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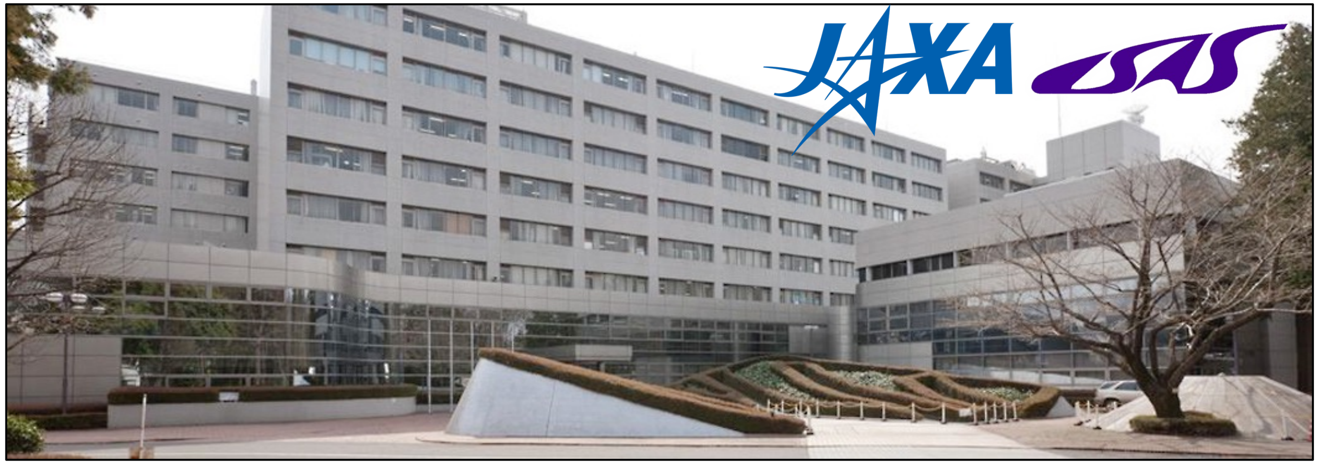

https://www.isas.jaxa.jp/about/outline/

SPECTRAL HETEROGENEITY OF RYUGU SAMPLES DUE TO SPACE WEATHERING REVEALED BY MICROMEGA.

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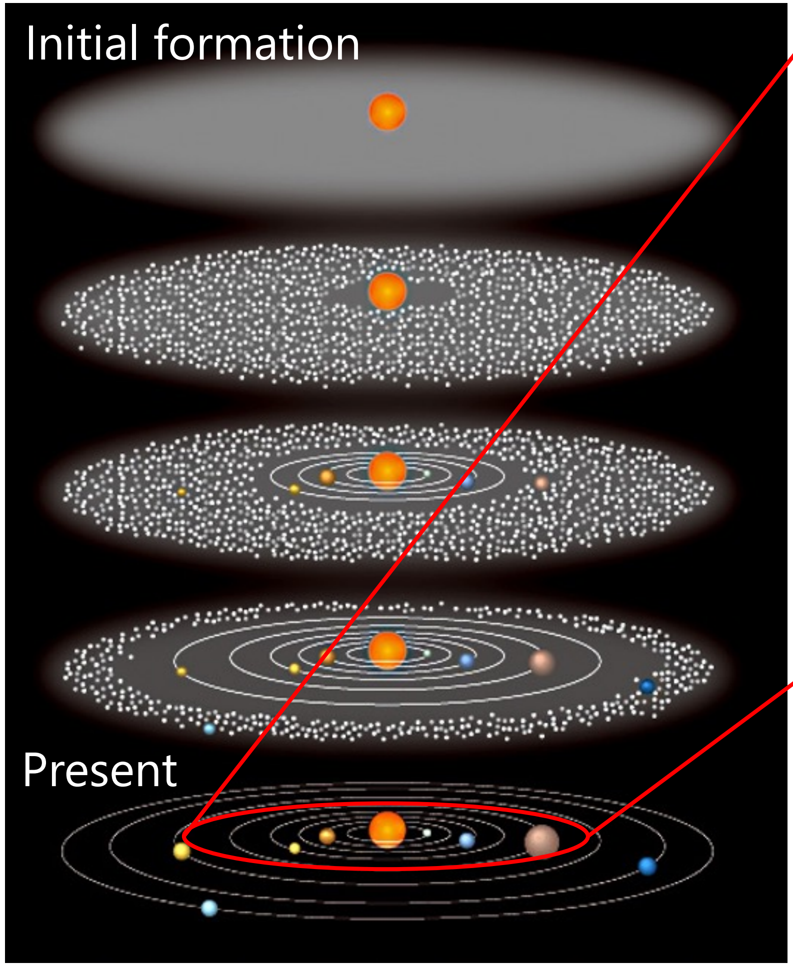
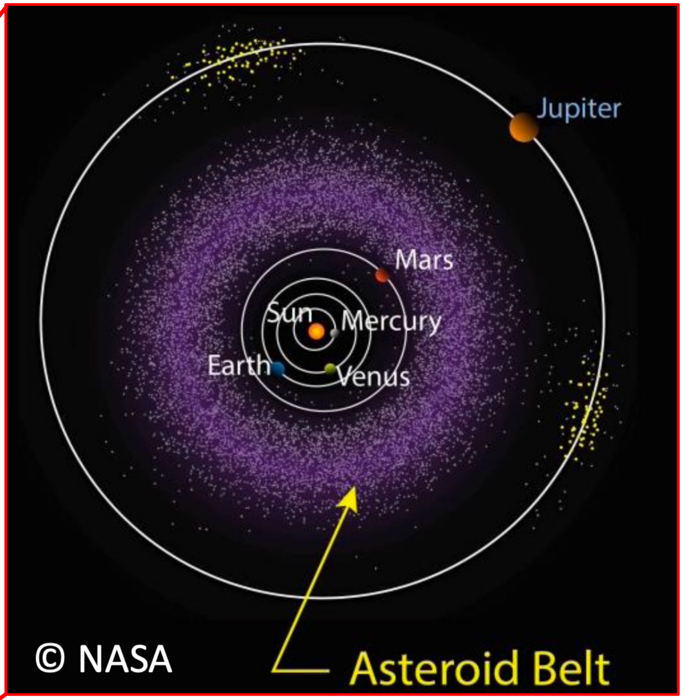
Introduction 1

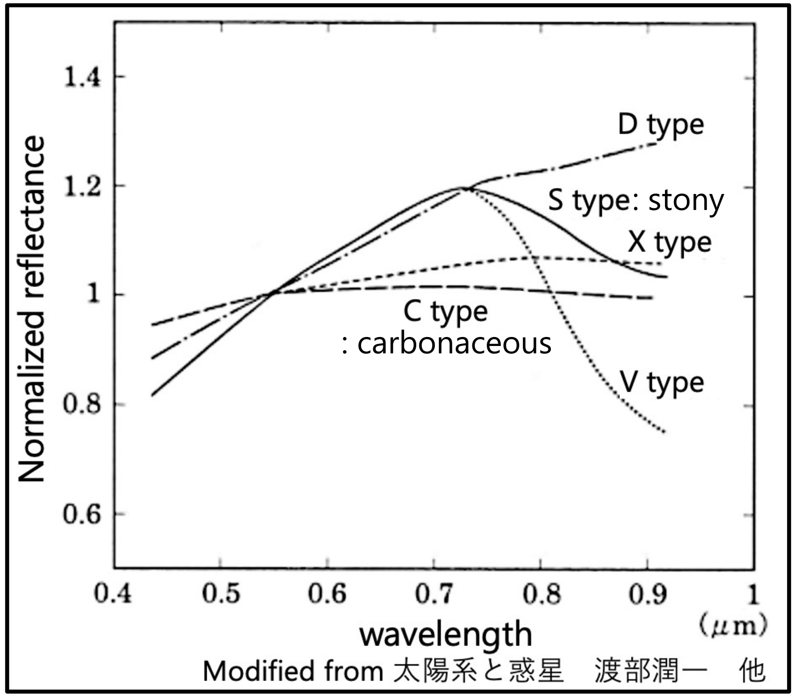
Asteroids and spectral measurements

Asteroids: primitive small Solar System bodies

Formation of the Solar System







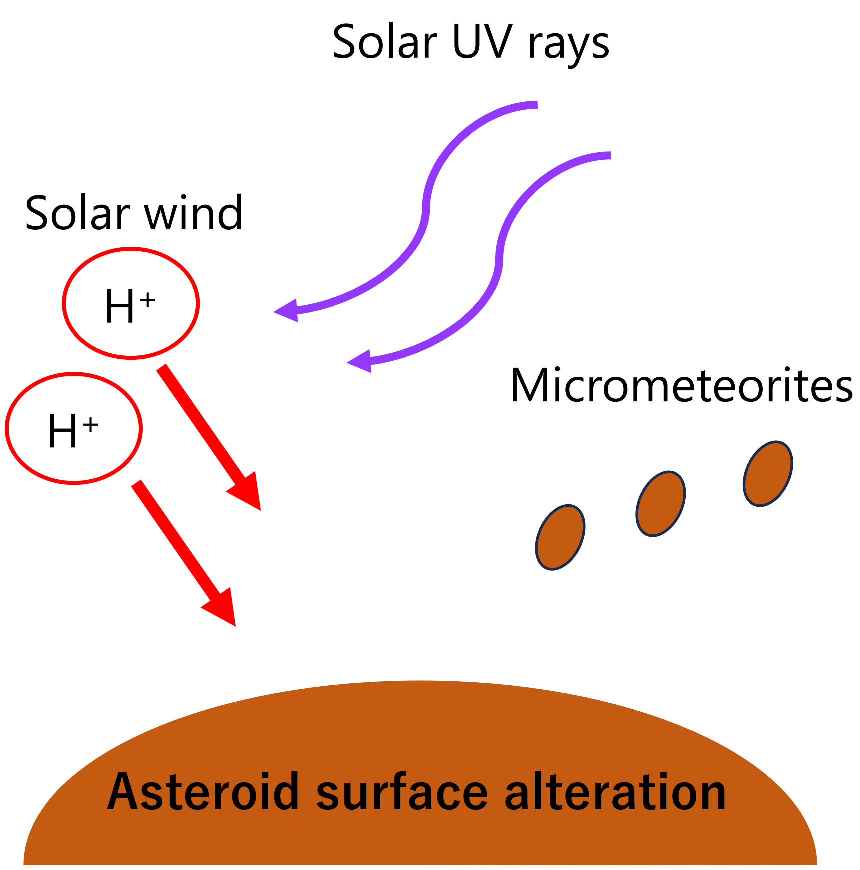
- Leftovers from the Solar System formation
- The record for the early Solar System
- Asteroids are classified by spectroscopy and spectral profiles
- C-type are interesting that are thought to be primarily stony but rich in water and organics.

