Synchrotron Light Illuminates the Origin of the Solar System and Life

Tomoki Nakamura and initial analysis team STONE

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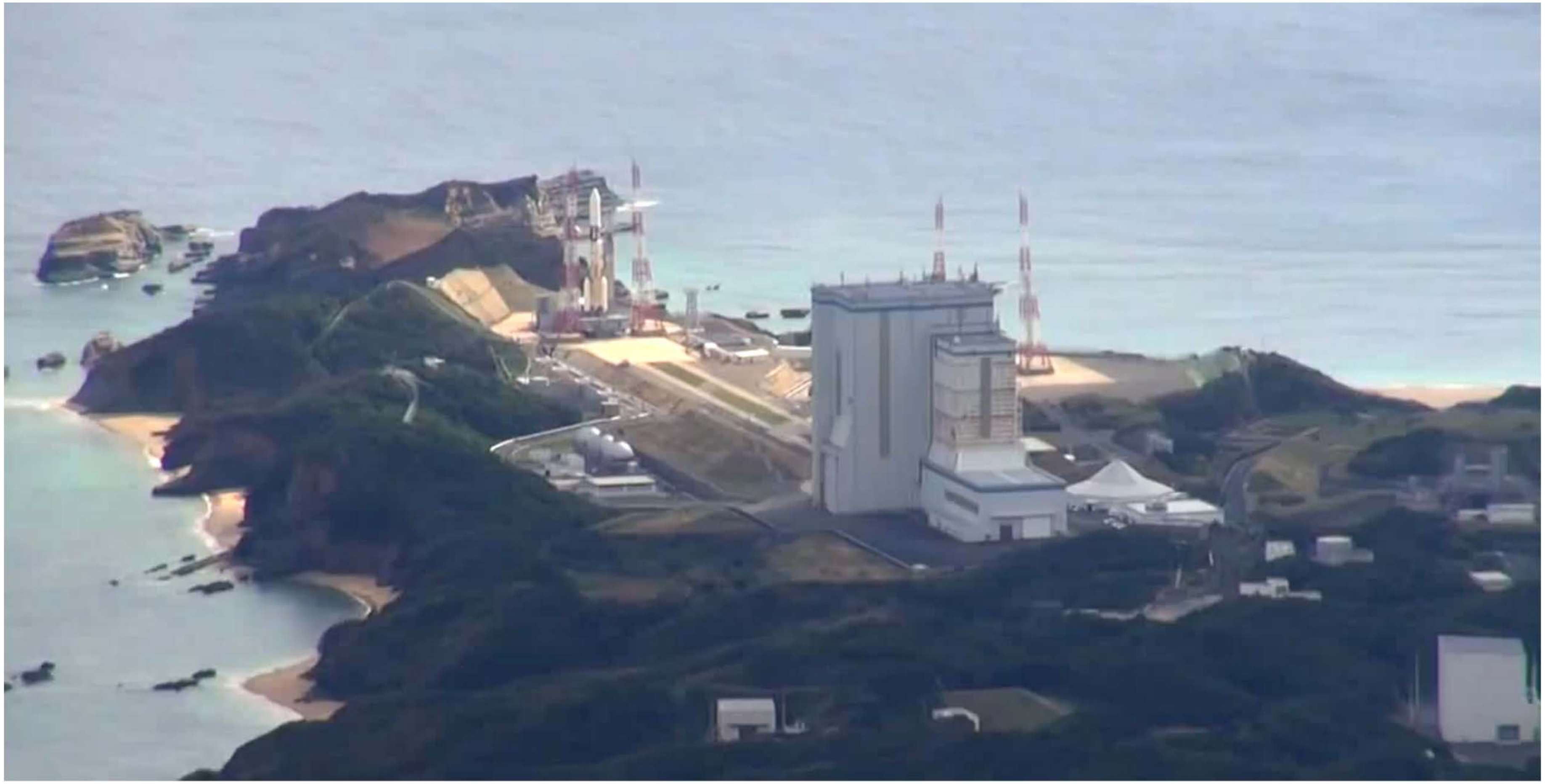
Hayabusa2 sample return mission from C-type asteroid Ryugu

Launch at 13:22pm JST on Dec 3rd, 2014

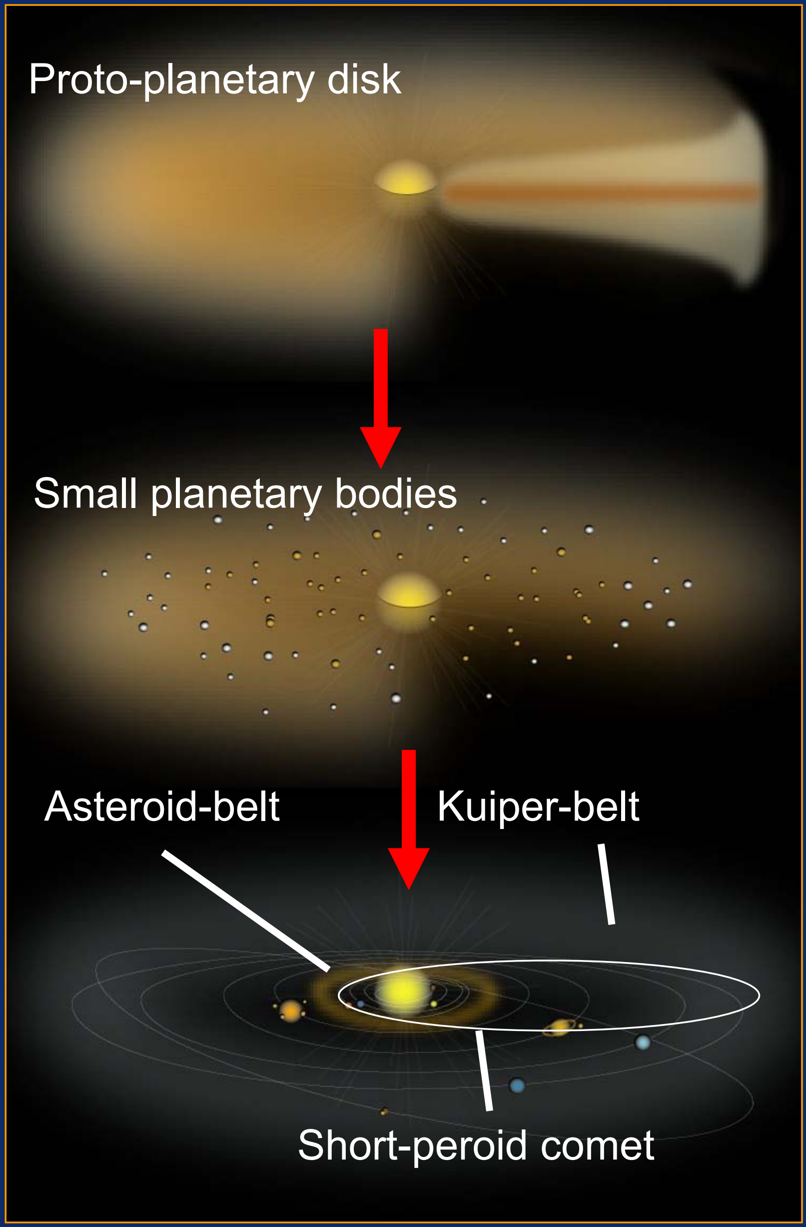


Why Asteroids?

What we know from return sample analysis

Early evolution of the solar system is recorded **only in the asteroids** and comets.

C-type asteroids are important because they might have delivered water and organics to the early Earth.



Basic characteristics

- Spinning-top shape

  Rotation T: 7.63h (past ~ 3.5h)

  Diameter ~900m

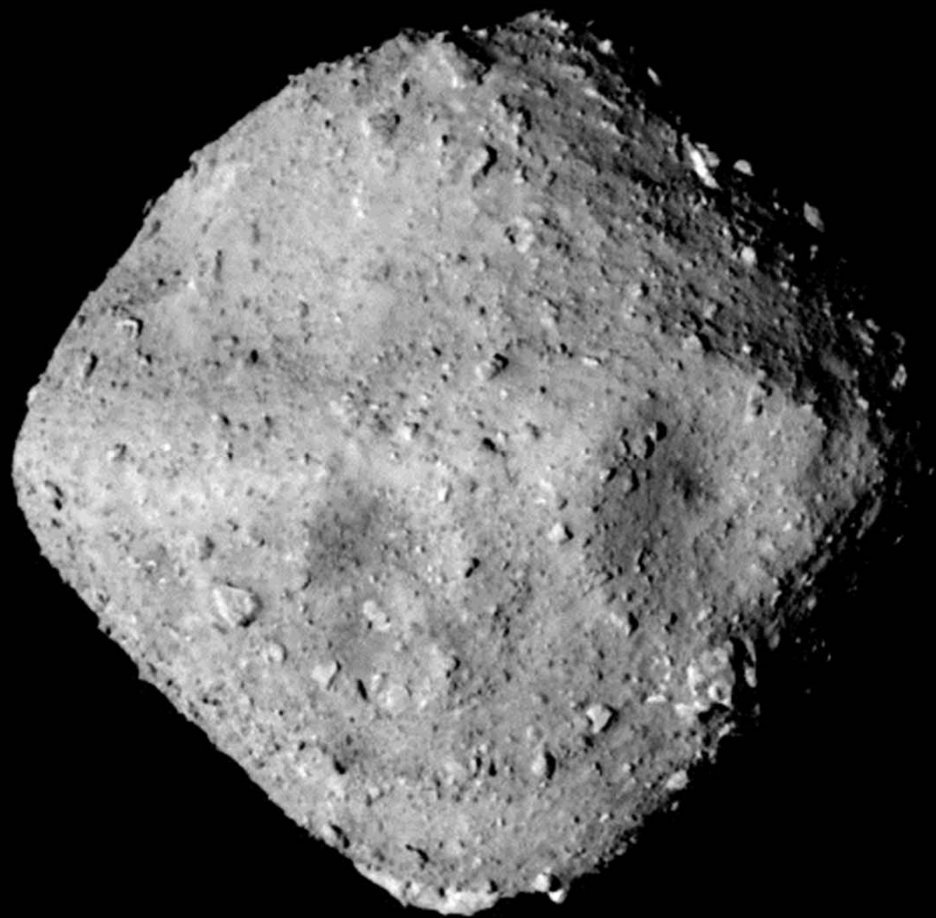
  Density 1.2 g/cc (very porous > 50%)

