Three-dimensional description and characterization of lithologies in Ryugu sample

Léna Jossé[1], Zélia Dionnet[1], Alice Aléon-Toppani[1], Rosario Brunetto[1], Andrew King[2], Emmanuel Gardés[3], Eva Heripré[4], Donia Baklouti[1], Zahia Djouadi[1], Cateline Lantz[1] and Kentaro Hatakeda[5]
[1]*CNRS, Institut d'Astrophysique Spatiale, Université Paris-Saclay, Orsay, France*
[2]*SOLEIL Synchrotron, Gif-sur-Yvette, France*
[3]*Laboratoire Magmas et Volcans, Clermont-Ferrand, France*
[4]*Procédés et Ingénierie en Mécanique et Matériaux, Paris, France*
[5]*Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (JAXA), Japan*

Ryugu is a rubble-pile asteroid. Similarly to CI chondrites, the samples returned by Hayabusa2 mission showed the presence of adjoining fragments of different lithologies [1, 2]. These fragments are different in mineralogy, petrology, physical structure (size, porosity) and testify the heterogeneity of Ryugu's asteroid, its complex geological history and evolution [3]. So far, several lithologies have been observed and described partly in polished sections [1, 2, 3]. In this work we used micro-computed tomography (µ-XCT) to observe, analyze and investigate lithologies in 3D. We analyzed their properties (internal structure, shape, size, composition, porosity) and their assemblages with each other in a Ryugu millimeter-sized sample with the objective to better understand Ryugu's heterogeneity and its complexity in term of formation and evolution.

We studied the 3D lithologies of the mm-sized (1.45×2.85×2.1 mm) sample A0159 from Chamber A. Data were obtained at PSYCHÉ beam-line of Synchrotron SOLEIL (France) using a monochromatic X-ray beam operating at 25 keV. Our analysis was conducted on 3D reconstructed images (CT-images, or "slices") with a voxel volume of 1.295 μm^3 and based on the linear attenuation coefficient (LAC). As a first method of data processing, we used pixel segmentation, which classifies each voxel into 5 major domains by its LAC value. The domains are, sorted by increasing LAC, 1-porosity, voids, fractures, 2-matrix, 3-carbonates, 4-sulfides and oxides. Some LAC values were difficult to associate with a specific domain so we classified them as 5-uncharacterized. This method allows us to obtain the proportion of each component within each slice and then in the entire sampl5, but also the 3D reconstruction of each component.

Contrary to the first method, the local histogram segmentation considers areas of 49×49 voxels. For each area, the calculated histogram of the proportion of pixels for a given LAC value gives access to i) the number of pixels for each of the 5 previously cited domain and ii) the LAC histogram data distribution. Then, each area was locally described in regard to composition and physical properties giving rise to lithologies. This method allowed us to obtain a 3D reconstruction of each lithology in the sample. Tomviz software was used for 3D representation and visualization.

Our preliminary results from the pixel segmentation method showed that, on average, A0159 is made of 42.0±7.0 % of matrix component, 1.2±0.5 % of sulfides and oxides, 4.7±2.8 % of porosity, voids and/or fractures and 27.5±4.7 % of uncharacterized material (undefined components, or technique artifacts). Finally, carbonate components represents 24.1±2.5 % of the sample, a much higher value than previous studies [4]. The 3D reconstruction of carbonates shows a mm-sized vein going through A0159 (fig. 1), indicating important fluid circulation. The vein is about 1100×900×100 µm and it is the largest vein observed so far in a Ryugu sample. Its presence explains the high proportion of carbonate material in A0159. We detected two highly fractured plans along both sides of the vein. The vein ends up with coarse and elongated to rounded carbonate grains with inter-grains voids. In other studies, a complex and elongated structure of size >100 µm was observed in sample C0041 and found to have a wide range of (Mg-Fe)-carbonate composition between siderite–magnesite (or breunnerite) [5, 6]. In sample C0009, [3] found elongated Ca-carbonates forming a chain that they proposed to be a potential remnant of a vein. The detection of a mm-sized vein in A0159 suggests that Ryugu's parent-body has probably undergone notable water flow through, at least, a mm-sized fracture and that carbonate precipitated as a vein.

