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Analysis of Uncontaminated Extraterrestrial Materials from Asteroid Ryugu: Alone We Can Do So Little; Together We Can Do So Much

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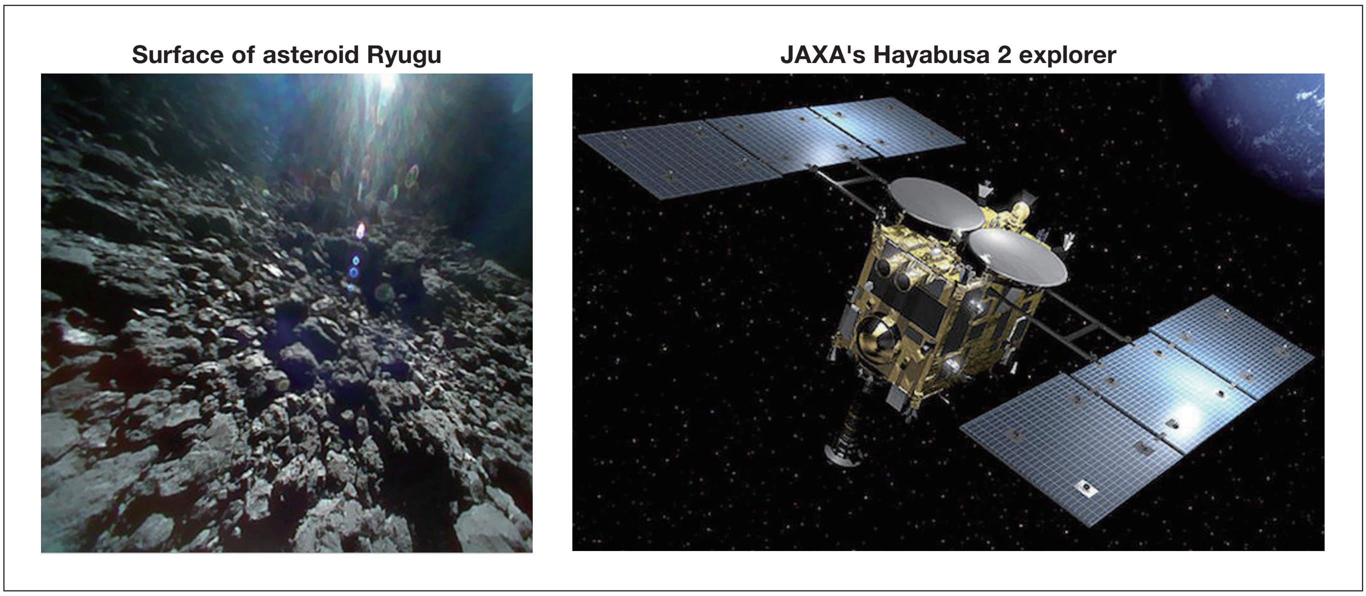
1. The Hayabusa 2 Explorer

What comes to mind when you hear the phrase asteroid Ryugu (Figure 1)? Common responses might include a separate world more than 300 million kilometers from Earth, an unimaginable dreamscape, and wow, our solar system (our universe) is really, incredibly big! But for those of us who spend our lives doing research in Earth and planetary science, asteroid Ryugu is a special name indeed—and one that has many important things to teach us about the formation of our Earth and our solar system.

The history of our Earth has witnessed such an extensive sequence of transformations and reconfigurations—due to heating and other factors—that information dating back to the time of Earth's formation has been lost. In contrast, asteroid Ryugu—which is classified as a C-type asteroid, meaning its primary constituents are carbon-containing substances—is thought to have been relatively unaffected by heat. This means that organic matter, minerals, and other substances on Ryugu may contain historical records describing the formation of our solar system some 4.6 billion years ago1). Moreover, studying these substances may not only illuminate the history of our solar system, but might also shed light on questions such as the origins of water on Earth and the evolution of organic matter into life as we know it today. For these reasons, researchers have long awaited the acquisition of direct samples of matter from Ryugu.

The most common instances of extraterrestrial matter that we know of are meteorites. Of the many varieties of meteorites, C-type asteroids are thought to be particularly closely related to carbonaceous chondrite, with carbon-containing compounds accounting for roughly 2 percent of their mass2). Most of this exists in the form of what is known as insoluble organic matter—macromolecular organic compounds with complex molecular structures—but the presence of amino acids and aromatic hydrocarbons has also been reported3,4). Thus, when Hayabusa 2 visited asteroid Ryugu, it found water and organic matter in abundance—a marked contrast to what the first Hayabusa mission found on the S-type ("stony") asteroid Itokawa. Ryugu is believed to be a mixture of 4 constituents: anhydrous minerals (that is, minerals containing no water, which are abundant on Earth as well—with olivine as one example), hydrous minerals (such as serpentine), minerals whose formation involved water (such as carbonate minerals), and organic matter. The minerals present on Ryugu may turn out to be intimately related to the composition of our Earth's core; similarly, the water on Ryugu may be related to the Earth's oceans, while the organic matter on Ryugu may be related to organic matter on Earth—and thus to the very origins of life as we know it. This point alone may suffice to convince readers of the enormous scientific value of studying asteroid Ryugu.