  Rotation axis perpendicular to ecliptic plane

- Numerous craters and boulders

- Reflectance spectra of VNIR
  Very dark
  Similar to C chondrite meteorites
  2% reflectance at v band (rich in organics)
  Small 3 micron absorption (hydrous silicates)

Ryugu is rubble-pile, spinning-top shape,
carbonaceous and hydrated asteroid
Many boulders larger than craters



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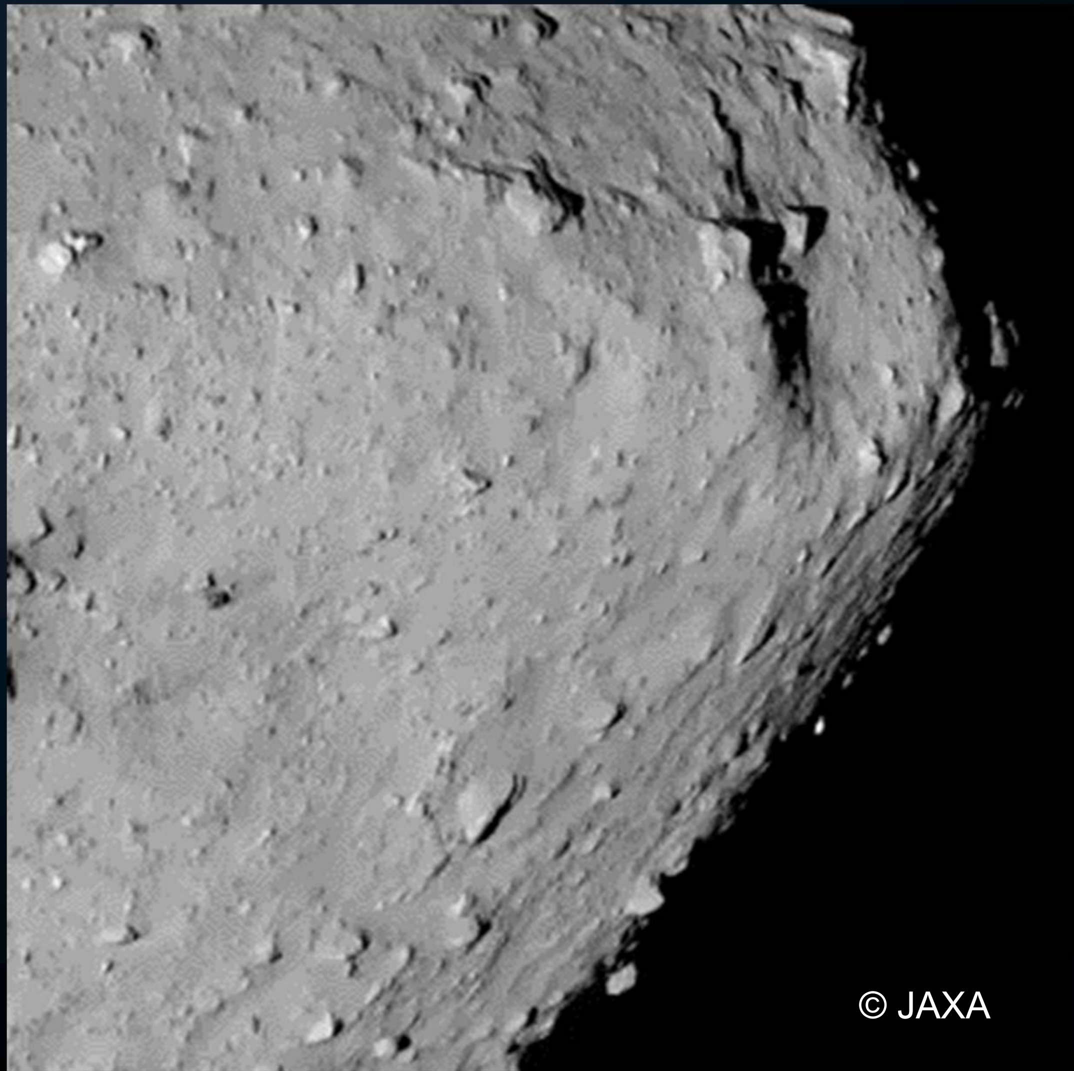
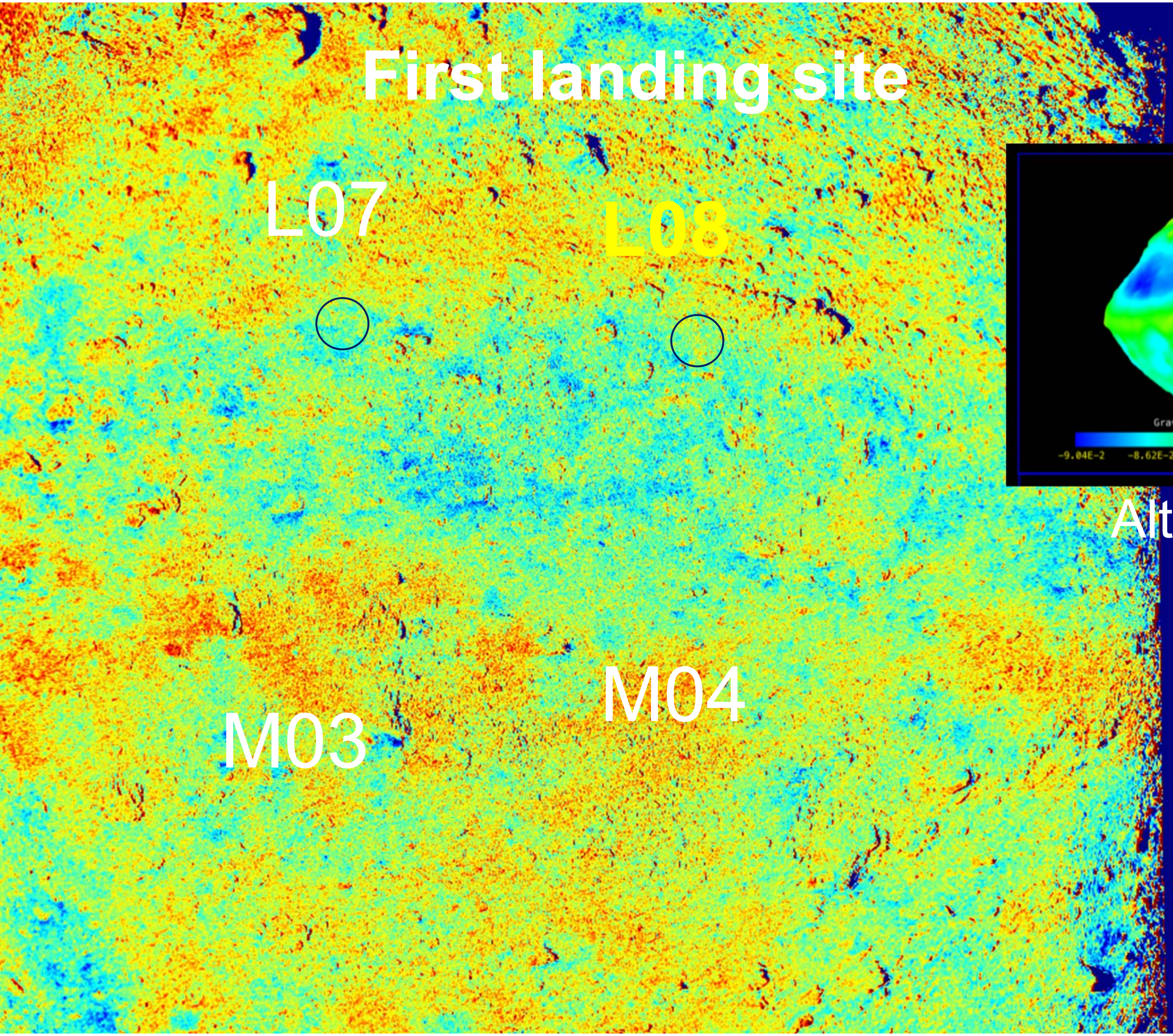
HY2 JAXA/ONC team

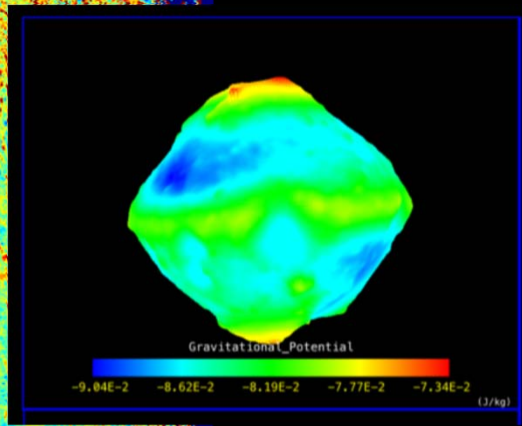
Asteroid Ryugu

Equatorial ridge

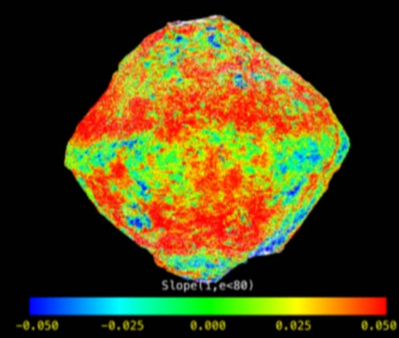
Shrap edge
Large boulders and craters
Slightly brighter