Introduction 2

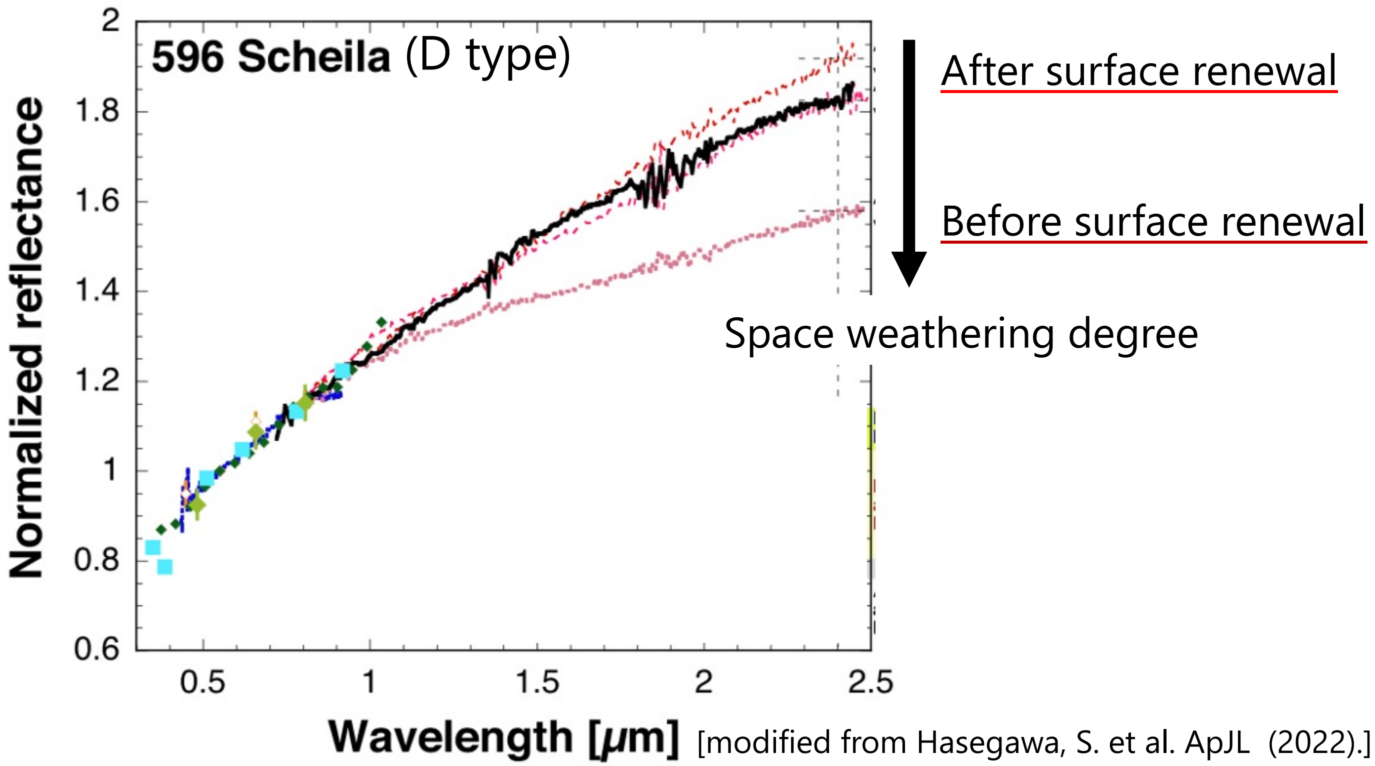
Space weathering and spectral measurements

Space weathering

Types of space weathering



Spectral profiles are changed by space weathering



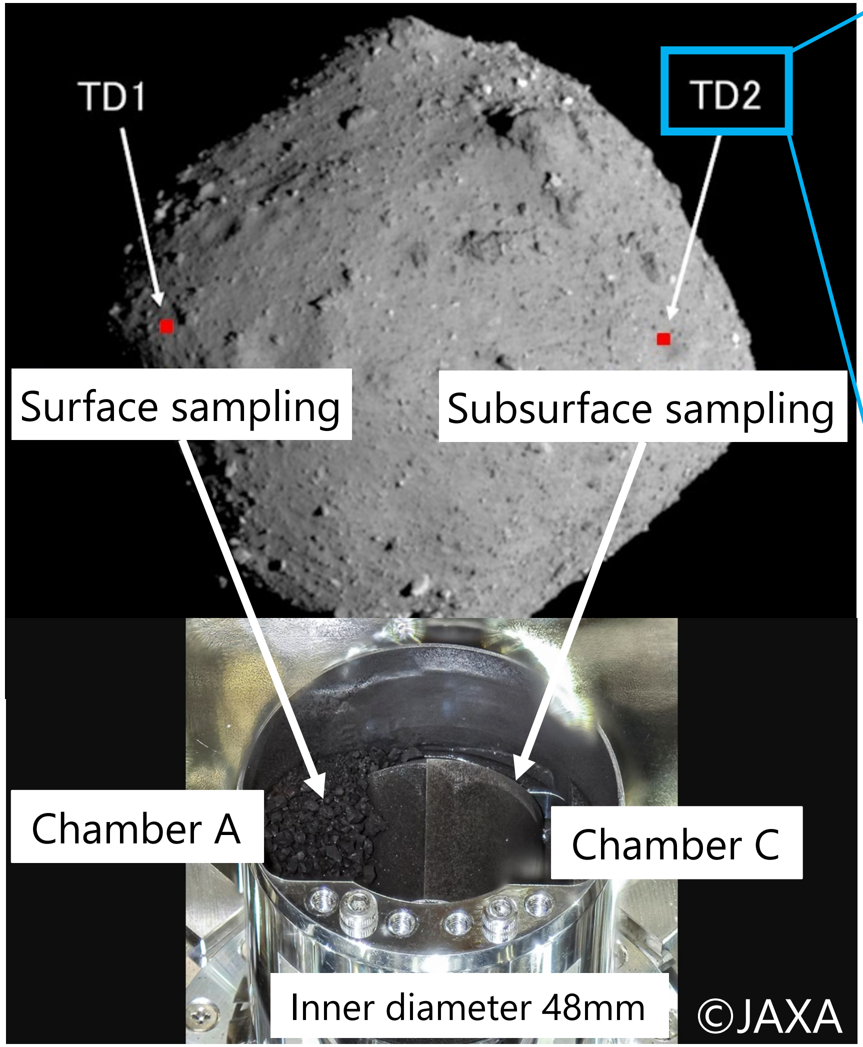
[modified from Hasegawa, S. et al. ApJL (2022).]

- Scheilia can be observed spectral changes due to space weathering by comparing before and after surface renewal

Introduction 3

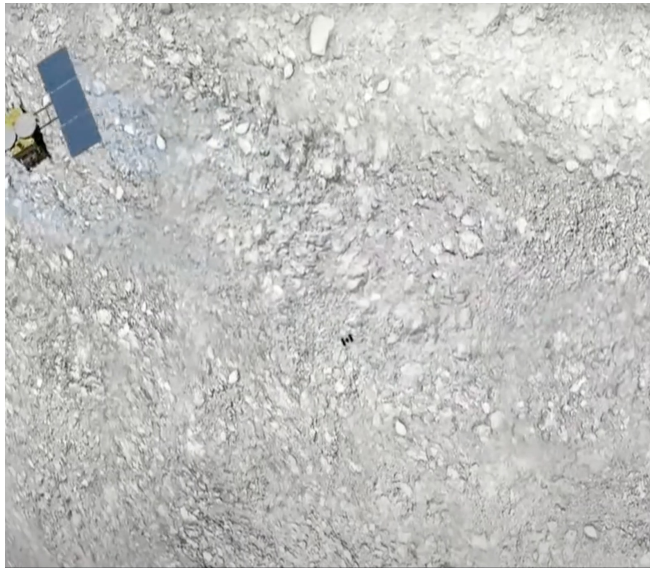
The C-type asteroid: Ryugu and Sampling

Ryugu: C-type asteroid



TD2: Sampling materials excavated by SCI impact

Impactor : SCI



[Arakawa, M. et al. (2020)]
https://www.youtube.com/watch?v=8Cp4UrWT0HM

- C-type & Rubble pile asteroid
- Target of JAXA's Hayabusa2 project.
- Hayabusa2 brought back two type Ryugu samples about 5.4g.

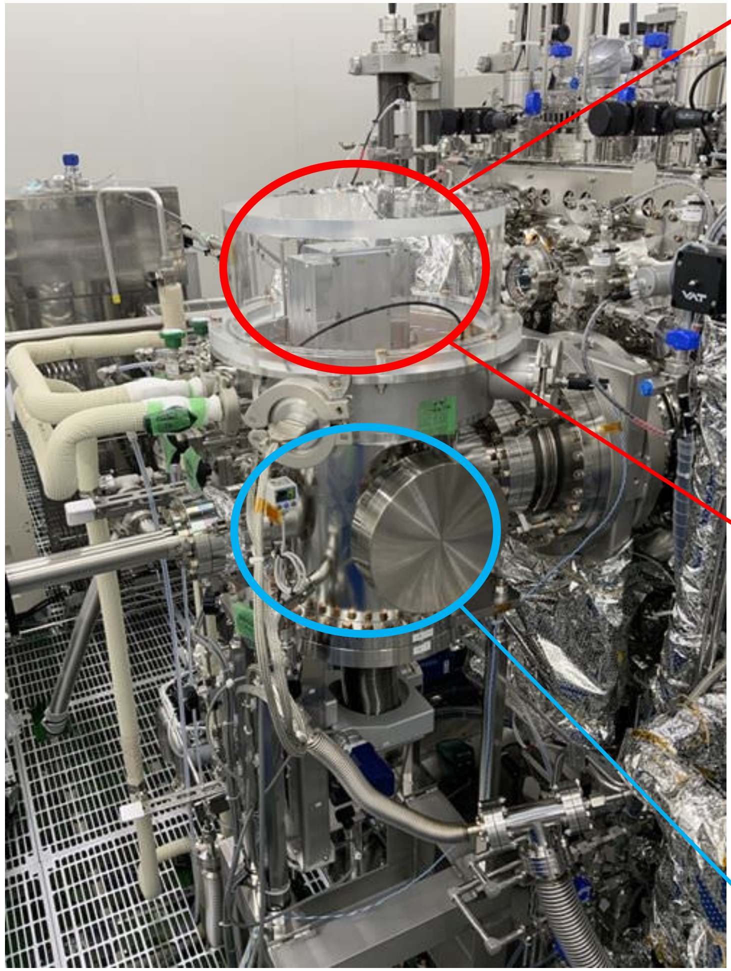
Chamber **A** samples
Surface samples

Chamber **C** samples
Subsurface samples

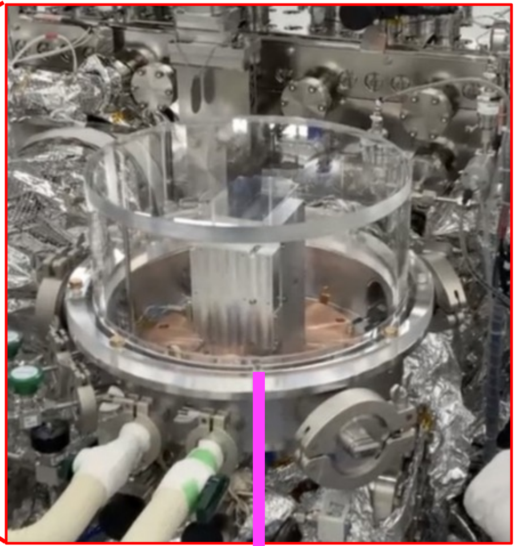
Introduction 4

One of the initial analysis instruments: MicrOmega

MicrOmega: A near-infrared hyperspectral microscope

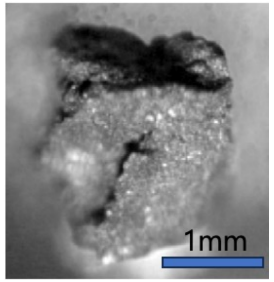


https://curation.isas.jaxa.jp/sample-curation/facility/



through a sapphire window

a sample placed on an integrated gold mirror in this



A0009 [MicrOmega-Curation DARTS Server]

