Update of the initial descriptions and distributions of individual Ryugu samples and preparation for curation of OSIRIS-REx returned samples

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After the return of Ryugu samples by Hayabusa2 in Dec 2020, they have been described in the Extraterrestrial Sample Curation Center (ESCuC) of JAXA and distributed to the initial analyses and phase-2 curation teams for further detailed analyses. In order to provide fundamental information of the samples to researchers, a series of initial descriptions on bulk and individual Ryugu samples has been conducted non-destructively under purified nitrogen condition such as optical microscopic observations, weight measurements, infrared spectral measurements with an FT-IR, an infrared microscope MicrOmega, and visible spectral measurements using a monochronic microscope with six filters [1, 2]. These initial descriptions data are open to the public at the website of the Ryugu Sample Catalog (https://darts.isas.jaxa.jp/curation/hayabusa2/).

So far, 604 individual Ryugu grains are handpicked and described, which comprise nearly 40wt% of bulk samples recovered from the Chamber A and C. As noted previously [1], Chamber A samples corresponds to those from the first touchdown site and Chamber C corresponds to the second one where is close to the artificial crater produced on the asteroid by the Small Carry-on Impactor of Hayabusa2 [3]. Their mass distributions are shown in Fig. 1. The power index of the cumulative mass distribution of both Chamber A and C is -1.28, which is slightly steeper than the result of catastrophic impact experiments (-0.4 to -1.1) [4]. This indicates fragmentation after the past catastrophic disruption of the Ryugu parent body and re-accretion to the Ryugu body may have occurred on Ryugu's surface. The infrared spectral results with FT-IR (264 grains) and with MicrOmega (174 grains) are under detailed evaluations. So far, 202 grains have been analyzed for their visible spectra with the monochronic microscope with six filters. Their data are detailed in [5].

The first announcement of opportunity (AO) for Ryugu samples was announced from last Dec. In the 1st AO, 57 proposals were submitted and 40 of them were selected for sample distributions. The distributions of Ryugu samples to the selected PIs will be finished soon. The application of proposals for 2nd AO will be closed in the beginning of this Nov. After a series of reviewing and selection processes, the sample distributions to the selected PIs will start in the beginning of next year.

Based on the Memorandum of Understanding (MOU) between JAXA and NASA, JAXA will receive 0.5wt% of returned samples (estimated to be approximately 1.25g [6]) by the OSIRIS-REx. In order to curate the allocated OSIRIS-REx samples, a new clean room has been prepared in the ESCuC, and new clean chambers, which are designed based on the Hayabusa2 clean chambers, will be installed in the next fall. The initial analyses and subsequent distribution of the OSRIS-REx samples are still under discussion, though we aim to primarily focus on comparative studies between Ryugu and Bennu samples.

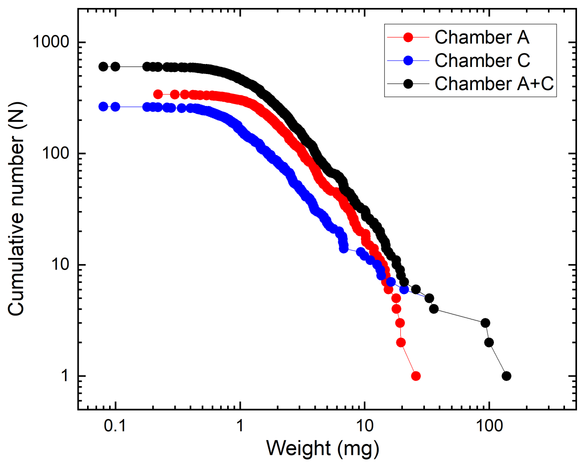

Fig. 1. A cumulative mass distribution of individual Ryugu grains from Chamber A, C, and A+C. The cumulative mass distribution from Chamber A shows a regular straight distribution whereas that from Chamber C appears irregular in >10mg weight range. This might indicate that the SCI impact by the Hayabusa2 might have disturbed the weight distribution of surface regolith on 2nd touchdown point [3].

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The Direct Asteroid Redirection Test (DART) – Preliminary Findings

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The Double Asteroid Redirection Test (DART) is the first successful full-scale demonstration of the kinetic impactor technology to deflect an asteroid. While an asteroid impact large enough to cause regional devastation on Earth is unlikely, and no known asteroid poses a threat to Earth, the consequences of such an impact would be severe (e.g., Defending Planet Earth, 2010; National Near-Earth Object Strategy and Action Plan, 2018). Here we provide a quick overview of the objectives of the DART mission, and some preliminary results.

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Radiolytic solar wind water in rims on an Itokawa regolith grain

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Introduction: The detection using electron energy-loss spectroscopy (EELS) of OH/H_2O *in-situ* in vesicles within sputtered rims on interplanetary exposed to the solar wind for ~10^4-10^5 years provided the first direct evidence that the interaction of the solar wind with oxygen-rich silicates produces water; additional confirmation was provided by detection of water using EELS in the sputtered rims on silicate mineral standards following proton irradiation at solar wind fluences [1]. The results are consistent with OH/H_2O signatures on the surface of airless bodies observed by remote spectroscopy, e.g. [2]. Regolith from the S-type asteroid Itokawa returned by the Hayabusa mission enables us to further explore the effects of solar wind irradiation on airless bodies. Enrichments in water and hydroxyl in the solar wind-irradiated rim of an Itokawa olivine grain and a lab-irradiated olivine standard have been detected using atom probe tomography [3]. Here we describe detection of OH/H_2O in the surface of another Itokawa olivine grain using electron energy loss spectroscopy (EELS).

Experimental procedure: Hayabusa regolith particle RA-QD02-0332 was carbon-coated for imaging and element-mapping in a focused ion beam-scanning electron microscope (FIB-SEM: FEI Helios 660 with Oxford Instruments EDS), and FIB sections of selected regions were extracted at Univ. Hawai'i using Pt protective straps. These were further analyzed on (scanning) transmission electron microscopes at the Molecular Foundry (S/TEM: FEI Titan ChemiSTEM with EDS, TEAM 1.0 with Gatan Continuum GIF for EELS).

Results: RA-QD02-0332 is a ~48µm grain that consists of olivine, pyroxene, plagioclase and, likely, K-feldspar. In SEM imaging, glassy melt splashes with degassing vesicles are visible in multiple locations on the surface. Fractures are observed as well as significant fine-grained adhering material, including angular fragments and spheroidal particles with melt droplet appearance. Two FIB sections crossing fine-grained material contain small mineral crystals of albitic plagioclase and fayalitic olivine with lesser amounts of high-Ca pyroxene and iron-sulfide. Fine grain sizes range from ~100 nm to several microns across, and grain shapes range from angular to euhedral to rounded, consistent with some brecciation on the parent body. Another FIB section contains a ~4 µm plagioclase grain with fracture and defects in the interior consistent with shock, an amorphized rim on one face that has lost most of its Na and some Ca relative to the underlying crystal, and surficial lacy Fe-rich material that is likely remnants of the impactor.

A FIB section through an olivine crystal shows melt splash glass and a ~40 nm in thick vesiculated amorphous rim on the surface (Figure 1a). Energy dispersive spectral mapping shows that the amorphous rim has a composition similar to the underlying olivine but with minor additional Al and Ca present. An EELS spectrum from one of the vesicles shows features at ~8 and ~13.5 eV features. These features correspond to the energy gap and H-K core scattering edge from hydroxyl and/or molecular water, like those we previously observed in rims on IDPs, water in a liquid cell, proton irradiated silicate standards and electron beam-damaged talc and brucite [1,4]. Weaker features are observed in the amorphous rim off the vesicle.

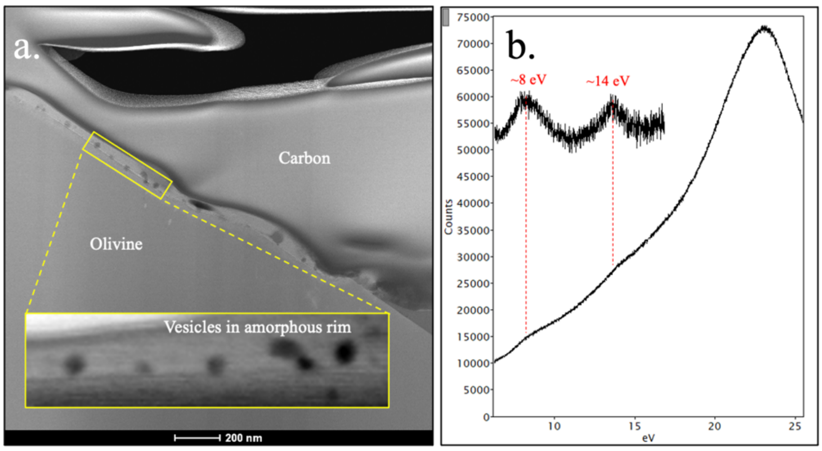

Figure 1: *(a) Darkfield image and higher-magnification inset show vesicles in amorphous rim on Itokawa olivine,.(b) EELS low-loss spectrum shows ~8 eV and ~13 eV features from one of the vesicles superimposed on the amorphous rim volume plasmon.*

Discussion: The vesiculated amorphous rim on the olivine crystal in Itokawa grain RA-QD02-0332 establishes that it was exposed to the solar wind on the surface Itokawa. Detection of water by EELS confirms the prior atom probe tomography detection of water in another solar wind-irradiated rim on an Itokawa olivine [3]. The relatively low intensity of the features observed here from the vesicle in the amorphous rim on Itokawa olivine compared to those observed in some vesicles in IDPs (Fig 1c), may be a consequence of a shorter (solar wind) exposure ages of Itokawa regolith grains relative to IDP orbital exposure ages.

