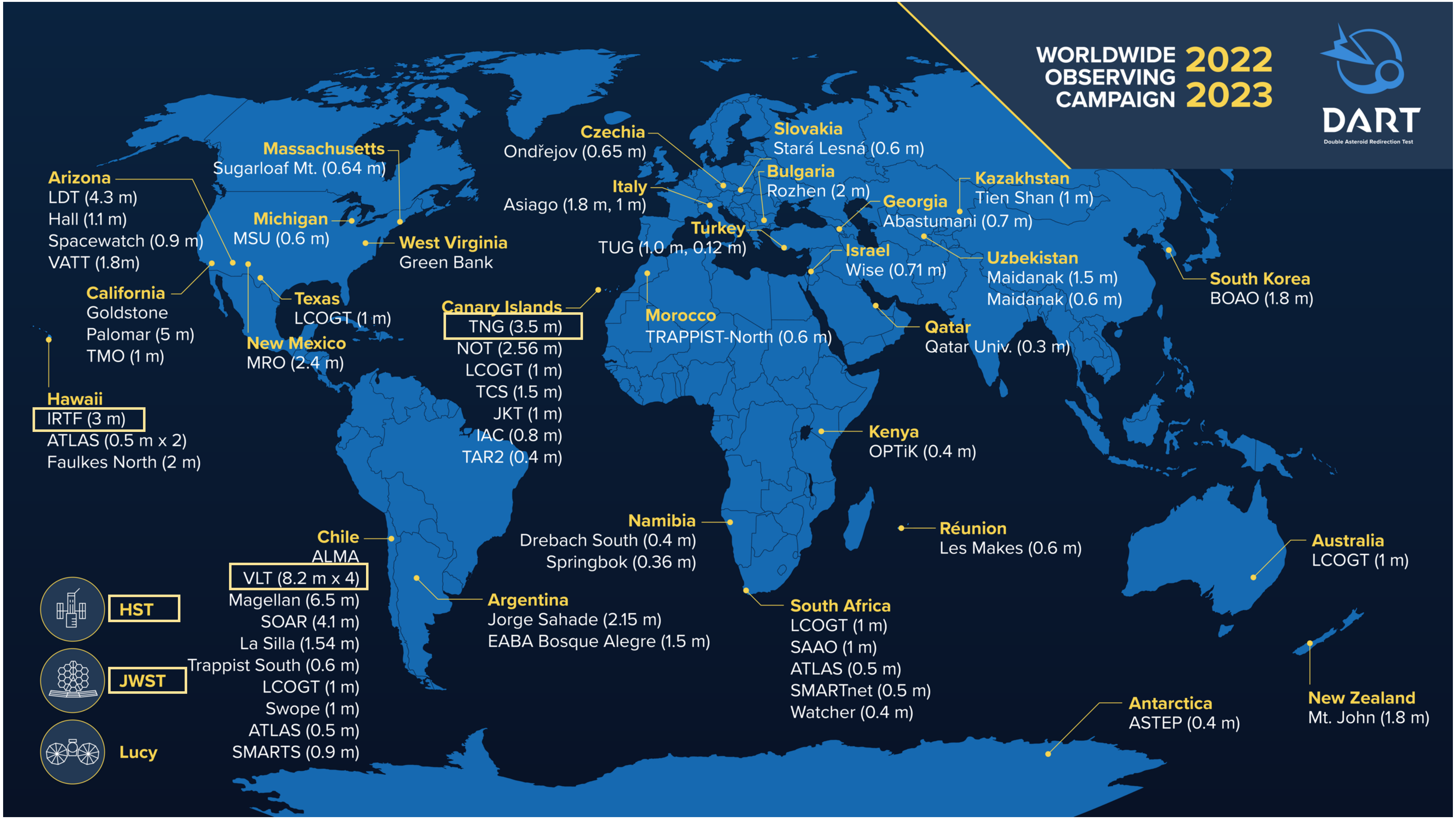


Ejecta formation and evolution

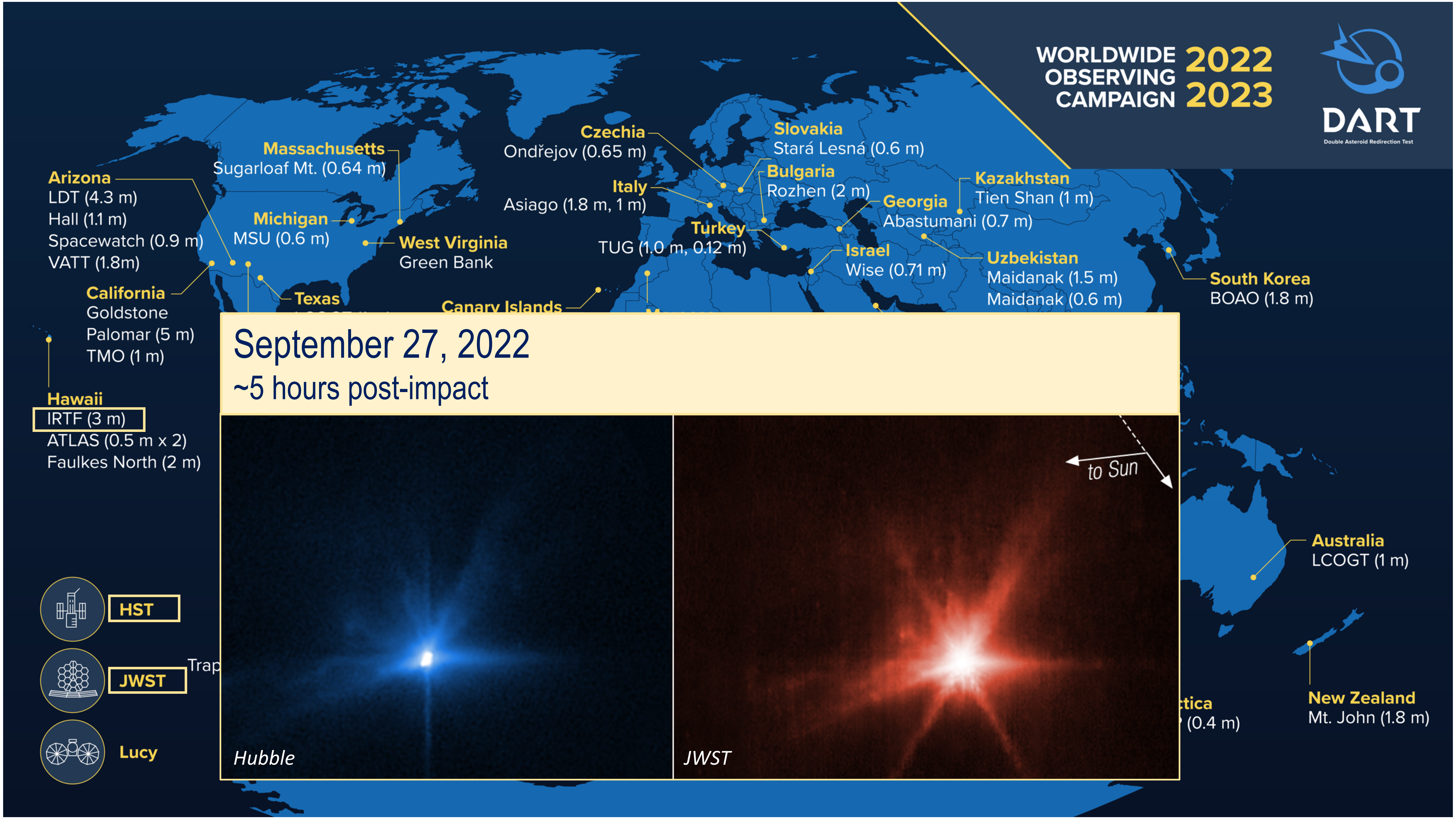
Raducan et al., 2024

- ✓ Physical properties of Dimorphos derived from the DART impact + SPH simulations
- ✓ More than 0.3% and up to 1% of Dimorphos's mass was ejected – consistent with observations
- ✓ The surface boulder volume fraction on Dimorphos is less than 40 vol%
- ✓ Dimorphos' bulk density is equal or lower than 2400 kg/m3
- ✓ Dimorphos' surface/shallow sub-surface cohesion is less than 50 Pa. Best fit, < 1Pa

Didymos-Dimorphos – NASA/DART-ASI/LICIACube



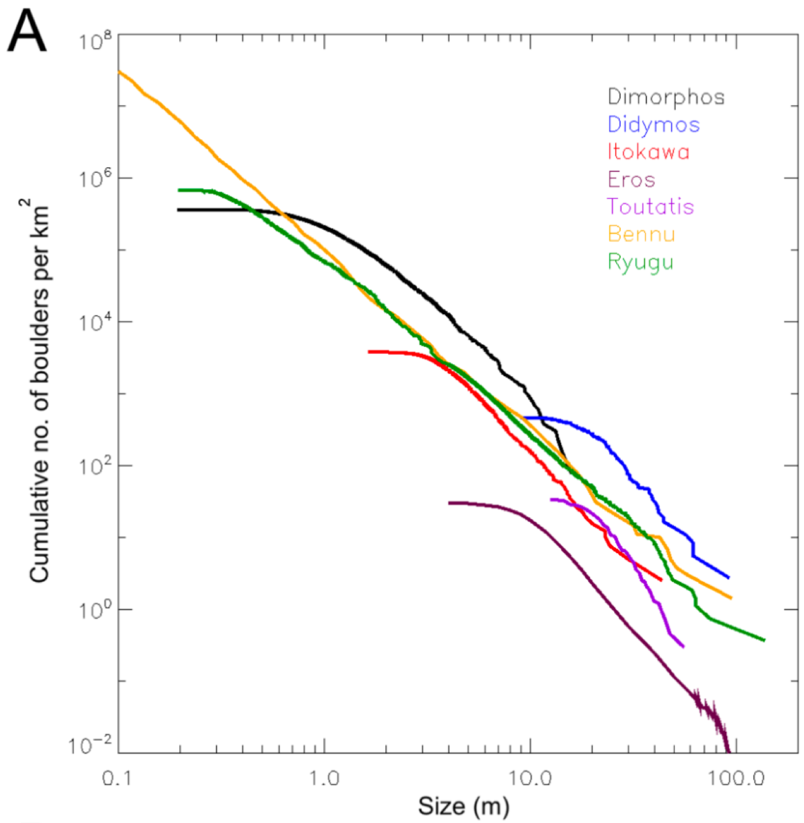
Didymos-Dimorphos – NASA/DART-ASI/LICIACube



Didymos-Dimorphos – NASA/DART-ASI/LICIACube

September 26 – October 25, 2022
European Southern Observatory,
Very Large Telescope, Chile
0 – 29 days post-impact

Didymos-Dimorphos – NASA/DART-ASI/LICIACube



B

Group	NEA	Power-law index α	±	Size limit
Stony	Dimorphos	-3.4	1.2	≥ 5 m
	Didymos	-3.6	0.7	≥ 22.8 m
	Itokawa	-3.05	0.14	≥ 5 m
	Eros	-3.25	0.14	≥ 10 m
	Toutatis	-4.4	0.1	≥ 20 m
Carbonaceous	Bennu	-2.5	0.1	≥ 0.2 m
	Ryugu	-2.65	0.05	≥ 5 m

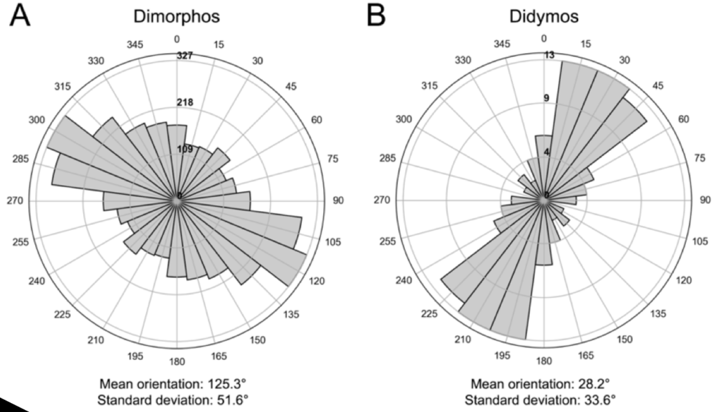
Dimorphos boulders (< 5 m) have size best-fit by a Weibull distribution

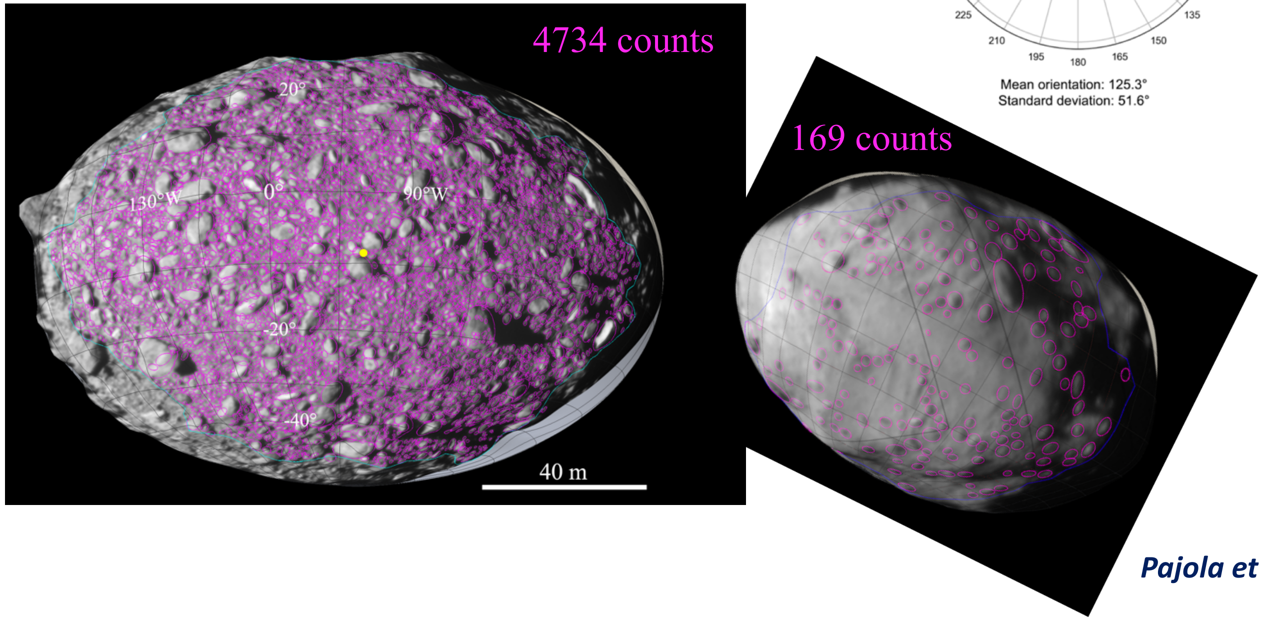
→ Boulders formed through multi-phase fragmentation process

→ Dimorphos formed through the spin up and mass shedding

DART DRACO: Dimorphos and Didymos to scale 2.5 minutes before DART's impact 580 miles (930 km) distance

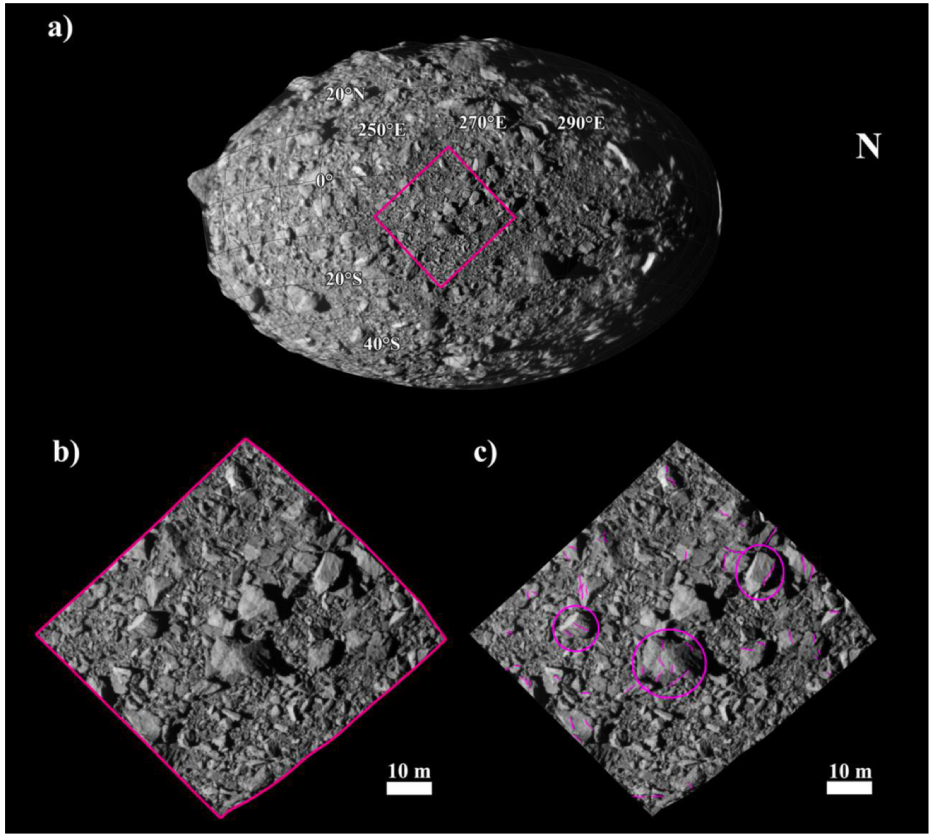
There is a preferential alignment of boulders, due to migration? rotation? tides?