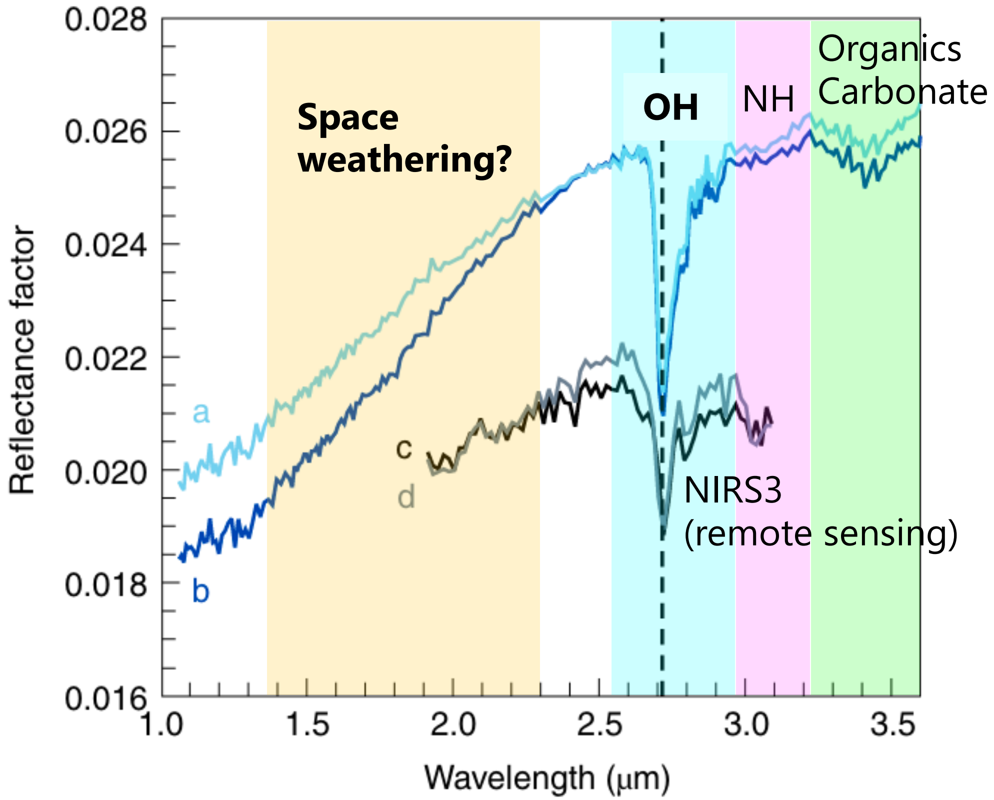
- Developed by IAS, France
- Installed at ISAS for initial analysis
- Nondestructive measurements
- Each sample is about 1-5 mm in diameter and is black to the naked eye

MicrOmega Specifications	
FOV	250 × 256 pix^2, 5 × 5 mm^2
Resolution	22.5 μm/pix
Wavelength range	**0.99-3.65 μm**
Detectable main profiles	Hydrates, Organics

Background

Near-infrared spectral profiles of the Ryugu samples

- **Continuum around 2.0μm → Space weathering?**
- **Absorption band at 2.7 μm → OH group**
- Absorption band at 3.1 μm → NH group
- Absorption band at 3.4 μm → Organics and carbonates



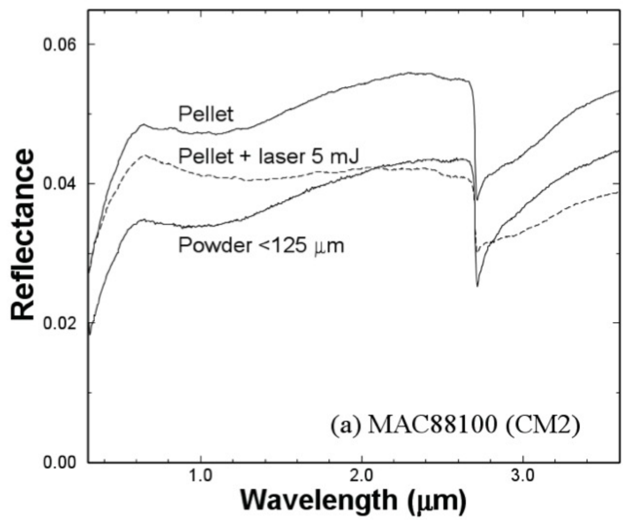
[modified from Pilorget, C. et al. (2022)]

Continuum around 2.0μm

The slope of the continuum around 2.0μm may varies with space weathering

Space weathering simulations for carbonaceous chondrites

- a gentler slope around 1.0-2.5 μm
- a lower depth of the 2.7 μm absorption



[Yamada, M. et al. (1999)][Hiroi, T., Sugita, S. (2010)]

On the other hand,
remote sensing of Ryugu in the Vis (0.48-0.86 μm)

- Steeper slope due to space weathering [Morota, T. et al. (2020)]

It still remains poorly understood how the NIR slope changes with space weathering.

Background and Objectives

Near-infrared spectral profiles of Ryugu samples

Absorption band at 2.7 μm

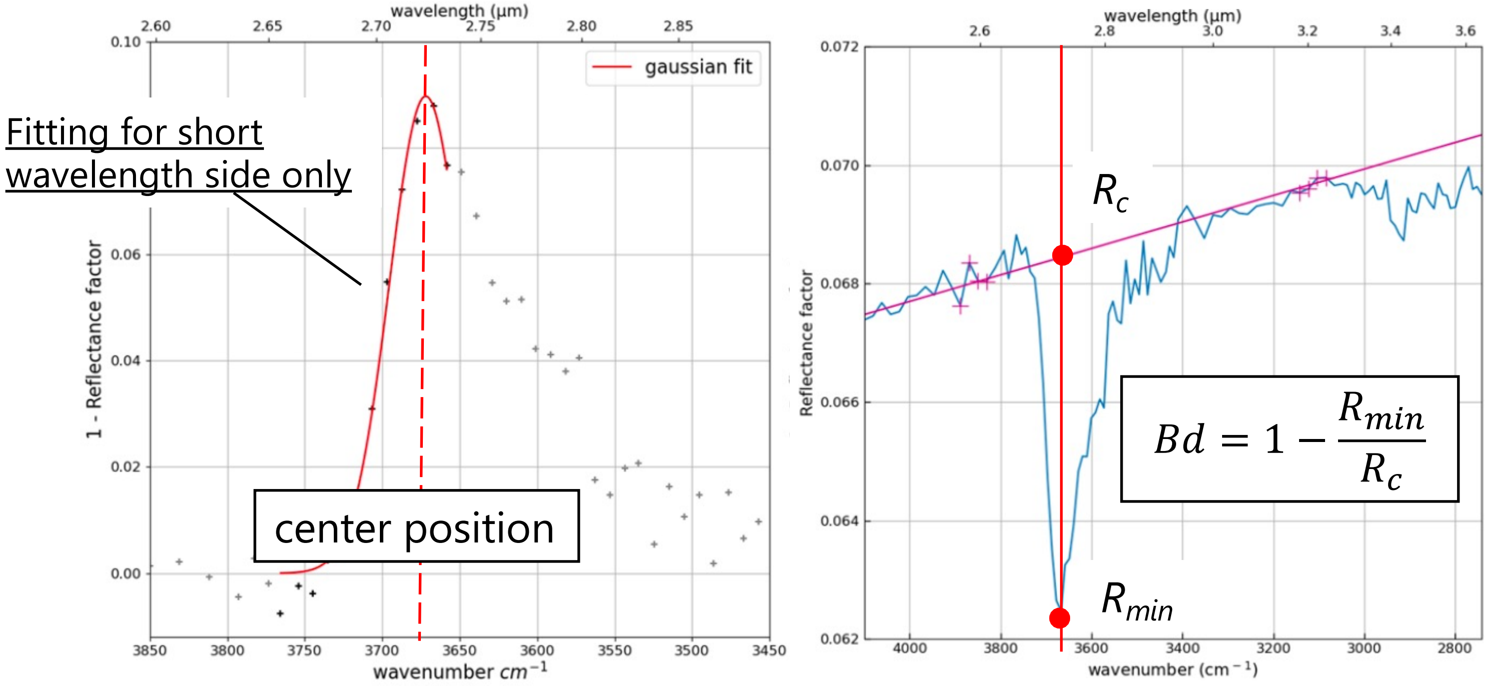
- Corresponding to OH vibrations bonded to Fe or Mg cation

  [Pilorget, C. et al. (2022)] [Le Pivert-Jolivet, T. et al. (2023)]

- Depth reduction due to OH bond breakage by space weathering

  [Noguchi, T. et al. (2022)], [Hiroi, T., Sugita, S. (2010)]

- A previous study for 2.7 μm absorption band↓



[modified from Le Pivert-Jolivet, T(Tania). et al. (2023)]

Objectives

- **Investigate changes in the NIR spectral profiles of the asteroid Ryugu due to space weathering**
  - Calculate of the slope of the continuum around 2.0μm
  - Estimate the position and depth of the entire 2.7 μm absorption band
  - Compare between surface samples and subsurface samples
- **Discussion the effects and mechanisms of space weathering on the asteroid Ryugu**

Samples & Methods
Original fitting analysis methods

Samples and spectral data used in this study

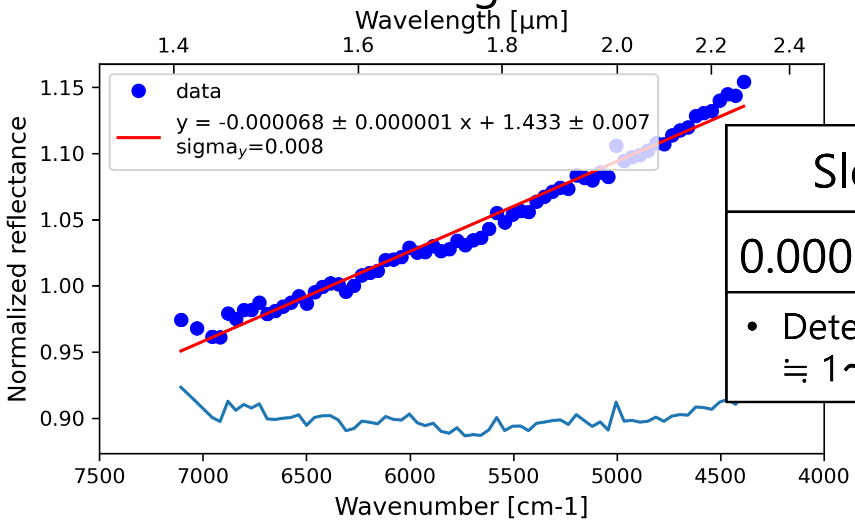
Spectral data in MicrOmega-Curation DARTS Server

Spectral profiles	2.0 µm continuum	2.7 µm absorption
Analysis range [µm]	1.4 - 2.3	2.55 - 3.25
Number of samples(A, C)	(99, 64)	(99, 64)

total 160↑

Slope analysis around 2.0µm

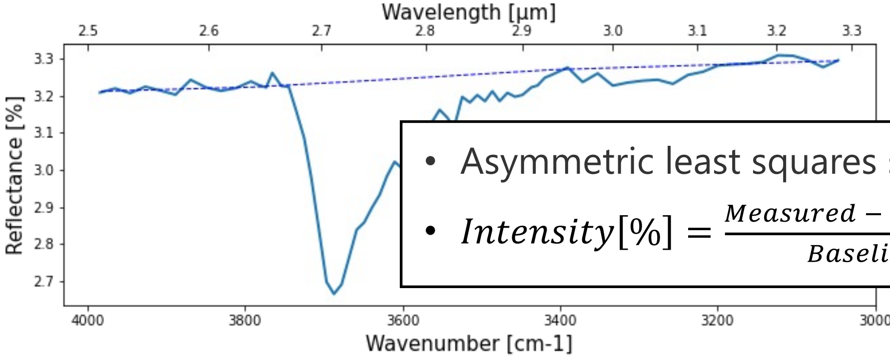
Linear Function Fitting



Slope [%/cm^{-1}]
0.000068 ± 0.000001
• Determination factor R^2 ≒ 1∼0.8

2.7µm absorption band analysis

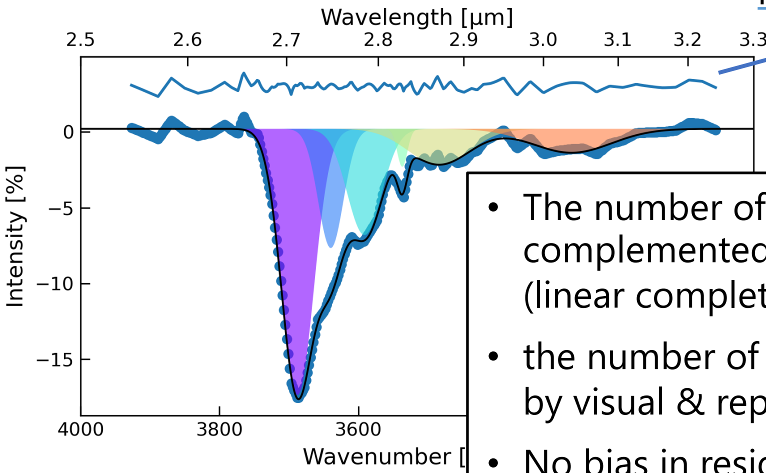
1. baseline estimation



- Asymmetric least squares smoother
- $Intensity[\%] = \frac{Measured - Baseline}{Baseline} \times 100$

