**Title:** Preliminary analysis of the Hayabusa2 samples returned from C-type asteroid Ryugu.

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**Introductory Paragraph**

C-type asteroids1 are considered to be primitive small Solar-System bodies enriched in water and organics, providing clues for understanding the origin and evolution of the Solar System and the building blocks of life. C-type asteroid 162173 Ryugu has been characterized by remote sensing2-7 and on-asteroid measurements8,9 with Hayabusa210. However, the ground truth provided by laboratory analysis of returned samples is invaluable to determine the fine properties of asteroids and other planetary bodies. We report preliminary results of analyses on returned samples from Ryugu for its particle size distribution, density and porosity, spectral properties, textural properties, and results of a search for Ca-Al rich inclusions (CAIs) and chondrules. The bulk sample mainly consists of rugged and smooth particles of millimeter to submillimeter size, preserving physical and chemical properties as they were on the asteroid. The power index of its size distribution is shallower than that of the surface boulder observed on Ryugu11, indicating difference in that of the returned Ryugu samples from that of observed boulders. The average of estimated bulk densities of Ryugu sample particles is 1282 ± 231 kg m-3, which is lower than that of meteorites12 suggesting a high micro-porosity down to millimeter-scale, which is extended from centimeter-scale estimated by thermal measurements5,9. The extremely dark optical to near-infrared reflectance and the spectral profile with weak absorptions at 2.7 and 3.4 microns implying carbonaceous composition with indigenous aqueous alteration matches the global average of Ryugu3,4, confirming the sample’s representativeness. Together with the absence of CAI and chondrule of larger than sub-mm, these features indicate Ryugu is most similar to CI chondrites but with low albedo, higher porosity and more fragile characteristics.

<272 Words>

**Main Text**

On 6th of December 2020 in South Australia, samples from the C-type asteroid 162173 Ryugu were returned to Earth in the hermetically sealed container within the reentry capsule13, and transported to the curation facility in Sagamihara, Japan. Samples were recovered to perform the initial descriptions before delivery for in-depth investigations by the nominated analytical teams and for future researches worldwide, in a non-destructive manner and under a strict contamination controlled conditions. The asteroid Ryugu is the fourth extraterrestrial body whose samples have been returned to the Earth by spacecrafts, following the past sample return missions after Apollo14, Luna15 and Chang’e-516 from the Moon, Stardust from comet 81P/Wild217 and Hayabusa from near-Earth S-type asteroid Itokawa18,19. The Ryugu sample has sizes ranging from ~8 mm, the largest average diameter, down to fine dusts of sub-mm, with millimeter-scale particles being the most common (see Extended Fig. 1).

A total of 5.424 ± 0.217 grams has been collected from Ryugu (see Extended Fig.1), and this has been kept as physically and chemically pristine as possible, with handling only in vacuum or in purified nitrogen without exposure to Earth’s atmosphere. From Chamber A, 3.237 ± 0.002 grams of samples were recovered, which was collected during the first touch-down sampling (TD1) at the equatorial ridge region of Ryugu10. We assume these samples represent the surface materials of Ryugu at the uppermost centimeter-scale layer, and this layer is influenced by insolation, radiation, temperature cycling, and micro-meteoritic impacts. From Chamber C, 2.025 ± 0.003 grams of samples were recovered, and these were collected during the second touch-down sampling (TD2) at a proximal site10 to the artificial crater excavated by the Small Carry-on Impactor (SCI)6,20. We assume part of the samples in Chamber C represent subsurface materials excavated by the impact experiments, and that these samples have not experienced long-term exposure to space.