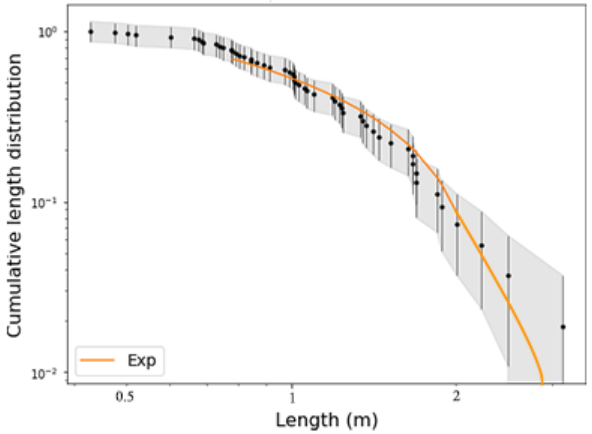


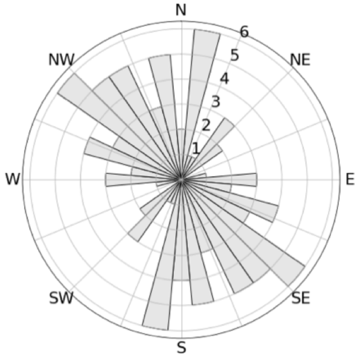


Pajola et al., (2024), NatComm

Didymos-Dimorphos – NASA/DART-ASI/LICIACube

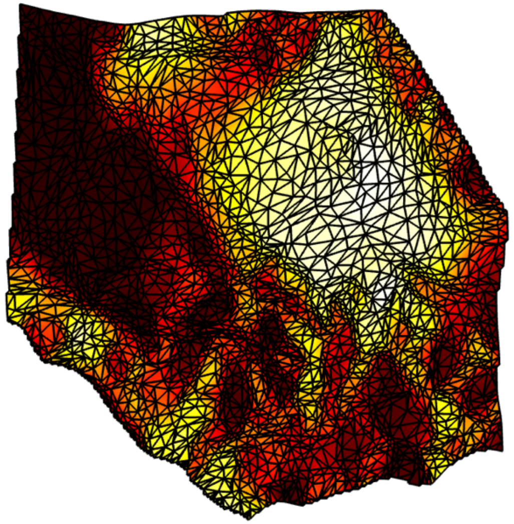


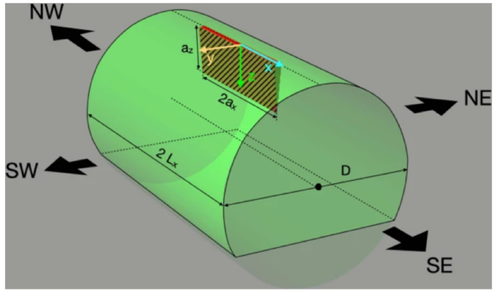




Dimorphos boulders' fractures

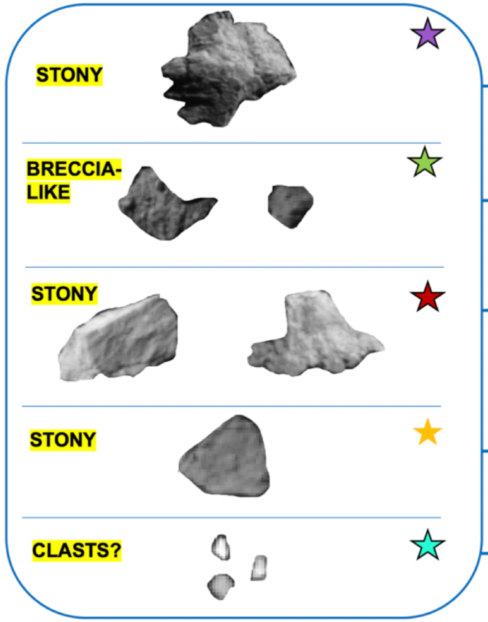
- ✓ the size-frequency distribution and orientation of the mapped fractures are consistent with **formation through thermal fatigue.**
- ✓ The fractures' preferential orientation supports that these have **originated in situ on Dimorphos boulders**
- ✓ Based on thermophysical and fracture propagation modelling, we propose that thermal fatigue on rocks exposed on the surface of S-type asteroids can form **shallow, horizontal fractures in much shorter timescales (100 kyr) than in the direction normal to the boulder surface (order of Myrs)**.





Lucchetti et al., (2024), NatComm

Didymos-Dimorphos – NASA/DART-ASI/LICIACube



- Massive
- Mid reflectance
- Very angular shape
- Erosional fractures
- Rough Texture sandstone like
- Competent

- Hummocky breccia like
- Dark reflectance
- Non angular shape
- No/superficial fractures
- Rough Texture
- 'Breccia Erosion'

- Massive blocks
- bright reflectance
- angular shape
- Deep fractures
- Slight rough Texture
- High competence

- Massive block
- Bright reflectance
- angular shape
- Deep fractures
- Parallel Fracturation
- Smooth Texture
- 'Blocky erosion'

- Bright reflectance
- Rounded shape
- smooth
- No other characteristics

MODAL ANALYSIS

1 ★ 40.9%
3 ★ 41.2%
4 ★ 12.3%
→ Stony Lit.

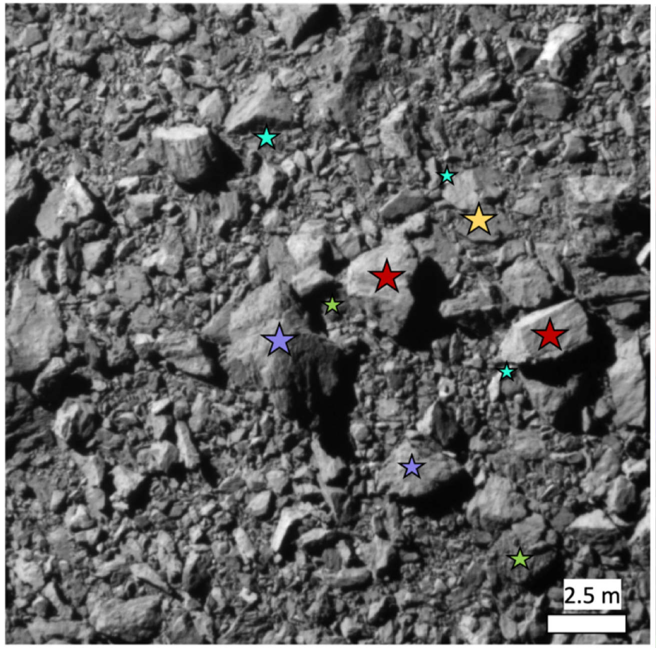
2 ★ 5.2% → Breccia Lit.

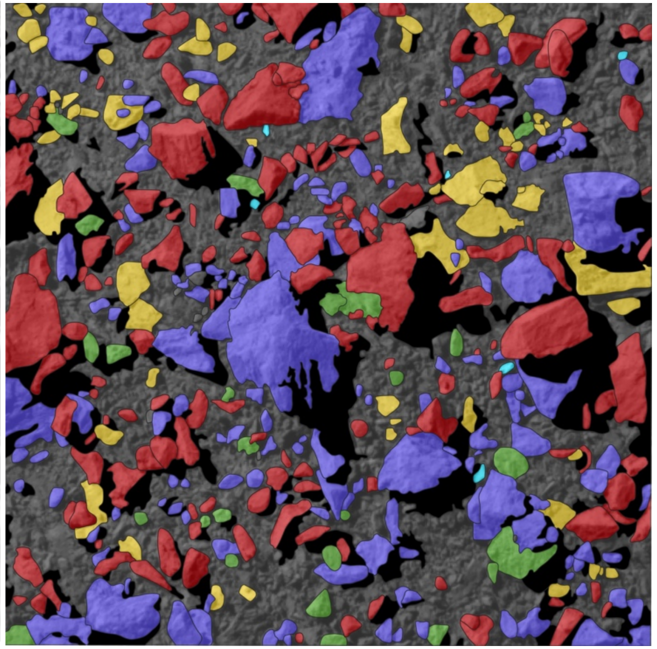
5 ★ 0.3% → Clasts/Inclusion Lit.

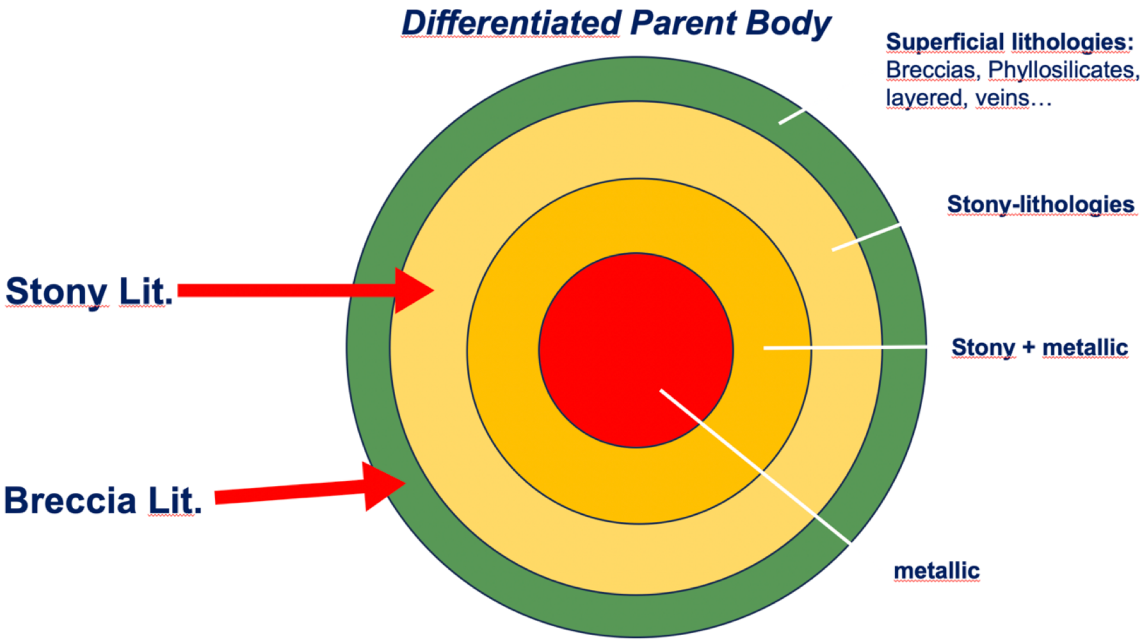
Boulders' Lithologies analysis

↓

History and evolution of the NEA and its parent body



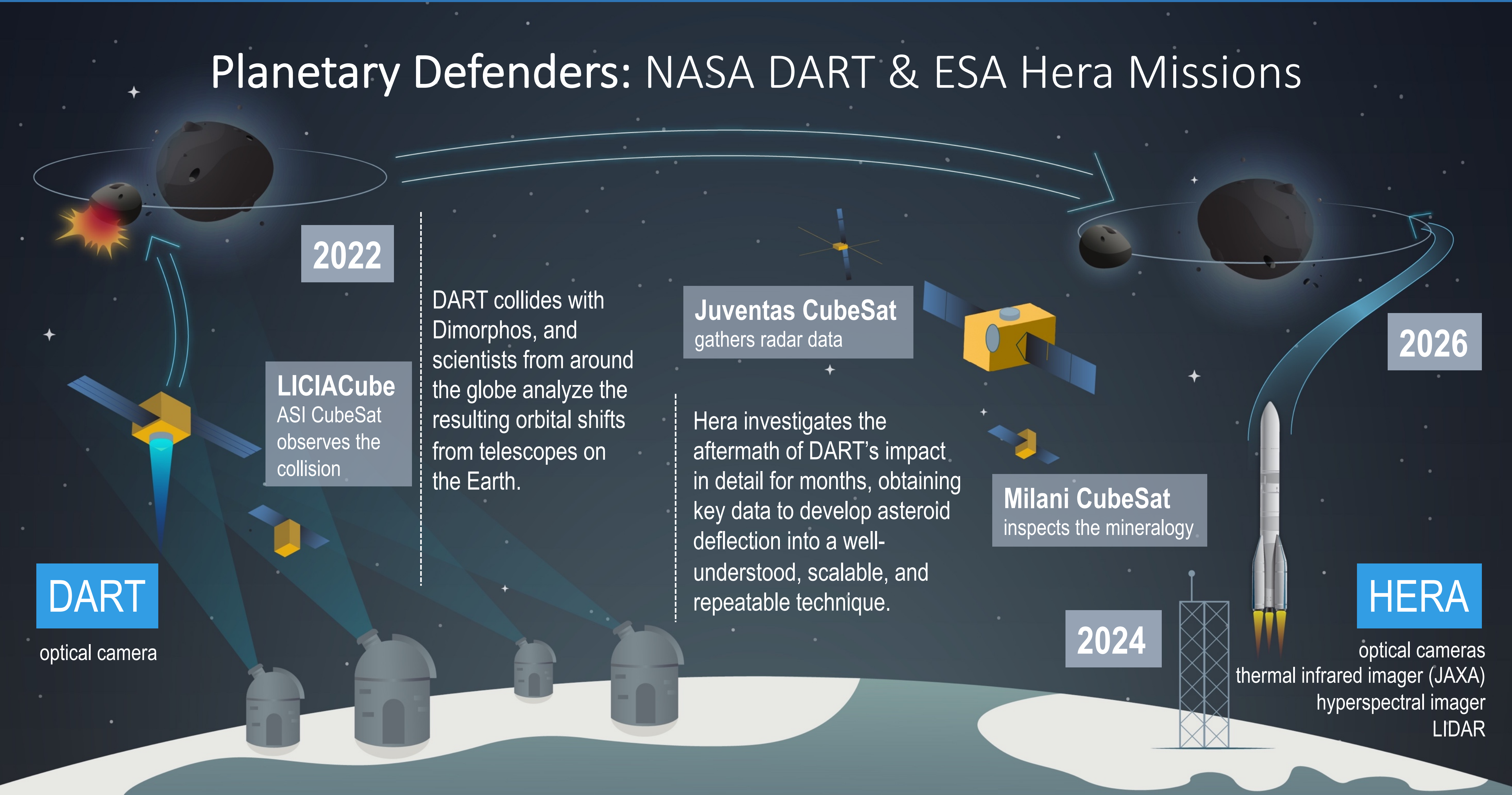




LITHOLOGICAL MAP

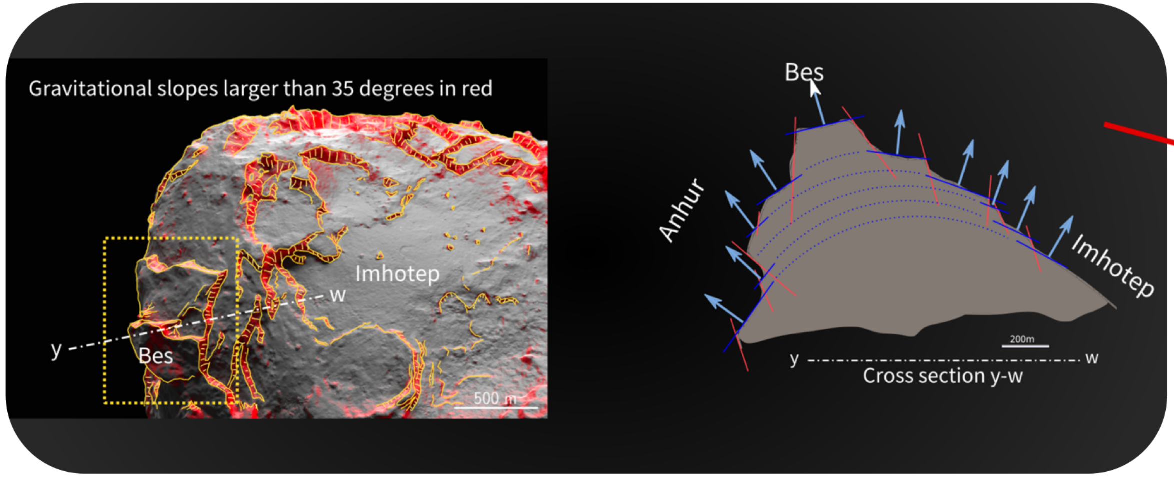
Tusberti et al., (in prep.)