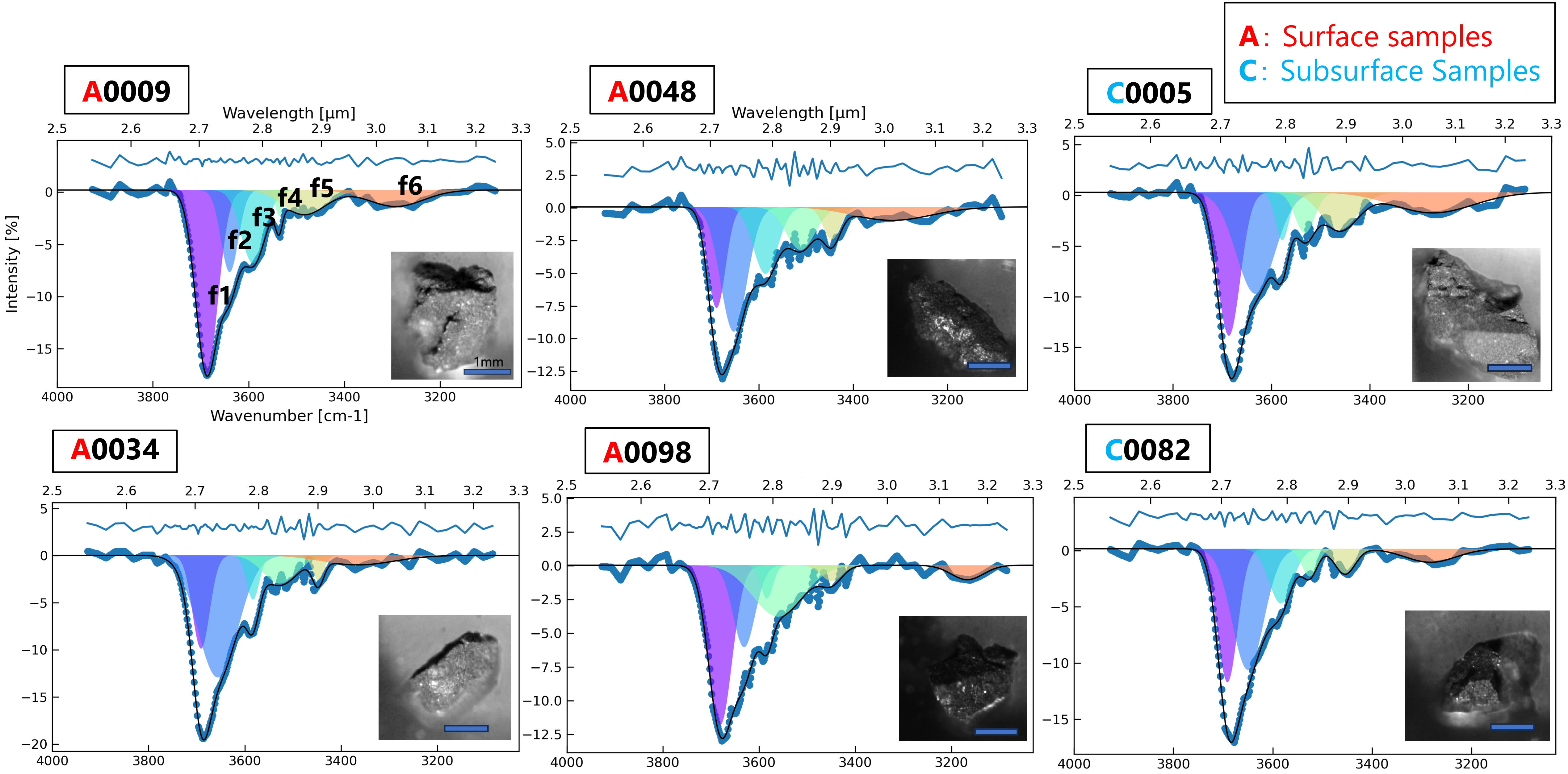
2. Multi-Gaussian Fitting

residual spectrum



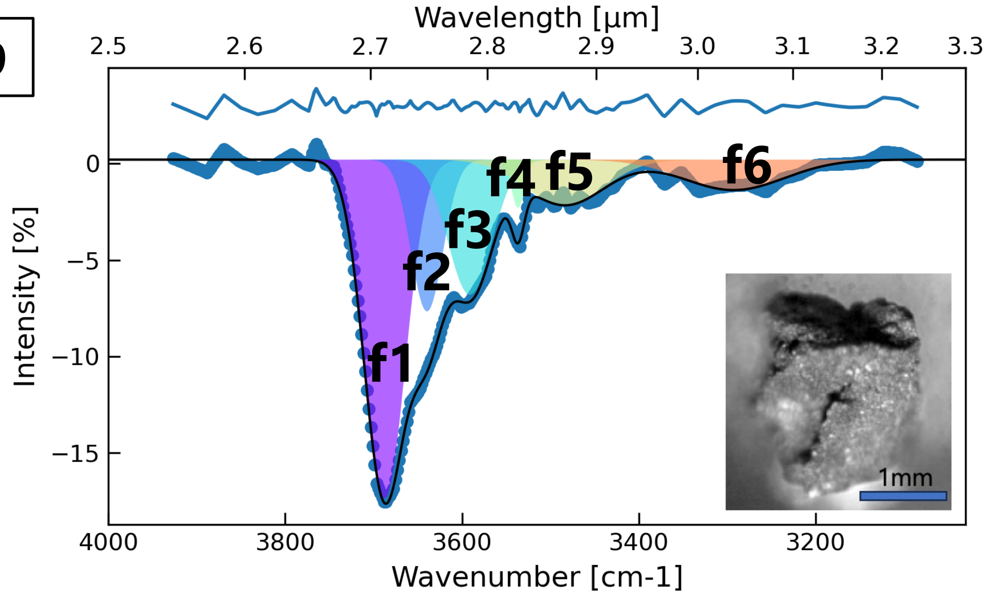
- The number of data points was complemented by a factor of 6 (linear completion)
- the number of Gaussian estimated by visual & reported
- No bias in residuals & determination factor R^2 ≒ 1∼0.9

R 1: Examples of analysis results for the 2.7 μm absorption band



R 2: Possibility the 2.7μm absorption band is composed of 6 bands

A0009



bands	**Peak position [μm]**	depth[%]
f1	**2.712 ± 0.001**	17.57 ± 0.88
f2	**2.748 ± 0.001**	7.874 ± 0.413
f3	**2.785 ± 0.001**	7.014 ± 0.809
f4	**2.828 ± 0.001**	2.517 ± 0.316
f5	**2.870 ± 0.001**	2.362 ± 0.262
f6	**3.037 ± 0.025**	1.579 ± 0.106
composite waveform	**2.713(f1-f6) ± 0.002(f1-f2)**	17.64(f1-f6) ± 0.98(f1-f2)

f1–f2: OH ?

f6 → NH ?

Table 1 Major absorption bands of minerals and organics, which could be identified by MicrOmega

Wavelength range	Band width	Minerals	Assignment
0.99–2.30 μm	> 50 nm	Iron (ferrous and ferric) oxides; pyroxenes; olivines, Fe-bearing plagioclases	Electronic processes (Crystal Feature Absorption)
1.3–3.65 μm	10–50 nm	Phyllosilicates; Hydroxides; Amphiboles, Hydrated aluminosilica and glass; AmpZeolites; Carbonates; Sulfates; Chlorides; Nitrates; Phosphates; Perchlorates	Combinations and overtones of fundamental O-H, X-OH (X = Al^{3+}, Fe^{3+}, Fe^{2+}, Mg^{2+}, Si), C-O, Si-O, N-O, P-O
2.7–3.65 μm	10–50 nm	Adsorbed/confined water, Hydroxyl	Fundamental and overtones of OH & H_2O
		Organics and its assignments	
2.80–3.0 μm	> 40 nm	1st overtone of carbonyl C = O	
2.94–3.12 μm	> 50 nm	N-H and NH_2 group (stretch and 1st overtone of N-H bend)	
~ 3.0 μm	> 20 nm	Alkyne ≡ C-H stretch	
3.27–3.29 μm	> 20 nm	Aromatic CH stretch	
3.38–3.39; 3.41–3.42 μm	> 20 nm	Aliphatic CH_3; CH_2 asymmetric stretch	
~ 3.45 μm	> 20 nm	CH_2 Fermi resonance	
3.38–3.50 μm	> 20 nm	Aliphatic CH_3 asymmetric stretch	

[Bibring,. J.-P. et al. (2017)]

R 3: Different trend of the 2.7 µm absorption band in Ryugu samples

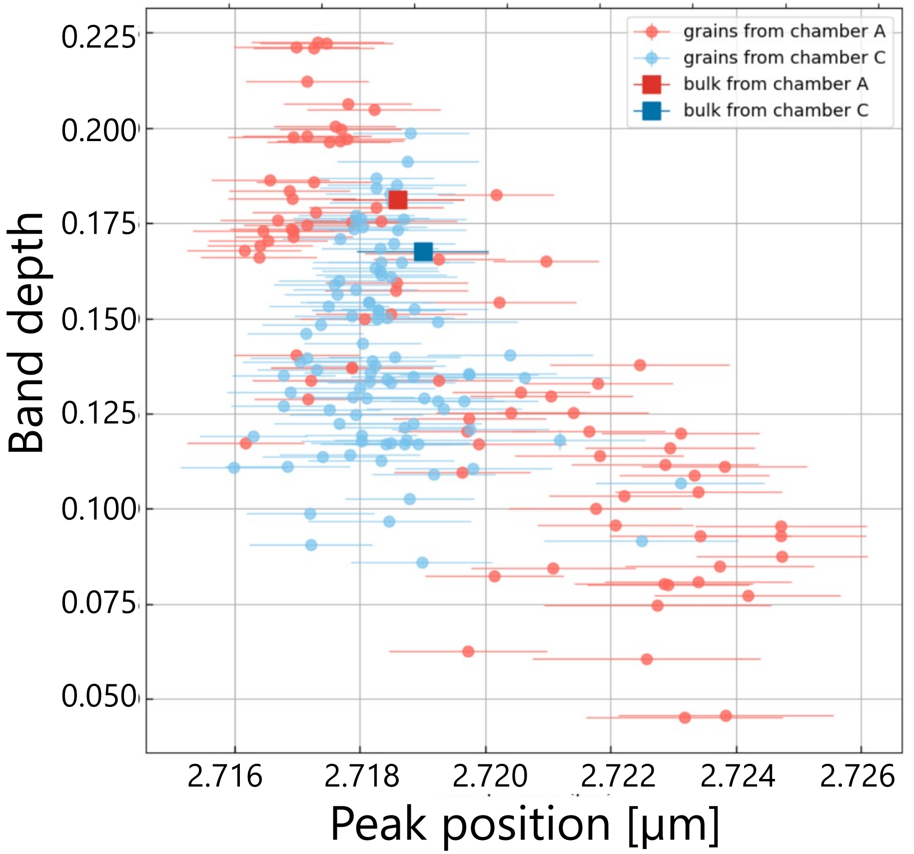
Peak position vs depth of the 2.7µm absorption band