Altitude



Red/Blue

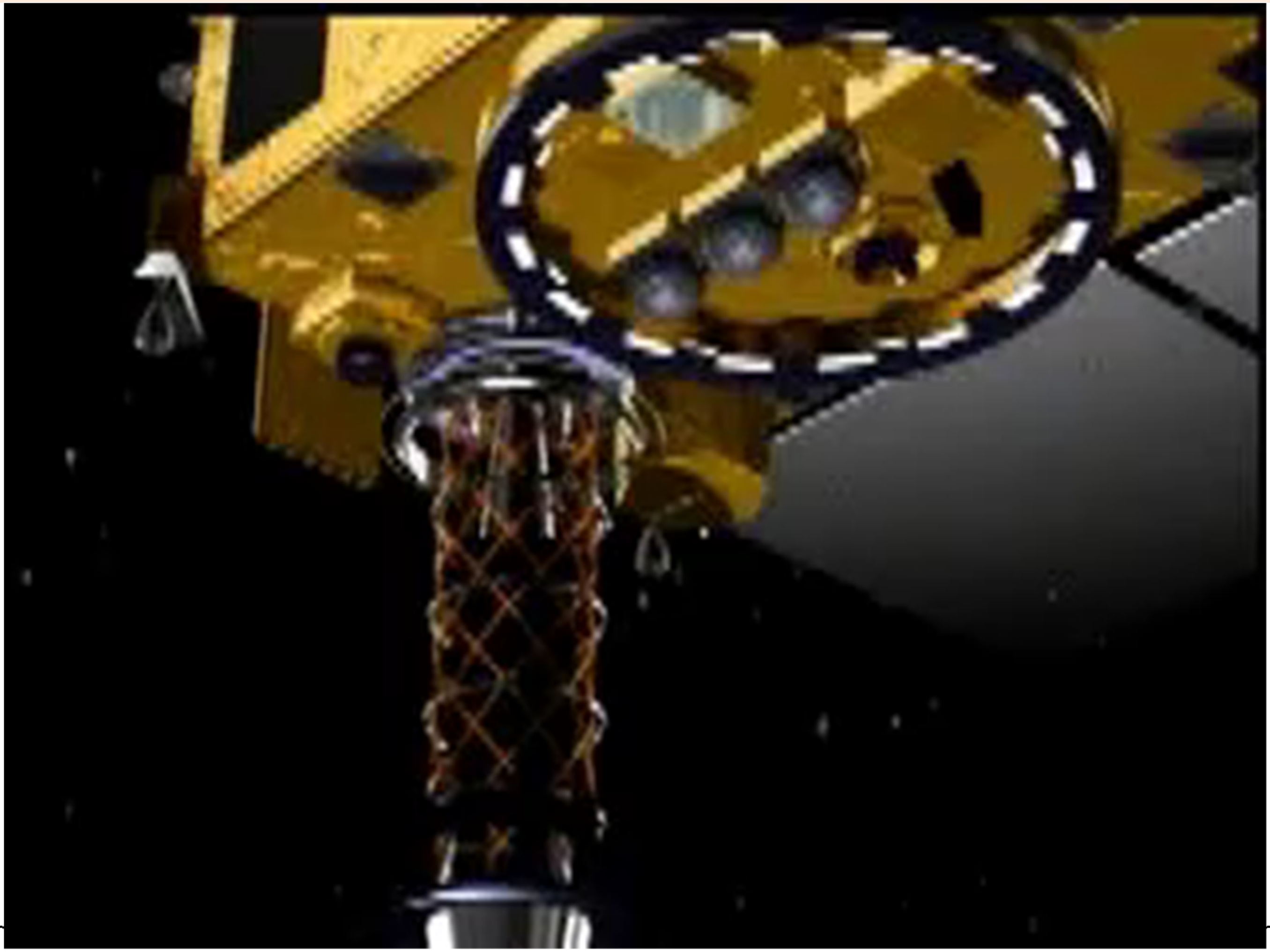
Space weathering and land slide?

Blue/red distribution in each site

1. L site blue/ M site red
2. M08 has a large blue area,

(Tatsumi and ONC team)

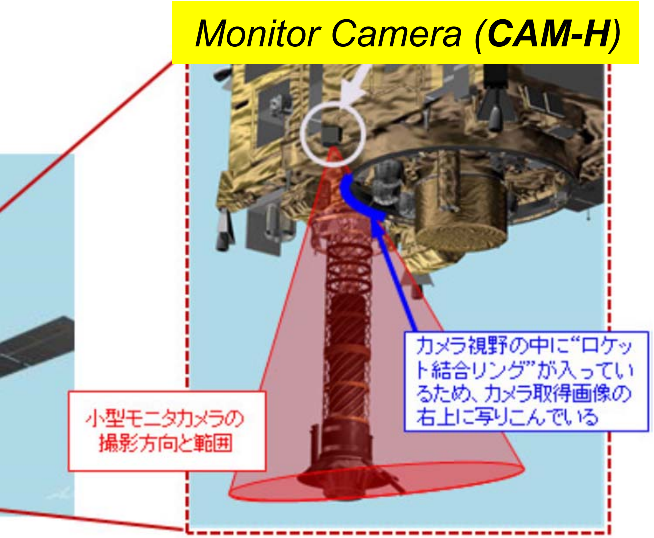
Touch down sequence



Touch down 1st operation: Feb 20th 2019

Successful imagining before and after touchdown with CAM-H (animation)

- TD moment captured at 1 fps timing.



(Animation plays at 5x speed)

（Image credit：JAXA）

Initial analysis of Ryugu samples

Team stone（PI: Tomoki Nakamura, Tohoku U）

Obtain reflectance spectra of coarse-grained return samples to estimate the material distribution on the surface of asteroid Ryugu. Perform nondestructive material analysis using synchrotron radiation high-energy X-ray beams to determine the three-dimensional internal structure and elemental distribution of returned samples. Microstructural observation will be performed using a high-resolution electron microscope. Physical properties such as thermal conductivity will also be measured.

All data will be integrated to model the formation process of the asteroid Ryugu.

World-wide synchrotron network

Team Stone

Sample analysis of coarse grains

Numerical simulation of Ryugu formation

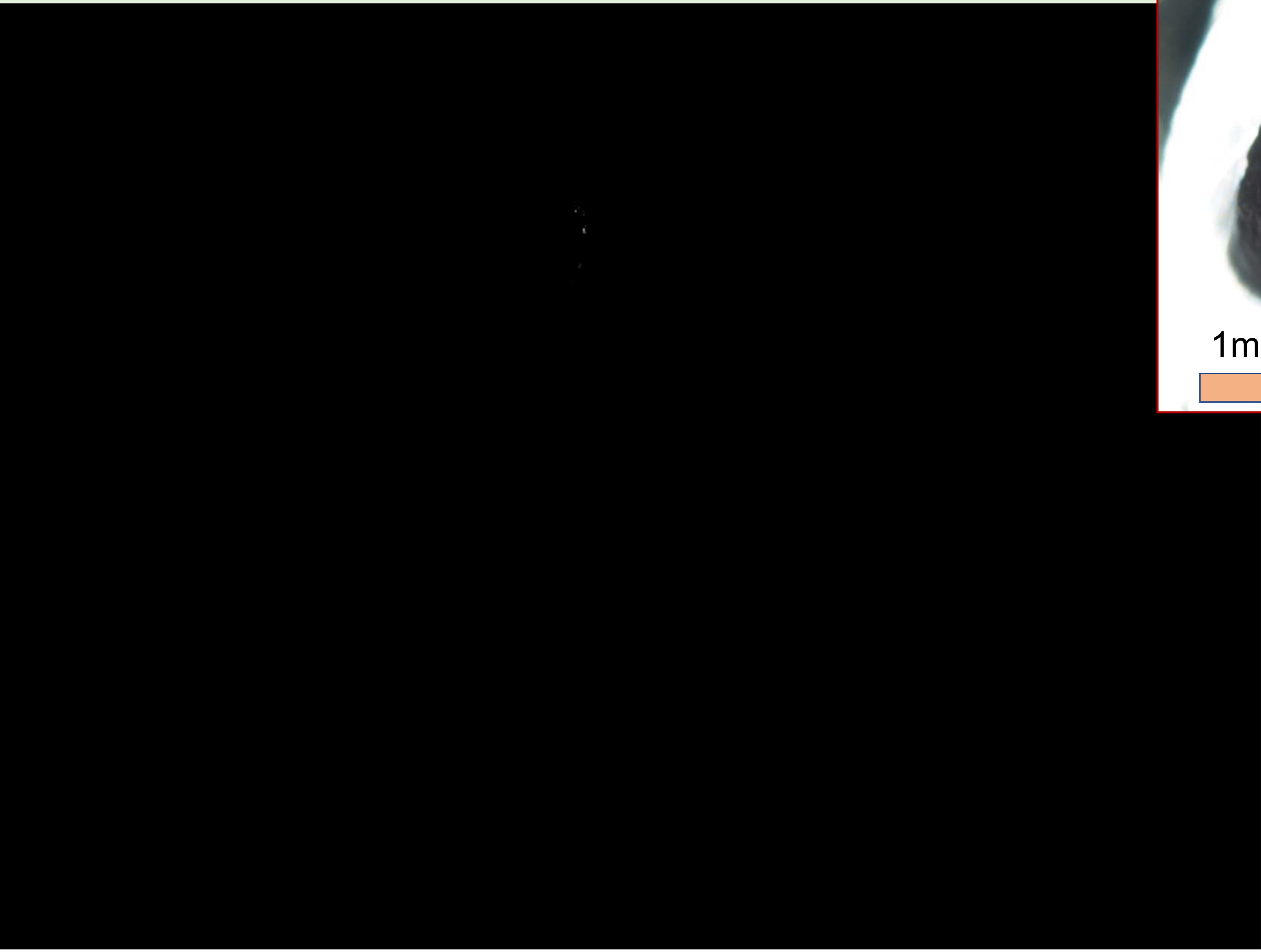
Stone team (~150 people from all over the world)

Sixteen mm-size samples (Stones)
Two powders for spectroscopy

<u>Scientific Objectives</u>
Elucidate formation and evolution process of Ryugu's parent asteroid.