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Importance of Material Properties on the Thermal Evolution Models of Parent Bodies

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Introduction: A majority of the chondritic materials in our solar system originated and were partially processed in the first ~10 million years after time 0, defined as the time when calcium-aluminum inclusions (CAIs) condensed [e.g., 1]. The primary heating mechanism for the parent body asteroids was radiogenic heating due to the decay of ^{26}Al [1]. Thermal evolution models alongside experimentally determined physical properties, such as the specific heat capacity, have been used to place constraints on the sizes and times of formation of various chondritic asteroid parent bodies [2–4]. These models allow an understanding of the processes in small bodies that formed early in the solar system history, and are a link to the shapes and geology of the asteroids observed during flyby or sample return missions.

While there are several sources of error in thermal evolution models that vary in their significance, we investigated the effect of uncertainty in some of the material properties, namely aluminum abundance, specific heat capacity, and thermal diffusivity. We adopted the thermal evolution model for the parent body of asteroid Itokawa described by [5], determined uncertainty ranges for the aforementioned material properties, and placed new constraints on the radius and formation time of Itokawa's parent body.

Methods: Our thermal evolution model follows the common approach of approximately solving the radial heat conduction equation using finite difference methods. This calculation also incorporates assumptions about the material properties and the initial and boundary conditions for the system, for which we followed the recipe from [5]. Temperature data from the thermal evolutions calculated by this model were interpolated over the whole range of realistic formation time and radius values, and then compared with known thermal constraints on the parent body of Itokawa [5]. Subsequently, we determined uncertainty ranges for the material properties from the literature: -10% to +10% for specific heat capacity [2, 6], -10% to +200% for thermal diffusivity [6, 7], and -14% to +16% for aluminum abundance [2, 8], and repeated the calculations to ascertain the effects of these uncertainties.

Results: Without accounting for any uncertainties, our model predicts a radius greater than 20.5 km and a formation time range between 1.87 and 2.24 Ma after the formation of CAIs for the parent body of Itokawa. This is in agreement with previous results [5; >20 km, 1.9-2.2 Ma]. Accounting for the uncertainty in all three parameters results in a minimum radius of 18.5 km and a formation time range between 1.6 and 2.5 Ma after CAIs.

Discussion: Although the minimum size for Itokawa's parent body reduced only by about 10%, the formation time range is significantly expanded, after taking the uncertainties into account. We observed that 10% uncertainties in both specific heat capacity and aluminum abundance contributed approximately an additional ±0.1 Ma onto the computed range of valid formation times of the body. Though the exact effects of uncertainty in material parameters on the accuracy of thermal evolution models is likely highly dependent on the specific form of the model, and the values and conditions used therein, aluminum abundance and specific heat capacity are fundamentally important to all thermal evolution models. The efficacy of such models is therefore significantly dependent on the existence of precise measurements of these material properties.

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Molecular descriptors for dictating the aqueous-alteration-induced organic decomposition in carbonaceous chondrites and return sample from Ryugu asteroid

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Background. Carbonaceous chondrites (CCs) are among the most primitive material in our Solar System. Organics such as amino acids are ubiquitously found in CCs and have been invoked to serve as life's building blocks to promote the origin of life on Earth and possibly elsewhere. Meanwhile, the chemical diversity of amino acids records the chemical evolution events prior to and after the accretion of their parent bodies. In the past decade, the advancement of analytical instrumentations, an increasing supply of samples from various CC subgroups, and the development of a more accurate petrographic classification system of CCs have facilitated the study on how parent body processes have shaped the organic distributions. However, there is a large discrepancy between experimental results and meteoritic records. Previous studies show that amino acids can be synthesized in aqueous solution containing primordial molecules, suggesting that amino acids would have accumulated upon extended aqueous activity. Nevertheless, amino acids are found to be depleted in more aqueously altered CCs, pointing to a potential "Water Paradox".

In our previous study [1], we discovered a new low-temperature geo-electrochemical process which provides a possible solution to the "Water Paradox" and proposed a new molecular descriptor of aqueous alteration degree. The geo-electrochemistry model was proposed based on the redox gradient that could be generated via water/rock interaction (Fig. 1). H_2 gas, generated through water/rock interaction, serves as the electron donor to drive the geo-electrochemical alteration of amino acids at the interface of mantle fluid and minerals. We found that three model amino acids (glycine, alanine, and valine) were decomposed to their amine and hydroxy acid analogs, and both of these two compound classes were found to coexist with amino acids and enriched in heavily aqueously altered CR chondrites. These results suggest that decomposition of amino acid dominates the chemical evolution of the parent body of CR chondrites. However, the discussion was only limited to CR chondrites due to insufficient data of amine and hydroxy acid abundances in other CC subgroups.

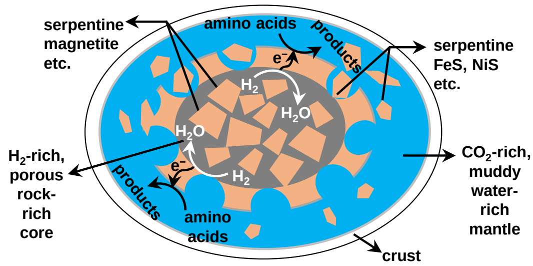

Figure 1. Model of geo-electrochemical alteration of amino acids induced by water-rock interaction in icy planetesimals (a parent body of CCs). A difference in the water/rock mass ratio (W/R) between the core (grey) and mantle (blue) leads to gradients in pH and redox.

Recently, we extended this model to other types of amino acids and found that the electrolysis of glutamate (Glu) and asparate (Asp) generates γ-aminobutyrate (γ-ABA) and β-alanine (β-Ala), respectively, via reductive decarboxylation. The enrichment of these products with respect to their amino acid precursors is found in heavily aqueously altered CR 2.0–2.4, CI as well as a return sample from asteroid Ryugu. These data suggest that the relative enrichment of derivative products can serve as a general descriptor of aqueous-alteration-induced organic decomposition. A geochemical model based on the water-rock differentiation in the parent icy plantesimals [2] was proposed to account for the observation.

Experiments and results. Electrolysis of amino acids was conducted at ambient temperature (25 ºC) in an electrochemical cell made of two compartments separated by a proton-exchange membrane. In the cathodic chamber, iron or nickel sulfide catalysts were placed on a carbon paper electrode in a pH-7 phosphate buffer containing 20 mM of Glu or Asp. An anoxic condition was maintained by continuous argon gas flow during electrolysis. Using these two sulfides as catalysts, the conversion of Glu and Asp to various products, including decarboxylated products (γ-ABA and β-Ala, respectively), α-hydroxy acids (2-hydroxyglutarate and malate, respectively) was observed after 14-day electrolysis of amino acids at −0.5∼−1.0 V versus standard hydrogen electrode (vs. SHE). The electrode potential represented the magnitude of the redox gradient (H_2 enriched core versus bicarbonate-buffered mantle) and is equivalent to the reduction potential of H_2/H^+ redox couple under specific pH and temperature conditions. A more negative electrode potential corresponds to a condition with more alkaline pH or higher temperature.

Discussion. The well-documented abundances of these four chemically related amino acids (namely, Glu, Asp, γ-ABA, and β-Ala) among different CC subgroups allow a general comparison of amino acid distribution and discussion on the impact of aqueous-alteration-induced decomposition processes (Fig. 2). Although no clear tendency can be deduced from the absolute abundances of these amino acids (Fig. 2a-2d) among different CCs, obvious enrichments of γ-ABA over Glu (Fig. 2f) and β-Ala over Asp (Fig. 2e) were discovered among heavily aqueously altered CR2.0–2.4, CI chondrites; contrastively, such enrichments are not observed in CM1–2.9 and primitive CR2.7–2.8 chondrites. Such difference implys that the impact of geo-electrochemical decomposition of amino acid highly depends on the chemical composition, degree of water-rock differentiation and the location of parent bodies in the early Solar System (Fig. 2i-2j). While we do not rule out parent body formation at various locations to account for different degree of aqueous-alteration-induced organic decomposition, here we propose another senario where CI, CM and CR sample different regions of water-rock-differentiated parent icy planetesimals formed beyond the CO_2 snow line. The accreted CO_2 ice and H_2O ice were melted by the heat generated via the decay of short-lived radionuclides. The icy planeteismal experienced water-rock differentiation and features a rock-rich core and water-rich mantle as discussed by Kurokawa et al. [2]. The low water/rock mass ratio (W/R) in the core generated alkaline, H_2-rich fluid upon water/rock interaction. In contrast, the high W/R ratio in the mantle generated neutral to weakly alkaline, CO_2-rich fluid where geo-electrochemistry proceeded and decomposed Glu and Asp to γ-ABA and β-Ala, respectively. Therefore, in light of the high abundance ratio of γ-ABA/Glu and β-Ala/Asp in CI and CR 2.0–2.4 chondrites, it is possible that these chondrites originally sourced from the mantle (Fig. 2i-2j). This is consistent with the observation of similarly high enrichment in the samples obtained from the surface of Ryugu asteroid (Fig. 2e~2h), which was suggested to be CI-like body with an outer Solar System origin [5, 6] and processed by low temperature aqueous alteration (30 ^{o}C) [6]. In contrast, the very low abundance ratios revealed in CM1–2 and CR2.7–2.8 chondrites indicate that they were sourced from the rock-rich core, as no geo-electrochemical alteration of amino acid could proceed there. CR chould span a wide range of rock/mantle transition region, thus show a wide range of decomposition degree. Based on these results and discussions, we propose that the relative abundance ratios of derivative products/organic precursors can serve as a general molecular descriptor for dictating the aqueous-alteration-induced organic decomposition as well as sheding insight into the water/rock differention status of icy planeteismals at their early evolution period [2]. This can shed implications on the chemical evolution and cycling within the parent bodies, as well as provide chemical models for guiding the future space missions to asteroids and return sample analyses.