- Similar trends to previous research
- Compared to the previous research, the peak position shifts to shorter wavelength
- <u>**Chamber A samples distributed in two regions (α, β)**</u>

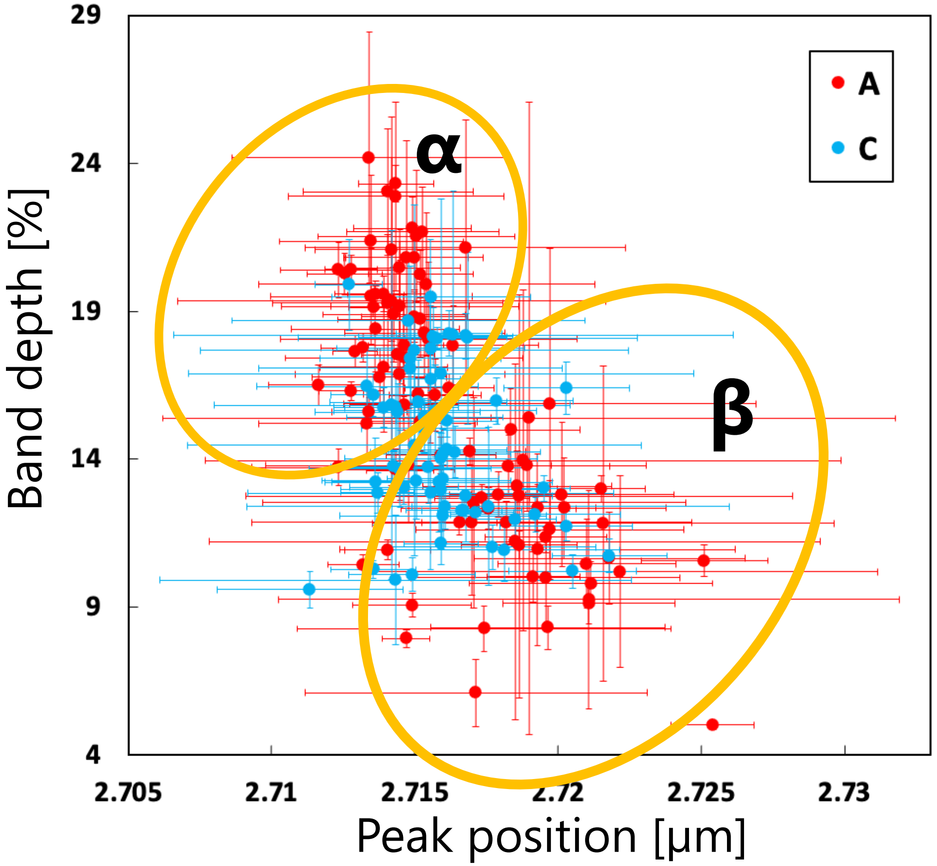
A（α, β）: Surface samples
C：Subsurface Samples

Previous research

[modified from Le Pivert-Jolivet, T(Tania). et al. (2023)]

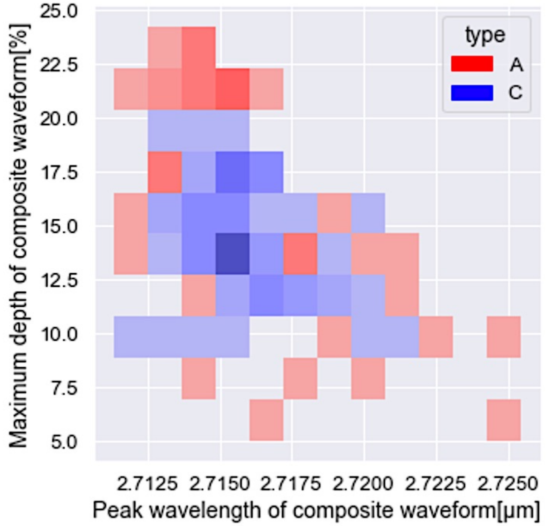


This research



α: shorter than 2.7167 µm and greater than 13 %.

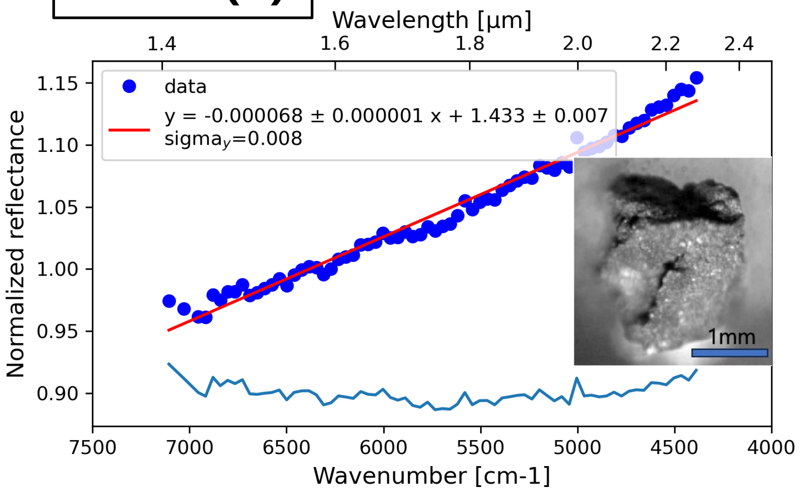
β: All others



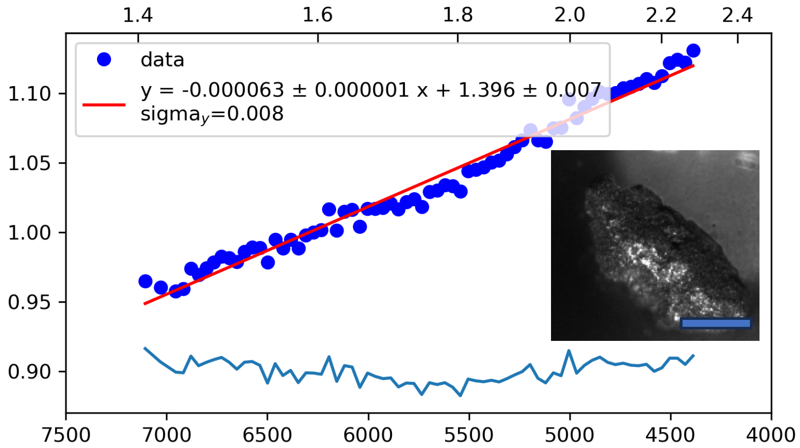
R 4: Examples of 2.0μm slope analysis results

A(α, β): Surface samples
C: Subsurface Samples

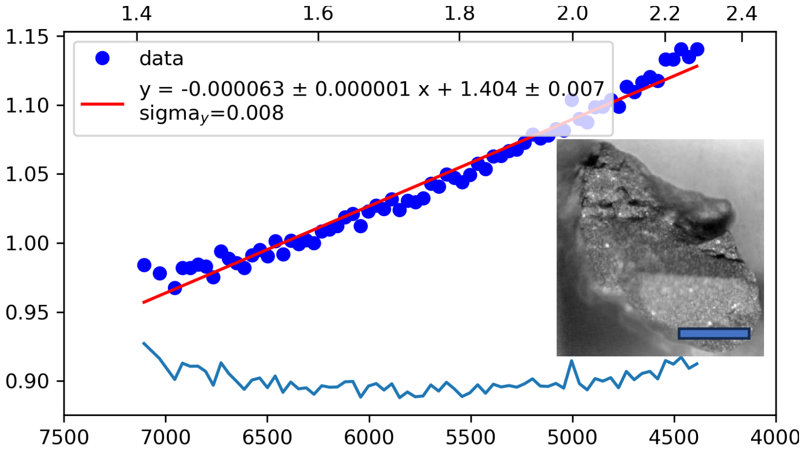
A0009(α)



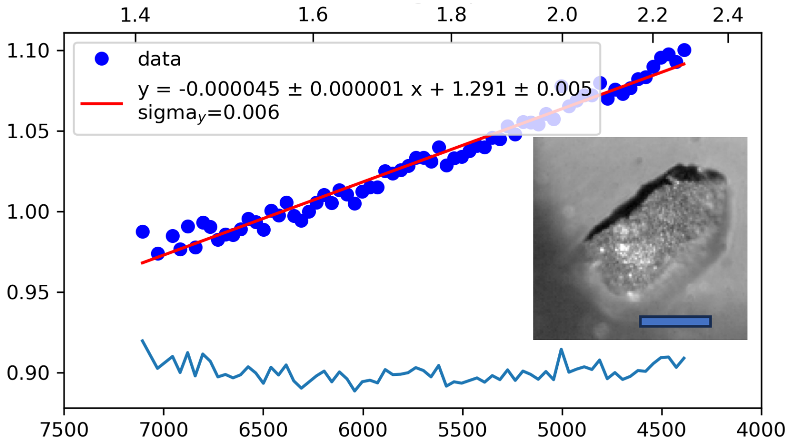
A0048(β)



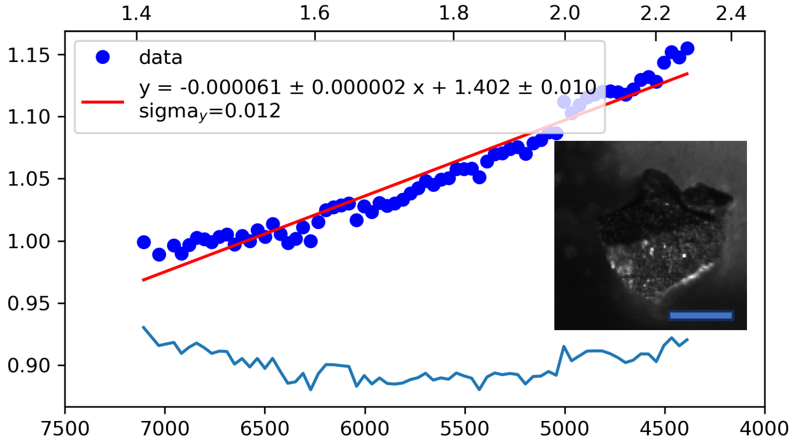
C0005



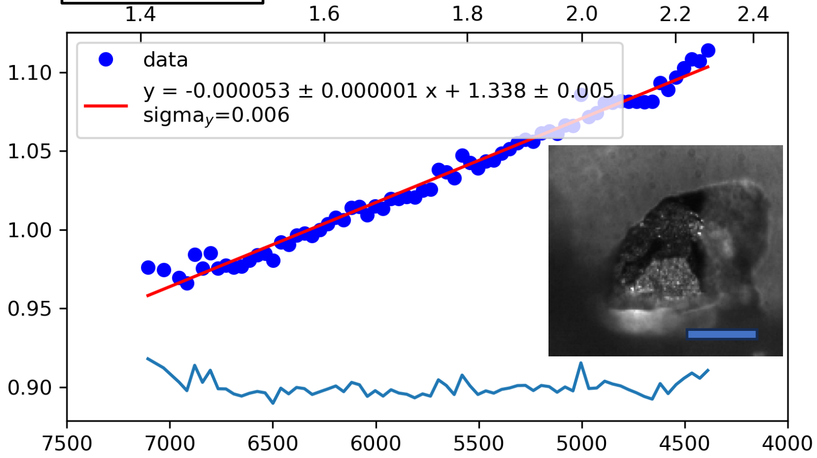
A0034(α)