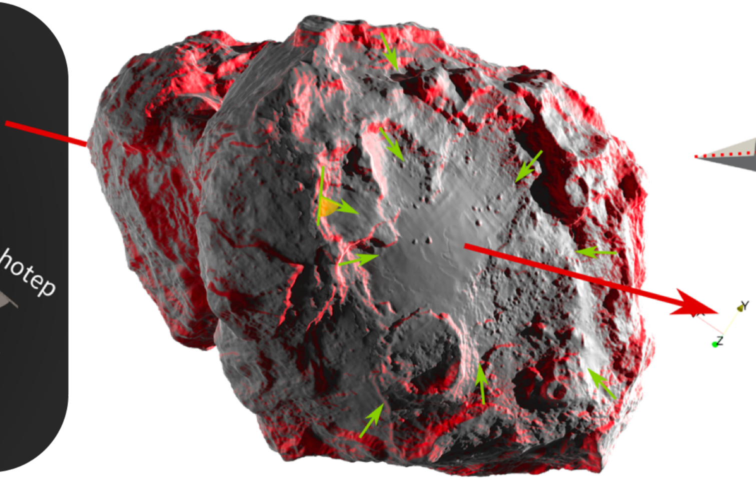
Didymos-Dimorphos – ESA/HERA

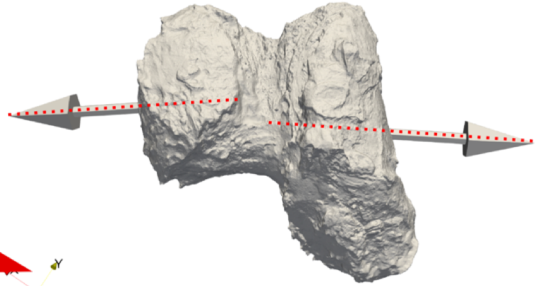


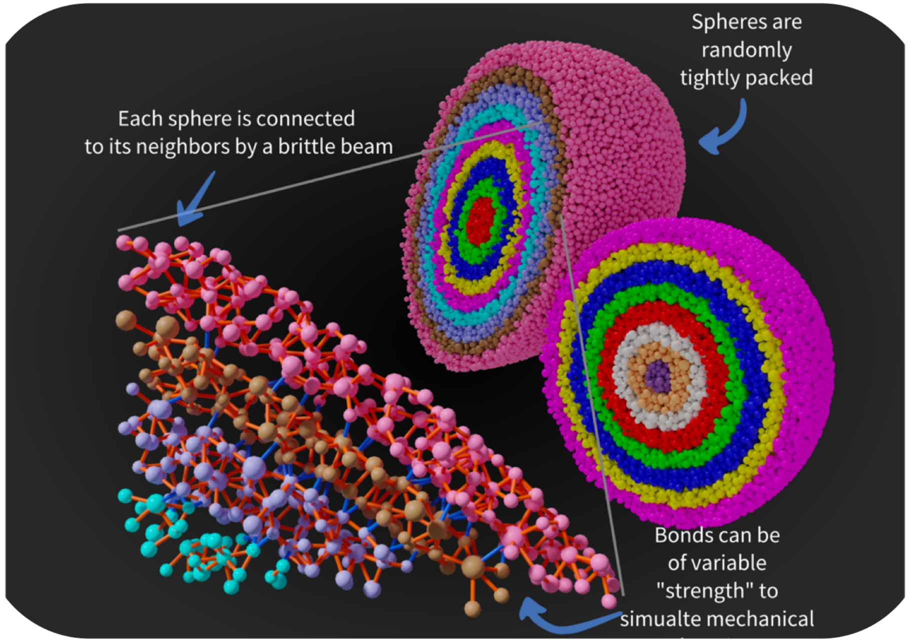
Comets

Cliffs on comet 67P shows a peculiar alignment, their normals seems to point toward an imaginary pole along the junction axis of the two lobes

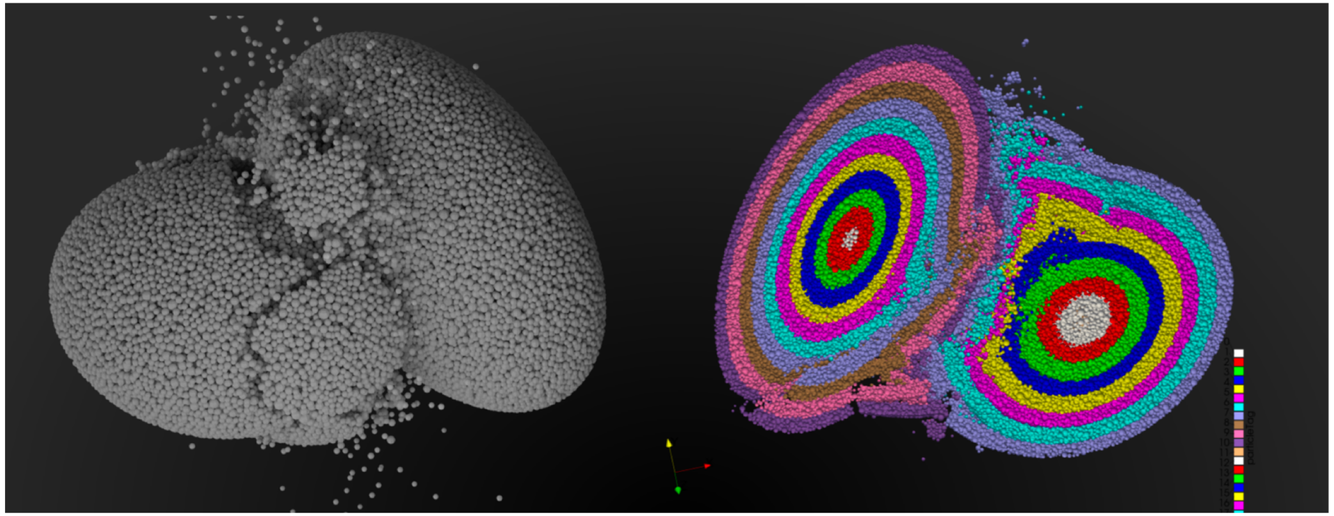








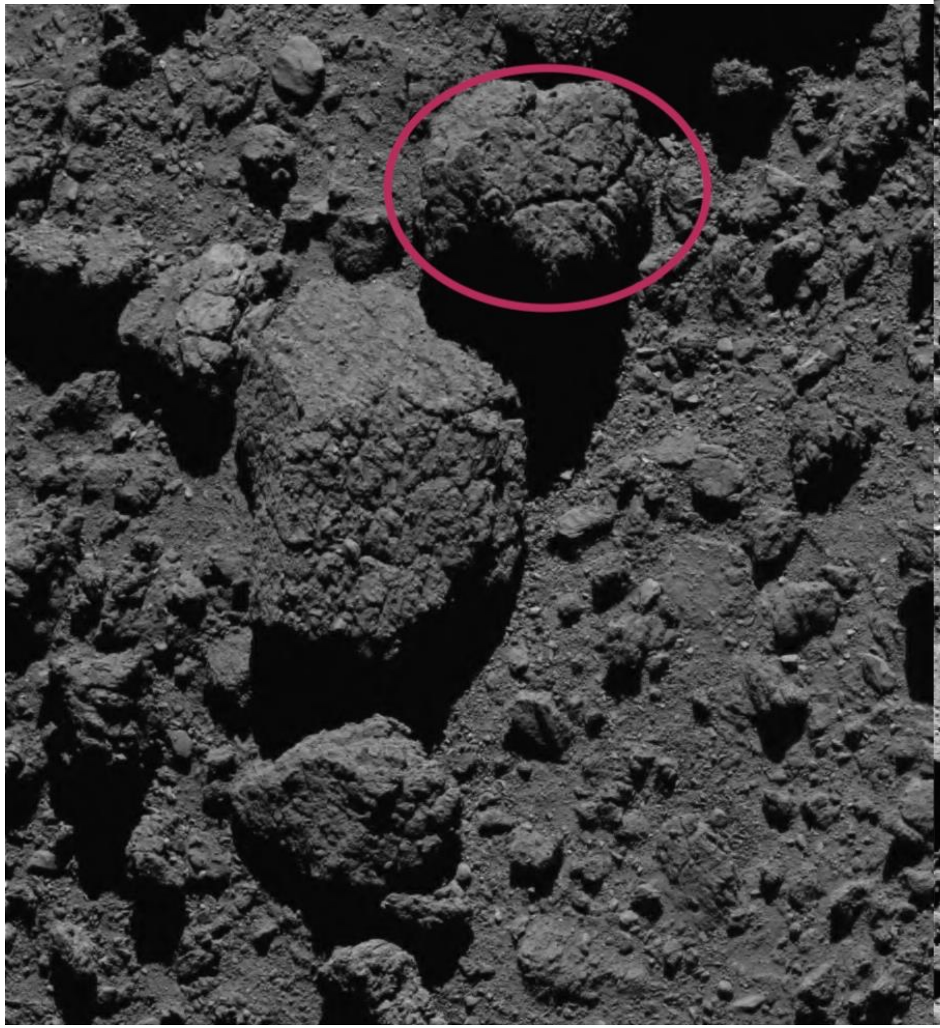
Simulation of the comet formation through E-sys particles software

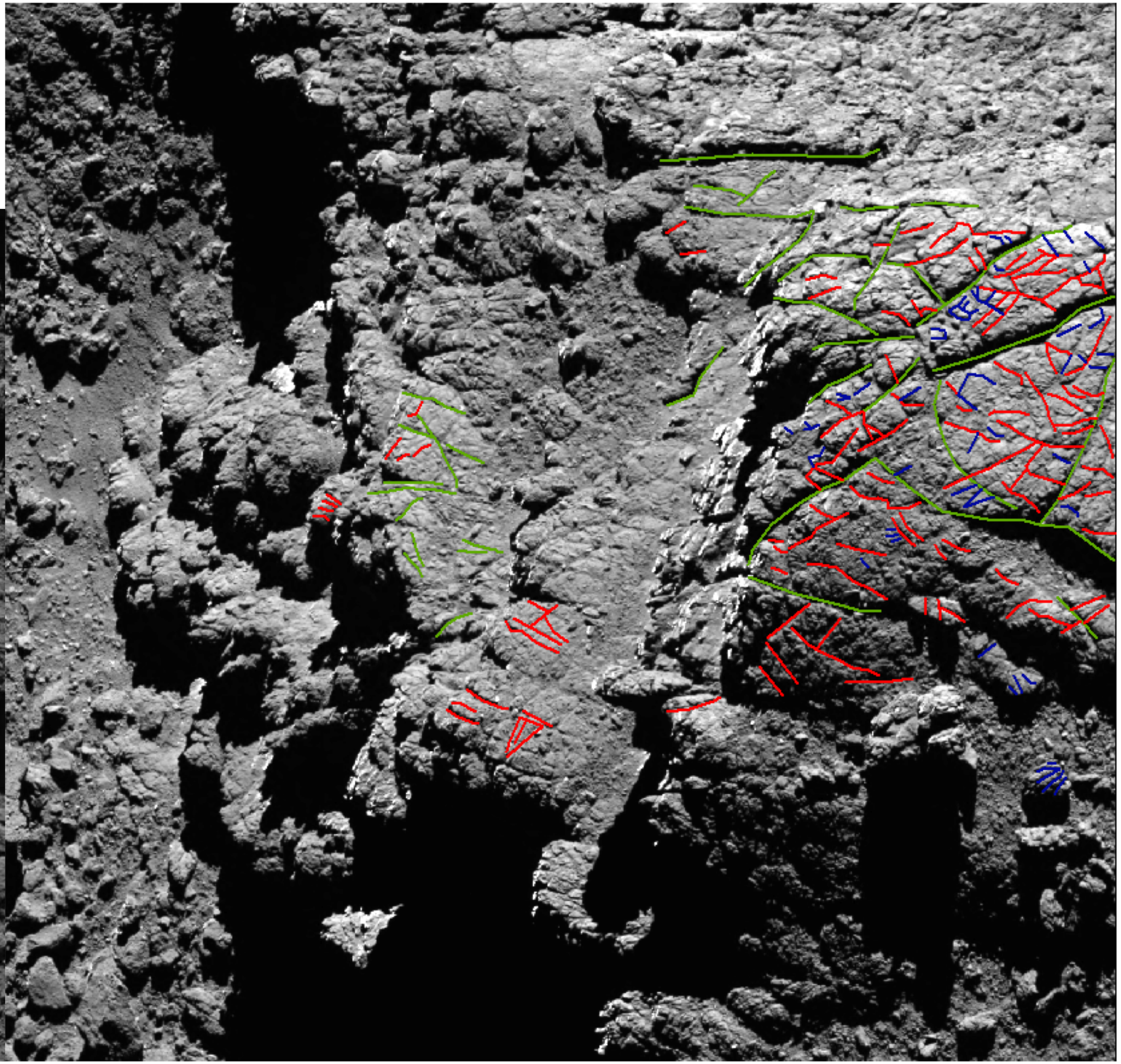


Penasa et al., (in prep)

Comets

Fractures analysis on both cliffs and isolated boulders to establish the **thermal fatigue origin** (mapping, thermal models and cracks propagation model)

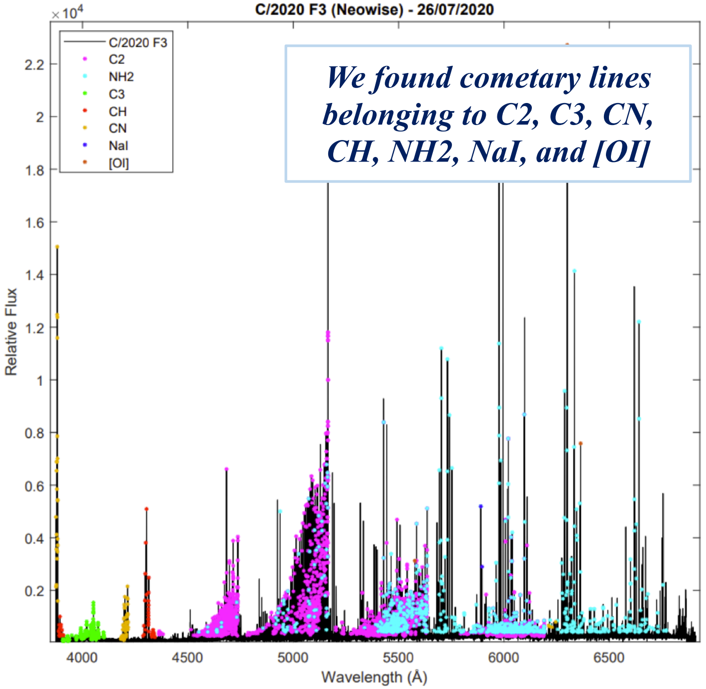




Comets

Ground based observation → comet C/2020 F3 (NEOWISE)

- 2 high resolution spectra: 26 July and 5 August 2020
- HARPS-North Echelle spectrograph @ TNG (R=115000)
- Spectral range: 383-693 nm



Catalog of emission lines representing a useful tool for future studies of comets

Cambianica et al., (2021)

Table 3
Absolute production rates of C/2020 F3 on 26 July at 0.72 AU. Ratios with respect to water and CN, as well as their logarithms, are also provided.