The size frequency distributions for particles larger than 1 mm handpicked from Chambers A and C bulk samples were reconstructed from individual particle measurement (Fig. 1). The distribution in sample size has a slope of -3.88 ± 0.25 in the power index. This power index of Chamber A + C particles is steeper than the global average index (-2.65 ± 0.05) obtained for boulders (5 to 140 m in size) on Ryugu or the power index (~-2) for gravels (0.02 m to several meters in size) at the local touchdown sites11 observed by the telescopic Optical Navigation Camera (ONC-T)21. The steeper power index in the returned particles implies a higher relative abundance of the smaller particles, however several interpretations for the steep power index arise including: the fragile nature of samples from Ryugu through further fragmentations during impact sampling using a bullet and the cone-shaped collector22, the shock and vibration experienced during Earth entry in the sample container mounted inside the reentry capsule23, possible artificial fractionation effects of the better transference of smaller particles through the sampler horn22, and/or a sampling bias caused by particle handpicking with vacuum tweezers by several personnel as mentioned in the Methods. The power index of Chamber A particles, -4.59 ± 0.44, is steeper than those of Chamber C, -3.15 ± 0.20, which shows a much shallower power index in the size range larger than 3 mm. This larger size enrichment in Chamber C could indicate that such larger particles might have been excavated from regolith below the Ryugu’s surface by the SCI impact close to the TD2 site10,20.

From the micrographs of Ryugu particles and their weight measured using a balance, the bulk densities of Ryugu particles can be estimated, based on assumptions mentioned in the Methods. Their average is 1282 ± 231 kg m-3 in total (see Fig. 2). This average bulk density is lower than the average bulk density of CI chondrites24 at 2110 kg m-3, as well as lower than the density of Tagish Lake meteorite25 at 1660 ± 80 kg m-3, the most porous meteorites ever found on Earth. Assuming mm-scaled sample grains have the same grain density as CI chondrite (Orgueil; 2380 ± 80 kg m-3)24, we estimate the micro-porosity of Ryugu samples to be 46%. Our value is consistent with that determined by remote thermal imaging, by the Thermal Infrared Imager (TIR)26 and on-site thermal measurements9 with the radiometer (MARA) on the Mobile Asteroid Surface Scout (MASCOT)27, which is lower than that of meteorites suggesting that thermal measurements made remotely at the cm-scale are confirmed by laboratory sample measurements made at the mm-scale. Thus the microscopic observations and weight measurements for the Ryugu samples imply their low density and/or high micro-porosity. The calculated bulk density of Ryugu’s samples is comparable to that of Ryugu’s rock estimated from bulk density of Ryugu and linear mixture packing theory, 1380 ± 70 kg m-3 within the range of variation28.

Such high micro-porosity materials have never been discovered in any meteorites found on Earth, probably due to breakup through their fragile nature during entry into the Earth’s atmosphere, or a higher abundance of lower density materials like carbonaceous materials (1300-1400 kg m-3)29 compared to any other carbonaceous chondrites. The global average density (bulk density) of Ryugu is 1190 ± 20 kg m-3, indicating a macro-porosity of 7% which is contrary to large macro-porosities required for primitive asteroids when typical meteoritic density is assumed30, provided that the returned samples collected from the two sampling sites on the surface of Ryugu are representative of bulk materials on Ryugu. The low macro-porosity of Ryugu is probably consistent with the packing model using the size-frequency distribution of Ryugu31. No substantial difference in density distribution is found between Chambers A and C, consistent with the same thermal properties inside and outside of the artificial crater32. There are particles denser than 1800 kg m-3 (> 2σ) in Chamber A, that being within the density range of typical meteorites found on Earth12, and indicating Ryugu might consist of a mixture of particles from different origins32 or different degree of alteration processes in the parent bodies5,32.