1. Characterize mineralogy of stone samples.
2. Measure reflectance spectra
3. Analyze element abundance by X-ray and muon.
4. Measure physical properties of stone samples.
5. Make a chemical model of aqueous alteration.
6. Simulate the thermal evolution and impact disruption of Ryugu' parent asteroid based on 2~5.

CT scan of a large Ryugu sample C0002



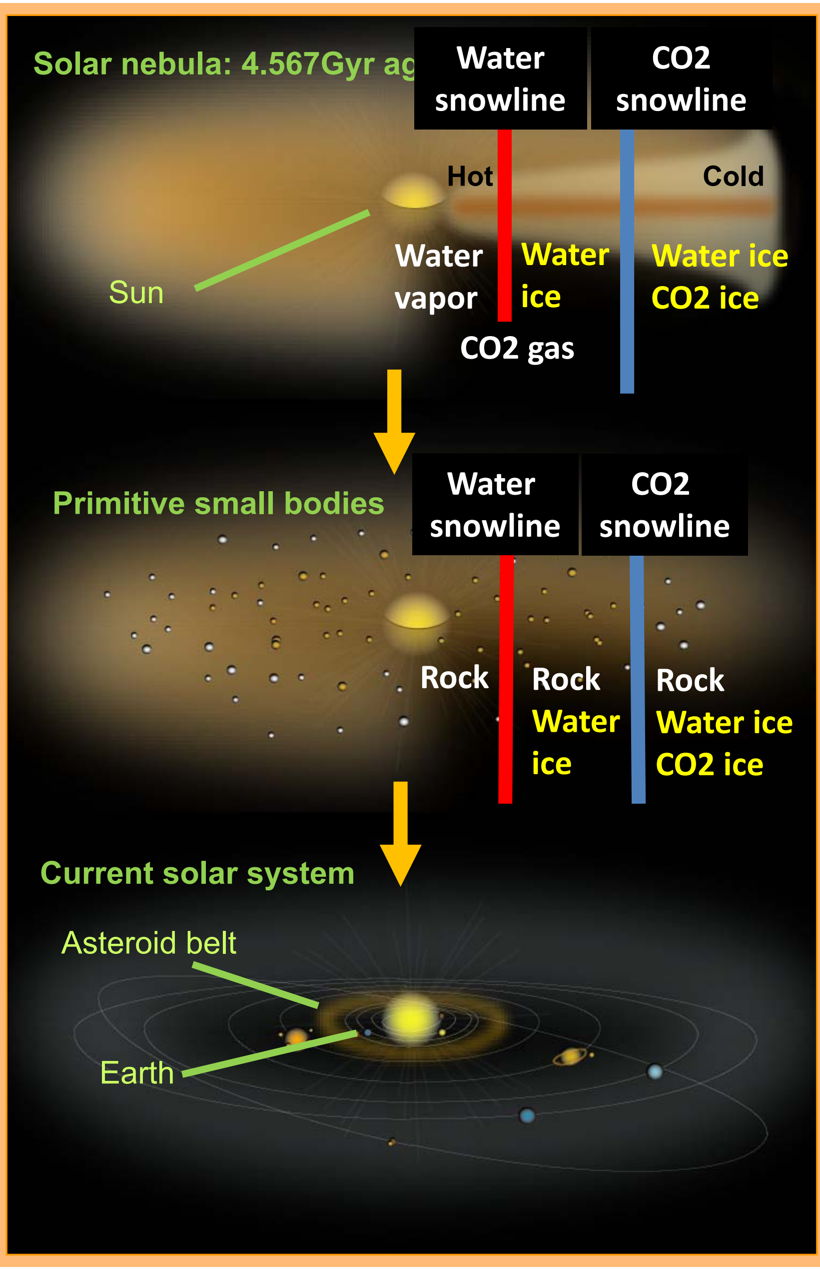
SPring-8 beamline 20XU
CT image resolution < 1 μm

Fine-grained phyllosilicate rich lithology.

No well-distinct chondrules and CAIs are found.

CI chondrite lithology

Where in the solar nebula did Ryugu form?