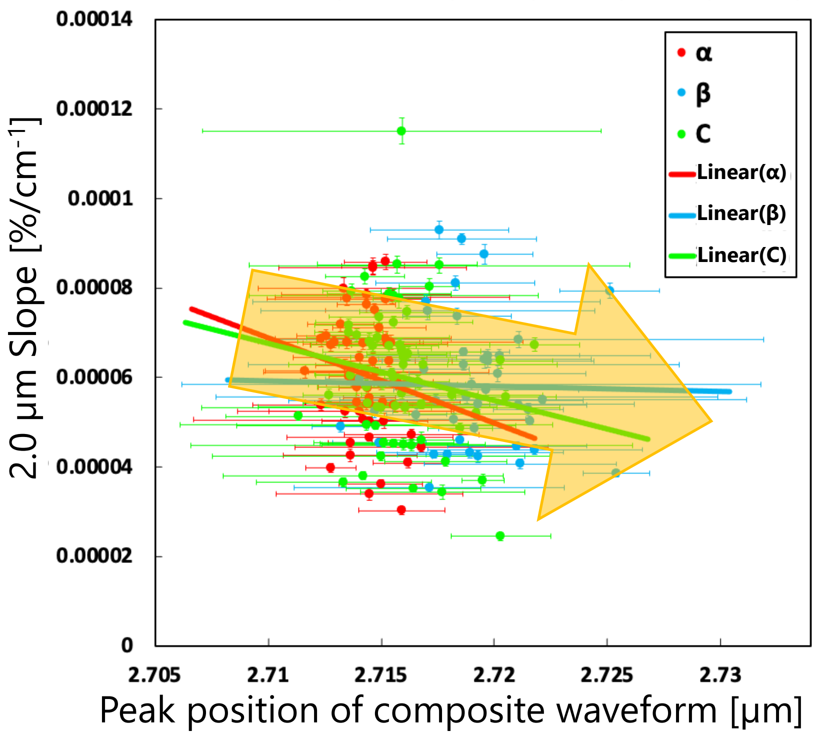
A0098(β)

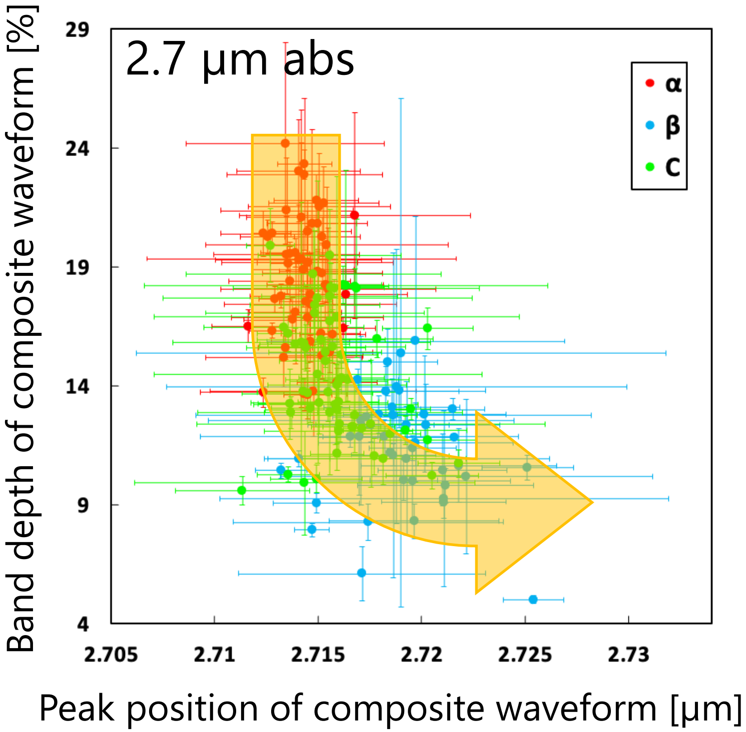


C0082

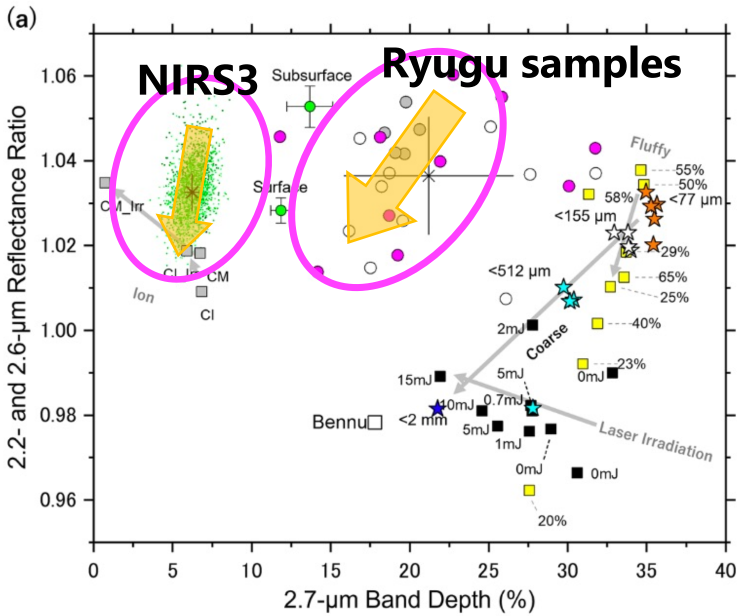


R 5: Relationship between 2.0 µm slope and 2.7 µm absorption band





A(α, β): Surface samples
C: Subsurface Samples



[%/cm^{-1}]	α	β	C
average	6.05E-05 ±1.31E-05	5.83E-05 ±1.42E-05	6.01E-05 ±1.51E-05

- Slope magnitude: α>C>β
- Correlation between peak shift and slope change: α>C>β

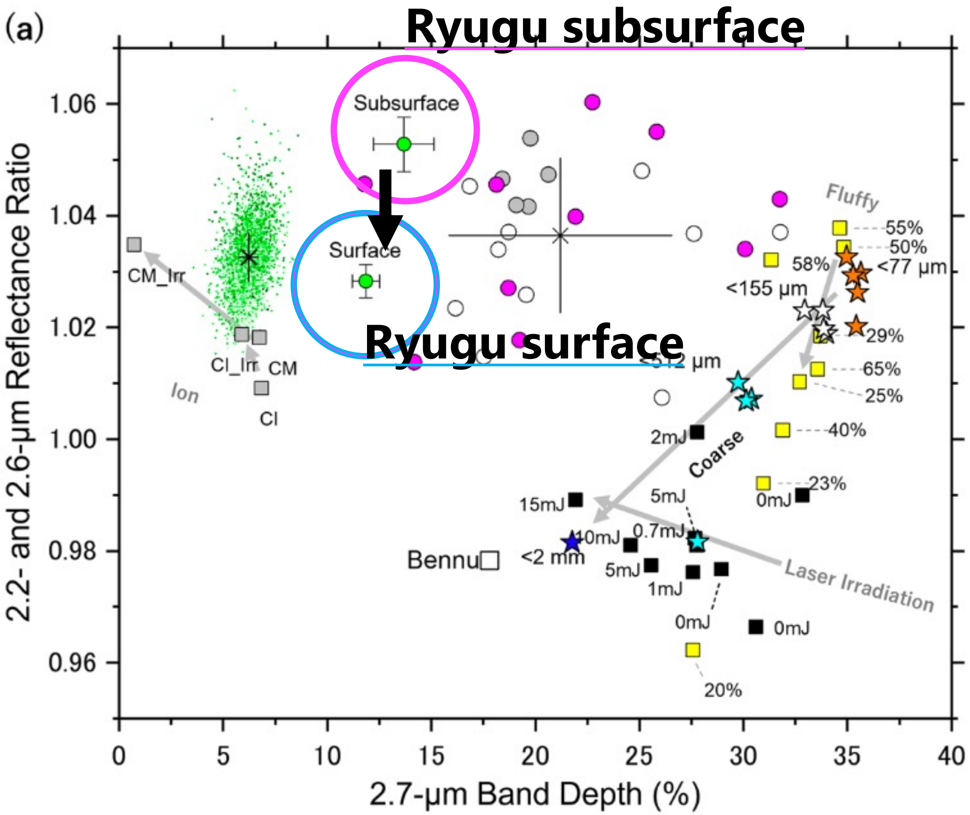
The gentler the 2.0 µm slope, the smaller the depth and the longer wavelength the position of the 2.7 µm absorption band.

Similar trend
in remote sensing: NIR3
[modified from Matsuoka, M. et al. (2023)]

D 1: Spectral heterogeneity due to space weathering

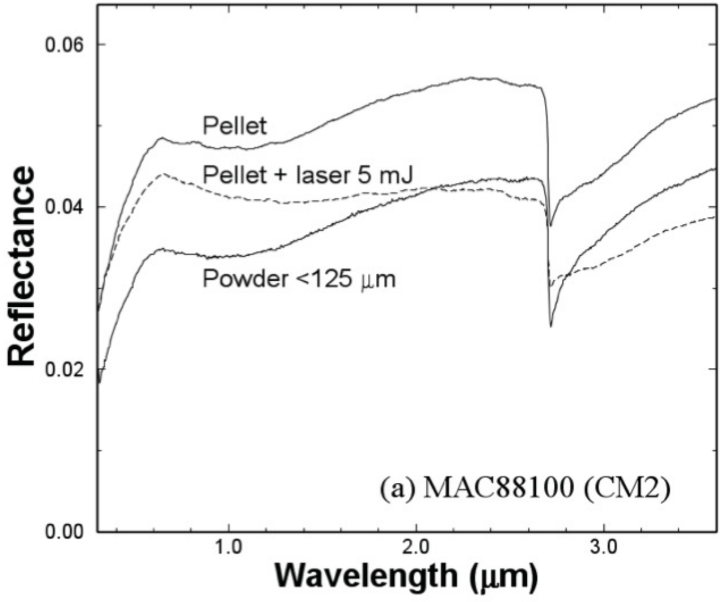
A (α, β): Surface samples
C: Subsurface Samples

Remote sensing of the asteroid Ryugu by NIR3



"Surface" (more affected by space weathering) tends to have a gentler slope than "Subsurface".
[modified from Matsuoka, M. et al. (2023).]

Space weathering simulation on carbonaceous meteorites

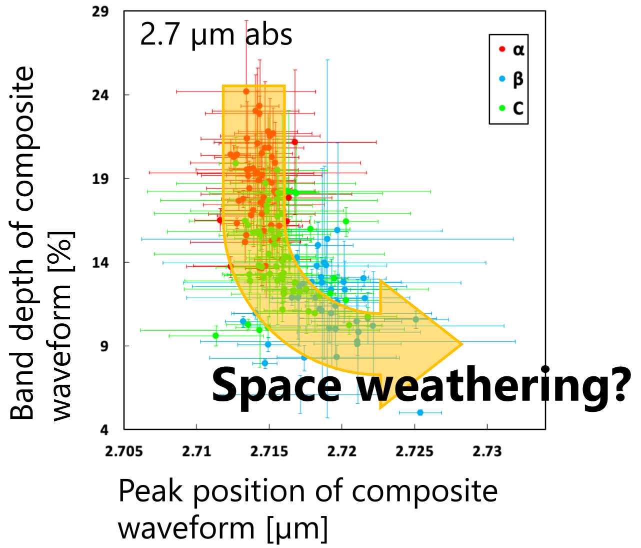


Space weathering causes a gentler slope of the near-infrared. [Yamada, M. et al. (1999)] [Hiroi, T., Sugita, S. (2010)]

Space weathering reduce the depth of the 2.7 μm absorption band due to dehydration. [Noguchi, T. et al. (2022)]

This research:
The gentler the 2.0 μm slope, the smaller the depth and the longer wavelength the position of the 2.7 μm absorption band.

space weathering: α < C < β ?