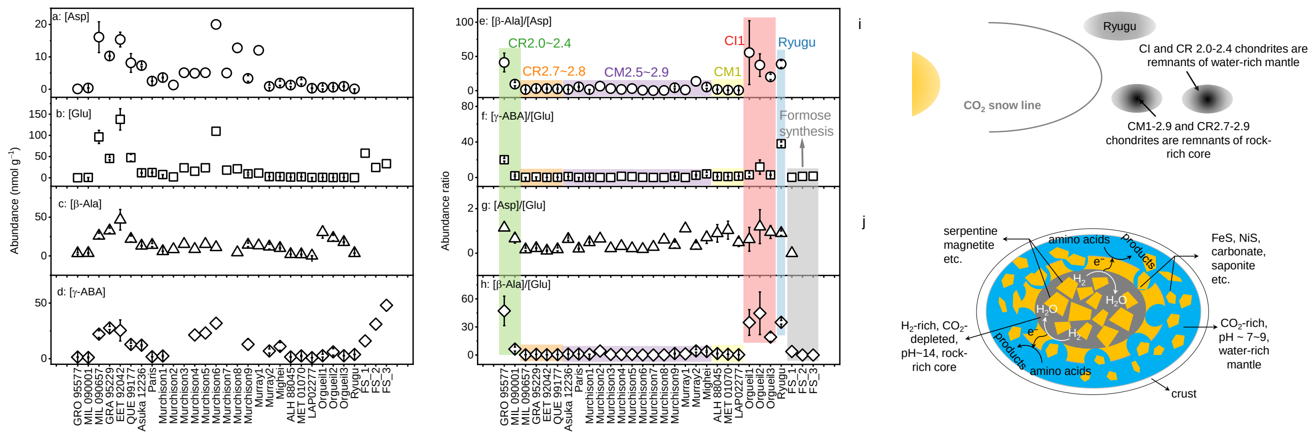

Figure 2. The molar abundances of aspartate (a), glutamate (b), and the decarboxylated products β-Ala (c), and γ-ABA (d) in different carbonaceous chondrites and Ryugu sample reported recently [3]. FS_1–3 indicates the Formose-type synthesis results at 90–150 ^{o}C reported by Kebukawa et al. [4]. e, f, g, and h plotted the molar ratios of β-Ala/aspartate, γ-ABA/glutamate, aspartate/glutamate, and β-Ala/glutamate, respectively, in these samples. i and j depicted the model that can explain the different decomposition degree in e–h among different carbonaceous chondrite subgroups resulted from geo-electrochemistry in a water-rock differentiated parent body.

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The reproduction experiment of radial pyroxene chondrules using aerodynamic levitator furnace in a reduced condition

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We performed reproduction experiments of radial pyroxene chondrules (RP chondrules) using the aerodynamic levitator furnace in a reduced condition that simulates the environment in the protoplanetary disk [1]. Chondrules were formed by flash heating of solid precursors and crystallization during subsequent cooling. They show characteristic texture that refracts thermal histories and the local environment of the protoplanetary disk [2]. In this study, we attempt to constrain the thermal history of the RP chondrules, which formed at high temperature by total melting of the precursor material.

The experiments were performed using the aerodynamic levitator furnace at Tohoku University [3]. The sample spheres were levitated by Ar-H_2 gas (Ar = 97 %, H_2 = 3 %), heated to melt by a CO_2 laser (LC-100NV from DEOS), and cooled to crystallize in a non-contact state. The cooling rates were from 1 to ~1000 °C/s in the temperature range from 1600 °C to 500 °C. During cooling small glass particles called "seed" impacted the molten sample to crystallize pyroxene. The furnace was enclosed in an acrylic container and the inside of the container was replaced with Ar-H_2 gas to achieve a reducing atmosphere of ΔIW from -1.5 to -0.5. The starting material was a mixture of oxide powders (SiO_2, MgO, FeO, CaO, Al_2O_3, and Na_2O) with three different compositions similar to natural RP chondrules [4-6]. No metallic Fe was used. During the experiment, images of the samples were taken with a CCD camera (ELMO) and a high-speed monochrome camera (Photron FASTCAM-Net Max). The temperature of the samples was measured with a radiation thermometer (LumaSense Technologies ImpacIN140/5-H). After the heating experiments, the samples were then buried in an epoxy resin and polished. The microstructure was observed and chemical composition was determined using SEM/EDS (Hitachi S-3400N) and FE-SEM/EDS (JOEL JSM-7001F).

The experiment reproduced RP chondrules: radial pyroxene crystals growing from one or more points, mesostasis glass filling in between the pyroxene crystals, and two types of metallic iron with different morphological characteristics. Pyroxene crystals have dendritic shapes with linear surface contours, or are an aggregate of fine crystals similar to that in cryptocrystalline chondrules, indicating rapid crystallization from a supercooled melt. The Mg# of the pyroxene crystals reflect Mg/(Mg+Fe) ratios of the starting materials. Some samples have Fe-rich overgrowth on large (> 1 μm) Mg-rich pyroxene crystals, suggesting that the rapid crystal growth was followed by continued slow crystal growth due to slow cooling (1-10 °C/s).

The metallic iron in the samples was classified into two types based on the texture: one was primary metal which is variable in size from μm to mm, crossing the radial pyroxene crystals. SEM observations showed that relatively small (< 10 μm) primary metals are incorporated into the pyroxene crystals and that radial crystals of pyroxene were aligned along the surface of the larger primary metals. The other was submicron-size metallic inclusions (hereafter secondary metal) that occurred only in mesostasis glass (Fig.1). The secondary metal is spherical or dendritic in shape, sometimes clinging to the surface of pyroxene crystals. In addition, they were found in a portion of the sample, not in the entire sample. Both primary and secondary metals were produced by reduction of Fe oxides due to low oxygen fugacity around the molten samples (Ar-H_2 ambient gas), because no metallic iron was added to the starting material. However, the timing of formation was different between the two inferred from their texture and observation.

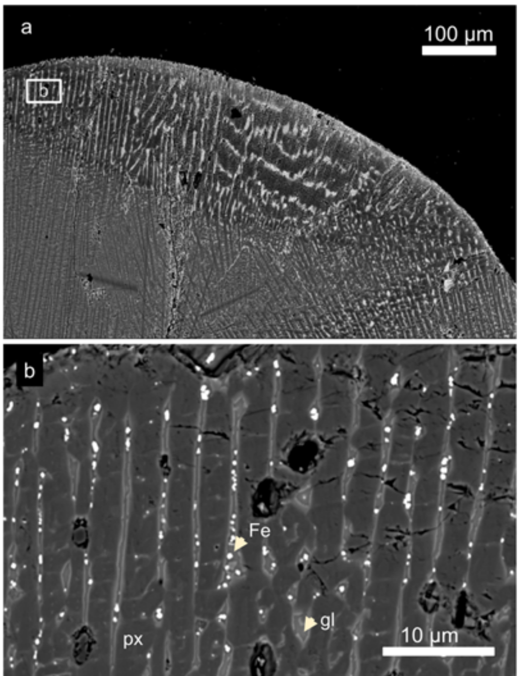

Figure 1. (a) Back-scattered electron (BSE) image of a RP chondrule produced by the experiment. Dendritic radial pyroxene crystals spread over the sample. (b) Enlargement view of the white box in (a). The spherical secondary metals are abundant in mesostasis glasses. Px; pyroxene and gl; glasses.

The primary metal was formed during total melting of the starting material. We succeeded *in-situ* imaging of the formation of the primary metal using high-speed camera: the metal sphere forms in the melt when the sample was heated for about 10 or more seconds. In addition, the textural observation indicates that the metal solidified in a silicate melt during cooling, prior to the pyroxene crystallization. On the other hand, the secondary metal is considered to have formed at temperature between the pyroxene crystallization and the glass transition (mesostasis glass formation). Secondary metal was observed in some samples cooled slowly (cooling rate is 1-10 °C/s) from the crystallization temperature to 500°C, while it was not observed in the glass of samples cooled rapidly after crystallization of pyroxene. The secondary metal formation only by slow cooling is interpreted as the time required for the reduction reaction and for the diffusion of Fe in the glass.

Similar primary type-metal inclusions are found in the natural RP chondrules, suggesting that the large metallic spheres were formed immediately after total melting by the reduction of iron oxide during chondrule formation, or they were present in the precursors. On the other hand, the metallic spheres of submicron size are universally found in natural RP chondrules, and their microstructure is similar to that of secondary metal produced in this experiment. This indicates that RP chondrules cooled at < 10 °C/s after crystallization of pyroxene and before glass solidification in a reduced condition to make secondary metallic inclusions.