Surface of asteroid Ryugu

JAXA's Hayabusa 2 explorer

Fig. 1 The surface of asteroid Ryugu and the Hayabusa 2 explorer.
Image credit: JAXA/Phase2 Kochi

The Hayabusa 2 explorer spacecraft was launched aboard a H2 rocket from JAXA's Tanegashima Space Center on December 3, 2014, with its mission to rendezvous with asteroid Ryugu (1999 JU3). For a period of roughly 1.5 years, starting in June 2018, Hayabusa 2 studied Ryugu via remote-sensing observations—and in detail via the small rovers MASCOT and MINERVA-II—and reported information on the shape, density, and composition of the asteroid, as well as physical-chemistry data[5-7)].

Among the most eagerly anticipated aspects of the Hayabusa 2 mission was its ability to take material samples at the asteroid's surface and return these samples to Earth. The spacecraft was equipped with a sample collector that operated by firing tantalum bullets at the asteroid surface and capturing some of the resulting debris; this collector was designed to take samples at a maximum of three distinct locations, up to a total mass of 100 milligrams for all samples, including particles a few millimeters in size[1)]. In addition to surface samples, the spacecraft also incorporated a mechanism for sampling matter beneath the asteroid surface: a pure copper bullet known as the "small carry-on impactor (SCI)," which, when fired into the asteroid's surface, created a man-made crater, exposing—or scattering throughout the vicinity—subsurface matter that Hayabusa 2 was able to sample[1)]. The Hayabusa 2 explorer successfully achieved touchdown on Ryugu two times—in February and July 2019, largely following the planned schedule for the mission—and took samples at both locations. Also, in April of that year, the SCI was successfully deployed, leaving a large crater on the asteroid surface whose existence was confirmed[8)]. The second touchdown, in July, not only achieved a successful landing on the asteroid's surface, but managed to do so in a region that appeared to contain abundant subsurface matter from the vicinity of the man-made crater, from which Hayabusa 2 collected samples[9)]. All in all, Hayabusa 2 carried out a truly heroic mission, returning to Earth with samples of both surface and subsurface matter taken from two distinct locations on Ryugu[10)].

The Hayabusa 2 sample capsule containing material from asteroid Ryugu returned to Earth on December 6, 2020, landing in Australia's Woomera desert; the capsule was recovered and delivered to JAXA's Hayabusa 2 curation facility three days later, on December 9. When the capsule was opened on December 14, researchers found a greater abundance of black particles than had been anticipated; subsequent reports noted that the total mass was around 5.4 grams and that, in addition to large numbers of millimeter-sized particles, the samples also contained centimeter-sized and larger particles[11,12)]. By pursuing a multidimensional research program—combining the remote-sensing data previously acquired near Ryugu with detailed information on chemical composition and mineralogical properties obtained by analyzing the material samples returned to Earth—researchers hope to obtain a clear picture of the entire 4.6-billion-year history of our solar system. During the first year of this program, 8 teams, led by researchers in Japan, analyzed the material samples returned from Ryugu[13)]. One of these teams—the Phase-2 Kochi team, led by the author of this article—is based at the Kochi Institute for Core Sample Research at the Japan Agency for Marine-Earth Science and

Technology and includes team members from research institutions both in Japan and overseas (including Japan's National Institute of Polar Research [NiPR], SPring-8/JASRI, the Institute for Molecular Science / UVSOR, JAXA, the Open University, UCLA, Nagoya University, Tokyo Metropolitan University, and Osaka University).

2. Crash Course in Ryugu Dissection Science

Some readers may be surprised to learn that research institutions in Earth and planetary science—like museums and art galleries—often include teams specializing in curation. The goals of curation in our field are to collect geological samples for scientific purposes, create new scientific value by using chemical-analysis data to classify these samples, and share the results with the scientific community by distributing them for research purposes; clearly, the curation of planetary matter plays a key role in helping us to learn about the formation of the Earth and other planets—and about their future. In Japan, the most well-known curation organizations for Earth and planetary sciences are the Antarctic Meteorite Research Center of the NiPR, which has been gathering and classifying rock samples for many years; the Ice Core Research Center, also part of NiPR, which collects samples of ice sheets and glaciers from the Earth's poles; the Kochi Core Center, jointly managed by JAMSTEC and Kochi University, which serves as a repository for excavated ice-core samples; and, since 2010, the JAXA Planetary Material Sample Curation Facility13), which handles samples returned from asteroids (Itokawa and Ryugu).