Molecule	$Q(10^{26}\frac{mol}{s})$	$\frac{Q}{Q(H_2O)}$	$\log\frac{Q}{Q(H_2O)}$	$\frac{Q}{Q(CN)}$	$\log\frac{Q}{Q(CN)}$
CN	1.55 ± 0.39	$(4.45 \pm 1.25) \cdot 10^{-4}$	-3.35 ± 0.12	1.0	0.0
C_2	1.76 ± 0.32	$(5.05 \pm 0.86) \cdot 10^{-4}$	-3.30 ± 0.07	1.14 ± 0.47	0.06 ± 0.19
C_3	0.32 ± 0.12	$(0.90 \pm 0.12) \cdot 10^{-4}$	-4.04 ± 0.06	0.20 ± 0.06	-0.69 ± 0.18
NH_2	10.58 ± 3.64	$(3.04 \pm 1.0) \cdot 10^{-3}$	-2.43 ± 0.15	-2.52 ± 0.15	6.84 ± 0.27
H_2O	3481.32 ± 3.48	1.0	0.00	2249.63 ± 634.18	3.35 ± 0.12

Munaretto al., (2023)

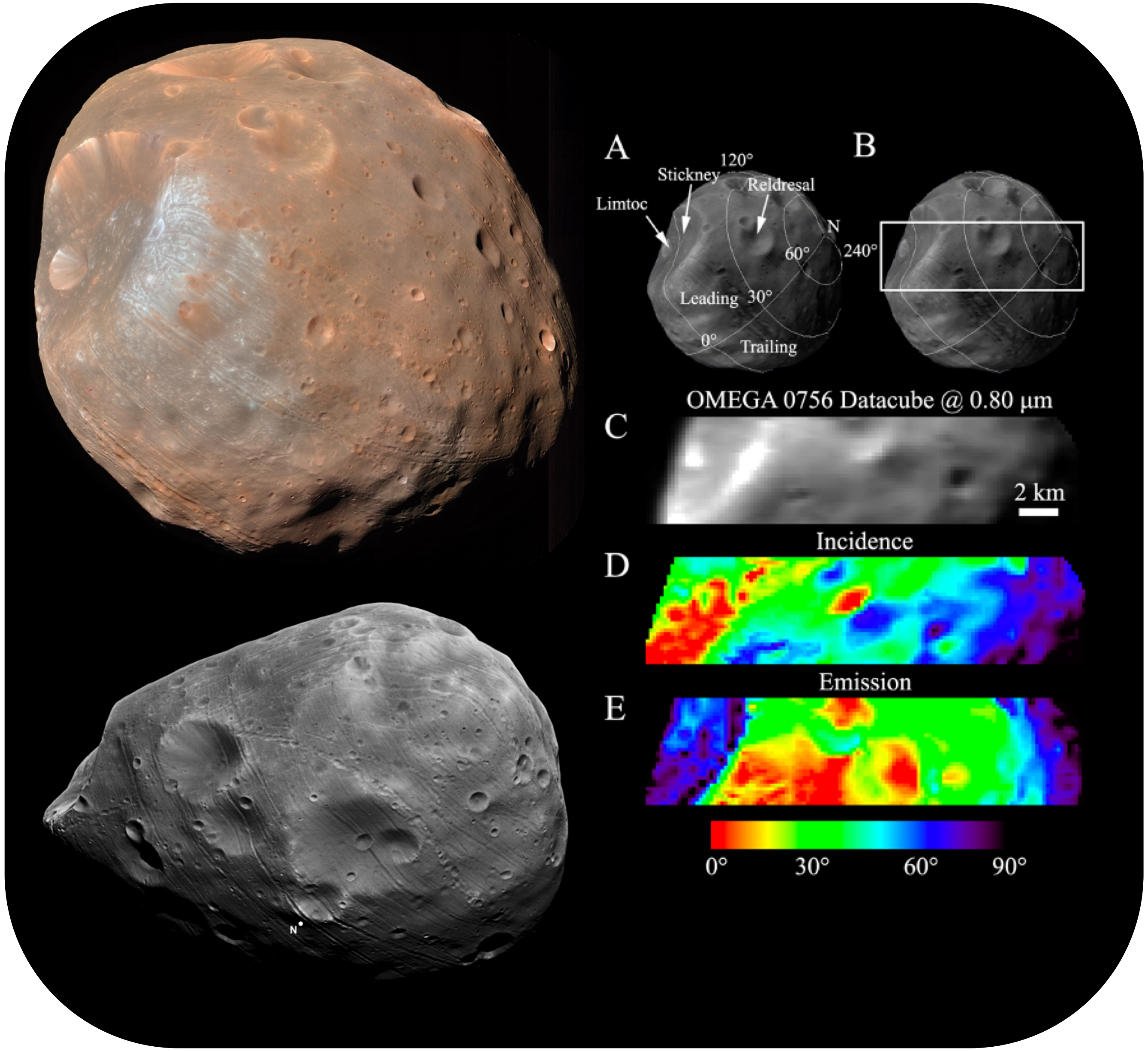
The calibrated comet spectrum was used in combination with the line identifications to measure the fluxes of given bands of molecules CN (388.3 nm band), C2 (516.5 nm band), C3 (405.0 nm band), NH2 (577.4 nm band) and O(1 D) (630.0 nm line).

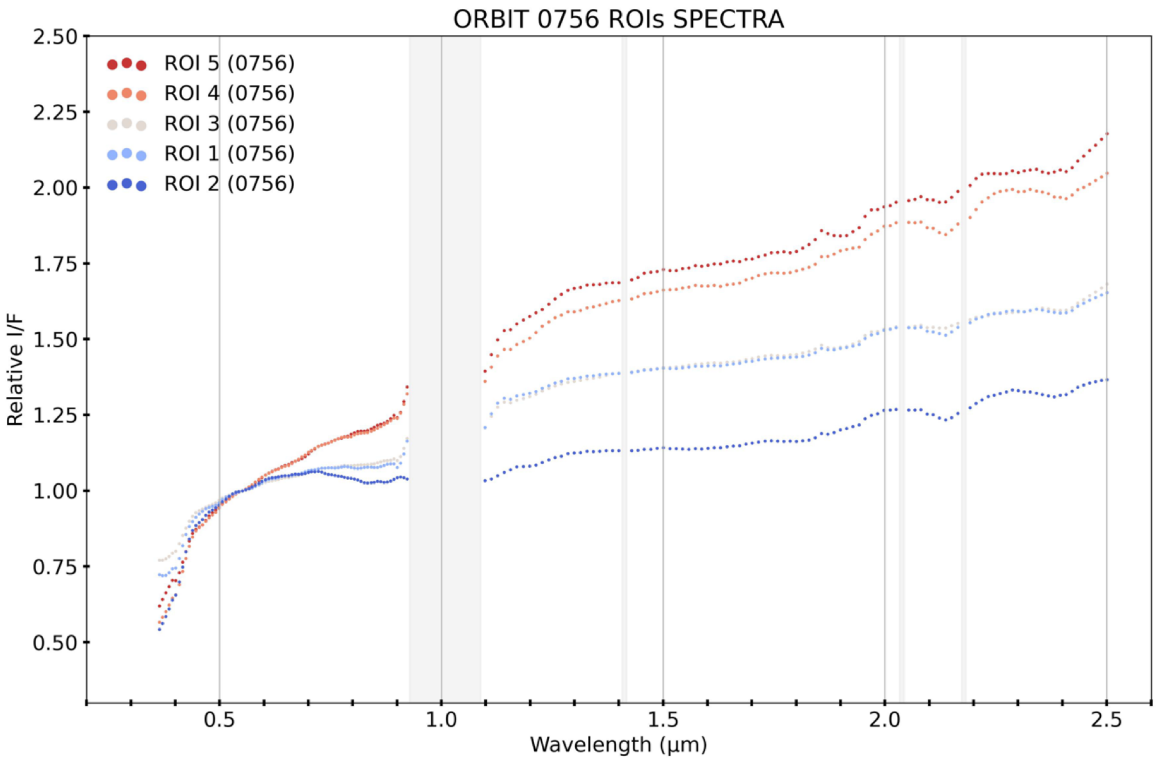
Ground based observation → Comet C/2023 A3 (Tsuchinshan-atlas)

- ✓ 6 observations @ TNG – DOLORES > March-June 2024
- ✓ 2 proposals (TNG-HARPN-N + LBT) > October-November 2024

Phobos

Spectral analysis to determine the Phobos composition → *see poster Joel Beccarelli*





Scientific participation in JAXA/MMX (Martian Moon eXplorer)

Icy worlds

- ✓ The exploration of the icy satellites in the outer Solar System (Jovian, Saturnian, Uranian and Neptunian) shows a stunning **variety** in these **bodies'surface geology**;
- ✓ Icy satellites are interesting from an **astrobiological** perspective because they are "**ocean worlds**", hosting or possibly hosting an internal liquid ocean;
- ✓ Understanding both the geological processes that shape the icy satellites' surfaces and the link between the subsurface ocean and the surface itself is pivotal to give new insights into their current states and **geological histories** and/or **evolution**.

Which are the geological processes that modelled or are still modelling the surfaces of icy satellites? Are they still active?

Are they hosting or have hosted internal liquid ocean? Which are the astrobiological implications?

Which is the composition of icy satellites in the outer SS? How much does it differ between bodies?

How common are the geological features, such as landslides, boulders, fractures, cryovolcanic regions on the different icy satellites?

Which is the role of the tectonic resurfacing or cryovolcanism?

Which is the link between the surface and the subsurface?

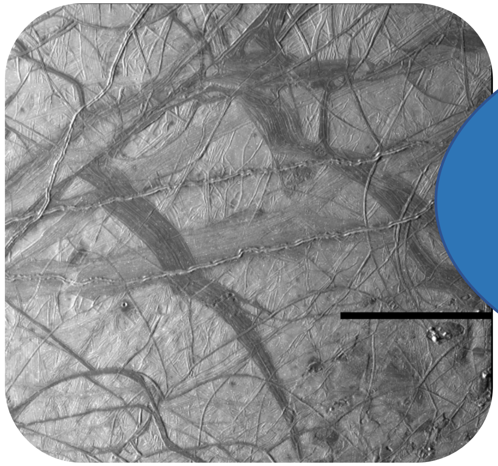
Which is the correlation between geology, composition and the surrounding environment?

Are the icy satellites experienced a common evolution history?

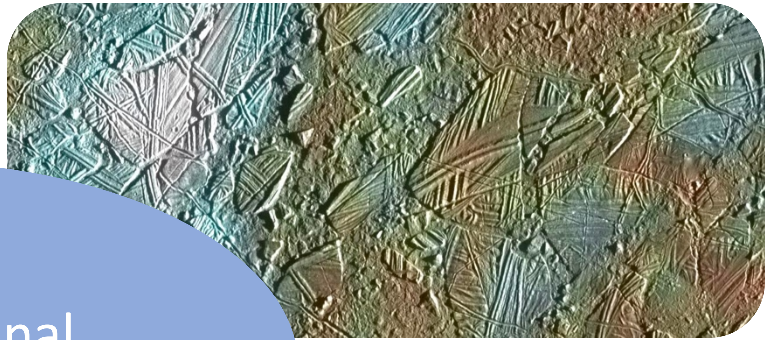
Icy worlds

Icy bodies are extremely geologically complex and witness the presence of different processes that act on the outer objects of the Solar System

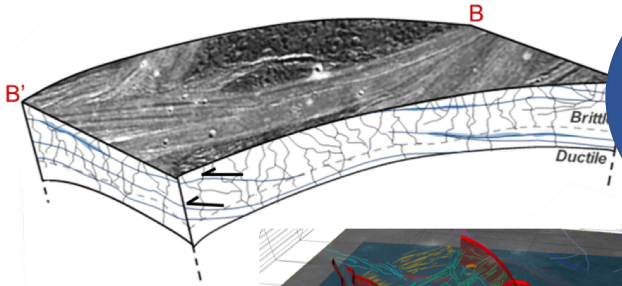
Comparative analysis through a multidisciplinary approach to advance the knowledge of the icy worlds of the outer Solar System

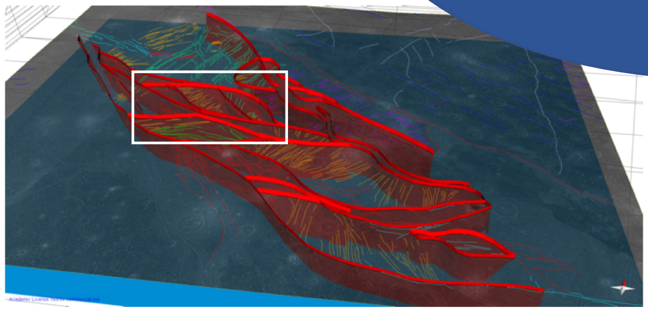


Geomorphological analysis (images)



Compositional analysis (spectra)





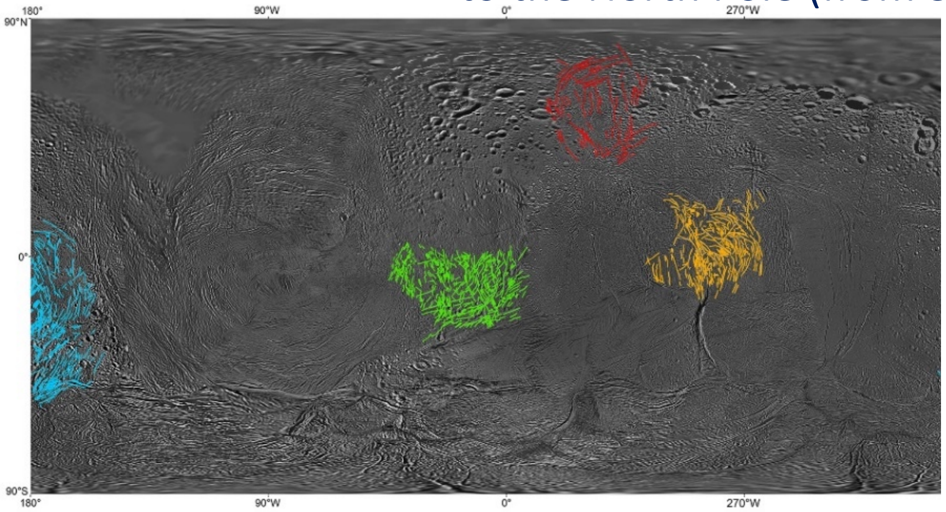
3D analysis (Digital Terrain Models)

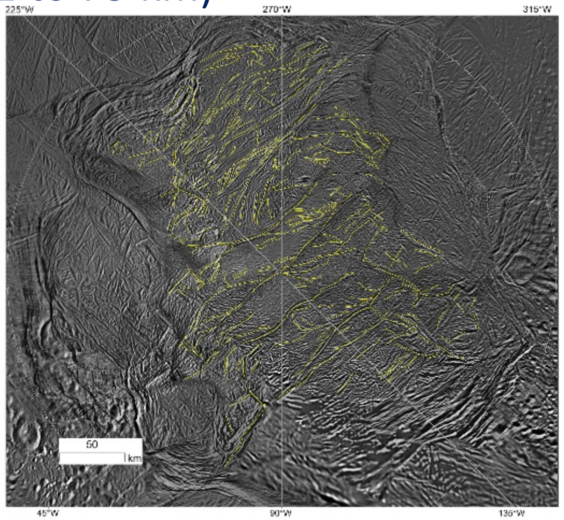
Terrestrial analogues (field campaigns)

Icy worlds | Fracture analysis

Determine the **DEPTH OF FRACTURE PENETRATION IN ICY CRUST** by performing a fractures **self-similar clustering** and **length distribution** analysis

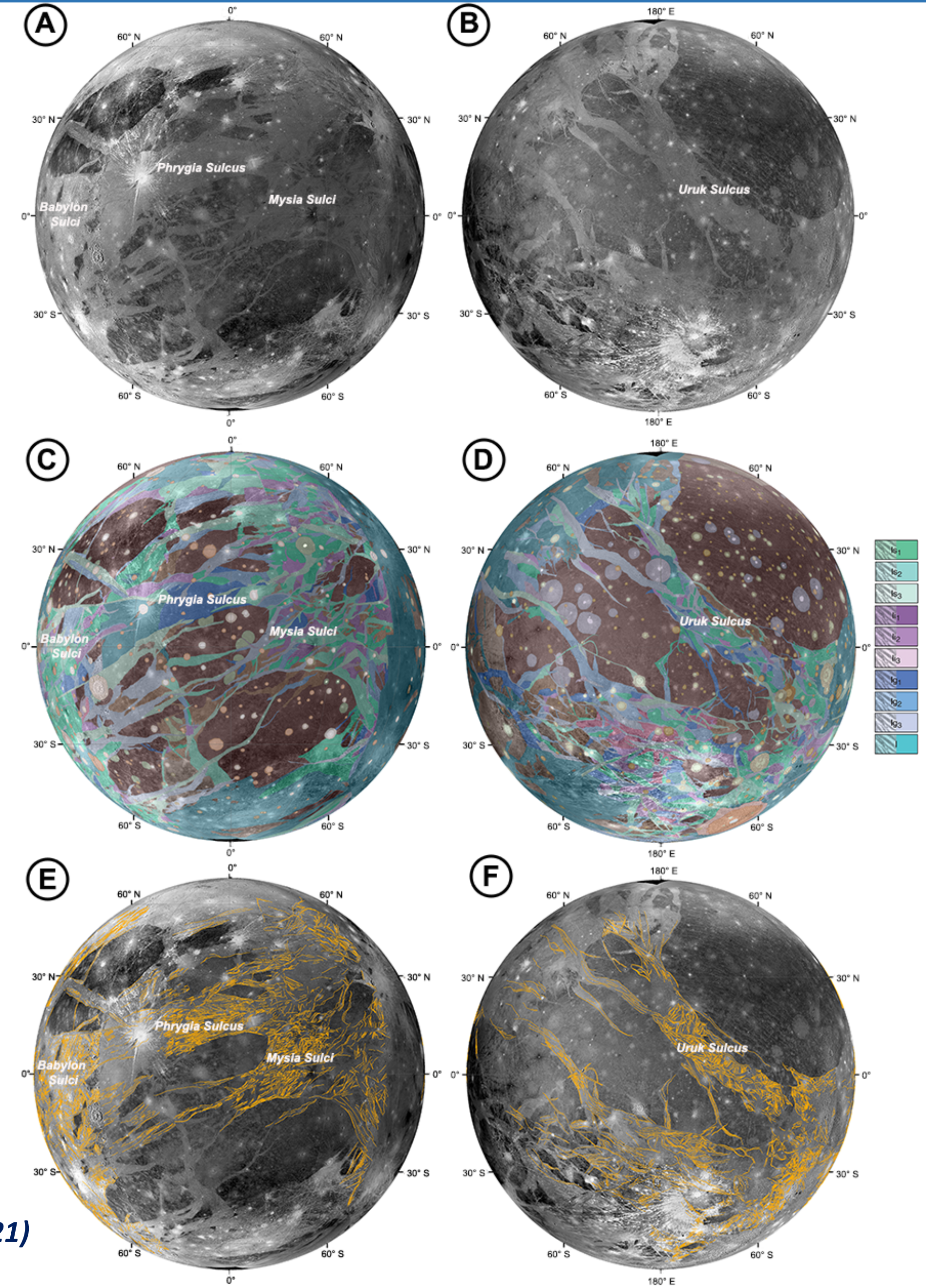
Enceladus: Brittle ice shell thickness increases from the South to the North Pole (from 31 to 75 km)