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Curation Challenges Associated with the Apollo Next Generation Sample Analysis Program

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Introduction and Overview

From 1969 to 1972, the Apollo missions collected 2196 individual samples of rock and regolith from the Moon (382 kg total mass). Over the past 50 years, there have been over 3300 Apollo sample requests, utilizing >10,000 subsamples from 2190 of the original 2196 samples. These myriad studies have shaped our understanding not only of the Earth-Moon system, but also of the terrestrial planets, airless bodies like asteroids, the formation locations of the gas giants, and have even acted as a record of the radiation history of our solar system as it has revolved around the galaxy for the past 4.6 Ga. Despite all of these studies and all of this knowledge gained, there is still more to be learned from the Apollo samples. To this end, NASA solicited proposals to study unopened or specially curated Apollo samples as part of the Apollo Next Generation Sample Analysis (ANGSA) Program. Prior to the ANGSA program being initiated there were six Apollo samples that had never been opened: (1) unsealed regolith drive tubes 73002 and 70012 (drive tubes are 35 cm long and 4 cm in diameter); (2) vacuum sealed regolith drive tubes 69001 and 73001; (3) vacuum sealed bulk soil sample 15014; and (4) frozen basalt sample 71036. Additionally, there were portions of other Apollo 17 regolith samples that have been stored frozen since shortly after they were returned, as well as a suite of Apollo 15 sealed regolith samples (15012/15013) that were opened, processed, and continuously stored since then in a He-purged environment (all other pristine Apollo samples are stored in N_2-purged environments). These samples were purposefully saved to be opened or studied at a future date where instrumentation had improved enough to give scientists the chance to maximize the scientific return on the samples.

NASA selected nine consortia of scientists to study a subset of the previously unexamined samples. The samples selected were: unsealed drive tube 73002, sealed drive tube 73001 (part of a double drive tube pair with 73002), and a suite of frozen samples including unexamined basalt sample 71036. These samples were selected for a variety of reasons, including: (1) The 73001/2 drive tubes were collected near Lara Crater at Station 3 in the Taurus Littrow Valley, and are spatially associated with both landslides and a fault; (2) the sealed and cold samples have obvious ties to the upcoming Artemis missions; and (3) from a practicality standpoint, having an unsealed core that could be studied immediately (without having to extract the gas) would allow for the program to start more quickly.

Curation Methodology

Each of the samples included in the ANGSA program had their own unique challenges during the curation process. Sample 73002 was the first drive tube sample to be opened in over 25 years. This meant that all of the equipment that was needed for the extrusion and dissection process had to located, cleaned, assembled, and tested (including procurement of replacement parts where needed). Similarly, the procedures for sample dissection had to be reviewed and modernized, which included building a full-sized cabinet mock-up and extensive testing with analog samples. During the actual dissection process, several non-standard dissection procedures were implemented such as time-sensitive sampling and mm-scale subsampling in the top two intervals (top 1 cm). Multi spectral imaging was performed on the 73002 core [1] during processing, as well as on the 73001 core from outside the cabinet [2], as well as inside the cabinet (after dissection was complete [3]).

After dissection was complete, making continuous core thin sections required that the entire core vacuum impregnation and curing devices had to be rebuilt. Additionally, a Keyance automated petrographic microscope was used to map all eight of the 73002 continuous core thin sections at a resolution of a few microns per pixel (and will similarly be used when the 16 of the 73001 sections are complete). These maps were provided to the ANGSA science teams to serve as base maps for the electron- and ion-beam work that would come later.

With sample 73001, the most obvious hurdles were related to how to get the gas out of the outer vacuum container (OVC) and Core Sample Vacuum Container (CSVC) prior to opening the samples. This involved building two bespoke pieces of hardware, a gas-extraction manifold built at Washington University in St. Louis [4] and a piercing tool built at ESA [5], as well as the actual assembly, integration, and operation of this equipment within the materials constrained environment of the JSC clean rooms.

The ability to process frozen samples at -20˚C was not a capability that existed at JSC prior to ANGSA, and an existing Apollo glovebox had to be retrofit to work at those temperatures. Significant facility modifications to the walk-in freezer in the JSC Experimental Impact Lab to make it material and environmentally compliant with processing of Apollo samples was also required [6]. Similarly, the procedures for how to process the samples under these extreme conditions had to be developed and implemented [7].

This was the first time that X-ray Computed Tomography (XCT) was used as part of the curation process for drive tube dissection. Whole-core scans were made of both 73002 and 73001 prior to extrusion and dissection at the University of Texas High-Resolution X-ray Computed Tomography (UTCT) Facility for high-resolution scanning (Figure 1). Both of these scans had unique challenges that were overcome to give excellent data sets that proved invaluable to both the curation and mission science teams [8]. Over 350 particles in the 4-10 mm and >10 mm size particle size fractions were separated during dissection, individually bagged in Teflon (3 bags), and scanned by XCT at NASA JSC [9]. These scans allowed for the identification of different lithologies within the particles (Figure 1), which greatly helped with the request and allocation process [10].

Summary

The ANGSA program was designed to help us prepare for the upcoming Artemis missions, while at the same time getting important new scientific results from the Apollo samples. Each of the samples included in the ANGSA program had their own unique challenges related to the curation process, and the work on this program has greatly enhanced our readiness for the next batch(es) of lunar samples to come back.

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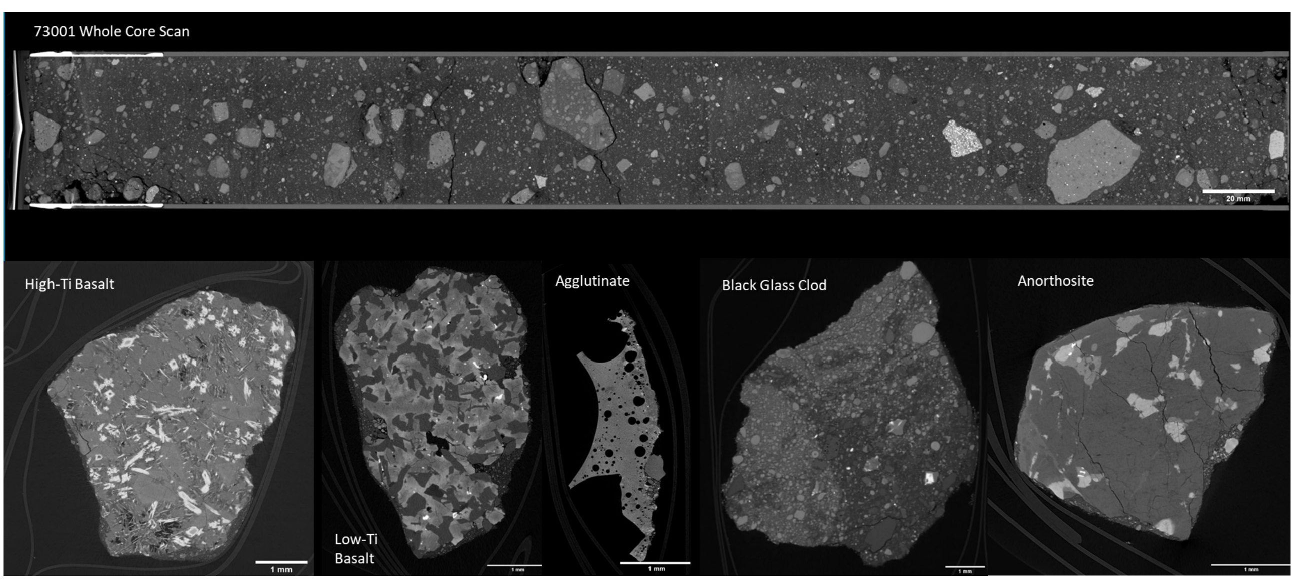

Figure 1. X-ray Computed tomography images of the entire 35 cm long 73001 core (top image), as well as individual soil particles sieved from the 73001 and 73002 cores representing a variety of lithologies observed.

Sample Return and Preliminary Examination Processes for the OSIRIS-REx Mission

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The OSIRIS-REx spacecraft collected a sample of asteroid (101955) Bennu on October 20, 2020 [1, 2] and departed the asteroid in May 2021. On September 24, 2023, the spacecraft will fly by Earth and release the Sample Return Capsule (SRC), which will land four hours later in the desert of the U.S. state of Utah. Once the SRC is located within the landing ellipse, the OSIRIS-REx recovery team will be flown via helicopter to retrieve the SRC and take it to a temporary cleanroom for initial processing. In the cleanroom, the SRC will be opened, a high-purity nitrogen purge will be established, and the sample canister assembly will be packed for transport to the OSIRIS-REx curation facility at NASA's Johnson Space Center (JSC).