D 2.1: Factors of heterogeneity in Ryugu samples

- **ChamberA samples:** Less (α) and more (β) particles affected by space weathering at different depths
- **ChamberC Samples:** ① to ③

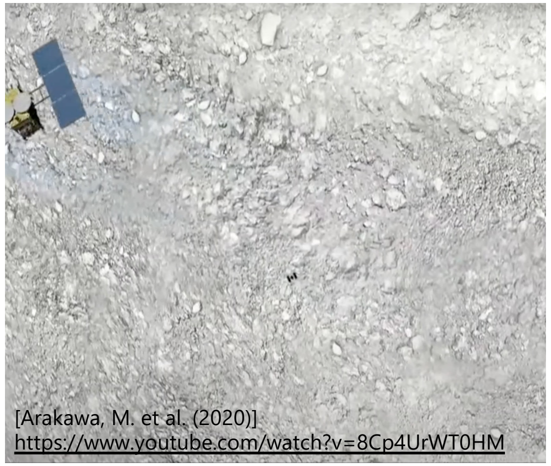
A (α, β) : Surface samples
C : Subsurface Samples
Space weathering: α<C<β?

① **β particles with exposed α due to SCI impact**

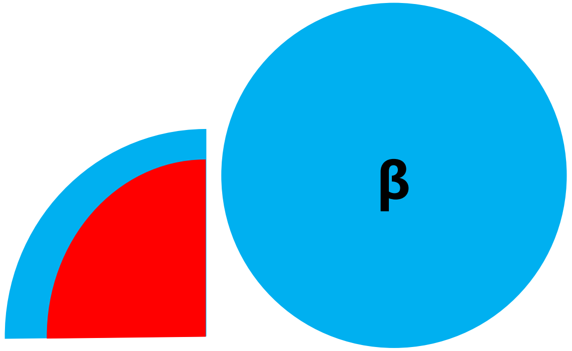
② α particles were ejected up by SCI and affected by solar UV rays during the trajectory until sedimentation.

③ Chamber A and Chamber C samples are different substances to begin with.

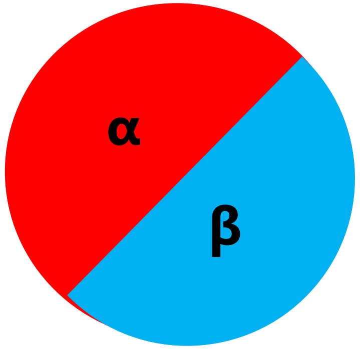
Impactor : SCI
Artificial craters were created by impacting the Ryugu surface



β particles
Only the particle's surface may be affected by space weathering.



Chamber C Particles
Internal α exposed?



Crushed by SCI
Easily crushed due to high porosity
[Sakatani, N. et al. (2021)]

D 2.2: Factors of heterogeneity in Ryugu samples

- **ChamberA samples:** Less (α) and more (β) particles affected by space weathering at different depths
- **ChamberC Samples:** ① to ③

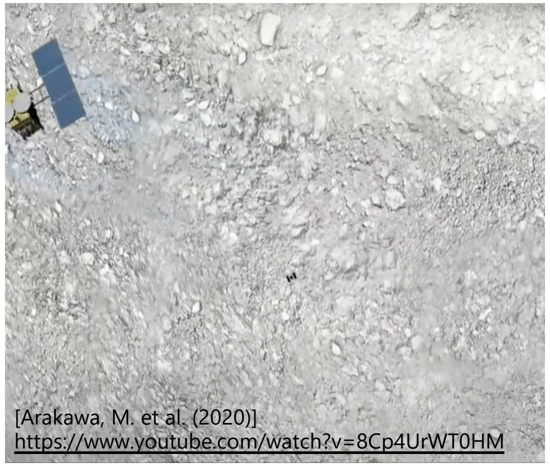
A(α, β)： Surface samples
C： Subsurface Samples
Space weathering: α<C<β?

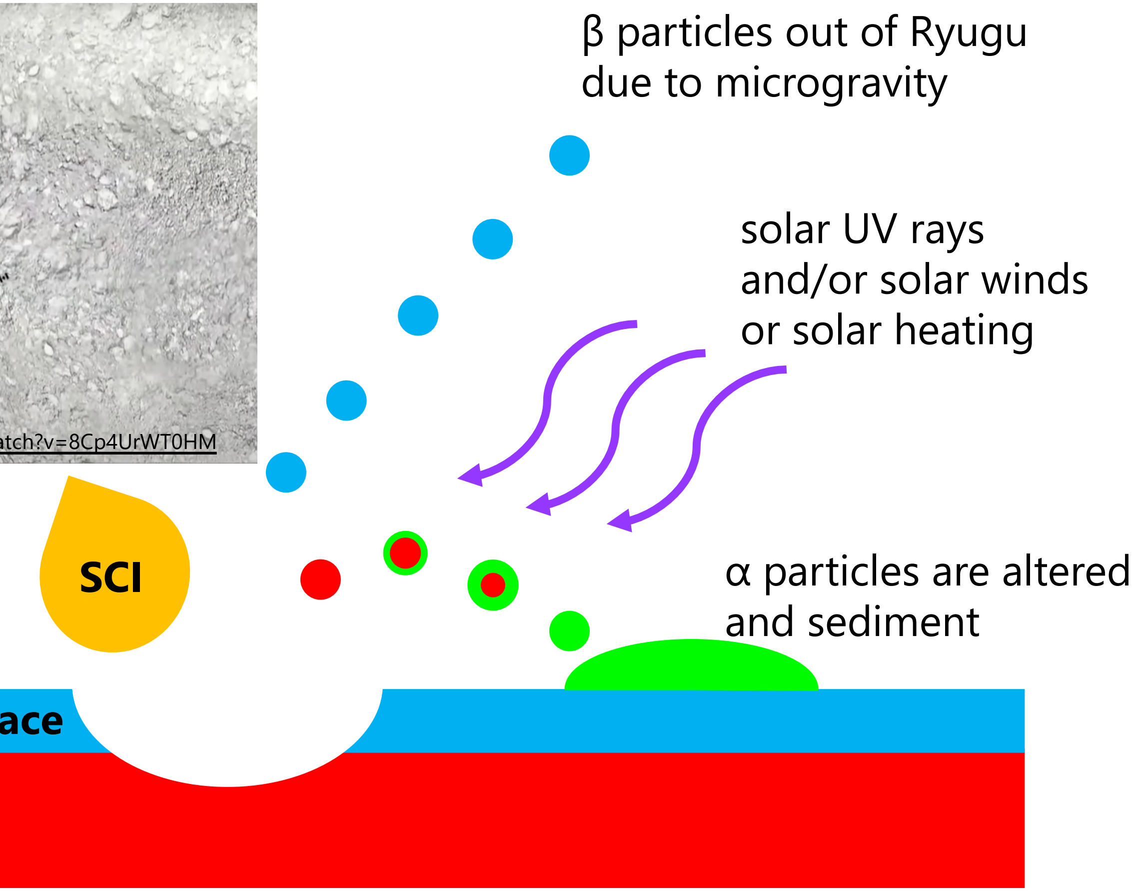
① β particles with exposed α due to SCI impact

② **α particles were ejected up by SCI and affected by solar UV rays during the trajectory until sedimentation.**

③ Chamber A and Chamber C samples are different substances to begin with.

Impactor：SCI
[Arakawa, M. et al. (2020)]





Concluding Remarks

Conclusions

- Original quantitative analysis of the near-infrared spectral profiles of more than 150 Ryugu samples.

↓

- The gentler the 2.0 µm slope, the smaller the depth and the longer wavelength the position of the 2.7 µm absorption band.

↓

- The order of α < Chamber C < β may be more affected by space weathering.

↓

- Proposed factors of heterogeneity in the Ryugu samples due to space weathering

Way Forward

- Verify the changes in spectral profiles found in this study through space weathering simulation experiments.

↓

- Understand the effects and mechanisms of space weathering based on the changes in spectral profiles.

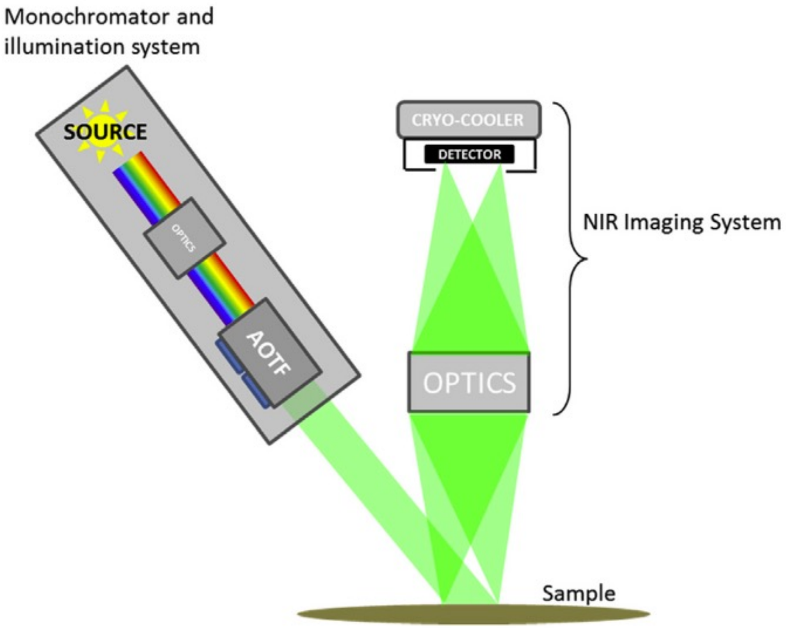
Acknowledgments
This study was supported by IGPEES, WINGS Program, the University of Tokyo.