Optical and near-infrared reflectance profiles of the samples measured using optical microscopy, Fourier-Transform Infrared spectroscopy (FT-IR) and the infrared hyperspectral microscope (MicrOmega)33, 34 show very dark features with an albedo of ~0.02 from 0.4 µm to 4µm (Fig.3 and 4), which is in good agreement with the global average of albedo3,4 observed by ONC-T and the Near Infrared Spectrometer (NIRS3)35. The surface composition and inclusions of each sample show some variety but most of them that are considered representative of the typical surface materials of Ryugu, having spectroscopically homogeneous and featureless characteristics without apparent high temperature components like chondrules or Calcium-Aluminum-rich-Inclusions (CAI) but with many bright and patchy fine inclusions (See Extended Fig. 1). Although full photometric measurements are needed to elucidate the optical properties of Ryugu samples, the apparent rarity of chondrules in Ryugu samples is consistent with prediction by the previous study28. The surface morphology of the samples is mainly classified into two patterns of rugged and smooth surfaces even at the millimeter to sub-millimeter scale, which is similar to the patterns found for centimeter to meter scale surfaces3,8 observed by ONC-T and by the imager on MASCOT (MasCAM)36. The presence of different types of surface morphology may indicate past mixing processes of materials of different origin or of the different degrees of alteration5,7,32. The shape distribution of particles, which has been studied in a separate paper13, shows variations in aspect ratios, including the elongated and flattened ones, consistent with the ejecta observed during the sampling operations13.

In order to perform reconnaissance sample analyses at this curation phase, a purely non-destructive and non-invasive characterization of the composition is performed by near infrared spectroscopy, through the two complementary instruments. Both FT-IR and MicrOmega analyses for bulk samples from Chambers A and C show spectral profiles, from of 1 to 4 µm wavelength range with a footprint e of ~6 mm diameter (See Fig. 3) by the FT-IR, and as hyperspectral image-cubes of 256x256 pixels (22 µm pixel size), with up to 400 spectral channels covering the 0.99 to 3.65 µm spectral range. Both exhibit clear absorptions at 2.7 µm and 3.4 µm, for both samples. The narrow and relatively deep (~15%) absorption feature peaked at 2.72 µm indicates presence of hydroxyls (-OH) in the samples, which is comparable to the 2.72 µm absorption feature detected from all over the Ryugu surfaces by NIRS34 but the absorption peak position is in better agreement with the materials excavated by the SCI impact experiment37. MicrOmega high spatial resolution enables us to identify a few submillimeter grains, with distinct and highly diagnostic spectral features. As an example, an absorption centered around 3.4 µm, also present in FT-IR spectra, corresponds to both carbonates and CH-rich phases. Similarly, an absorption centered around 3.1 µm is interpreted as related to NH-rich compounds, as it has been postulated to be similar to that observed on 1 Ceres38. These detections are evidence of aqueous alteration of Ryugu’s parent body, and are coupled to the non-detection of high temperature components like chondrules and CAIs. They point towards the Ryugu parent body being more similar to CI chondrites than to any other types of meteorites found on Earth (see Extended Table 1). Details of the MicrOmega findings are presented in a companion paper34.

High-resolution (5 µm/pixel) optical microscopic imaging through six filters, compatible with the ONC-T camera of Hayabusa23,7, was conducted for bulk samples from Chambers A and C (see Fig. 4). The disk-averaged spectra and reflectance of Earth-returned samples from 0.39 - 0.85 µm (ul to x band on ONC-T) agree well with the disk-averaged spectrum of Ryugu3; very flat spectra consistent with Cb type and low (0.02 at v band) reflectance under the geometric condition with incidence, emission and phase angles of 30°, 0°, and 30°, respectively. This agreement indicates that Earth-returned samples represent well the Ryugu surface materials. Both visible and infrared reflectance of the samples from the Chamber A and C are brighter than those of remote sensing data taken by ONC-T3,7,39 and NIRS34,37 beyond their observation and analytical errors (Fig. 3 and 4), which may be attributed to differences in surface conditions of samples between the asteroid surface and obtained samples and/or the possible contribution of reflected light from the bottom surface of the sapphire dishes. Infrared reflectance of the Chamber A bulk samples is brighter than that of the Chamber C in both data taken by the FT-IR and the MicrOmega, although some variations in wavelength exist in that of the MicrOmega results34. This tendency is inconsistent with results from the NIRS3 observation, which shows deeper absorption in 2.72 µm close to the TD2 site compared to other surface materials on Ryugu37. Although optical and infrared microscopic images show that Ryugu sample particles exhibit many bright spots (Extended Fig.1), most bright spots disappear at a different viewing geometry so that they are not intrinsic to compositional variation (e.g., CAIs and chondrules) but caused by different photometric conditions34. Many bright spots found on the surface of boulders in the on-asteroid images8, but most of them may be caused by photometric effects.