The Preliminary Examination (PE) period for sample analysis begins once the sample canister is opened at JSC. The focus during this time will be on disassembly of the sample canister, initial documentation of the sample, production of a sample catalog (to be completed within six months of Earth return), splits of sample for international partners, and the initial allocation of sample to the Sample Analysis Team (SAT). Within approximately one week after sample return, a Quick Look Tiger Team of the SAT will conduct a very preliminary characterization using a small amount of sample collected from the outside of the sample acquisition mechanism. Armed with information from the Quick Look sample analysis, the SAT will then focus on identification of distinct lithologies within the bulk sample using the mission imaging system known as QRIS (Quantitative Reflectance Imaging System), visual inspection, density calculations, and initial analysis on bulk oxygen isotope abundances as well as H, N, and C to enable decisions on which particles will be allocated to each planned science investigation. While the bulk sample is being processed for analysis, contact pads from the sample acquisition mechanism will also be processed.

The OSIRIS-REx team is preparing for sample return, recovery, and analysis with a series of reviews, team training activities, and readiness tests scheduled over the next year. The SAT is currently conducting a Sample Analysis Readiness Test (SART) which will conclude by June 2023, during which the SAT is demonstrating certification in key areas necessary for sample analysis. The SART is providing valuable lessons for revision of the mission Sample Analysis Plan (SAP) and is helping the team prepare for our July 2023 sample analysis readiness review. The SAT also completed two Sample Analysis Science Operational Proficiency Integrated Exercises (SA-SOPIEs), with a third scheduled in early 2023. These exercises use analog sample material to test instrumentation, initial sample characterization, and the selection of particles the SAT will use to address early mission science and the hypotheses outlined in the SAP.

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Coordinated Thermal and Physical Analysis of OSIRIS-REx Samples of Asteroid Bennu

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Remote sensing and sample analysis both provide insight into the thermal and physical properties — and thereby the origin and evolution — of asteroidal material. Remote determination of thermal properties can be used to infer the physical characteristics of boulders and regolith on asteroid surfaces and to predict the evolution of an asteroid's orbit due to the Yarkovsky effect. Analysis of returned particles and particle assemblages informs the interpretation of remote sensing data and can powerfully constrain models of dynamic events such as robotic sampling and impacts at different scales.

It is well-known that the strength of stony material obeys scaling laws, such that larger boulders (or bodies) are weaker than smaller ones and thus are more susceptible to collisional damage. It is also likely (but not yet as widely recognized) that thermal properties of boulder materials may depend on the size of the sample and/or the length scale of the remote sensing observations. Therefore, to link the properties of returned samples and relevant meteorite analogs to remote sensing data of asteroid surfaces, a coordinated physical and thermal sample analysis campaign with measurements across multiple length scales is necessary.

Below (Figure 1) is a summary of the physical and thermal measurements that are planned for the returned samples from Bennu. In addition to addressing specific hypotheses related to the formation and evolution of Bennu's boulders and fine regolith, we seek to collect coordinated sample data that can contribute to the development of a broadly applicable multi-scale thermal and mechanical model for primitive rubble-pile asteroids.

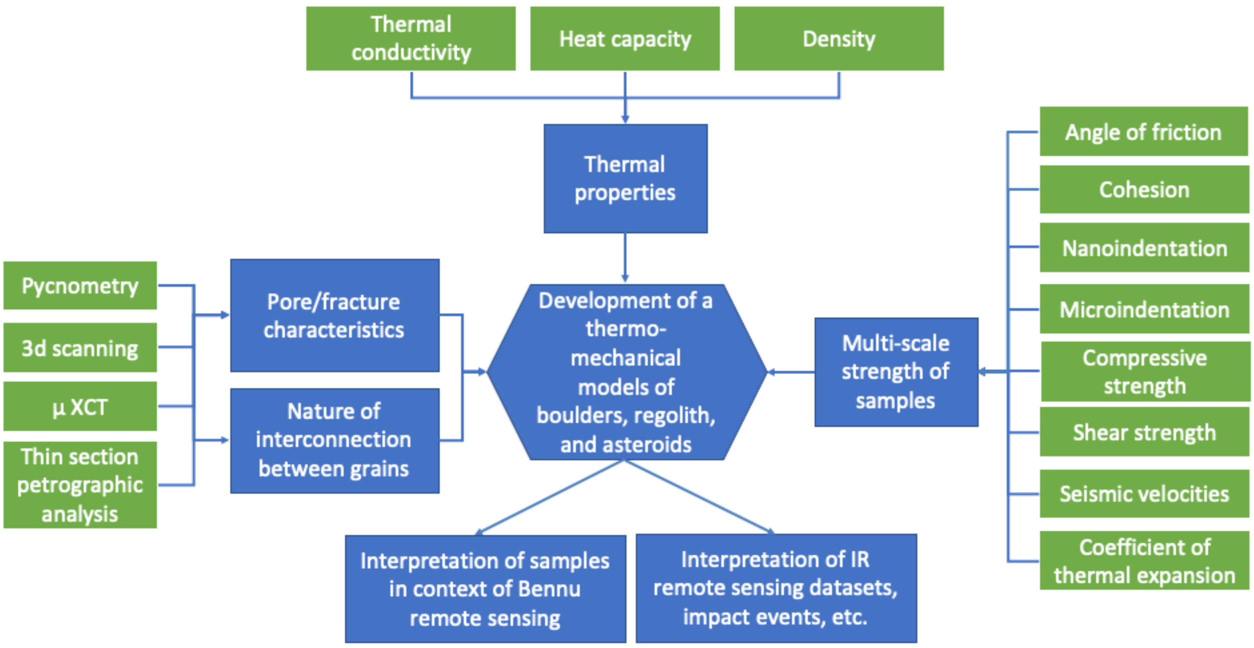

Figure 1. Planned OSIRIS-REx sample measurements (green) feeding into a multi-scale model for regolith, boulder, and asteroid thermophysical properties (blue).

Contamination monitoring of the OSIRIS-REx ISO5 asteroid sample cleanroom

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The OSIRIS-REx mission to asteroid Bennu successfully collected hundreds of grams of asteroid regolith in October 2020 [1]. The spacecraft departed Bennu in May 2021 for Earth return and will release the sample canister to be recovered in Utah in September 2023 [2]. Samples will be transported to the curation facility at NASA Johnson Space Center, where an ISO5 equivalent cleanroom has been designed in 2017 and completed in 2021. Aspects of the design and material selection for the cleanroom and its supporting facilities (air handling system, cleanroom floors and walls, filters, paints, etc.) were optimized to minimize effects of organic and inorganic contaminants and offgassing [3]. Since its completion, the lab has been carefully monitored to understand and establish a baseline with respect to multiple environmental aspects – measurement of particle counts, deploying Si wafer witness plates for organic and inorganic contaminants, deploying aluminum foils for a focus on organics with JSC in-house expertise, gas samples, and regular microbial and fungal measurements on selected surfaces and air samples in the cleanroom. This contribution will report on nearly one year of monitoring and highlight several specific aspects that have led to a better understanding of the new cleanroom environment.

Particle counts: particle counts are taken weekly in 6 different locations in the cleanroom, in high traffic and low traffic areas and distributed representatively throughout the lab. The particle counts have remained well within the ISO5 rating of the cleanroom and have only exhibited higher counts (but still well within the ISO5 limits) in cases where there has been unusual activity. One such example is the repair of fan filter units (FFUs) in September 2022. Careful coordination of particle count measurements during servicing of the FFUs led to a better understanding of how the counts are affected when ceiling tiles were removed and FFUs were adjusted, as well as providing baseline information on how quickly the cleanroom environment is restored to background levels after the cease of repair activities. Monitoring of such off nominal events will be done in the future as opportunities arise.

Si wafer witness plates (Balazs, Inc): Large area Si witness plates have been deployed several times over this period, with the goal of detecting possible organic and inorganic contaminants. For inorganic and organics, 8-inch polished semiconductor silicon witness wafers were exposed to the laboratory air for 24 hours each. After exposure, the witness plate for organics was sent to Balazs for Thermal Desorption Gas Chromatography Mass Spectroscopy (TD-GC-MS), yielding results for organic compounds from C6 to C28 (with limit of 0.1 ng/cm^2). The wafer for inorganics was analyzed by vapor phase decomposition inductively coupled plasma mass spectrometry (VPD-ICP-MS) which yielded data for 35 elements of interest (Al, As, B, Ba, Be, Ca, Cd, Ce, Co, Cr, Cu, Fe, Ga, Ge, Hf, In, K, La, Li, Mg, Mn, Mo, Na, Ni, Pb, Sb, Sn, Sr, Ta, Ti, W, V, Y, Zn, and Zr). Analyses for organics have yielded very low concentrations in general – lower than similar monitoring of the ISO4 equivalent Genesis lab, for example across a decade of monitoring. The few and very low species detected in early testing included TXIB (a plasticizer used in urethane elastomers and PVC piping), triacetin (a common plasticizer and solvent, 2-(2-butoxyethoxy) ethanol and texanol (used as a solvent for and in paints). These species have not been detected in measurementsts made in late 2022. Analyses for inorganics that were above detection limits included Al (from wall and ceiling struts), B (from the borosilicate glass in the Fan Filter Unit (FFU) ULPA filters), Cu, Sn, and Zn (could be from electrical or electrical conduit), and Fe (could be from stainless steel or electrical conduit). Continued monitoring of these elements will allow identification of problematic sources, but the levels detected are lower than other NASA curation labs, which is a testament to the careful selection of materials during the design and construction phase.