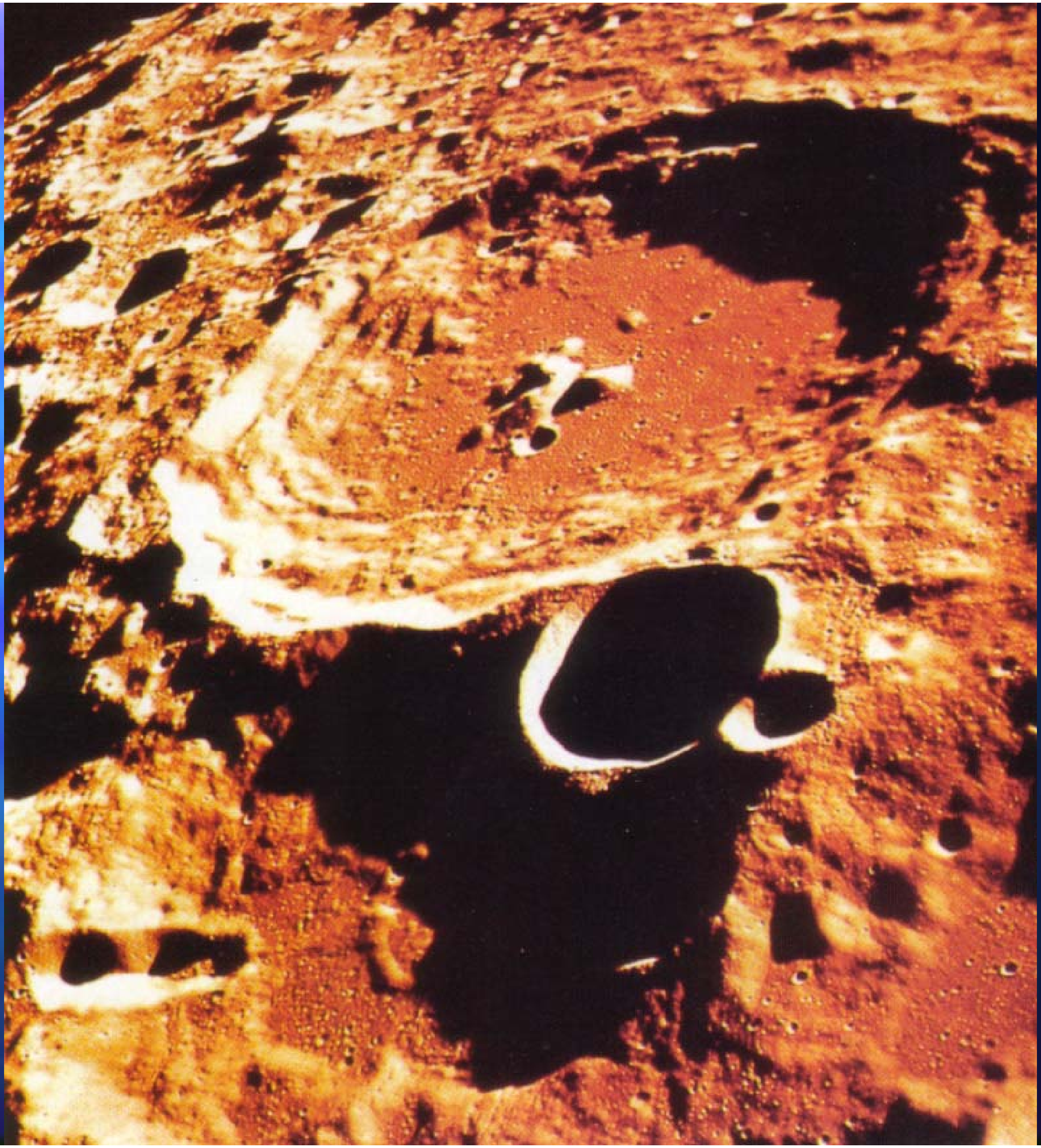
Craters on the moon

Numerous small craters on lunar highlands

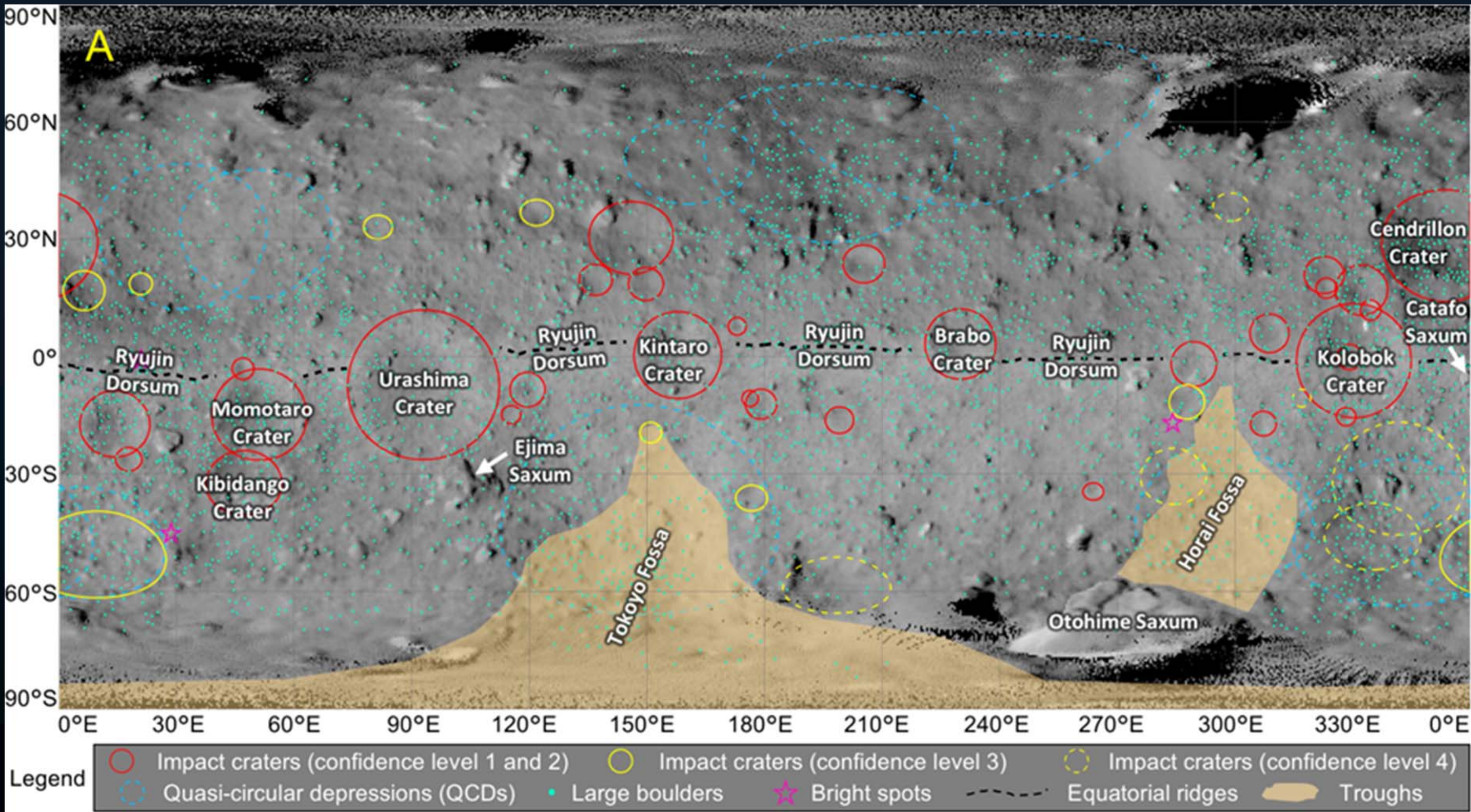
When the surface is formed?

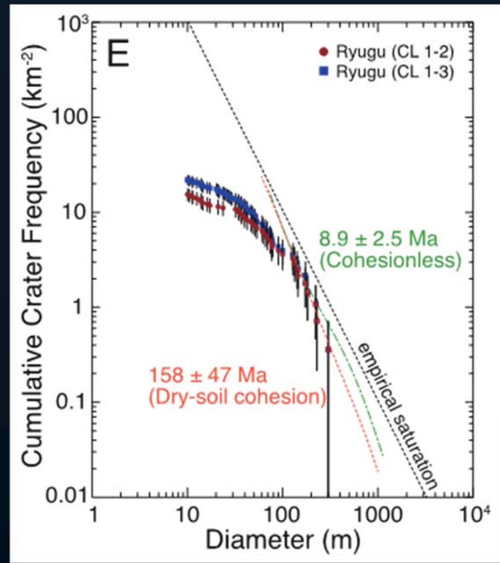
What is the particle environment on the moon?

Craters on Ryugu?



Crater and boulder distribution on asteroid Ryugu (Sugita et al. 2019)

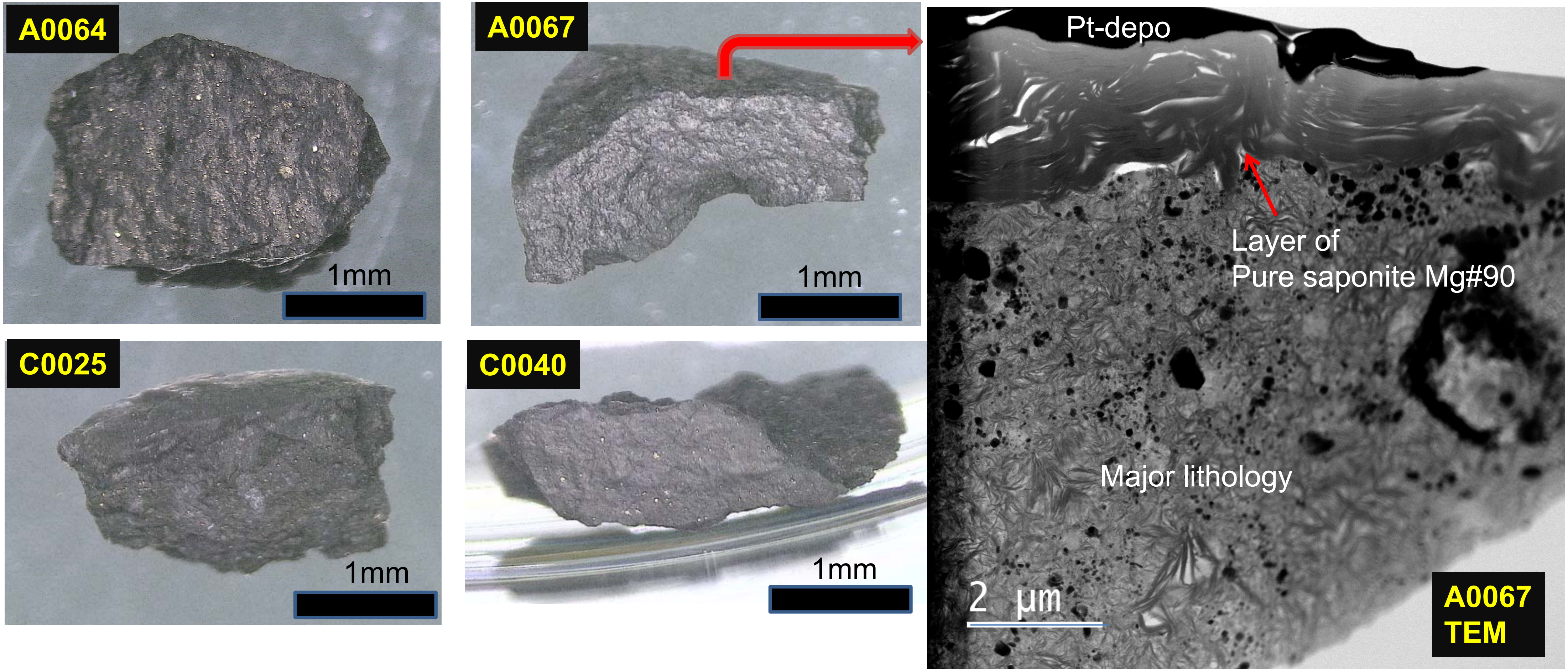




Conclusions

- Sixteen Ryugu stones measuring 1-8 mm consist mainly of phyllosilicates, carbonates, iron sulfides and oxides, and phosphates. The mineral composition indicates that Ryugu's parent asteroid experienced pervasive aqueous alteration.
- Many Ryugu stones are breccia consisting of small fragments (< 1mm). Some fragments retain the least-altered lithology with high abundance of anhydrous silicates. The aqueous alteration in Ryugu's parent asteroid changed an olivine-pyroxene rich lithology, remaining as the least-altered fragments in Ryugu samples, into phyllosilicate-carbonate rich lithologies, the predominant material of Ryugu samples.
- The high abundance of carbonates and the presence of CO_2-bearing water in pyrrhotite (Zolensky et al. 2022 LPSC) indicate that Ryugu's parent asteroid formed beyond the H_2O and CO_2 snow lines in the solar nebula, where, based on Ryugu mineralogy, very limited amounts of high-temperature objects including small chondrules and Ca, Al-rich inclusions were present.