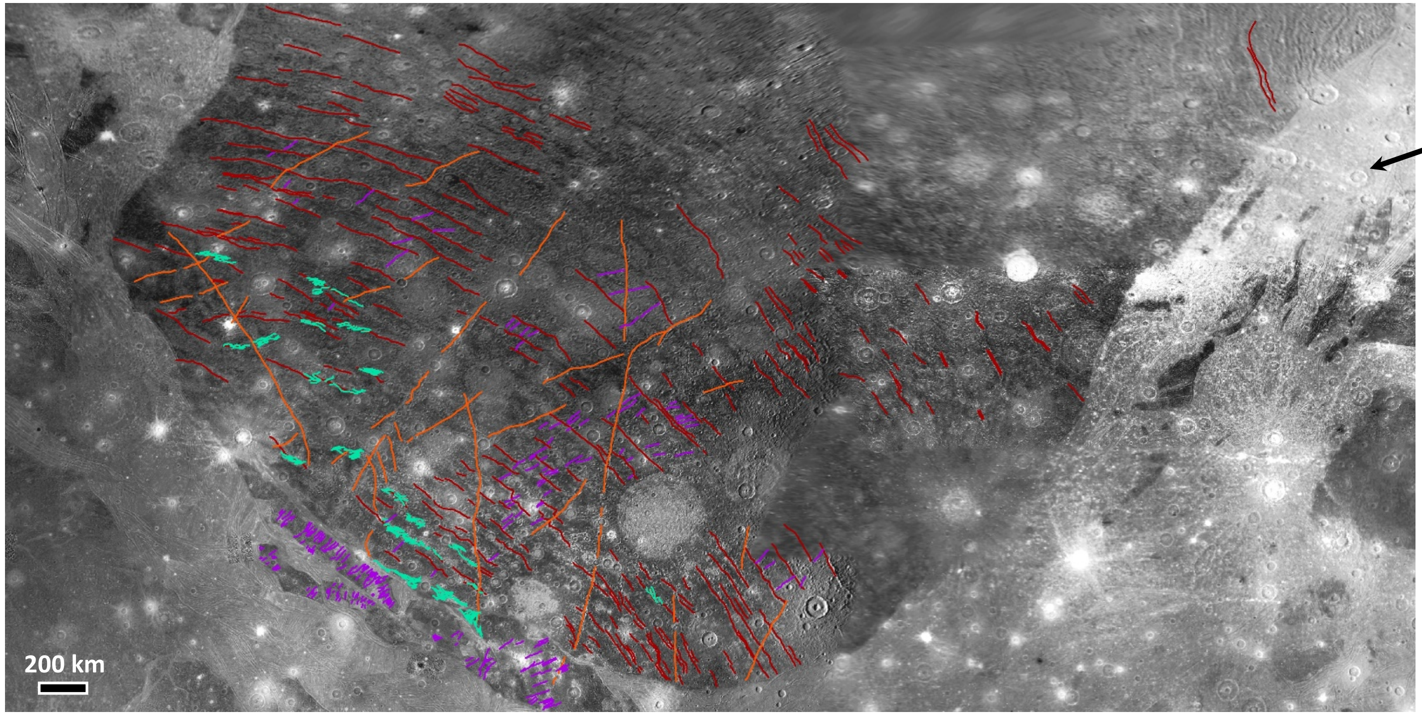
Lucchetti et al., (2017)

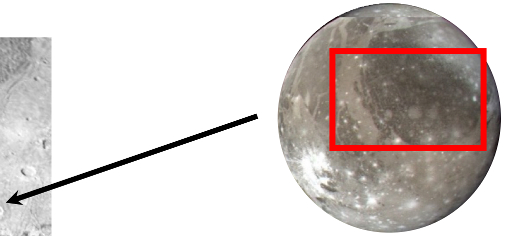
Ganymede: The presence of **icy solid crust with thickness of 100-130 km along the equatorial belt** of Ganymede which is in agreement with previous measurements (from 80 to 150 km)



Lucchetti et al., (2021)

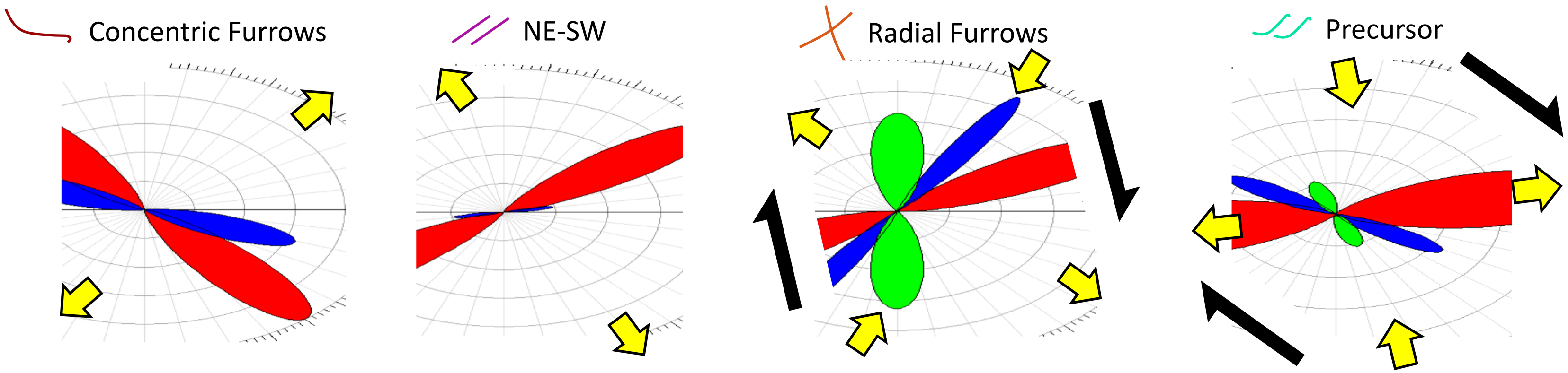
Icy worlds | Analysis of geological features





Analysis of **FRACTURES** to provide a structural analysis and an evolutive tectonic model for the region under study

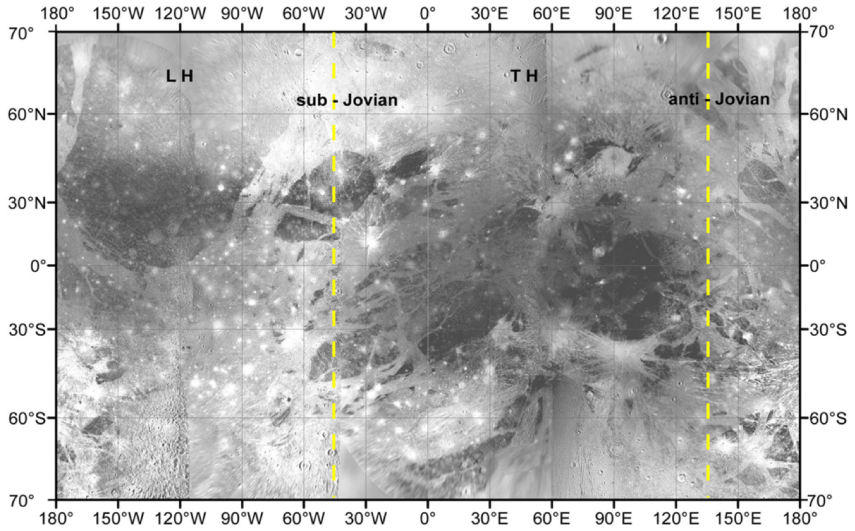
Structural geological mapping of **Ganymede** Galileo Regio

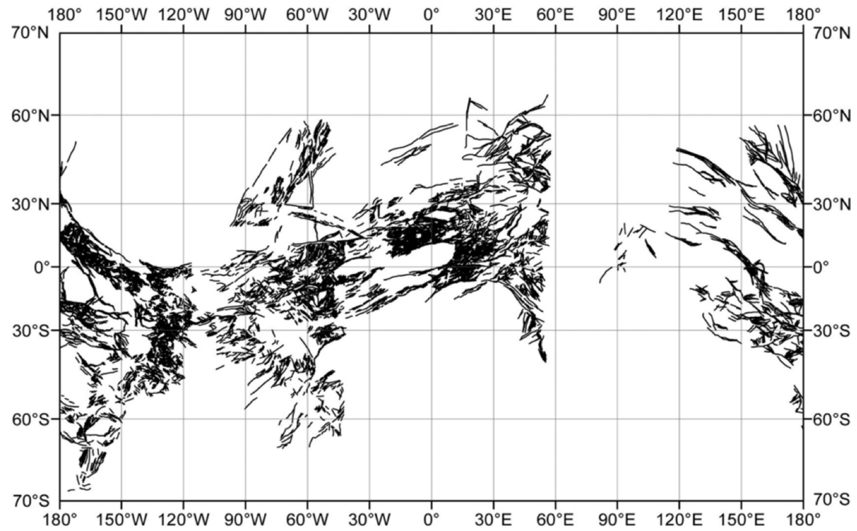


Azimuthal analysis of fractures systems and determination of stress fields

Rossi et al., (2022)

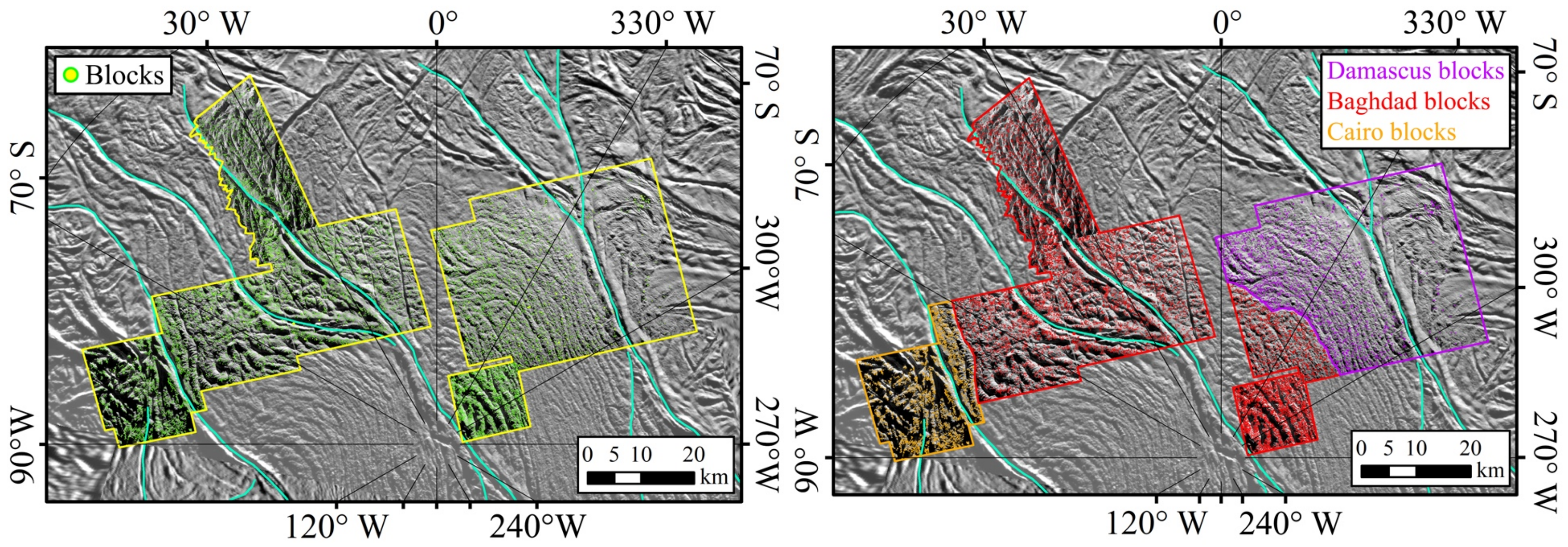
Icy worlds | Analysis of geological features





Structural geology of **Ganymede regional groove systems** (60°N–60°S)

(Rossi et al., 2018)

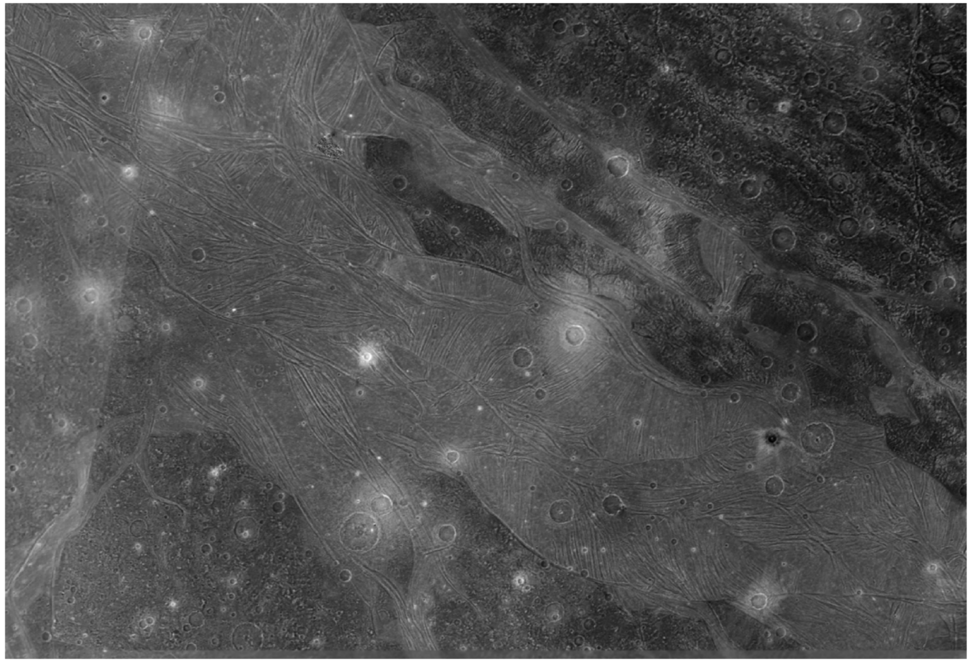


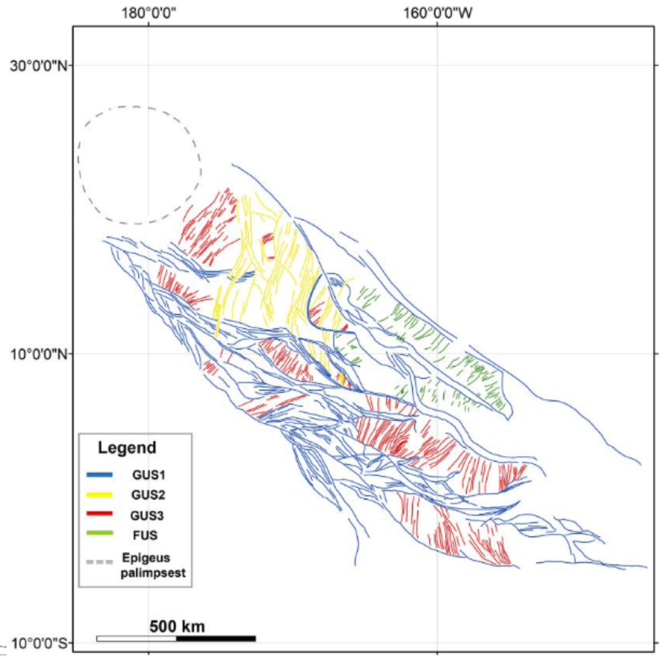
BOULDERS Size Frequency Distribution in the Tiger Stripes area (**Enceladus**)

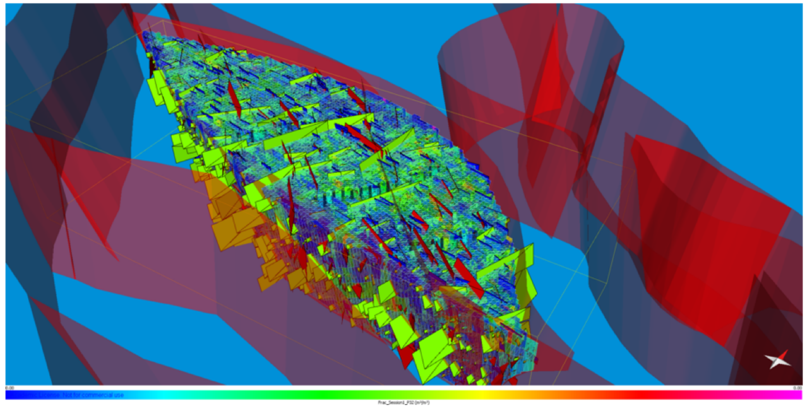
Different processes concur in the formation and evolution of such blocks, in particular sublimation and cryovolcanic ejection mechanisms, as previously hypothesized by Martens et al., (2015).