Our initial observations for the entire set of returned samples in the lab demonstrate that Hayabusa2 retrieved a representative and unprocessed (albeit slightly fragmented) Ryugu sample. Our data further expands an idea based on the remote sensing observations that Ryugu is dominated by hydrous carbonaceous chondrite-like materials, somewhat similar to CI chondrites, but with darker, more porous, and more fragile nature. This inference should be further corroborated by in-depth investigations hereafter by state-of-the-art analytical methods with higher resolution and precision. Those initial descriptions by Hayabusa2 provide a good showcase for future sample returns missions and their curation.

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<Total = 272 + 1933= 2205 Words> 205 words over the limit of 2000 Words

**Methods**

*Hayabusa2 sample recovery and transportation to the Curation Facility without leaking.*

On 5 December 2020,the reentry capsule was released from the spacecraft and entered the Earth’s atmosphere on 6 December 2020 , after a successful returning cruise from Ryugu to the Earth. The reentry capsule retrieval operation was carried out complying strictly with the Australian COVID-19 regulations. The landing area of the capsule was determined by receiving a beacon signal transmitted from the capsule using five antennas installed at different locations. The Marine radar systems and two Drones were also used for this retrieval operation of the capsule, the heat shields, and the parachute. The reentry capsule was located nearby the parachute, which was found from the helicopter observation. The safety check of the capsule was first completed at the landing location because pyrotechnic devices were used for the parachute deployment and separation. No damage to the capsule was observed, and the capsule was transported back to a Quick Look Facility (QLF) prepared in the Woomera Prohibited Area (WPA) with a permission from the Australian safety officer. The reentry capsule was recovered from the landing site in the WPA, South Australia five hours after its landing, and transported to the QLF. The capsule was introduced into the clean booth in the QLF and the sample container was extracted from the capsule and cleaned on its outer surface after the safety check (see also Extended Fig. 2). The temperature monitor attached to the sample container indicated that the container was never heated up to 65°C, which is much lower than outgas temperature of water, ~100 °C.

The container was installed on the Hayabusa2 GAs Extraction and Analysis system (GAEA). After the overnight evacuation of the vacuum line of GAEA, on Dec. 7, the bottom of the sample was pierced with a tungsten carbide needle to release sample volatile components held inside the sample container23. The container was in vacuum, indicating the container seal held during reentry and therefore experienced no terrestrial contamination. The gas extracted from the sample container was split into four gas tanks at room temperature, and the residual gas in the system was then trapped into two gas tanks cooled at liquid nitrogen temperature. A fraction of the gas was analyzed by a quadrupole mass spectrometer (WATMASS, Tokyo Electronics). The sample container was put into a nitrogen-purged anti-vibration transportation box and was safely transported to Extraterrestrial Sample Curation Center (ESCuC) in the Sagamihara Campus of JAXA on 8 December 2020(~57 hours after the capsule landing). Then a heat shield made of carbon reinforced plastic was removed from an outer lid of the container after drilling work with a milling machine to expose head of bolts and remove them. The Hayabusa2 sample container was sealed with the metal-to-metal sealing system22,23. The container lid was pressed against the container edge with a pressure load of ~2700 N through pressure springs. To open the container in the clean chamber designed for Ryugu samples in vacuum, the container was installed into the container opening system. The pressure springs and the outer lid with latches were then taken apart from the container while keeping the pressure load constant. The container with the opening system was then attached to the clean chamber, designed to maintain the Ryugu samples in vacuum, on Dec. 11 (132 hours after its Earth landing) and was opened on Dec. 14, 2020 after the chamber evacuation.