Gas sampling (Balazs and JSC): Cleanroom air samples were analyzed using two different approaches. Volatile organics in air were sampled with an adsorbent tube connected to a pump (100 mL/min.) for 6 hours. After exposure, the adsorbent tube was sent to Balazs for TD-GC-MS analyses for a wide range of hydrocarbons and volatile organic compounds (limit of 0.1 ng/L). A NASA-JSC based collection of 450 ml gas samples was followed by GC-MS. Both approaches have demonstrated very low levels of organics in general, with most species either (a) below detection limits, or (b) expected but present at very low levels (e.g., isopropanol, toluene, and xylene).

Al foils deployment: In addition to the Si wafers deployed for analysis by Balazs, the curation staff has also deployed monthly sets of aluminum foil witnesses that are being archived. These will also be analyzed using JSC in-house analytical techniques for amino acids. Results are not yet available at the time of writing of this abstract.

Microbial and fungal monitoring: Terrestrial contamination of asteroid or meteorite samples can lead to biological degradation, something we wish to avoid during short- and long-term curation. Swabs and sampling for microbial and fungal analysis have been collected regularly on various surfaces within the OSIRIS-REx cleanroom (as well as many other JSC cleanrooms [4]). Microbiological air samples were also collected by passing air through an electret filter at 200 L/min. Results of these analyses show very low levels in general, and decrease with time in any given area. When rates become more elevated, special cleaning procedures involving hydrogen peroxide have been developed to lower the fungal and microbial recovery rates.

Having the cleanroom completed more than a year in advance of sample return has allowed many important kinds of monitoring to be undertaken, lab environments characterized, and baseline established for any expected or unexpected contaminants. Future emphasis will be on maintaining the monitoring during outfitting of the lab (see details in [5]), as well as the presence of human processors in the lab for longer durations.

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A study of the curation protocol by sample analysis working team (SAWT) in Martian Moons eXploration (MMX) project

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Japan Aerospace Exploration Agency (JAXA) will launch a spacecraft in 2024 for a sample return mission from Phobos (Martian Moons eXploration: MMX). The major scientific goals of MMX are to constrain (1) the origin of Phobos and Deimos and (2) the evolution of the Mars-moon system [1]. The touchdown operations are planned to be performed twice at different landing sites on the Phobos surface to collect > 10 g of the surface materials [2]. After the return to the Earth, the Phobos samples will be collected from the individual sample canisters and introduced to the clean chamber installed at ISAS (Institute of Space and Astronautical Science). The Sample Analysis Working Team (SAWT) of MMX designed the procedure of Phobos sample analysis mainly conducted by the initial analysis teams [3]. For the next step, the SAWT will define the procedure of the curation process (mostly non-destructive analysis) of the Phobos samples, which will be presented here.

The protocols of the Phobos sample curation are illustrated in figure 1. First, the headspace gas from the sample container will be collected during the Quick Analysis phase. The Quick Analysis will be operated by the sampler and curation teams in ISAS/JAXA. The terrestrial leak and contamination from the sampling systems will be tested using a quadrupole mass spectrometer equipped with a gas sampling system. Second, the bulk Phobos sample will be observed in the clean chamber under purified-N_2 gas with an ambient condition (Pre-basic Characterization) within three weeks. This phase will be operated by the curation team in ISAS/JAXA and the instrument team of the MMX mission. The consistency between the data from the instruments in the clean chamber and the spacecraft will then be evaluated.

Subsequently, the curation will distribute the small amount of Phobos samples to the Initial analysis team of MMX to conduct the "Preliminary Examination". The objectives of the preliminary examination are to provide (1) feedback on the subsequent sample allocation process, (2) preliminary scientific results that will address parts of MMX mission goals, and (3) evaluation of the sampling system and terrestrial alteration on Phobos samples. Because multiple models are proposed for the origin of Phobos [1] (e.g., giant impact, the capture of asteroids), the chemical and mineralogical characteristics of Phobos must be assessed before the allocation of the samples to the individual Initial Analysis teams. The Preliminary Examination will start after about 1 month from the sample return. Simultaneously, the curation team in JAXA will observe the individual grains and aliquots of the samples in the clean chamber (Basic Characterization). The results obtained in Preliminary Examination will be investigated with several SSTs (Science Strategy Teams). Based on the results, the curation team will decide on the sample amounts to allocate to the Initial Analysis team. After 6 months from the Preliminary Examination, Initial Analysis will be started to perform the comprehensive analysis for Phobos samples within 1 year.

The curation protocols the SAWT proposes here are partly based on those in Hayabusa & Hayabusa2 missions [4]. However, our strategy enables us to utilize larger amounts of return samples compared to the previous sample return missions. Also, the chemical/mineralogical characteristics of Phobos will be quickly understood throughout the non-destructive and destructive analyses in the curation process.

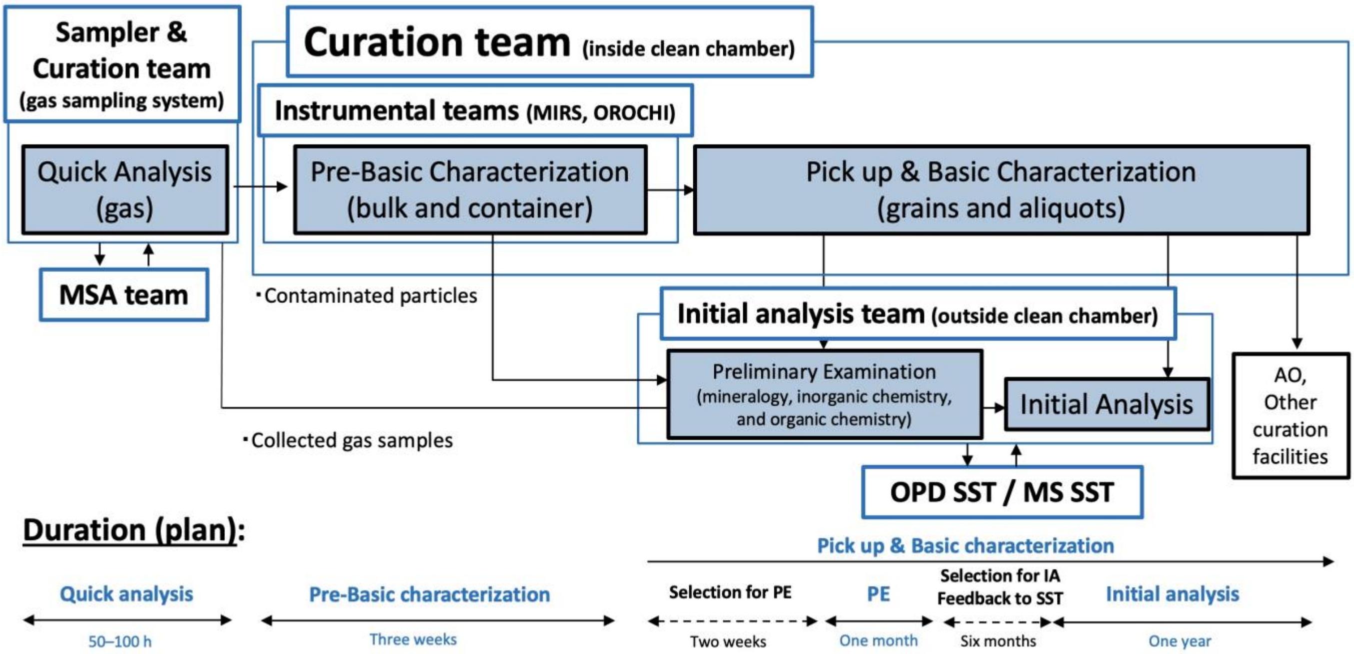

Fig. 1: Curation protocols for the Phobos samples.

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Bridging the gap - linking remote sensing, in-situ and laboratory spectroscopy

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Sample return provides us with "ground truth" about the visited body, verifying and validating conclusions that can be drawn by remote sensing (both Earth-based and by spacecraft) and via landed instruments on other bodies. The detailed investigation of the mineralogy and geochemistry of Ryugu plays a fundamental role in the understanding of its formation processes, and thereby gather further knowledge about the building blocks of the solar system. Based on the preliminary data from remote sensing measurements and laboratory-based measurements, Ryugu is rich in hydrated carbonaceous chondrite (CC) like material and more specifically it is very similar to Ivuna-like (CI) carbonaceous chondrites [1]. These meteorites are characterized by a high abundance of phyllosilicates and organic matter [2], which makes them have a low albedo. However, Ryugu seems to be even darker than CIs, as well as being more porous and fragile [1].
Back in August 2022, the Institute of Planetary Research at DLR (Berlin) received a fragment retrieved by the Hayabusa2 mission from asteroid Ryugu. The fragment assigned to us for analyses is sample A0112, from chamber A. Our investigation is based on two main goals. The first goal is to address a fundamental challenge in the interpretation of remote sensing data which was seen during the initial analysis of the Hayabusa 2 samples. Observations of planetary surfaces using spectroscopy have shown subdued contrast compared to measurements performed under laboratory conditions on analog materials. A strong focus of the work performed at PSL over the last decade has been to understand - and if possible minimize – the difference between laboratory and remote sensing observations (e.g. [3, 4, 5, 6]). Simulating the conditions on the target body as well as accurately reproducing the observing geometries have gone a long way towards that goal, however differences remain. A suggested explanation is the difference between terrestrial analog materials including even meteorites and the surfaces of planetary bodies. With Ryugu samples this hypothesis can be tested further, leading to a deeper understanding of the link between laboratory and remote sensing observations and thus benefiting not only the analysis of Hayabusa 2 data but of all remote sensing observations of planetary surfaces using spectroscopy. The second goal building on this is an investigation of the mineralogy and organic matter of the samples collected by Hayabusa 2, to better: a) understand the evolution of the materials characterizing asteroid Ryugu and therefore advance our knowledge of the mineralogy of the protoplanetary disk and organic matter (OM); b) investigate the aqueous alteration that took place in the parent body that lead to its current chemical and mineralogical characteristics; c) compare the results with data collected from pristine carbonaceous chondrite meteorites rich in hydrated minerals and organic matter.