Flat surfaces: A detector for regolith environment



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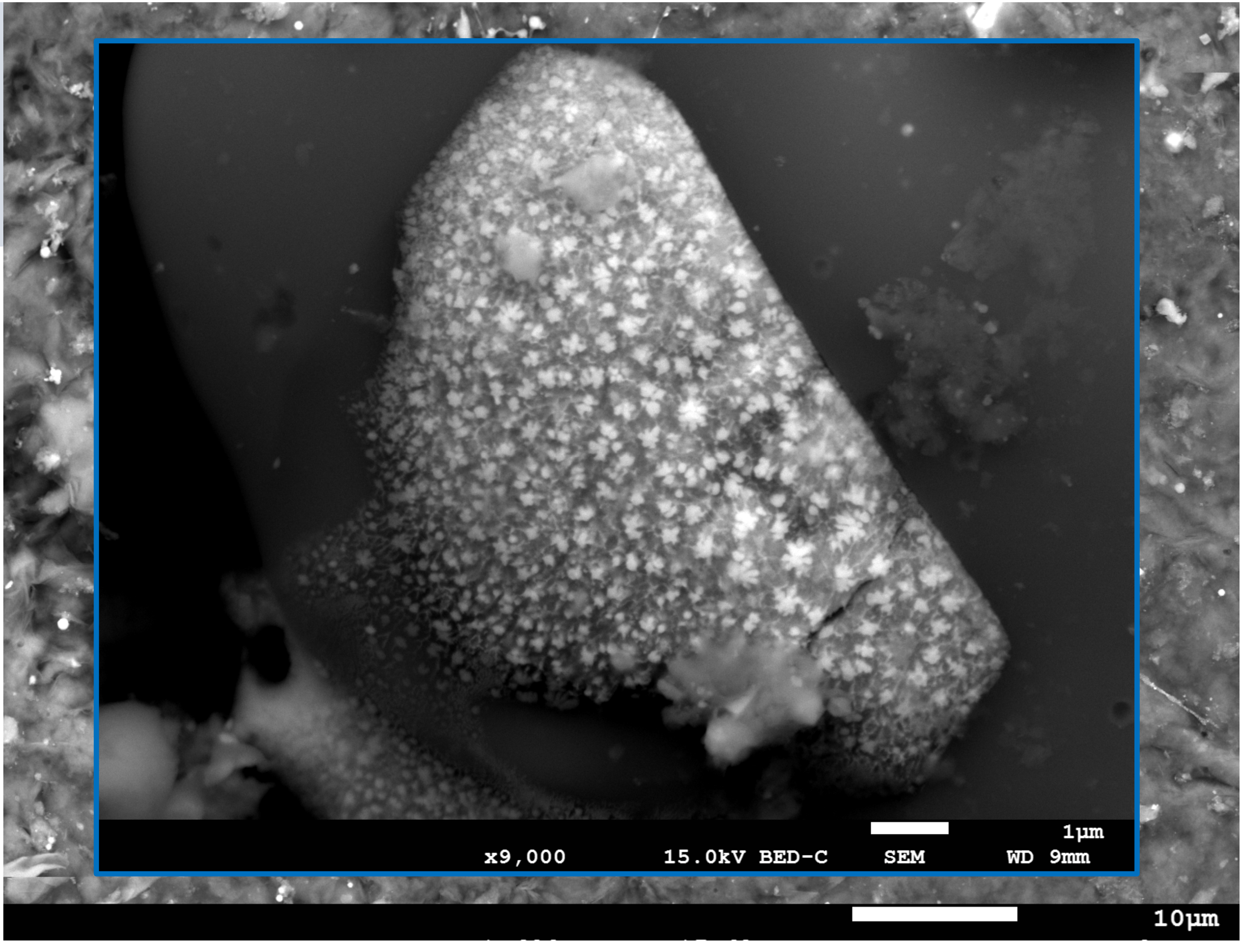
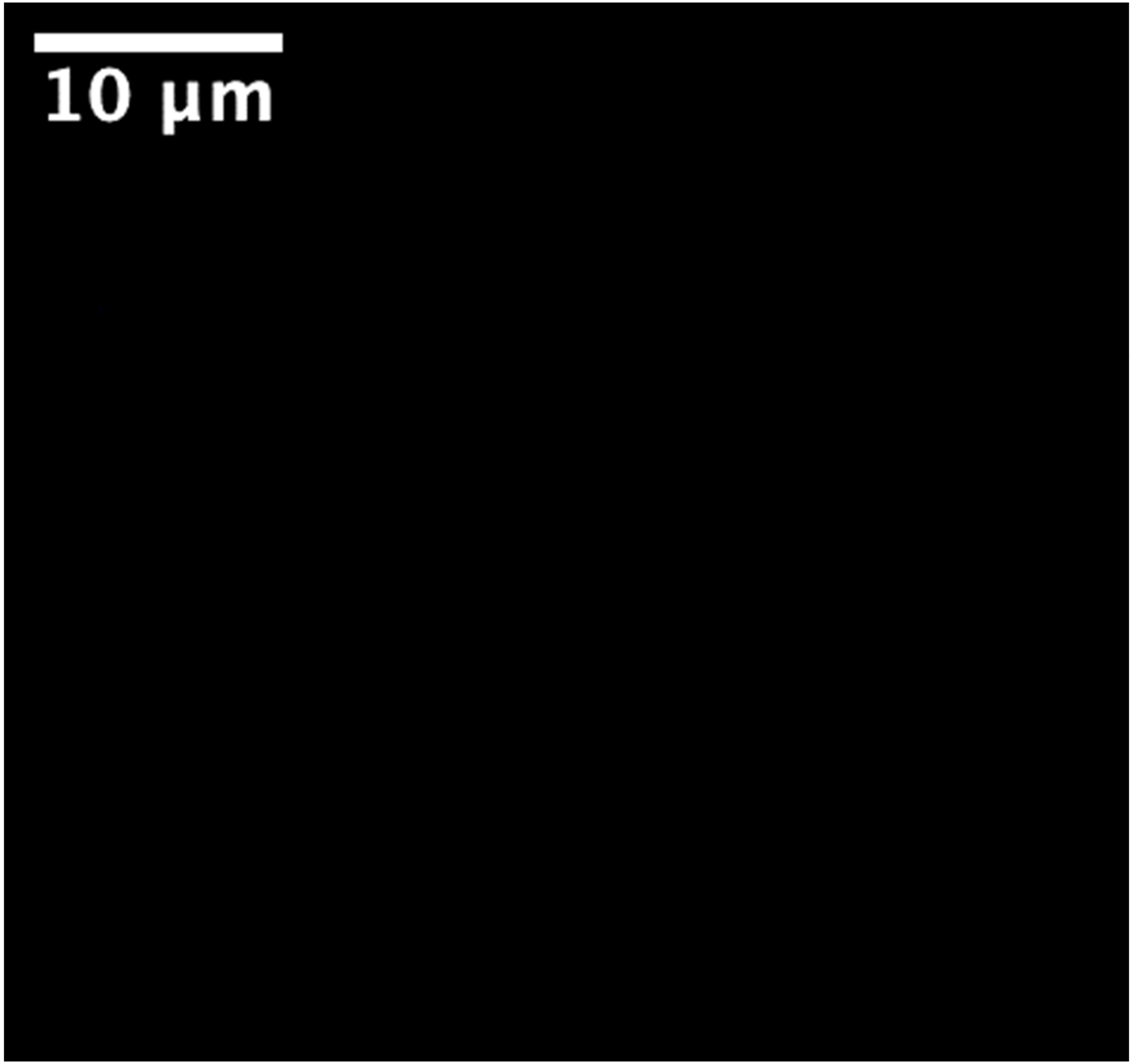
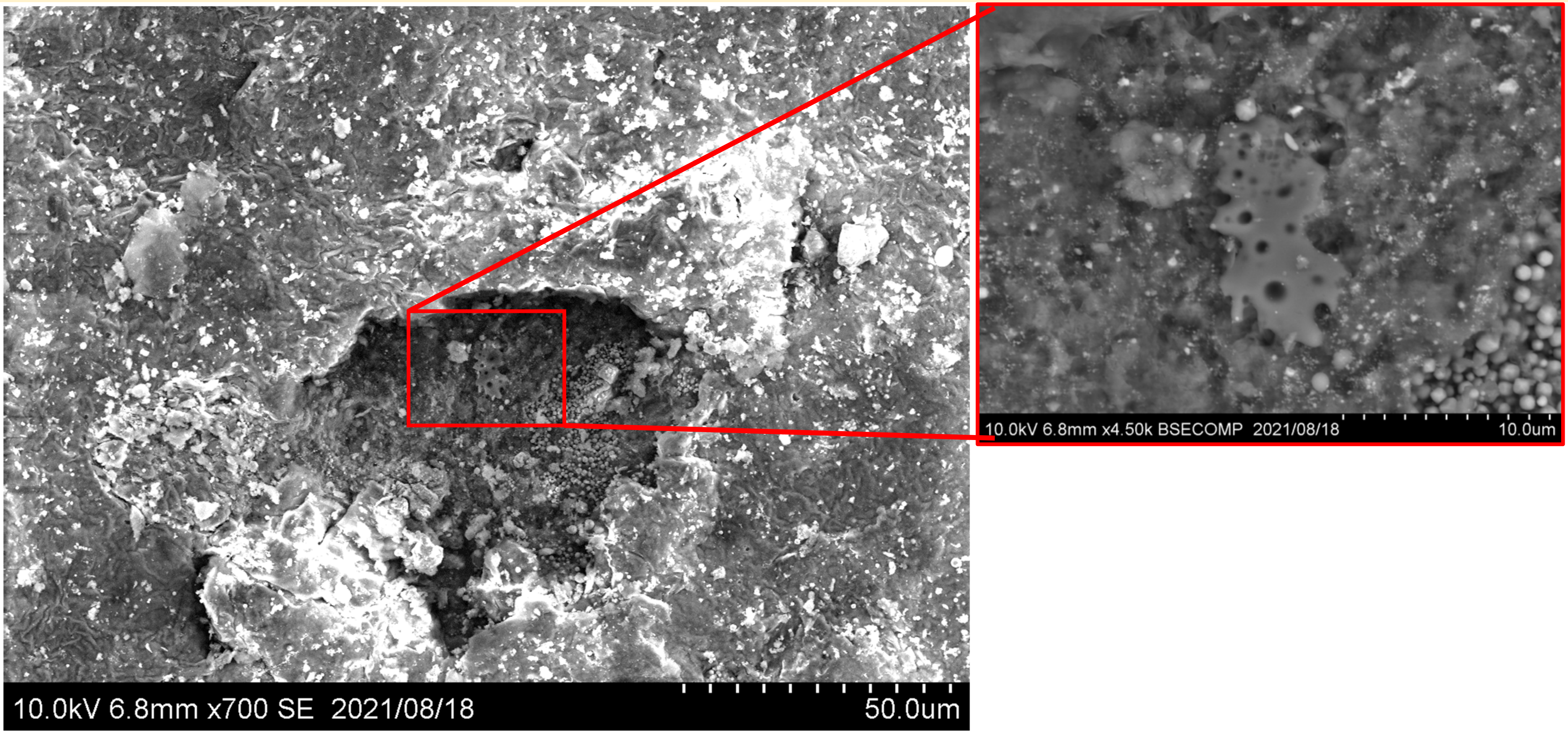
A0067
Melt splash