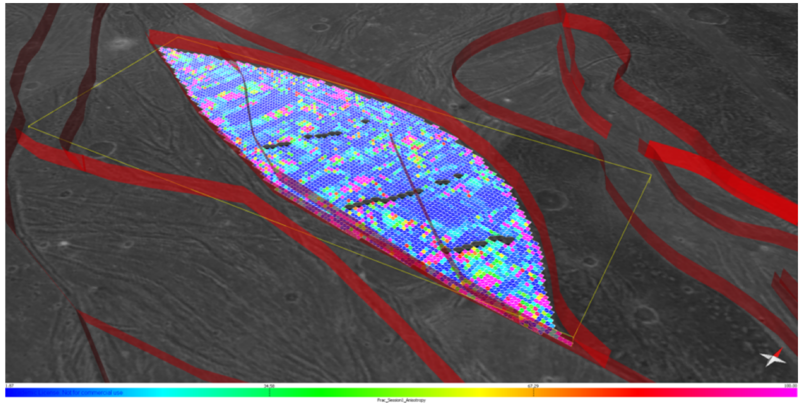
Pajola et al., (2021)

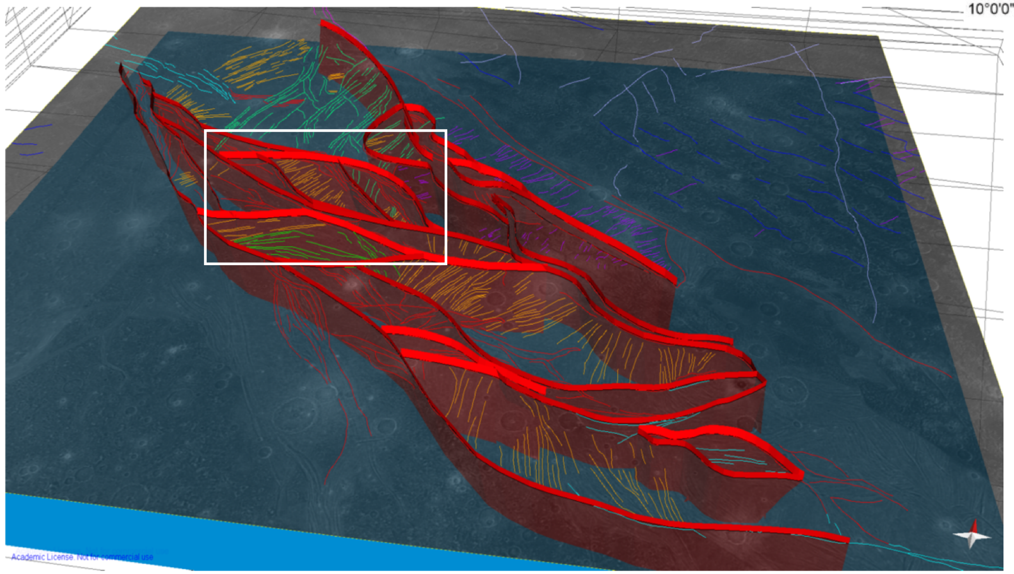
Icy worlds | 3D geological modelling











Move software

3D geological model of surface regions to determine the behavior of the evolution of the body

(Pozzobon et al., in preparation)

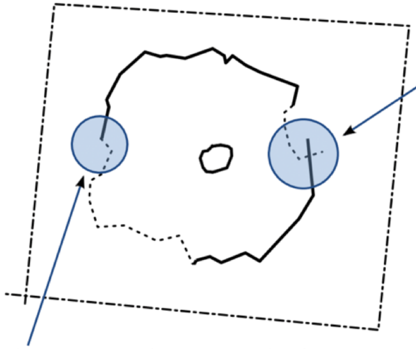
Icy worlds | Geological maps

Geological mapping tool development → Mappy (QGIS plugin)

Mapping strategy

A line layer for the contacts

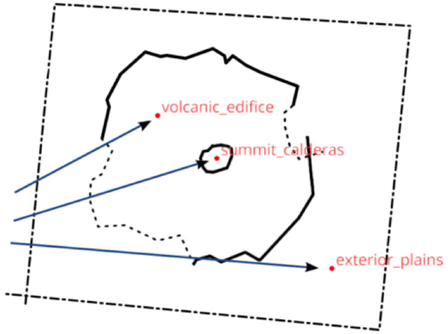
No need to do precise snapping, any intersection will just work



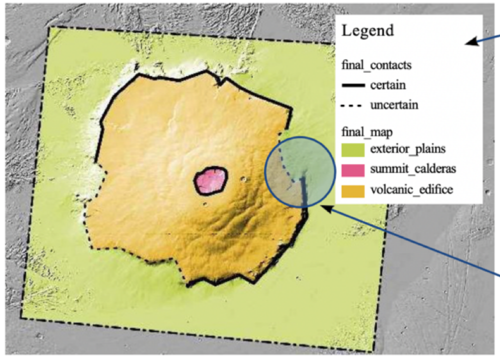
a single contact can be composed of multiple lines, each with different attributes (e.g. for certain/uncertain contacts)

A point layer for the unit's names

Points are used to define the properties of the resulting polygons (e.g. unit names)



Mappy takes care of generating the polygons

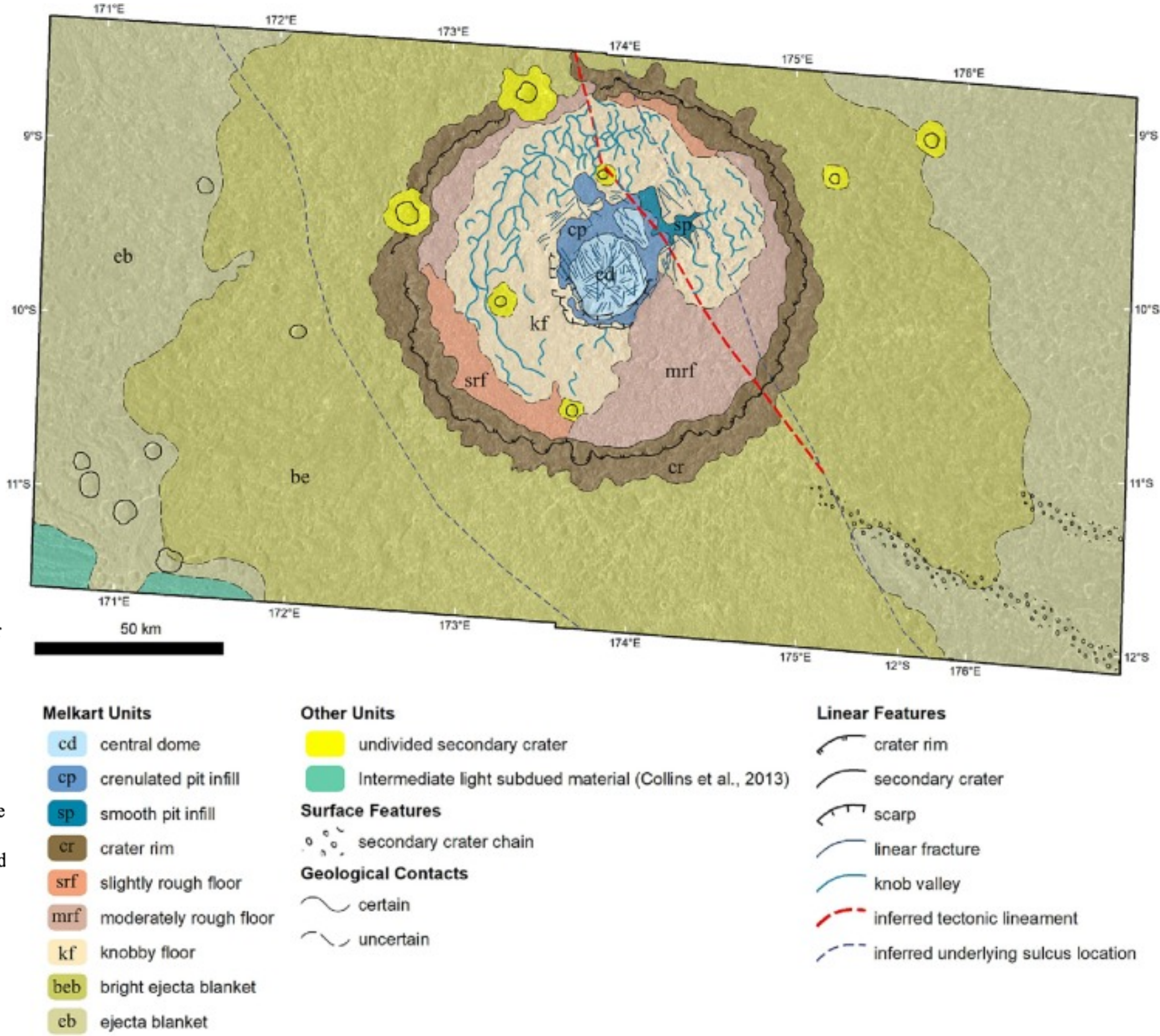


Attributes are automatically transferred to the polygons. Line attributes are also retained for final styling

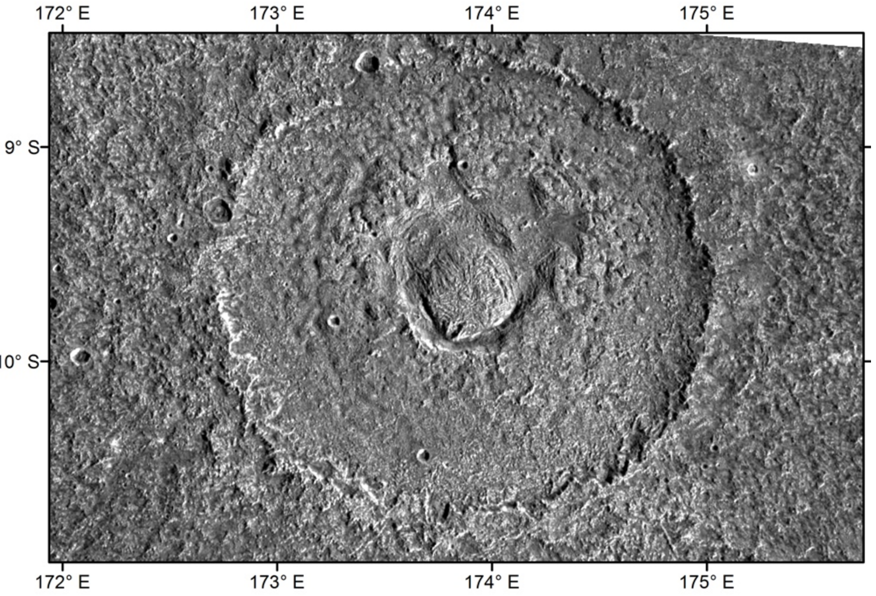
Unprecise contact intersections are taken care for, and a new layer without dangling ends is generated

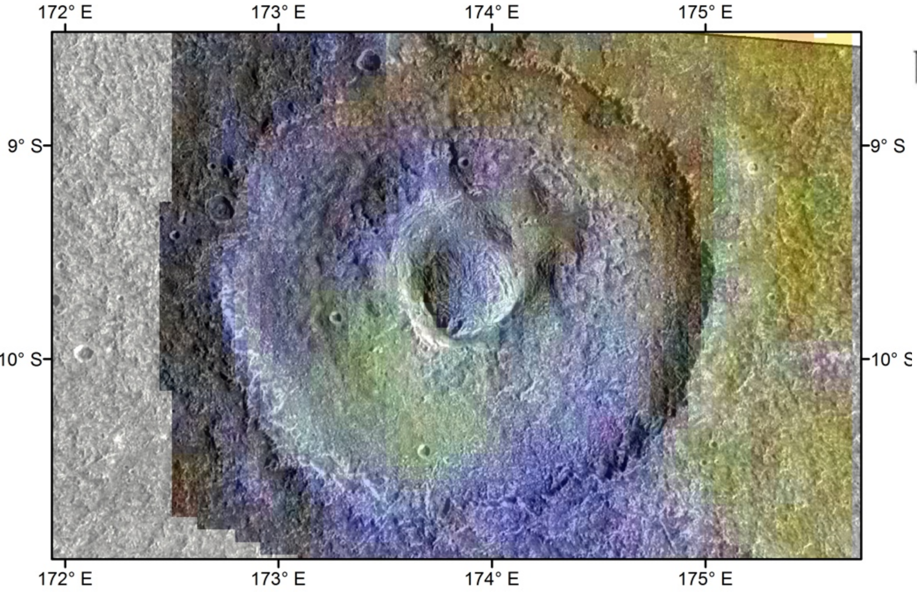
Penasa et al., (in prep)

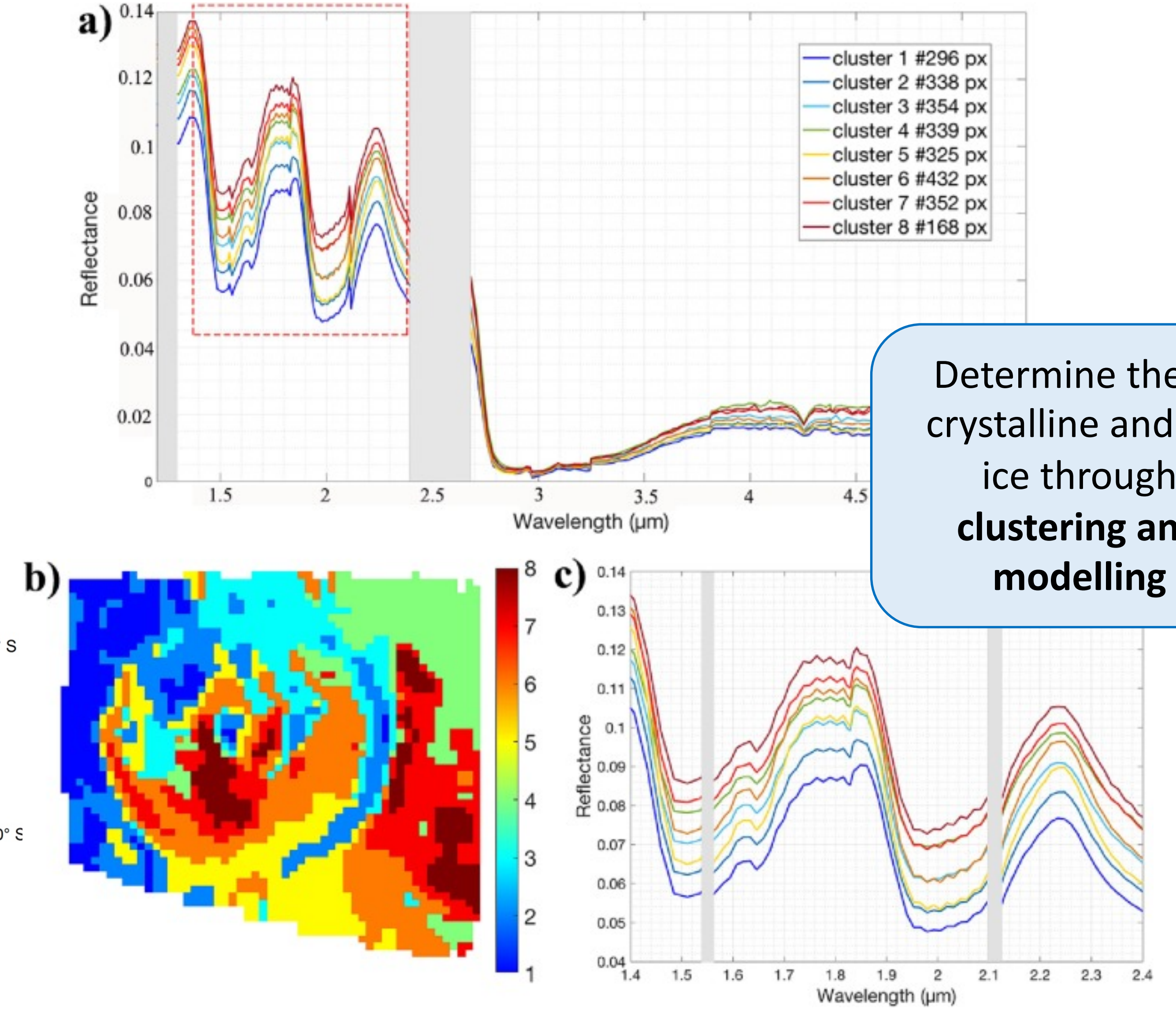
Melkart crater



Lucchetti et al., (2023)