As the outer surface of the container was cleaned, the outer lid was firstly anchored to access to an inner lid, then the inner lid was anchored with rods to remove the outer lid and a frame for latches. Finally, the inner lid was anchored with the container opening system (Extended Fig. 2).

*The Curation Facility for Hayabusa2 and its cleanliness control.*

The concept of Hayabusa2 curation is to initially make non-destructive measurements and to deliver it for further detailed investigations without any contamination of terrestrial materials or exposure to the terrestrial atmosphere. Therefore, the curation facility is equipped in the ISO 6 or Class 1000 clean room protocol (1000 dust particles of ≥ 0.5µm in diameter in cubic feet)40. The clean chambers (CCs) for Hayabusa2-returned samples are prepared for handling samples under vacuum or ultra-purified nitrogen atmosphere without exposing to terrestrial atmosphere41. They are composed of five independent chambers; CC3-1 for opening the container in vacuum, CC3-2 for opening the chamber A of the catcher and remove a few particles from the chamber in vacuum, CC3-3 for exchanging environment from vacuum to purified nitrogen, CC4-1 for dismantling the catcher to extract the samples from each chamber, and CC4-2 for observation and weighing the samples. All the sample containers, pick-up devices, handling tools, and other jigs and tools used in the clean chambers are specially cleaned to avoid contaminations and their materials are highly controlled to minimize the possibility of chemical reactions with the samples42.

*Pick-up of the Hayabusa2 samples from the container*

As the sample container opening system was connected to the CC3-1 with dry air purged condition, the chamber was evacuated to reach high vacuum as 10-6 Pa. Then the chamber was in static vacuum condition to open the inner lid of the container. Soon after opening the container, the chamber was evacuated again. The sample catcher which is combined with the inner lid was extracted from the container and bottom of the container was left behind the chamber. Then the catcher was turned upside down to make the cover of Chamber A of the catcher face upward, and it was transported from the CC3-1 to the CC3-2 and a gate valve between them was closed. In the CC3-2 of vacuum condition, the surface of the cover of the Chamber A was firstly cleaned with a Teflon spatula. Then all the screw bolts of the cover were unscrewed and the cover was removed with an electrostatic chuck to expose samples inside the Chamber A of the catcher. A large numbers of black particles of > mm size were observed inside the Chamber A.

A few particles of mm-size were removed from the chamber with a sample handling tool equipped with the CC3-2 and put into a quartz glass dish. A cover made of quartz glass was attached on the opening of the Chamber A of the catcher, and the catcher was transported from the CC3-2 to the CC3-3 and the gate valve between them was closed. The CC3-1 and CC3-2 continued to evacuate after that. The CC3-3 was slowly purged with purified nitrogen to reach atmospheric pressure. After that, the catcher was handled with tools and jigs manipulated with Viton-coated butyl gloves equipped in the CC3-3, CC4-1 and CC4-2. Firstly, a jig for handling was attached to the catcher and the screw bolts to connect the catcher with the inner lid were removed to separate the catcher from the lid.

Then the catcher was transported to CC4-2 through CC4-1 to measure its weight with a balance equipped in the CC4-2. Based on the design weight of the catcher and a tare weight of the attached jig, the total weight of samples inside the catcher is calculated to be 5.424 ± 0.217 grams. The balance used for weighing is Mettler-Toledo XP404s, with an outer cover modified from its original to one made of stainless steel 304 sealed with Viton and with power and signal cables modified from the originals to ones coated by Teflon.