We are currently collecting the first datasets, and for doing so we are applying a strict protocol to maintain the grain as pristine as possible. The first set of measurements is taking place keeping the sample within the N_2 filled sample holder it was delivered in. Just afterwards, we will open the protective holder to transfer the sample in the anaerobe bench to the Hayabusa1 holder (that we hosted in our institute too) and we will repeat those measurements. As a final step, we will remove the sample from this holder and let the sample be in contact with laboratory atmosphere.
Here is a description of the protocol:

1. The first step of our investigation consists in 3D imaging of the sample (Figure 1) with the use of a Keyence VHX-7000 4K High Accuracy digital microscope;
2. Mapping of the sample with Raman spectroscopy (Figure 2);
3. Mapping of the sample with IR microscope in the wavelength range 0.25 – 25 µm;
4. Collection of reflectance data in the wavelength range 0.25 – 25 µm;

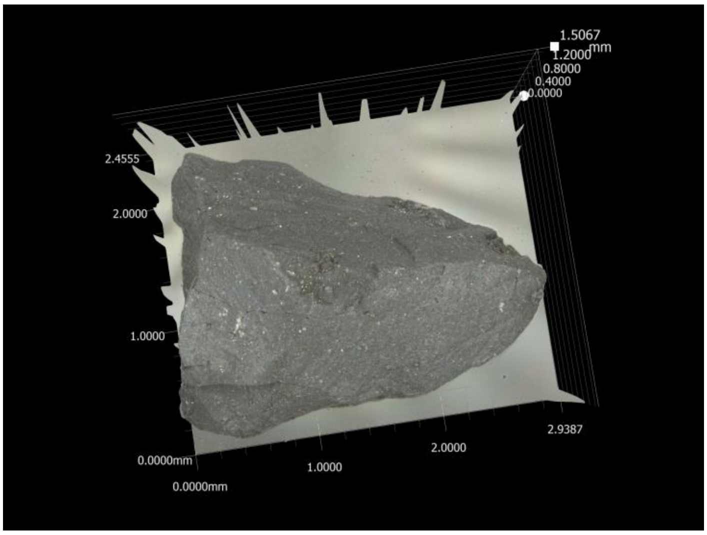

Figure 1: *3D scan of particle A0112 with a Keyence VHX-7000 4K High Accuracy digital microscope.*

5. Transfer of the sample to a dedicated holder previously created for the analysis of Hayabusa1 samples and repetition of the previous steps;
6. Sample open and exposed to air: stored in dry cabinets, spectroscopy measured in vacuum;
7. 3D imaging with the use of a Keyence VHX-7000 4K High Accuracy digital microscope
8. IR data collection in the wavelength range 0.25 – 25 µm
9. Raman mapping: in this case after the acquisition of IR data to minimize the reaction of organic matter with the laser;
10. SEM and EDX mapping at low voltage of uncoated and unprepared sample.

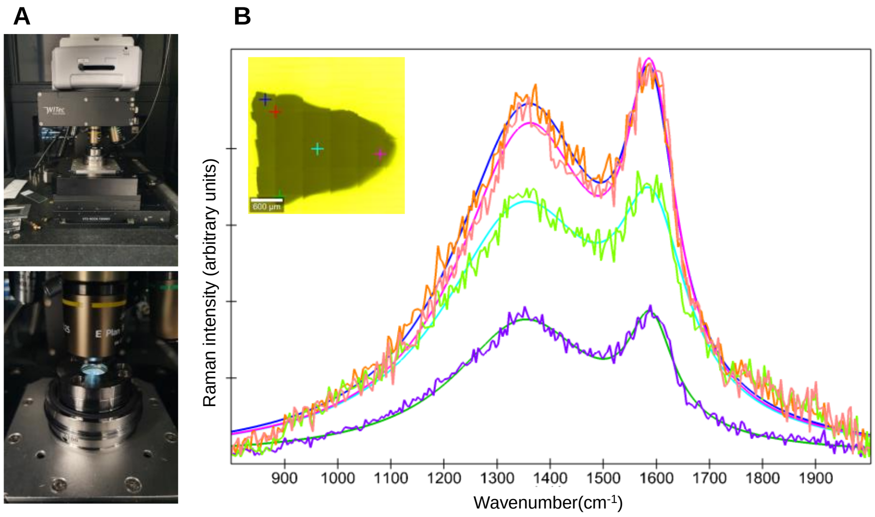

Figure 2: *Raman preliminary results.* ***A.*** *WITec Alpha 300 confocal microscope setup with JAXA's sample holder containing particle A0112.* ***B.*** *Typical Raman spectra of polyaromatic carbonaceous matter measured under N2 atmosphere in the unopened container showing typical D and G carbon bands and fitted with a Lorentz function to extract parameters such as bands' position, full width at half maximum (FWHM), and bands' intensities. Inlet: measurement points on particle's surface.*

Up to now, step 1 has been successfully executed as can be seen in Figure 1. The 3D measurements will help planning the next steps of the measurements. They are also an interesting result in itself as they will allow to determine the volume and thereby the density of this particle.

Step 2 has been started and Raman spectra were successfully acquired on the particle without opening the original container (as was executed for Hayabusa1 particles previously). Preliminary data show the typical carbonaceous matter signature typical of CCs from which their thermal history can be derived [8].

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An infrared look at Ryugu returned samples in the meteorite/asteroid perspective

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Laboratory analyses of materials originating from asteroids give us the opportunity to directly study the components that formed in the protoplanetary disk. However, collections of extraterrestrial materials available on Earth have strong biases, and the link between laboratory samples and their asteroidal parent bodies is often ambiguous. Furthermore, many classes of small bodies are likely absent from our collections [1]. Some of these limitations are overcome by sample return missions, such as Hayabusa2/JAXA that targeted and sampled the small and dark near-Earth asteroid Ryugu [2]. Ryugu has retained valuable information on the formation and evolution of planetesimals at different epochs of our Solar System history [3].

Samples originating from asteroids can be analyzed thanks to modern analytical techniques [4]. Among them, infrared spectroscopy is important for comparing lab measurements to remote sensing observations of small bodies. In addition, mid- and far-infrared (MIR, FIR) reflectance spectra of asteroids and meteorites contain fundamental vibrational bands which are diagnostic of their mineral and organic compositions. Infrared spectra of Ryugu were measured by NIRS3 on board Hayabusa2 in the near-IR range [5], however the MIR-FIR range was not available. The return of Ryugu samples collected by Hayabusa2 provide an excellent opportunity to measure the MIR-FIR spectra of Ryugu materials and to compare them with similar observations of meteorites and asteroid, in particular the remote sensing MIR-FIR spectra of B-type asteroid Bennu acquired by the OSIRIS-REx mission [6].

In this study we report IR reflectance measurements of two mm-sized Ryugu stones (A0026 and C0002), acquired at the SMIS beamline of synchrotron SOLEIL (France) and at Tohoku University (Japan), and we compare them with meteorite spectra acquired with similar setups, and with the available remote sensing spectra of different asteroids.

Generally speaking, the MIR and FIR reflectance spectra of the two Ryugu stones show similitudes with spectra of CI meteorites, both in terms of overall spectral shape and in terms of peak position of the main reststrahlen silicate features, although some differences are observed probably due to a different history of alteration (both in space and on Earth). The IR spectra of Ryugu samples are clearly different from those of CM meteorites and other ungrouped primitive meteorites. They also differ from the remote sensing spectrum of asteroid Bennu. Overall, the results indicate that Ryugu has both a mineral composition and a history of aqueous alteration that are more similar to those of CI chondrites than to those of CM chondrites and of asteroid Bennu. These observations confirm that Ryugu and Bennu, two small near-Earth asteroids that are so similar in many ways (size, morphology, density, etc.), have distinct IR spectra also in the mid-IR and far-IR, in agreement to what was previously shown in the near-IR range from orbital data [5,6].

Finally, the presence of different lithologies in C0002 [3] allows to trace the early evolution of Ryugu materials and the corresponding IR spectral variations. The parameters extracted from the micro-IR spectra of different clasts in C0002 draw an alteration pattern which is different from that of CM meteorites [7,8], and which helps to reconsider the general asteroid-meteorite connection in a different perspective.

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P-rich compounds within the Ryugu sample collection: a perspective from joint MicrOmega/Curation, the OU and Phase2 Kochi curation activities

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The JAXA Hayabusa2 mission has returned for the first time samples collected at the surface of a C-type asteroid, Ryugu [1,2]. They are now preserved at the Extraterrestrial Samples Curation Center of JAXA at ISAS in Sagamihara, Japan, where they are submitted to a first round of non-destructive and non-invasive analyses, while maintained in a purely non-altering environment since their collection [3]. Some of these grains have also been extracted to be further analyzed by - initially - 8 analytical teams, including Phase2 Kochi (Ph2K) curation [4,5], and later open to AOs.