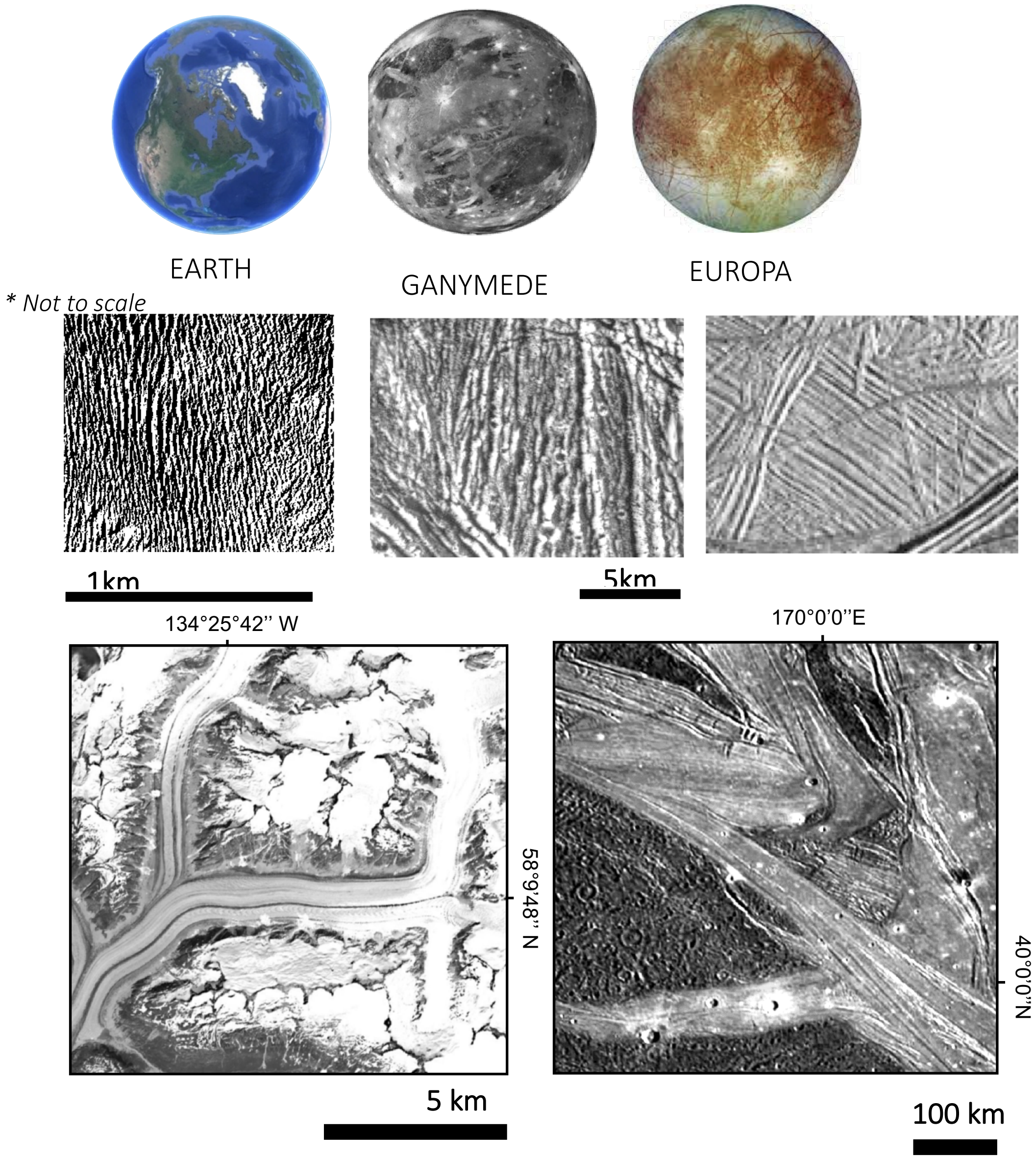


Determine the amount of crystalline and amorphous ice through **spectral clustering and spectral modelling analysis**

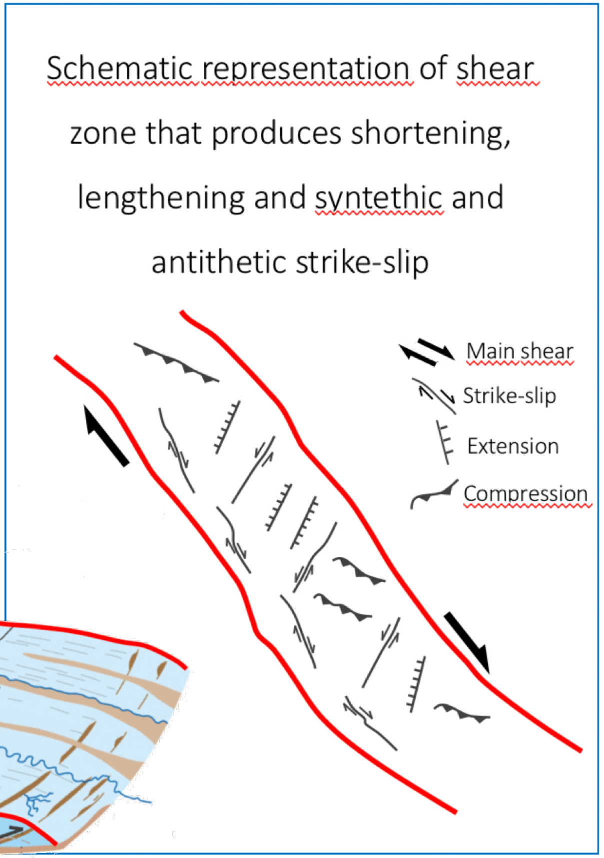
Lucchetti et al., (2023)

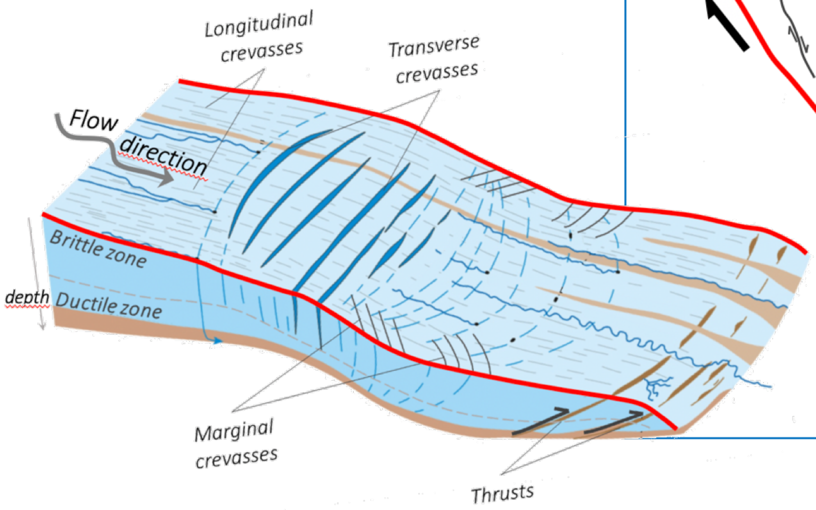
Icy worlds|Terrestrial analogues

STRUCTURES → Characterization and comparison of deformation structures on icy surfaces



SHEAR ZONES → Comparison of strcutural paterns and deformation style



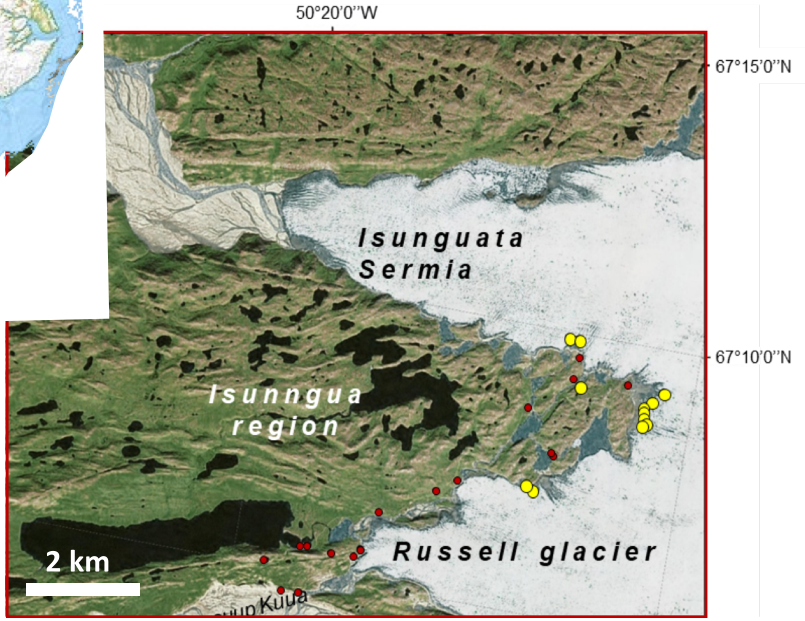


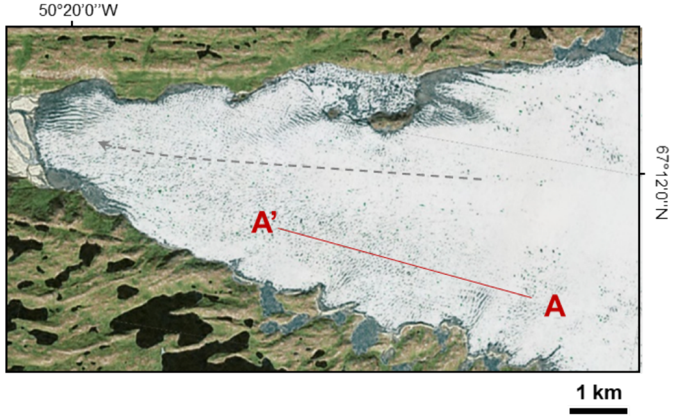
Glacier's profile and conceptual model of its structural setting (modified from Jennings, S. J. A., & Hambrey, M. J. 2021)

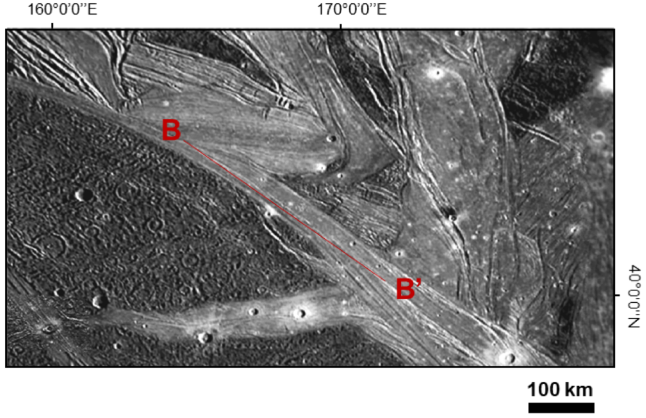
Icy worlds | Terrestrial analogues

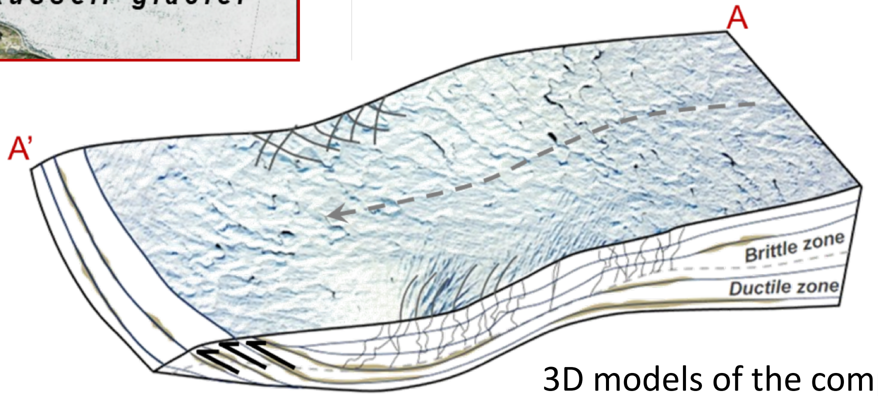
GREENLAND

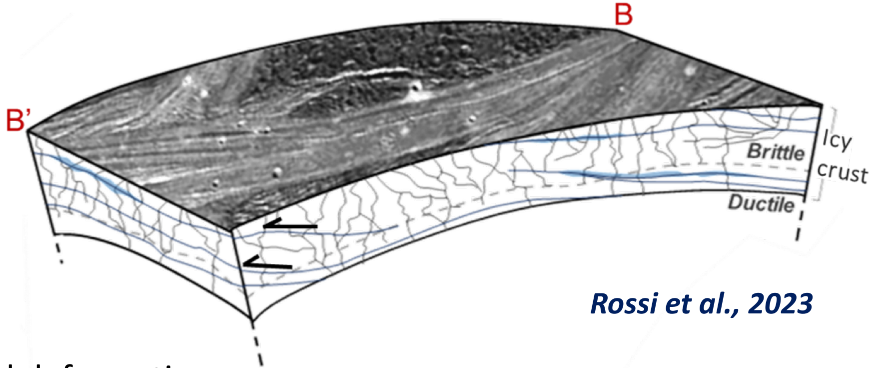
- ✓ Comparative analysis of field and remote sensing data of the glaciers
- ✓ Transfer of knowledge to shear zones of the icy satellites (Ganymede)











Rossi et al., 2023

3D models of the compared deformation on Greenland and Ganymede

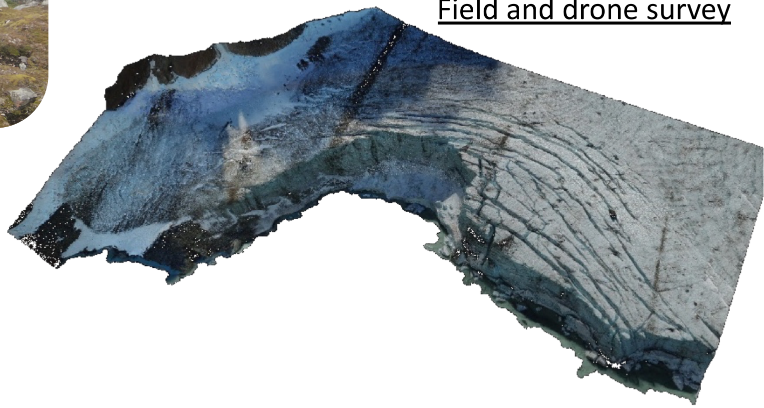
Icy worlds | Terrestrial analogues

PATAGONIA

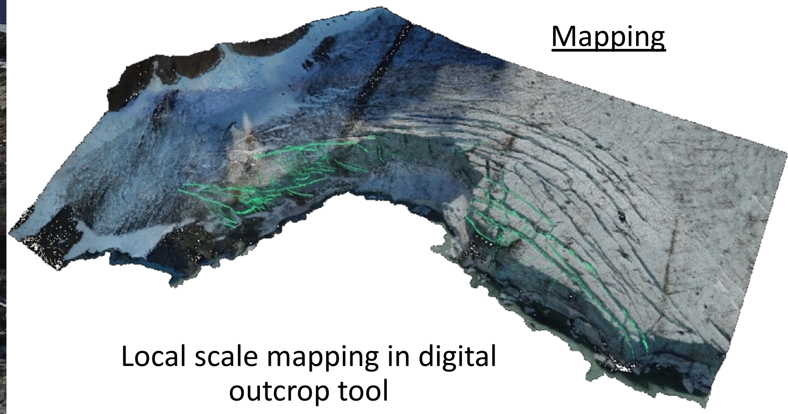
Rossi et al., (in prep.)