An optical microscope Nikon SMZ1270i with XYZ electric motors system is equipped above the CC4-2, and black particles inside the chamber A of the Catcher were photographed with the microscope. The catcher was then transported to the CC4-1 and it was dismantled with tools and jigs to extract samples from each of the Chambers (A, B and C) to containers made of sapphire glass (see supplement for its spectral feature), set underneath funnels made of stainless steel 304. After several large particles were handpicked directly from the opening of the funnels with a vacuum tweezer, samples from the Chamber A and C were divided from the funnels into three sapphire containers with a spatula made of stainless steel. Samples inside the Chamber B, which was exposed to the sampler horn after the TD1 and before the TD210, were also recovered into a sapphire container, which are only a small amount of powders of 13 ± 0.5 mg, indicating only a limited amount of samples should be mixed up between three Chambers. The samples in the sapphire containers were measured by weight with a balance, and spectrally characterized with FT-IR, MicrOmega and visible spectrometers. Next, particles of >1mm in size in the container were handpicked one by one with a vacuum tweezer having a nozzle made of stainless steel 304, and deposited into a sapphire dish for individual particles to be photographed, weighed, and measured with FT-IR and MicrOmega.

These obtained data are catalogued for further detailed researches that started in summer 2021. Further, the sample will be open to the community and distributed through the Hayabusa2 Sample Allocation Committee in summer 2022.

*Outline of measurements for sample description*

Multiband optical images of the Ryugu samples were taken using a nadir-viewing camera system with a macro lens and a monochrome CMOS detector (Kiralux CS895MU) with illumination at 30° from the nadir43. We used 6 filters (ul: 0.39 µm, b: 0.48µm, v: 0.55 µm, Na: 0.59 µm, w: 0.70 µm, x: 0.85 µm) compatible with the telescopic optical navigation camera (ONC-T) of Hayabusa23,22 to the illumination for macro lens measurements.

*Spectroscopy of Ryugu samples*

The FT-IR used for this study is JASCO VIR-300, equipped to the CC4-2. Its can measure infrared spectrum from 1.0 µm to 4.0 µm in wavelength. Its minimum beam spotsize in the focused position is 1 mm, and a nominal beam spot for bulk sample measurement size is 6 mm. The incident beam comes through a sapphire viewport to illuminate samples inside an FT-IR chamber attached to the CC4-2 of purified nitrogen condition. Before and after the sample measurement, the incident and emission angles of infrared light are designed as 16 degree, thus phase angle for the samples is 32 degree. The NIRS3 spectrum was created by averaging 128 spectra acquired on May 15, 2019 (see the Extended Data Table 2 of Kitazato et al. (2021)44 for details). Its reflectance values have been corrected to the same viewing geometry (incidence = 16˚, emission = 16˚, phase = 32˚) using the latest photometric model45. Error bars are 1-sigma. The instrument which includes incident and reflected light paths is purged with nitrogen to decrease influences of absorption of atmospheric molecules like H2O and CO2. Infragold is measured before sample measurement for compensation of the background. No obvious effect of sapphire containers is detected for the bulk samples‘ analyses.

The detailed method about MicrOmega is detailed in another paper34. MicrOmega is mounted on the dedicated chamber attached to CC3-3. The samples are on the XYZ and rotation position changeable stage within the cleaned conditions, and observed with the MicrOmega through the sapphire window.

*Size distribution and density determination of Ryugu particles*

The sizes of Ryugu particles are measured from their optical microscope images taken after their separation into individual containers. Note that separation of particles with the tweezer was made by curatorial members of the ESCuC, which might possibly cause a sampling bias. For the analyses of their size distributions, major and minor diameters are calculated based on eclipses circumscribed to the binarized images of particles, and averages of the major and minor diameters are used as the size of the particles. A cumulative number of particles to their average diameters is plotted as Fig. 1, and a power index fitting to the distribution is calculated by maximum-likelihood fitting methods with goodness-of-fit tests based on the Kolmogorov–Smirnov statistic46,47.

For the volume estimation of a handpicked particle, its size, *Dp*, is calculated as follows;

(1),

where *a* and *b* is its major and minor Fetet diameter, respectively, measured based on its optical microscopic image, and *t* is its thickness, measured by focusing top and bottom of the particle using the optical microscope. Using *Dp* calculated by (1), the volume of a Ryugu particle is calculated as a following formula based on the reference48;

(2).