The MicrOmega hyperspectral microscope operating in the near-infrared (NIR) range (0.99 – 3.65 µm) is performing the mineralogical and molecular characterization of the samples present in the Curation Center, down to the scale of a few tens of micrometers [6]. By the end of September 2022, >375 individual grains (a few mm in diameter) and 25 sub-bulks (a few tens of mg each) have been analyzed with MicrOmega, in addition to the 6 initial bulks from chamber A and C. It offers a global view on the Ryugu samples, preserved from any terrestrial contamination, and can be used to target specific grains and areas of interest with complementary techniques. In particular, while strong features at 2.7 µm – translating their OH-rich content - and 3.4 µm – diagnostic of the presence of organics – dominate at a global scale, key distinctive signatures have been identified at sub-mm scale [7,8,9,10]. Here we present the international collaborative curation work conducted with the Ph2K and the OU on Ryugu samples and focused on the P-rich compounds.

Specific grains of interest/inclusions have been identified with MicrOmega within the Curation Facility, for having a bright aspect (reflectance of ~10-20%) coupled to a very peculiar spectrum in the NIR: a broad and deep band at ~3 µm, with additional features, in particular a sharp band at ~2.7 µm shifted by ~10 nm compared to the one observed in the matrix [7]. Grains with such properties tend to occur as inclusions or loose grains with sizes up to a few hundreds of microns, similar to carbonates observed by MicrOmega [8] but with a much lower occurrence. Such signatures have been identified in the C0209 sub-bulk delivered to the Ph2K team in April 2022. Grains presenting these properties have been manually extracted and analyzed by SR-XRD at Spring-8 and then combined SEM/EDX at Kochi JAMSTEC, which revealed an enrichment in P, O and Mg elements, possibly pointing towards Mg-phosphates as suggested by other observations on a few samples [11,12]. These grains and the C0209 sub-bulk were then re-analyzed by a MicrOmega unit present at IAS [13]. The results confirmed the correlation between the IR signature and the P, O, Mg content detected by the EDX. Slight modifications of the IR spectra in the 2.7-3.0 µm range points towards a contact with the terrestrial atmosphere after the extraction of the grains from the Curation Center.

These results offer a new perspective on the characterization of the distribution and properties of such compounds over the entire collection. Further analysis of the grains is on-going to assess the possible couplings of the P-rich phases with other compounds (minerals and/or organics) and their origin by H, O isotopic ratios.

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Overviews of the Hayabusa2 mission and its integrated science

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The asteroid explorer Hayabusa2 performed its proximity operation around Cb-type asteroid (162173) Ryugu from June 2018 to November 2019, and returned to Earth with the surface sample in December 2020. More than 5 g of the particles in the sample catchers were successfully retrieved and the initial description and initial analysis were performed. The formation of the Solar System and the subsequent history of asteroid Ryugu will be discussed based on the proximity observations of Ryugu and analysis of the return sample.

From the initial analysis, the Ryugu sample was confirmed to be similar to CI (Ivuna-type) chondrites in terms of mineral assemblages and composition, and isotopic ratios [1–4]. Some differences were attributed to the effects of weathering and contamination on the ground suffered by CI chondrites, so that the Ryugu sample is considered to preserve the chemical and isotopic state of CI chondrites as they were in space. The presence of grains having large anomalies in the stable isotope ratios of H, C, and N was confirmed [5], suggesting that these particles were produced in the low-T environment of the solar parental molecular cloud and retained without undergoing isotopic equilibrium on the parent body. The organic carbon of the Ryugu sample is comparable to that of CI chondrites, whereas the carbonate content is significantly higher, and therefore the total carbon content is somewhat higher. The presence of CO_2-bearing aqueous fluid inclusions in a large iron sulfide (phyrrhotite) crystal [3], the IR absorption of NH in ammonium salts or organic nitrogen compounds [6], and the very low content of chondrules and CAIs [3] suggest that the parent body of Ryugu may have originated outside the snow lines of CO_2 and NH_3 (presumably outside Saturn's orbit). Near infrared spectrometer NIRS3 found a global 2.72 μm absorption on Ryugu, indicating omnipresence of Mg-rich phyllosilicates [7]. Return sample analyses clarified that aqueous alteration in the parent body had progressed in alkaline water with a temperature of ~310 K [1] generated by the decay heat of ^{26}Al in the interior of an about 100-km sized icy body at 5-6 million years after the formation of CAIs in the protosolar disk [3]. The presence of less altered grains in Ryugu particles suggests the difference in temperature between the near-surface and interior of the icy parent body at the stage of aqueous alteration [3]. Some of these less altered grains have particularly high micro-porosity, suggesting the formation of planetesimals from fluffy ice and stone particles. It is noteworthy that franboidal magnetite grains with a remanent magnetization of ~100 μT were found in several Ryugu particles [3], suggesting that the parent body had moved from the outer Solar System to the asteroid belt, where disk magnetic field is expected to have been strong enough, before/during a period of aqueous alteration.

These results are consistent with the scenario that carbonaceous chondrites' parent bodies are icy planetesimals with diameters of ~100 km that formed in the outer Solar System and were brought to the inner Solar System through scattering by giant planets. However, based on the reflection spectra and orbital analysis of Ryugu, its parent body is considered to be one of the collisional families in the inner asteroid belt [8]. Therefore, it is necessary to verify whether the scattering by giant planets could bring planetesimals to such an inner region of the asteroid belt. In any case, it is a great discovery that the parent bodies (at least one of them) of CI chondrites are collisional families in the inner asteroid belt.

Contrary to the parent body processes, the sample analysis information about the formation and evolution of Ryugu itself is rather little and the results from remote sensing observations are important. Low bulk density and abundant large boulders indicate that Ryugu is a rubble-pile object formed through re-accumulation of fragments produced by catastrophic disruption or cratering of the parent body [9]. Surface mean visible spectrum of Ryugu is similar to that of (495) Eulalia, and spectrum of the largest boulder Otohime is similar to (142) Polana, both asteroids are the largest members of the Polana-Eulalia collisional families. Assuming the collision frequency model for the asteroid main belt, the surface age of Ryugu is about 10 Myr based on crater chronology using crater-to-impactor size ratio of 130 after the SCI experiment [10]. The surface age is much younger than the estimated ages of the parent collisional family of Ryugu, either the Polana or Eulalia family. Thus, the surface age is considered to correspond to the top shape formation, probably global resurfacing events [9, 11], induced by the YORP spin-up long after the formation of Ryugu.

Much has also been learned about the post-formation history of Ryugu. From the analysis of the YORP effect using the shape models, Ryugu is now slowly spinning down and had a fast rotation in the past (~10 Ma) [12]. The analysis of the tilt angle distribution on the surface of Ryugu suggests that the top shape was formed by surface landslides when the rotation period was 3.5 to 3.75 hours [9]. Following a previous study [13], which suggested that the east-west asymmetry of the crater rims on Ryugu was caused by the Coriolis forces acting on crater ejecta during a high-speed rotation era, the analysis with precise topographic correction revealed that three large craters on Ryugu have significant higher rims both on the west and equatorial sides [14]. These craters are more susceptible to the Coriolis force than other craters at the stage of high-speed rotation, and the average tilt angle of each surrounding terrain is larger than that of other craters. These results as well as numerical simulations of top-shape formation [15] suggest that the top shape of Ryugu was formed during high-speed rotation era about 10 million years ago, and that the crater formation and space weathering were proceeded during the spin-down phase.

Several bluer (negative spectral slope in visible wavelengths) craters are sccattered in red (flat spectral slope) areas on Ryugu. Stratigraphic relationship between craters reveals that bluer craters are younger in this region, suggesting primordial material of Ryugu is bluer and distributed underground [16]. Suface reddening of the bluer material occurred by space weathering due to solar wind [17]. On the other hand, on (101955) Bennu, the OSIRIS-REx target, redder, flat spectral slope craters are scattered in blue areas, and the craters changed from red to blue due to space weathering, so younger craters are redder on Bennu [18]. This means that space weathering progressed in the opposite direction on the two bodies from the similar flat-spectral material.

The thermal infrared imager (TIR) onboard Hayabusa2 revealed flat diurnal brightness temperature profiles caused by surface roughness and derived global thermal inertia of 225 ± 45 J m^{-2} $s^{-1/2}$ K^{-1} [19, 20], indicating higher porosity of boulders on Ryugu than that of carbonaceous chondrites. In situ measurement by the Mobile Asteroid Surface Scout (MASCOT) also found low thermal inertia of 295 ± 18 J m^{-2} $s^{-1/2}$ K^{-1} [21]. In contrast, return sample measurement showed that the thermal inertia of a Ryugu particle with the thickness of < 1 mm is 890 J m^{-2} $s^{-1/2}$ K^{-1} [3], which is higher than the values on the asteroid surface. The thermal skin depth for the diurnal temperature change of Ryugu is about 10 mm, so that mm-scale cracks may be responsible for the thermal shielding effect on the surface layer of Ryugu. Some dark boulders on Ryugu have thermal inertia lower than 100 J m^{-2} $s^{-1/2}$ K^{-1}, which correspond to porosity >70% [22]. These boulders are considered to be the least processed materials on Ryugu and may preserve the structure of grain aggregates on the parent porous planetesimal.

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