A0067
Melt splash
3D structure



A0067: Melt splash in a crater

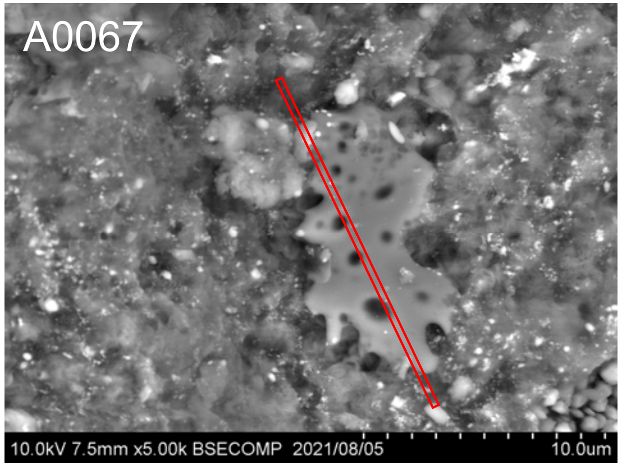


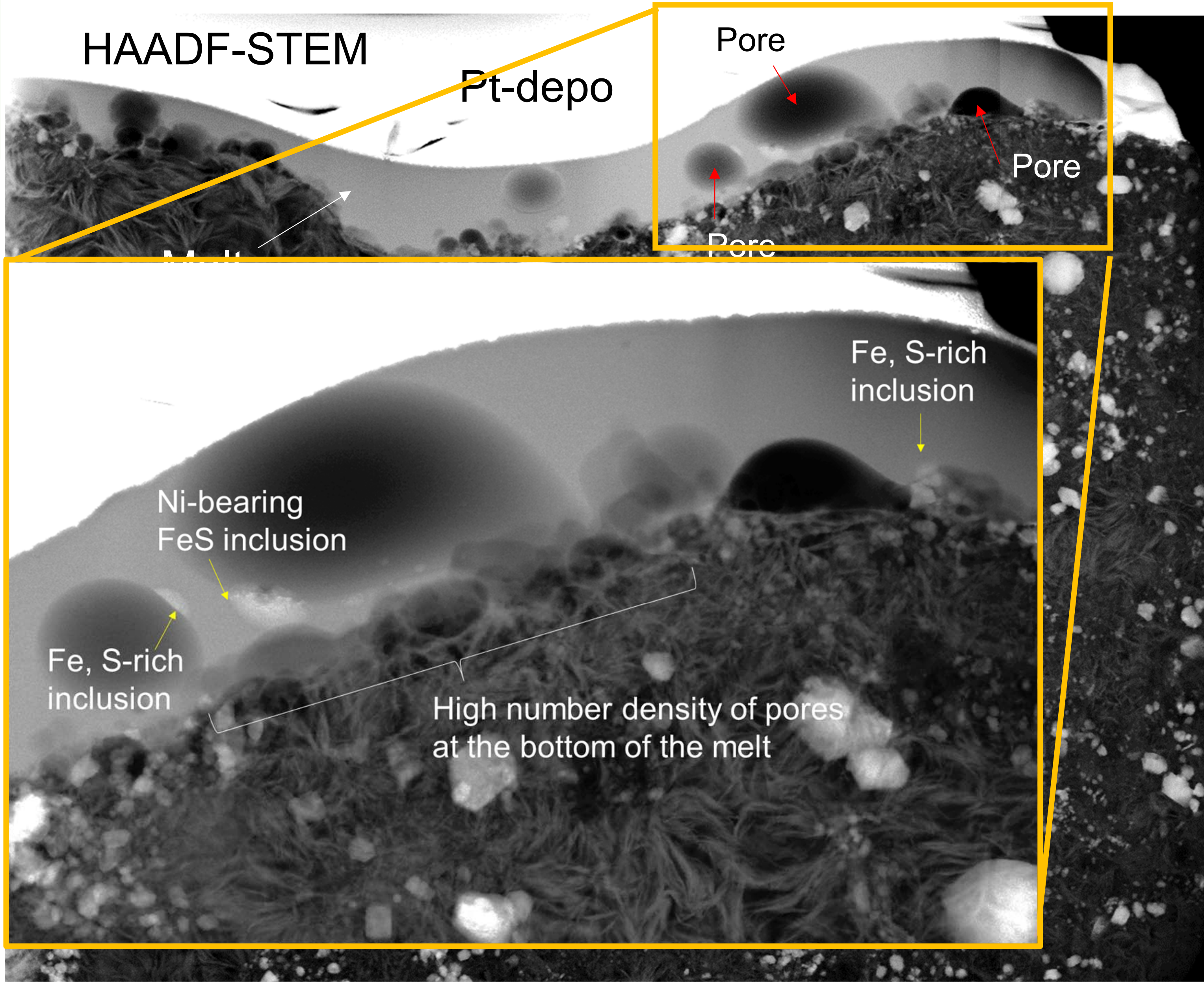
Melt splash microtexture

~ 500nm thickness

High density of gas bubbles filled with low-Z material

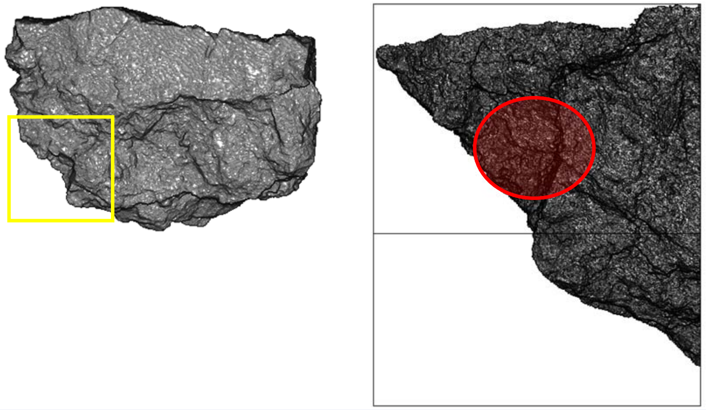
Dehydration of hydrous silicates beneath the melt



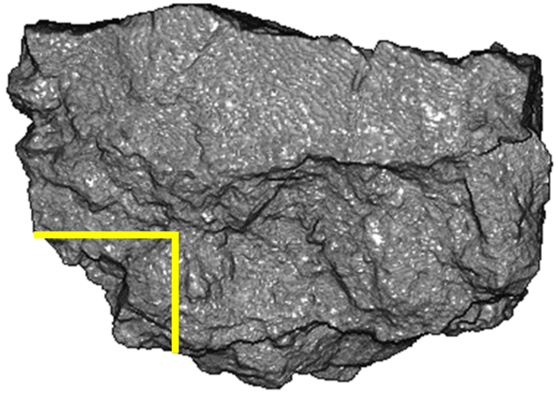


How to polish samples from Asteroid Ryugu

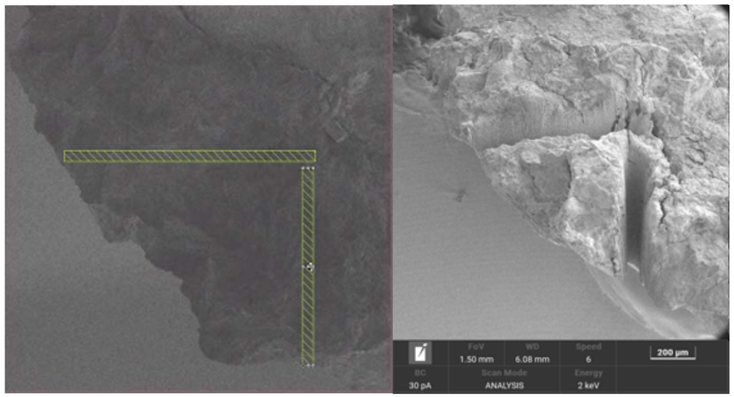
1) Finding a texture suitable for observation



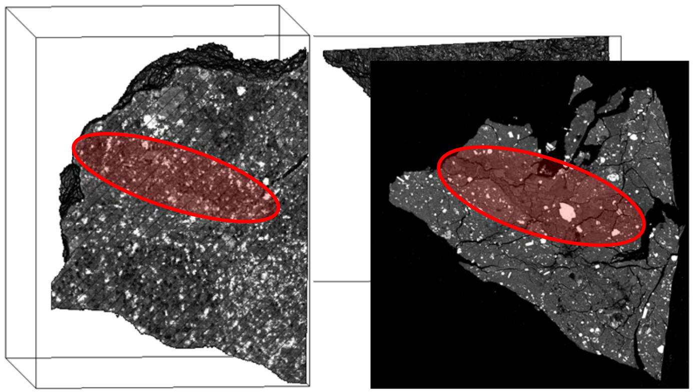
2) Illustrating where to cut off



3) Cutting off the sample using p-FIB

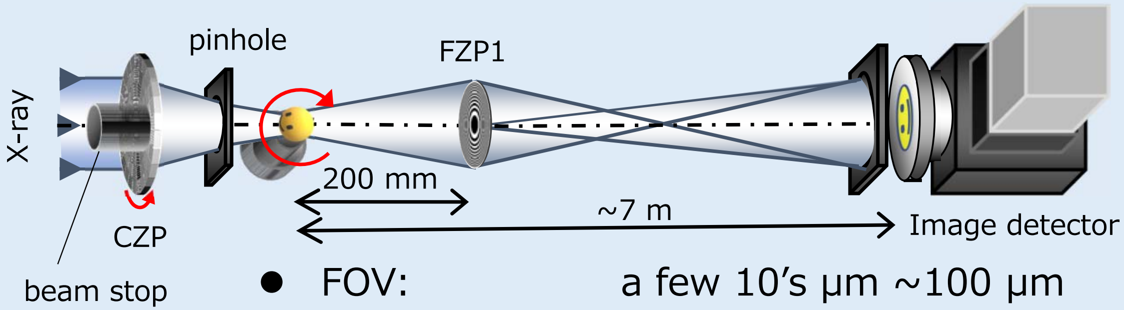


4) Polishing



Analytical X-ray nano-tomography at BL47XU of SPring-8

Imaging nanoCT（for Dual-Energy Tomography）



- FOV: a few 10's μm ~100 μm
- energy: 7, 7.35 keV
- **resolution: <100 nm**

DET (dual-energy tomography)