Model of Ojo del Albino glacier

Field and drone survey

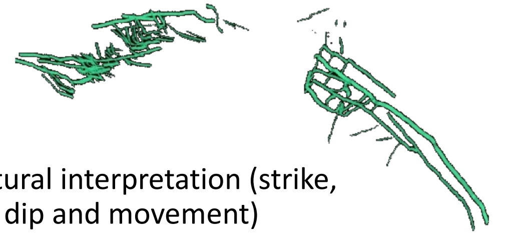


Mapping



Local scale mapping in digital outcrop tool

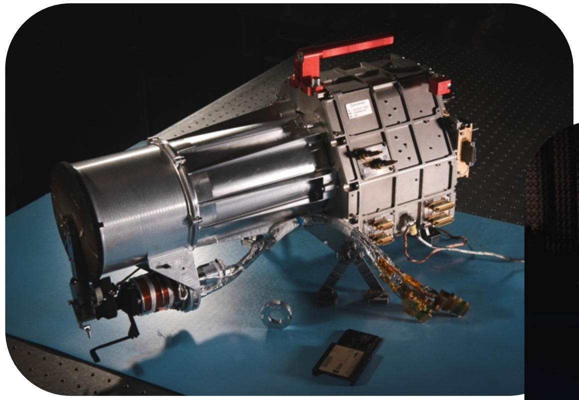
Interpretation

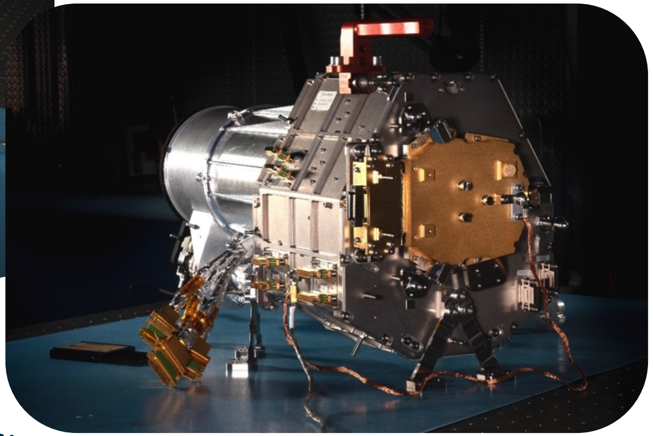


Structural interpretation (strike, dip and movement)

Icy worlds | ESA JUICE

OPTICAL HEAD UNIT (OHU)



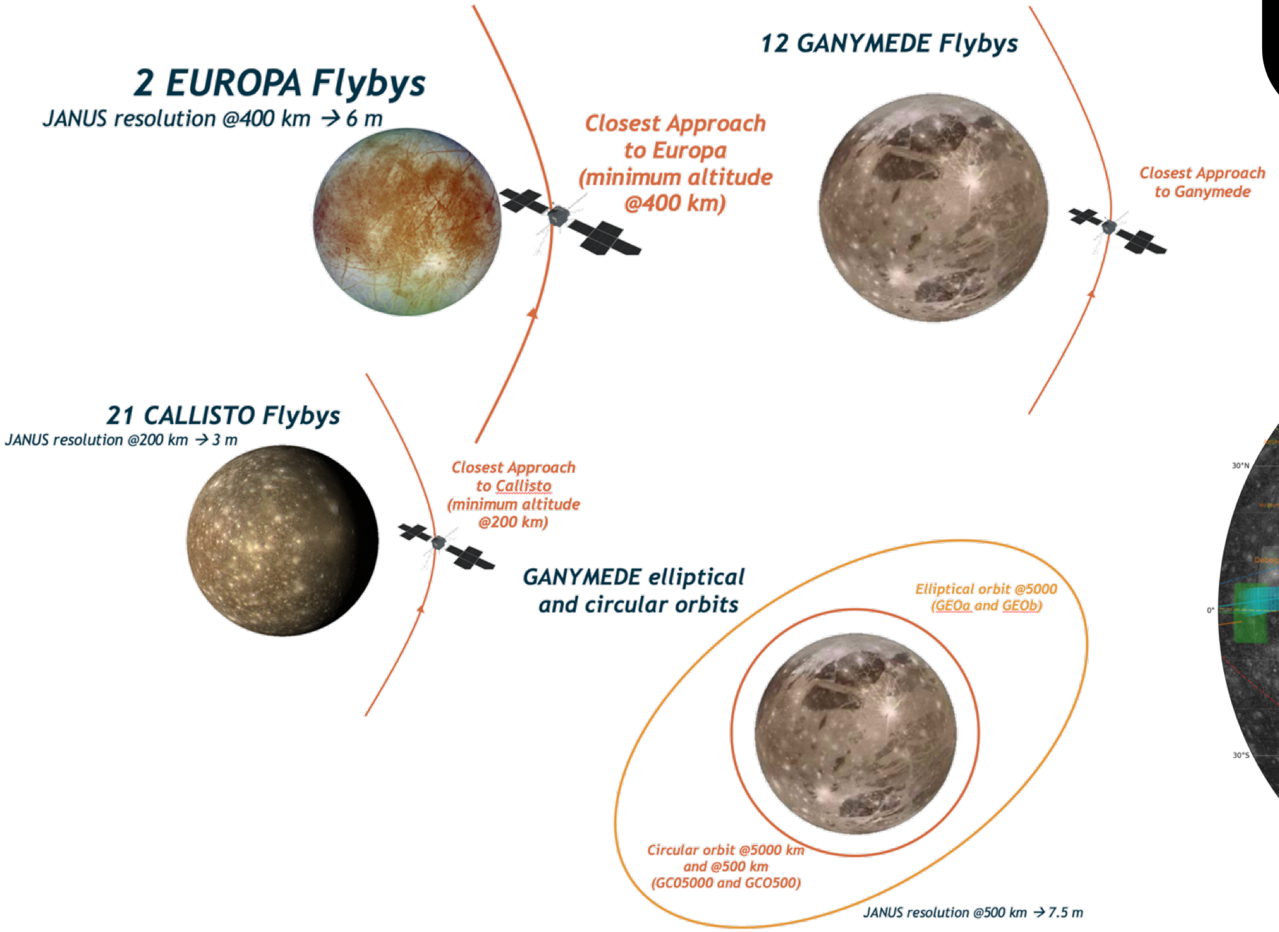


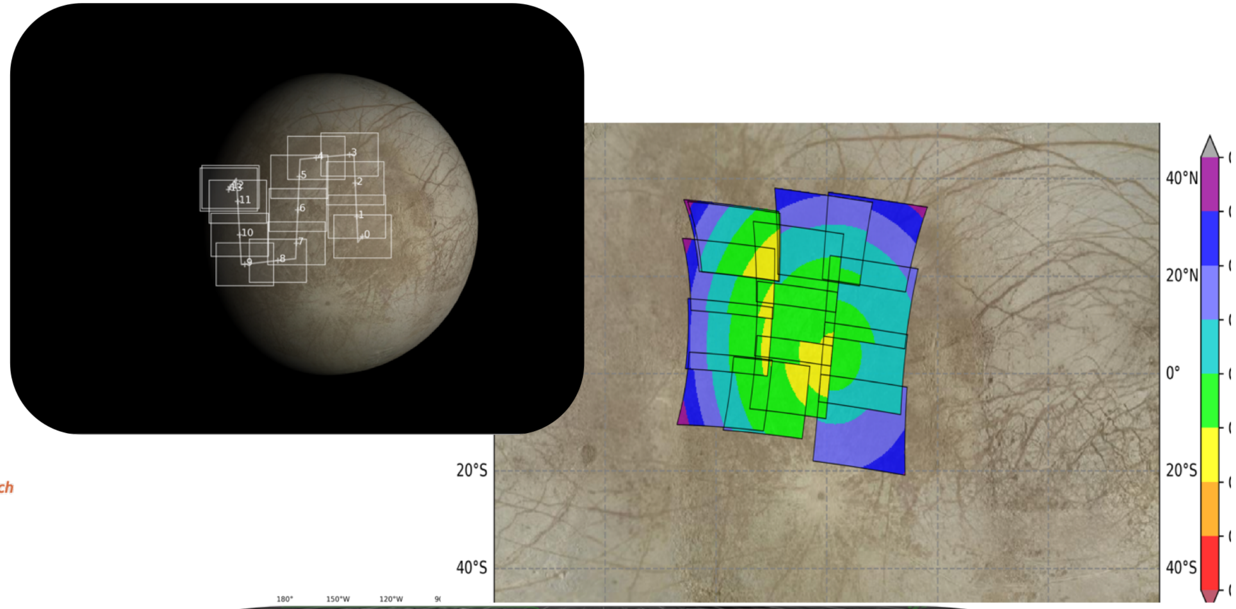
[Credits: Leonardo SpA, DLR]

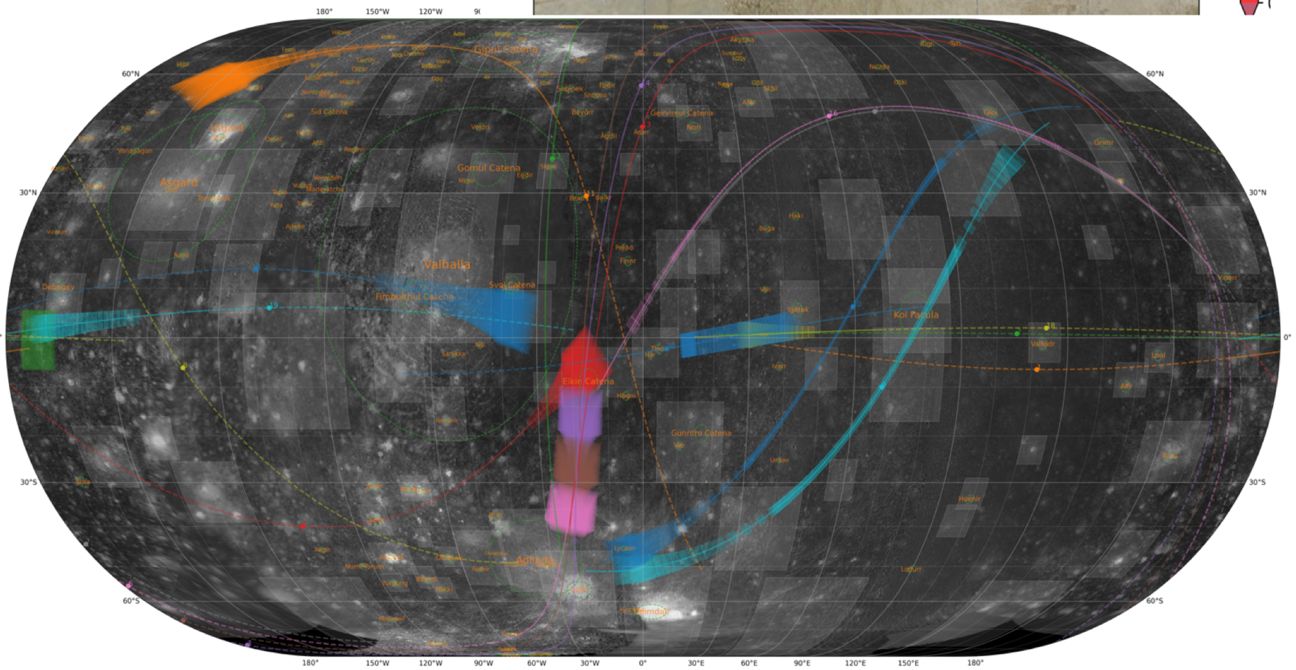
JANUS OHU main characteristics:

- Aperture: 116 mm
- Focal length: 467 mm
- FOV = 1.29° x 1.72° (along track x across track)
- Teledyne-e2v CMOS detector with 1504 x 2000 pixels
- Pixel size: 7 x 7 μm^2
- Resolution: 7.5 m/px at 500 km
- 13 filters covering the wavelength range 340 – 1080 nm
  (near UltraViolet, Visible, Near InfraRed)

- **Tools to determine the JANUS surface coverage during the mission**
- **Tools development for JANUS Science Planning**
- **Coordination of the team about the JANUS surface and composition science**

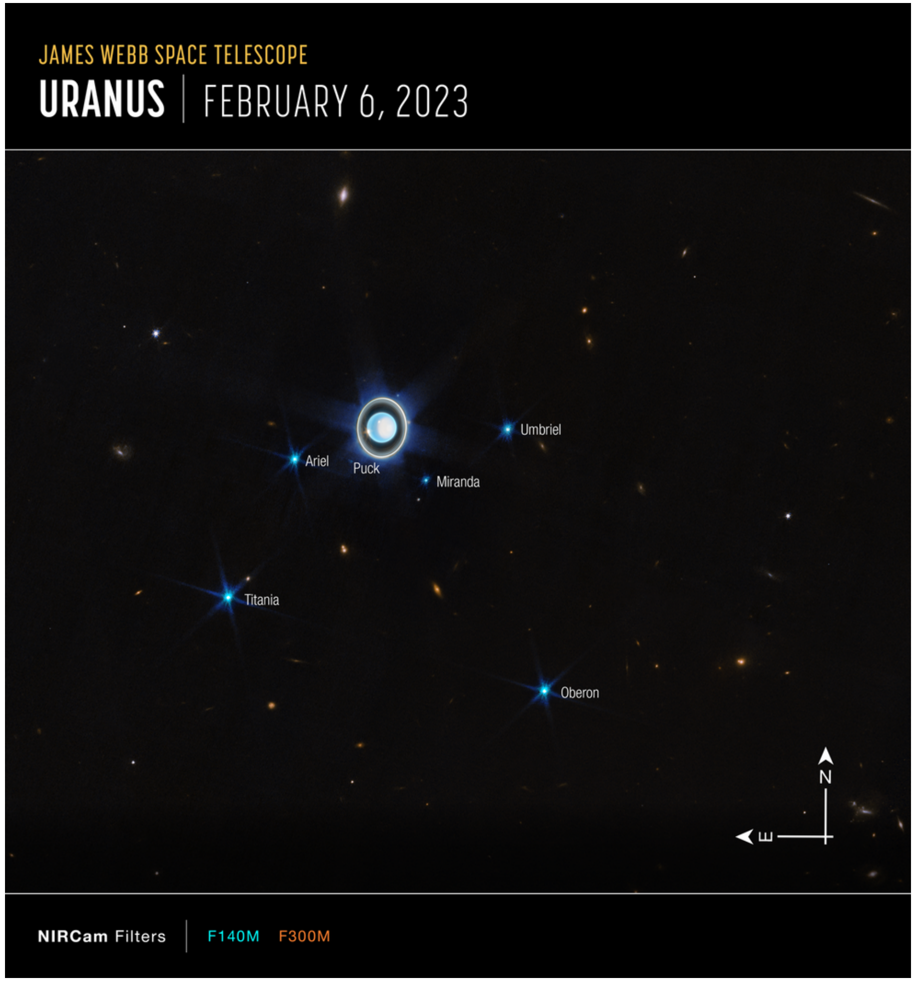


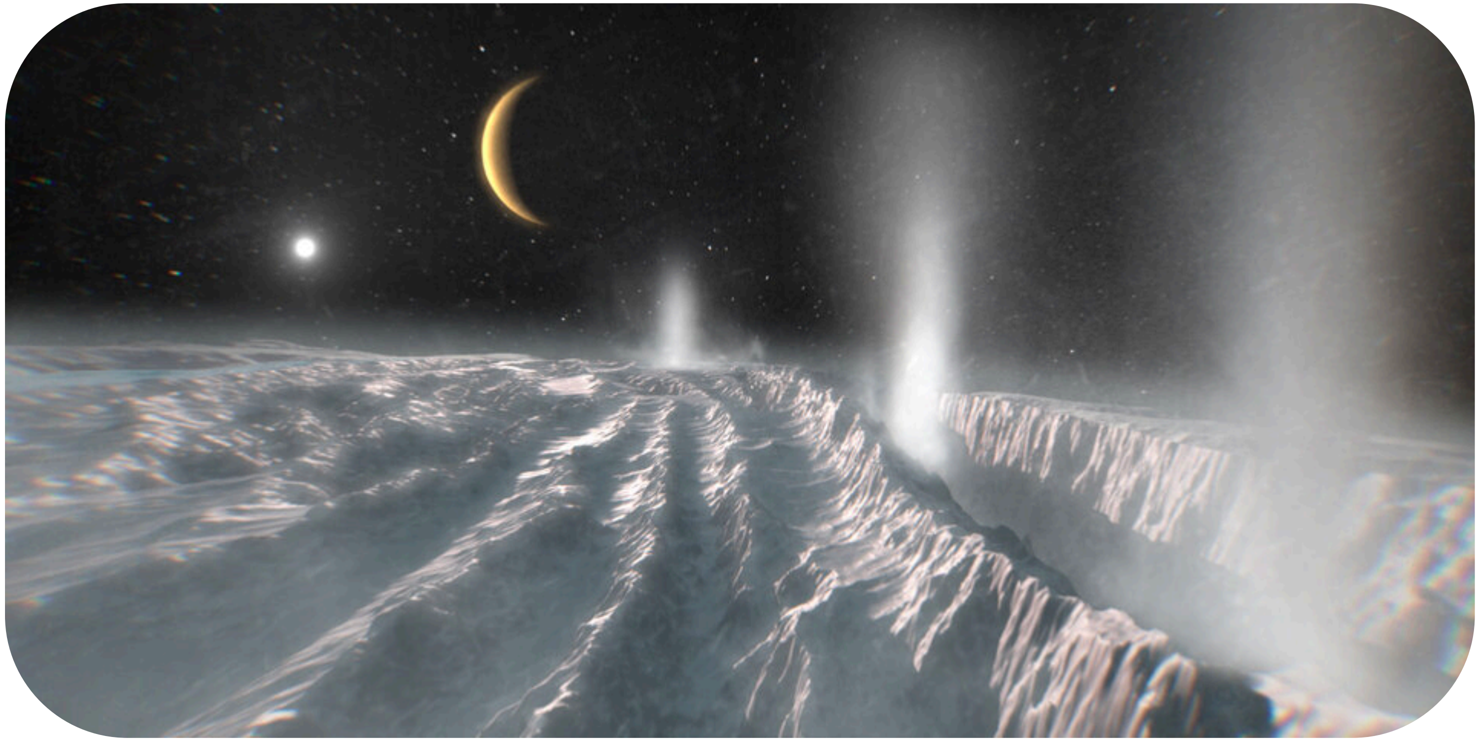




Icy worlds | Future missions

- ✓ Next L4 mission: candidate target Enceladus
- ✓ Next NASA Flagship mission: Uranus





Saturn's moon Enceladus top target for ESA

THANK YOU