＜主な指摘や質問等＞

- 長波長シフトの原因は宇宙風化とは限らない
  - 模擬実験によると宇宙風化によるシフトは確認されていない
  - リュウグウ粒子表面の宇宙風化を受けている部分の赤外分析では、シフトが確認されるものとされないものがある
  - Mg/Feでシフトする：Fe多いと長波長シフト
    →微小隕石衝突等による融解による組成変化の影響でシフトする可能性

一方、宇宙風化による深度低下は共通して確認される

Appendix 1: MicrOmega configuration and measurement conditions



Functional diagram of the MicrOmega [Riu, L. et, al. (2018)] [Leroi, V. et al. (2009)] [Bibring, J.-P. *et al.* (2017)]

＜ Equipment Configuration ＞

Ultra-compact filament lamp emits light with a wide wavenumber band

↓

AOTF (Acousto-optic wavelength tunable filters) extract monochromatic light at specific wavelength (0.99-3.65μm, every 20cm-1)

↓

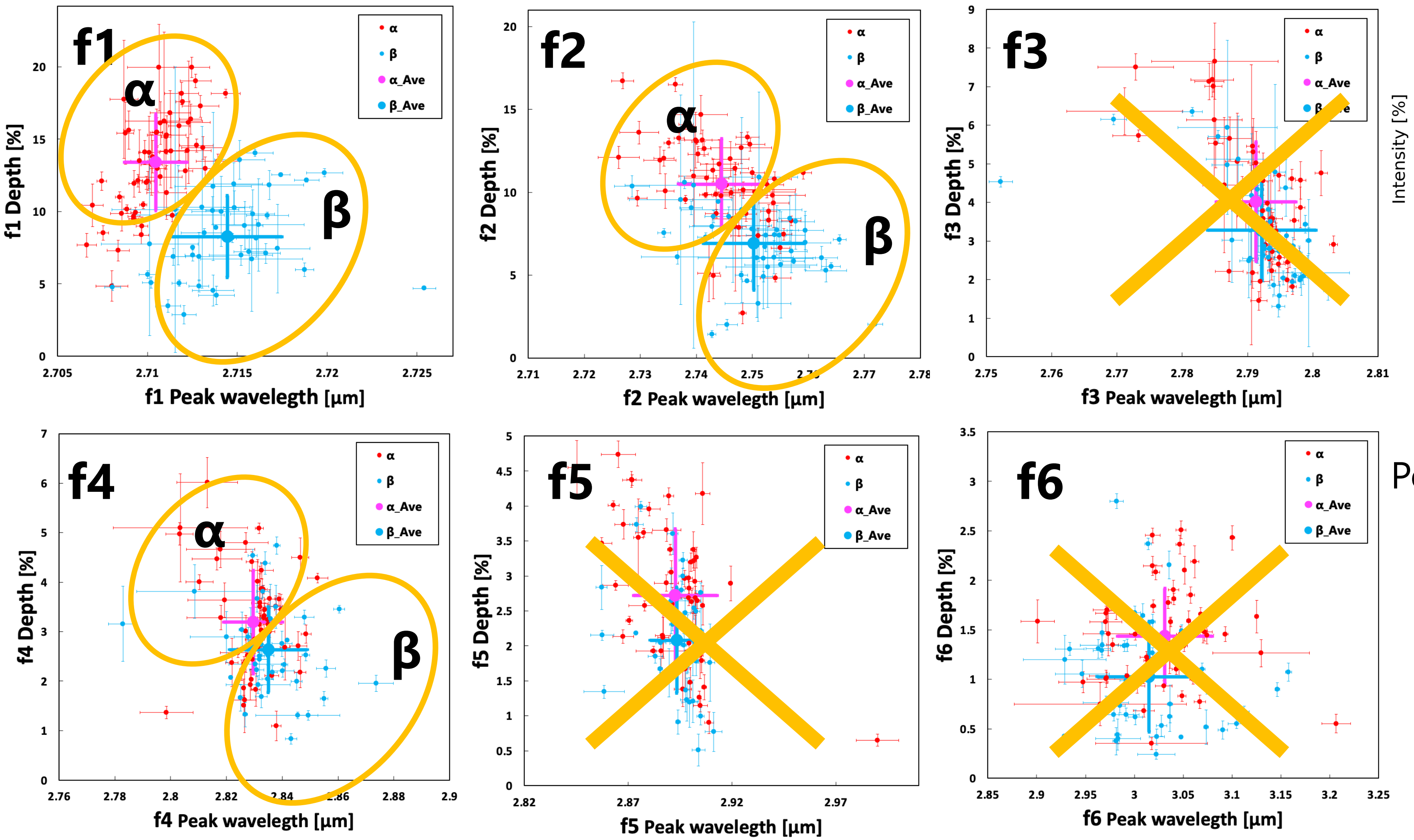
A sample illuminated by scanning monochromatic light at an angle of 35 degrees forms an image in the 2D HgCdTe detector array cooled by a cryo-cooler (3D (x,y,λ) hyperspectral cube is constructed).

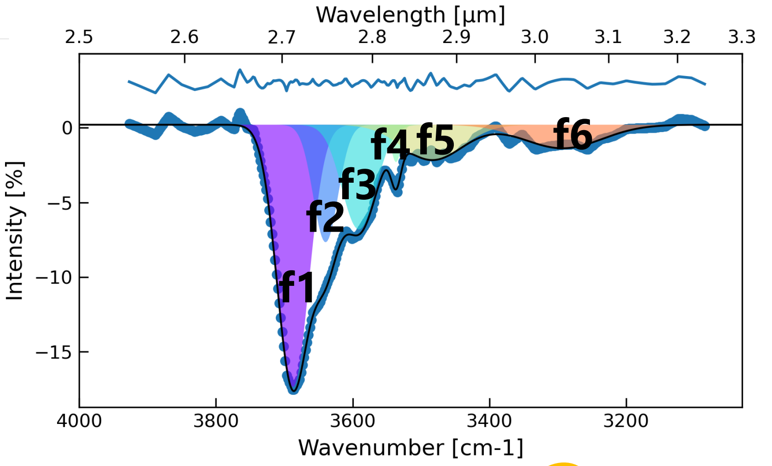
＜ Measuring conditions ＞

- Installed in an N_2-purged acrylic chamber to prevent air pollution and water ingress.
- A black cover is used to prevent stray light during measurement.
- A water-cooled copper plate is installed at the bottom of the instrument to maintain the temperature at 10℃.
- The detector is cooled to 110 K by a cryogenic cooler.
- The sample is measured through a sapphire window (the sample chamber is also under N_2 conditions and the sample is placed on an integrated gold mirror substrate).
- Rotating the stage affects shadows and specular reflection due to the shape of particles and inclusions (→ averaging may weaken the actual absorption band intensity)
- Use infragold and spectralon for calibration

Appendix 2: f1, f2 and f4 could correspond to the OH group

Peak wavelength vs. depth of f1 – f6 in Chamber A samples (α, β)





f1, f2, (f4)

↓

Possibly corresponding to the same functional (OH) group

- different vibrational patterns
- bonded to different atoms

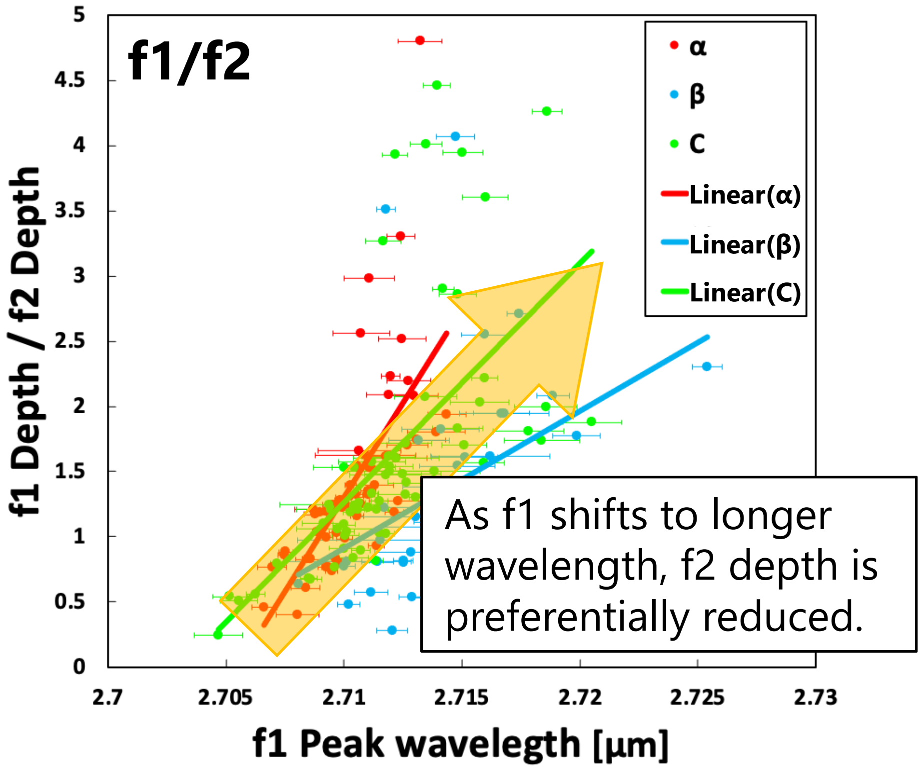
f3, f5, f6

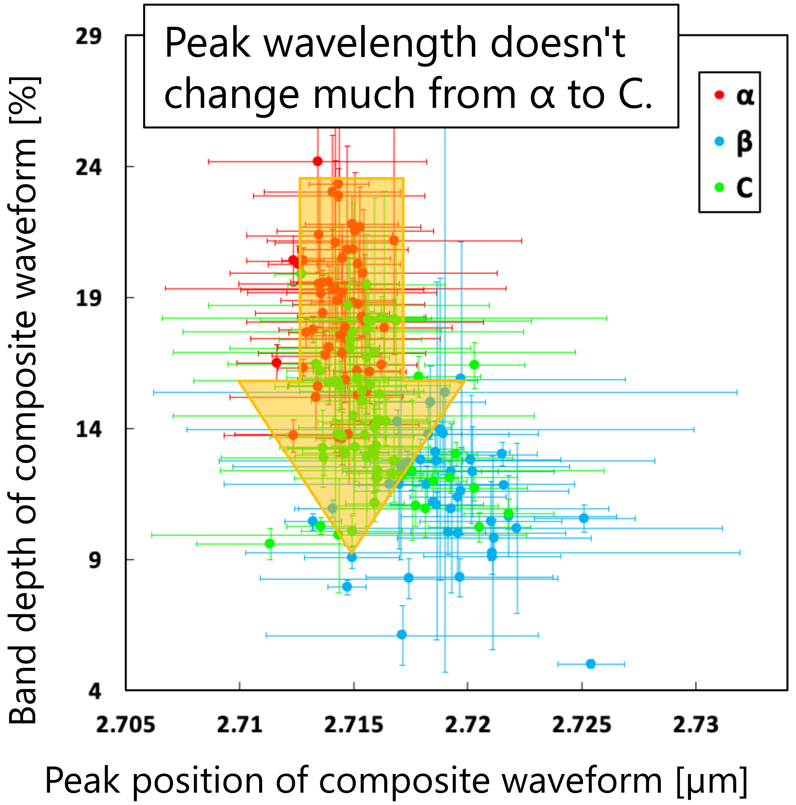
↓

Possibility corresponding to non-OH functional groups

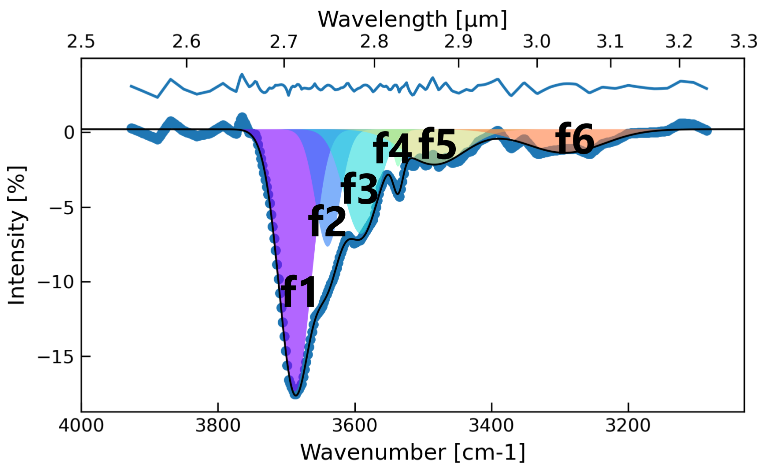
- For all f1~f6, the depth of β tends to be smaller than that of α
- The trend of longer wavelength shift from α to β was observed only for f1, f2, (f4)

Appendix 3: Mechanism of 2.7 μm band's changes due to space weathering





A(α, β)：Surface samples
C：Subsurface Samples
Space weathering: α<C<β?



【Mechanism of the 2.7 μm absorption band change due to space weathering】

1. The bond corresponding to f2 is preferentially dehydroxylated by space weathering. → α → C
2. The crystal structure of partially molten particles is disrupted due to micrometeorite impacts. [Nakato, A. et al. (2023)]
3. The vibrational modes of the bond corresponding to f1 diversify, the peak position shifts to the longer wavelength, and the depth decreases. → f1, f2, (f4) (R4).

(Items 2–3) → α → β