The densities of particles are calculated from the volumes calculated with the formula and weights measured with the balance in CC4-2 (Fig. 2). Typical errors in the density calculations range from 30 to 500 kg m-3, mainly due to uncertainties of estimation of their volumes. The estimated volumes should include all the pores inside sample particles, thus the calculated densities correspond to bulk densities of the particles, not grain densities, which are calculated based on volumes excluding pores inside the particles.

*Data Availability Statement*

Here we note that all source data for the figures in this article is provided in the Supplement Items.

(2146 words)

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Author Contributions Statement:

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**Extended Table 1:** Summary table of Ryugu samples compared with meteorites25,30,49-51, updated from Jaumann et al. (2019)8. Bold characters mean good matching to Ryugu, normal characters stand for moderately matches, and italic characters mean poor match.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Reflectance at 0.55 µm | CAIs (vol%) | Chondrules (vol%) | Bulk density (kg m-3) | 3 µm band adsorption |
| Ryugu | ~0.02 | Not observed | Not observed | 1282 ± 231 | Yes |
| CI | 0.063 | **<0.01** | **0** | 2110 | **Yes** |
| Tagish Lake | **0.02** | **rare** | *<17* | 1660 | **Yes** |
| CM | 0.065 | *1.21* | *20* | 2120 | **Yes** |
| CR | - | 0.12 | *55* | *3100* | **Yes** |
| CO | *0.10-0.13* | *0.99* | *40* | *2950* | *No* |
| CV | 0.086 | *2.98* | *45* | *2950* | *No* |

**Figures legends and captions:**

Fig. 1

Size distributions of Ryugu particles from chamber A and C. The power index of the particles in the Chambers A and C (shown as Chamber A + C, a black dashed line) is -3.88, which is much steeper than of the global average of Ryugu boulders of >5m, -2.6511. This might indicate further fragmentation could have occurred for smaller Ryugu grains before and/or after their recovery.

Fig. 2

Distributions of bulk densities of Ryugu particles from chamber A and C. Their average is 1282 ± 231 kg m-3, which is slightly larger than Ryugu bulk density (1190 kg m-3, vertical purple line)2, but much smaller than those of Tagish Lake (vertical green line)25 and CI chondrites (vertical orange line)24, indicating porous nature of Ryugu samples compared to known primitive chondrites.

Fig. 3

Infrared reflectance spectra of Ryugu bulk samples from Chamber A and Chamber C. (a) the spectra normalized to its continuum between 2.0 µm to 4.0 µm. Both spectra show 2.72 µm, corresponding to hydroxyl (-OH) absorption, and 3.4 µm, to organic molecule or carbonate adsorption, features. Faint 3.1 µm absorption is also confirmed in spectra of bulk samples analyzed by MicrOmega, indicating presence of a nitrogen-rich phase34. (b) those raw spectra are compared with remote-sensing data for Ryugu taken by NIRS34. 2.72 µm absorption feature observed with NIRS3 is confirmed by the Ryugu returned samples. The continuum of Ryugu samples is redden compared to that of NIRS3, which might reflect space weathering effect for the samples more obviously compared to remote-sensing data.

Fig. 4. Comparison of visible spectroscopic data for bulk Chambers A and C with that of ONC-T for Ryugu and other carbonaceous chondrites (CCs), of which red lines data are typical types of CCs from RELAB data3 and blue lines data are unusual types of CCs, from RELAB and Sugita et al. (2019)52. Note that each of CCs is powder samples within sizes ranging from <63 µm and <155 µm. Ryugu particles obtained from Chamber A and C show ~0.02 in albedo (reflectance factor at 30˚, 0˚, 30˚), which is comparable to remote-sensing data of Ryugu’s surface taken by ONC-T3,32. Globally, Ryugu is confirmed to be much darker than most meteorites.

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