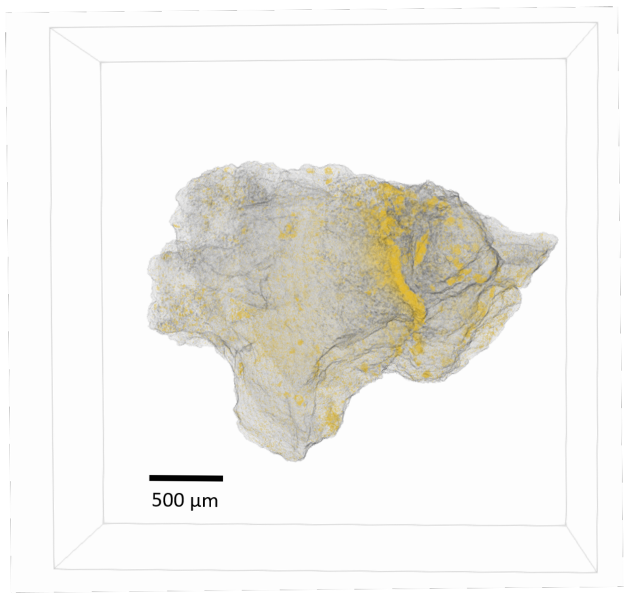

Figure 1: 3D reconstruction of the Ryugu sample A0159 (in grey) combined with the distribution of carbonates (in yellow).

The preliminary results of the second method allowed us to detect several different lithologies. A study is ongoing to determine the exact number of lithologies. These lithologies are mostly composed of matrix with various size and proportion of carbonates, sulfides, oxides, and porosity. One peculiar lithology is made of a compact matrix component, few carbonates, uncharacterized material, sulfides and oxides. This lithology could match the ”massive domain” seen by [1] in A0035 or the ”fine-grained dark lithology” in C0009 by [3]. The compact lithology is surrounded by long (up to 800 µm) and large fractures (up to 20 µm) and, similarly to [1], some fractures also cross the lithology. Another lithology is rich in rounded and elongated grains of carbonates about 50 µm in size and is located at the end of the vein. This lithology has many small fractures (up to 100 µm long and 10 µm large) which seem to be preferably located around the grains such as in A0037 [3]. However, crossing and surrounding fractures are not present in each lithology. The second method is still ongoing and it is not clear yet whether the carbonate vein crosses a single lithology. However, our preliminary results confirm that Ryugu is a breccia with adjoining fragments of various size (from 100 to 500 µm), composition and physical properties. The analysis of the fractures (distribution, size and shape) strongly indicates a heterogeneity in the mechanical properties of lithologies. All these observations testify the complexity of Ryugu and/or parent-body formation and evolution and its geological past.

References

[1] E. Nakamura, K. Kobayashi, R. Tanaka, T. Kunihiro, H. Kitagawa, C. Potiszil, T. Ota, C. Sakaguchi, M. Yamanaka, D. M. Ratnayake, *et al.*, “On the origin and evolution of the asteroid ryugu: A comprehensive geochemical perspective,” *Proceedings of the Japan Academy, Series B*, vol. 98, no. 6, pp. 227–282, 2022.

[2] T. Nakamura, M. Matsumoto, K. Amano, Y. Enokido, M. Zolensky, T. Mikouchi, H. Genda, S. Tanaka, M. Zolotov, K. Kurosawa, *et al.*, “Formation and evolution of carbonaceous asteroid ryugu: Direct evidence from returned samples,” *Science*, p. eabn8671, 2022.

[3] A. Yamaguchi, N. Tomioka, M. Ito, N. Shirai, M. Kimura, R. C. Greenwood, M.-C. Liu, K. A. McCain, N. Matsuda, M. Uesugi, *et al.*, “Insight into multi-step geological evolution of c-type asteroids from ryugu particles,” *Nature Astronomy*, vol. 7, no. 4, pp. 398–405, 2023.

[4] C. Pilorget, T. Okada, V. Hamm, R. Brunetto, T. Yada, D. Loizeau, L. Riu, T. Usui, A. Moussi-Soffys, K. Hatakeda, *et al.*, “First compositional analysis of ryugu samples by the micromega hyperspectral microscope,” *Nature Astronomy*, vol. 6, no. 2, pp. 221–225, 2022.

[5] D. Loizeau, C. Pilorget, L. Riu, R. Brunetto, J.-P. Bibring, A. Nakato, A. Aléon-Toppani, K. Hatakeda, K. Yogata, J. Carter, *et al.*, “Constraints on solar system early evolution by micromega analysis of ryugu carbonates,” *Nature Astronomy*, pp. 1–7, 2023.

[6] A. Nakato, T. Yada, M. Nishimura, K. Yogata, A. Miyazaki, K. Nagashima, K. Hatakeda, K. Kumagai, Y. Hitomi, H. Soejima, *et al.*, “Variations of the surface characteristics of ryugu returned samples,” *Earth, Planets and Space*, vol. 75, no. 1, p. 45, 2023.