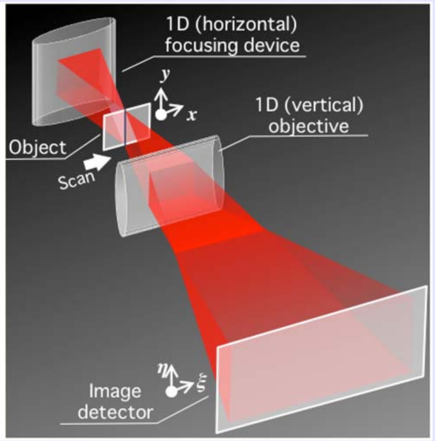
Absorption images below and above Fe-K edge energy (7 and 7.35 keV) enable mineral phase discrimination

- LAC (7) images: ~ Z contrasts
- LAC (7.35) images: ~ Fe contrasts

LAC: Linear attenuation coefficient

Tsuchiyama et al. (2013)

SIXM



- **Total X-ray intensity**
  - **→ Absorption images**
- **X-ray beam shift**
  - **→ Phase-shift images**

- FOV: ~100 μm
- energy: 8 keV
- **resolution: ~100 nm**

SIXM (scanning-imaging X-ray microscopy)

Phase-shift images are suitable for imaging of light-element materials

RID images: ~ density contrasts

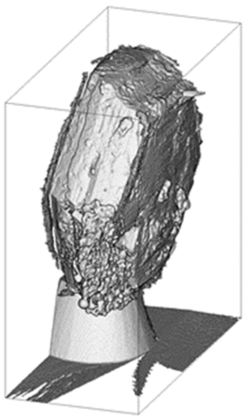
RID: Refractive Index Decrement
RID = 1 − R.I. ∝ density

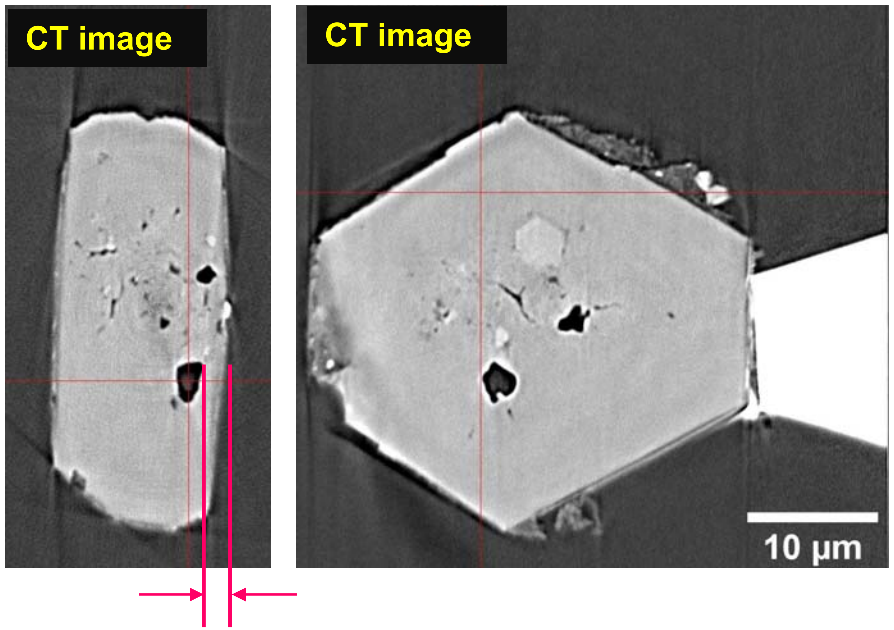
Takeuchi et al. (2013)

Combination of DET-SIXM gives **3D mineral maps** (as RGB-CT image: LAC(7)-LAC(7.35)–RID)

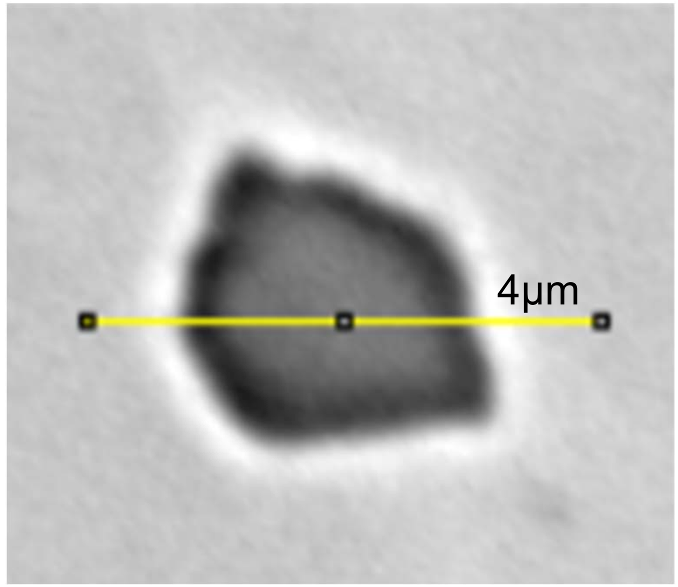
Fluid inclusion in hexagonal shape pyrrhotite $Fe_{1-x}S$

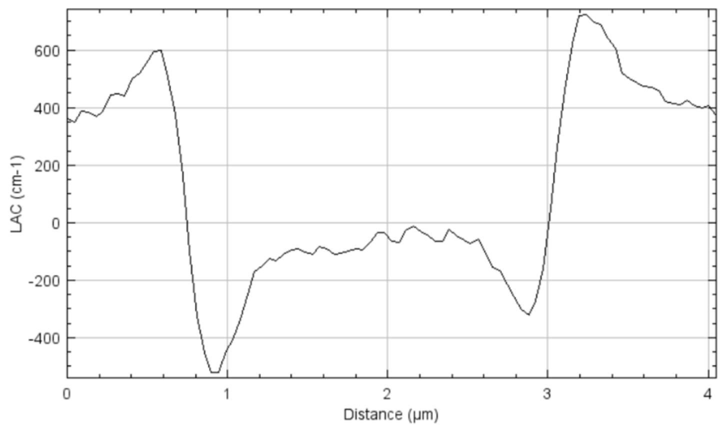
3-micron size inclusion that is completely enclosed in pyrrhotite is filled with homogeneous low-Z material.
The inclusion is completely enclosed in pyrrhotite.



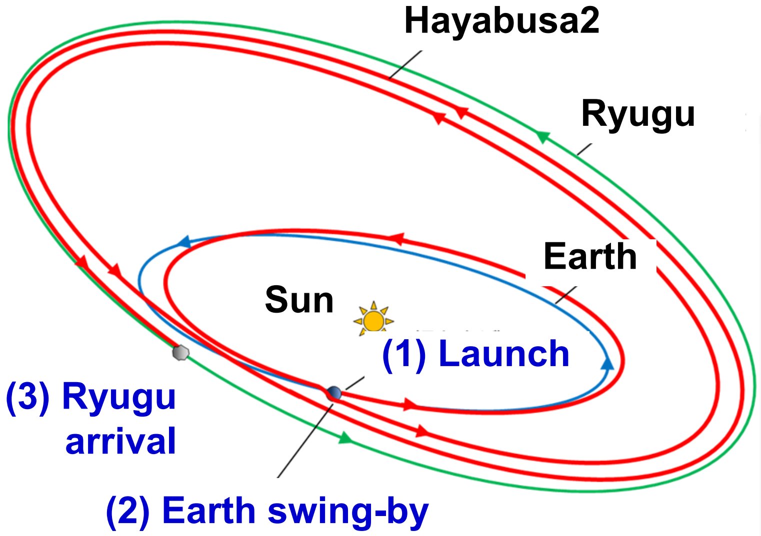


Depth from the sample surface to the inclusion (~2 um)



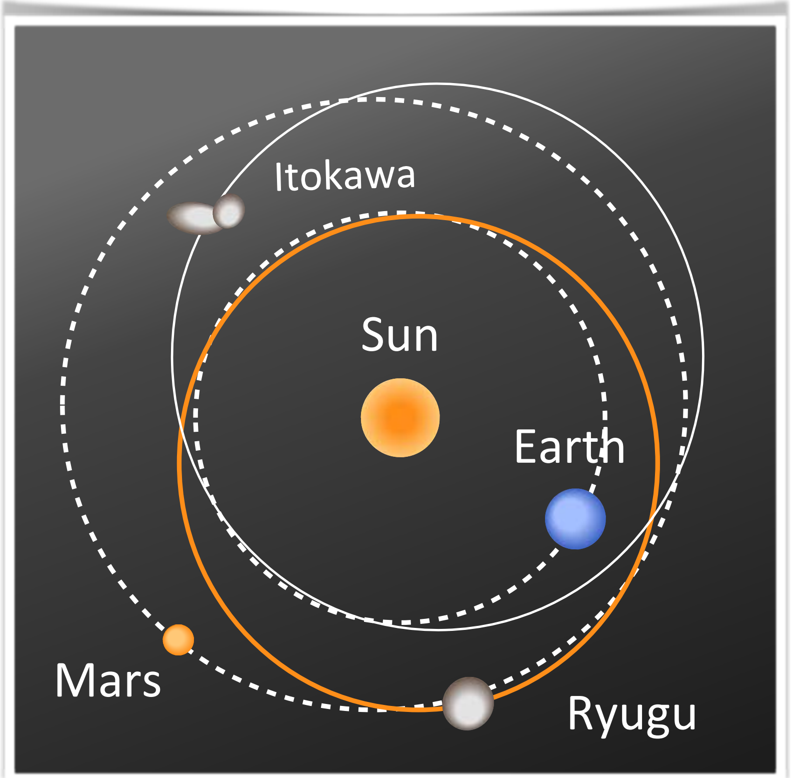


Hayabusa2 mission profile



Event	Date
Launch	**Dec. 3, 2014**
Earth swing-by	**Dec. 2015**
Ryugu arrival	**Jun. 2018**
Ryugu departure	**Dec. 2019**
Earth arrival	**Dec. 2020**

C-type Ryugu vs. S-type Itokawa



Ryugu C-type asteroid
Perihelion 0.96AU Aphelion 1.42AU
Revolution period: 1.30 yr