SMALL RYUGU FRAGMENTS ANALYZED BY IR MICRO-SPECTROSCOPY AND TOMOGRAPHY: A DESCRIPTION OF THE 3D HETEROGENEITY AT THE MICROMETRIC SCALE.

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Introduction: In December 2020, the Hayabusa2 reentry capsule returned 5.4 g of material collected on the asteroid Ryugu. This unique material was then recovered by JAXA and pre-characterized inside the ISAS curation facility [1,2]. A fraction of the collected grains is now the object of multiple studies with state-of-the-art techniques in laboratories worldwide (Initial Analysis Teams). The "Stone" team led by T. Nakamura investigates the mineralogy and petrology of the grains at a large scale [3]. Thanks to this sample return mission, we now have the opportunity to analyze samples from a primitive carbonaceous asteroid at different scales - from km, thanks to remote sensing down to µm in the laboratory. Fourier Transform InfraRed spectroscopy (FTIR) is a very valuable technique in this context. It builds a bridge between the observations of the asteroid's surface, performed by NIRS3 [4,5] and the chemical-physical processes characterized in the laboratory at smaller scales on the returned samples.

Methods: In this study, we will present the results of FTIR hyperspectral imaging on nine micrometric Ryugu fragments (ranging from 30 to 80 µm in size). These fragments originate from 3 bigger millimetric grains (A0064 from the first touchdown site, C0046 and C0002 from the second touchdown site). These grains were welded with platinum on tungsten or aluminum needles using two different FIB (Focus Ion Beam) microscopes in Saclay and Lille [6]. Then, we analyzed these fragments using an IR micro-tomography setup available at the SMIS beamline of the SOLEIL synchrotron (France). FTIR data were collected by using the Globar internal source of an Agilent Cary 670/620 micro-spectrometer. We worked with its internal Globar source. Multiple configurations were used: analyses in transmission by Infrared Computed Tomography [7] (IR-CT) and analyses in reflectance by Infrared Surface Imaging [8] (IR-SI). Complementary measurements were performed on a Continuum FTIR microscope equipped with a large range MCT/B-detector and using the IR synchrotron radiation as a source.

IR-CT allows us to assess the compositional heterogeneity in a 3D space inside the samples with a pixel size of 0.66 µm. This method, adapted for relatively small samples (< 50 µm), allows us to study the distribution of organic matter within its mineral context. In a complementary way, thanks to IR-SI, we obtain a set of reflectance maps at different angles around the grains and this allows us to assess the surface composition. In this case, we treat the grain as a planetary surface by projecting the 2D IR hyper-spectral maps on a 3D shape model. IR-SI is well suitable for larger grains to examine the heterogeneity of the mineral composition with a pixel size of 3.3 µm.

The 3D FTIR measurement is a non-destructive technique and when performed at the beginning of a multi-analytical sequence, it can be coupled to other techniques, including more destructive ones. After completing IR-CT, four fragments were sent back to Japan, to be analyzed at the BL47XU of SPring-8 synchrotron by XCT [9] to obtain complementary information concerning the 3D physical, chemical and morphological properties. Another fragment was sliced into 3-µm thin sections and analyzed in 2D with high resolution IR and Raman hyperspectral imaging and SEM-EDX.

Taking advantage of each technique, the preliminary results of the combination of the different measurements will be shown and discussed.

Results and discussion:

Average MIR signature: We will present the average IR spectra in the 2.5 – 12.5 µm range both in reflectance and transmission. Several grains showed IR signatures at ~ 2.7 µm, 3.0-3.1 µm, 3.4 µm, and 3.9 µm, in a good agreement with the bands identified by NIRS3 or by MicrOmega and FTIR in the JAXA curation facility [3, 4], plus several mid-IR signatures of great interest, such as bands attributed to Si-O stretching in phyllosilicates, and C=O stretching in organics and carbonates. It is interesting to notice that the diversity of phases identified at a larger scale (> 200 µm) [10] already exists at the scale of grains of ~20-30 µm. Indeed, few grains contain

phyllosilicates (mainly Mg-rich phyllosilicates), abundant sulfides, carbonates and organics: we will discuss the implication of such observation for the assembly of primitive matter.

Study of heterogeneity: We detected variability between the grains of the bands at 2.7 and 10 µm, possibly due to a structural / compositional variation of phyllosilicates. The most representative grain among the nine fragments (A0064-FO019) was sliced into thin sections to investigate variations amongst single fragments (at a scale smaller than 10 µm). Complementary measurements (SEM, Raman) were then coupled with high-resolution IR mapping to better constrain the mineralogy of these fragments. SEM-EDX revealed the presence of several-microns large 1/ areas with fibrous well crystallized Mg-rich phyllosilicates and 2/ areas with more fine-grained phyllosilicates mixed with Fe-rich sulfides. C-rich matter was observed as diffuse matter, mixed with the fine-grained phyllosilicate and as 200 to 800 nm size globules distributed heterogeneously in the sample.

*3D distribution of main components***:** Thank to IR-CT, we reconstructed the 3D spatial distribution of phyllosilicates, carbonates and organic matter inside several fragments. For four fragments, we superposed these IR reconstructions with the ones obtained by X-CT [11]. Generally speaking, there is a good agreement and complementarity between the two measurements. The presence of phases without any proper signature in the global MIR range (2.5-12.5 µm) could still be studied. For example, thanks to the identifications obtained by X-CT [9], we were able to assign one phase that has no proper IR signature to iron sulfides, as they modified the continuum and the shape of the MIR spectra. Carbonate-rich areas were identified in fragments from grains A0064 and C0002; we will discuss the assembly of phyllosilicate and carbonates at the micrometric scale. Co-localization of organic phases with the mineral components will be discussed as well, providing information on secondary processes undergone in the parent body of Ryugu.

Conclusion and prospect: IR tomography combined with FTIR spectroscopy on thin sections allowed us to study the co-localization of organics and minerals, helping us to understand the mineral context for the evolution of organic matter inside primitive samples. This analytical sequence presents promising prospects for the analysis of valuable samples, such as Bennu samples that will be returned to Earth in 2023 by the mission OSIRIS-REx.

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