Our Phase-2 Kochi Team has worked together with JAXA curation experts to develop a variety of technologies, including analytical techniques for research prior to the arrival of samples from Ryugu, specialized and general-purpose sample holders and jigs for various types of research instruments, and custom-designed vessels that prevent contamination by Earth while ensuring that samples are properly handled and may be safely shipped to destinations in Japan and overseas14-19). Typical examples include facility-to-facility transfer containers (FFTCs), used to transport samples, and individual sample containers made from sapphire (Figure 2) 14). These containers, which are routinely used in nitrogen-filled sample chambers at JAXA designed to handle material from Ryugu, are subject to a number of requirements: they must be easy to clean, they must be constructed from the same materials used to construct the sample chambers, they must be instantly recognizable as clearly distinct from Ryugu material samples—and, because they will be used by researchers around the world, they must be simple to open and close. Our FFTCs were designed primarily by SPring-8 researchers and fabricated by Sato Seiki, a firm specializing in metal processing. For sapphire-made individual sample containers, we combined multiple commercially-available components in effective ways to reduce costs and shorten development time. For sample holders used in experimental analyses, measures to prevent exposure to the atmosphere—and chemistry-based tests to detect such contamination—are particularly crucial, and we have devoted extensive effort to preventing cross-contamination by Earth substances when working with Ryugu samples16,17). Of course, when we first began working with actual Ryugu samples we encountered a number of issues that we could not have anticipated, which we have addressed by continually fine-tuning and improving our laboratory procedures. Our experience reminded us of a famous old line from a movie (paraphrasing slightly): Emergencies don't happen in conference rooms—they happen in actual laboratories!

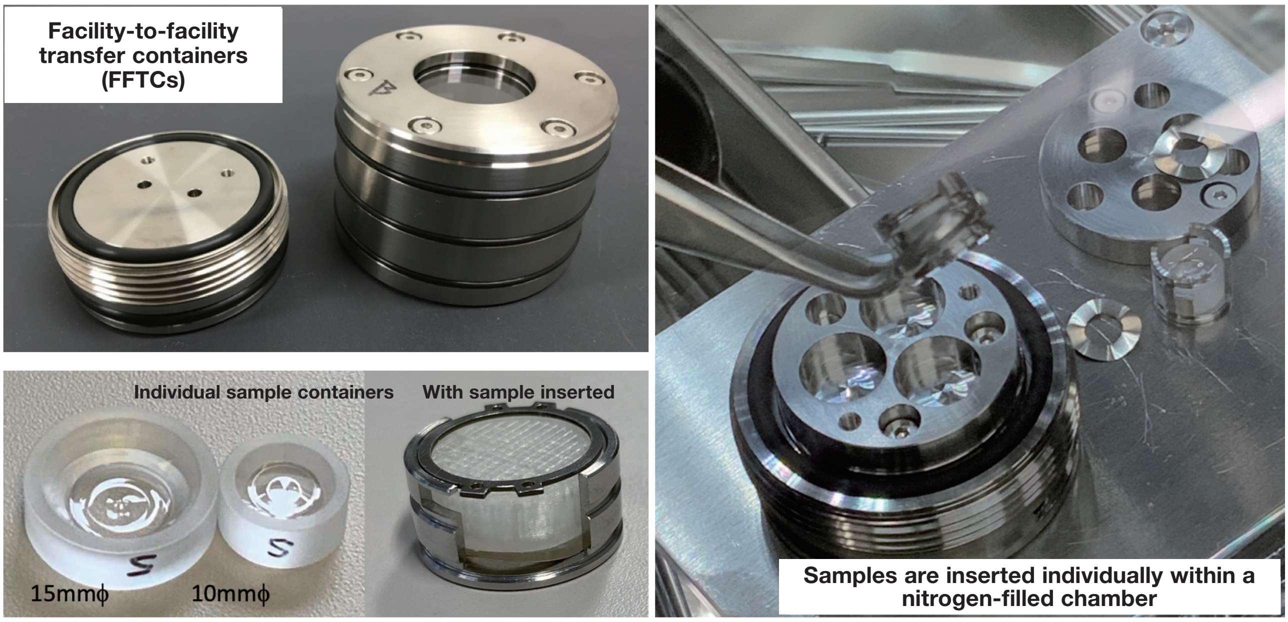


Fig. 2 Curation technologies developed by the Phase-2 Kochi team for transporting Hayabusa 2 samples.
Image credit: JAMSTEC/Phase2 Kochi

Meteorites and other extraterrestrial substances undergo a variety of processes before arriving in the hands of researchers. Some examples include: contamination due to human handling errors, such as touching samples by hand; chemical changes over long periods of time due to water or atmospheric gases on Earth; and heating induced by passage through Earth's atmosphere. Even in specialized research facilities or museums with carefully controlled temperature and humidity, the influence of such processes can never be entirely excluded. Thus, of all specimens available to us as researchers, the Ryugu samples returned by Hayabusa 2 are surely the most pristine of all extraterrestrial substances (Figure 3). Nonetheless, minerals and organic matter in these samples coexist in complex configurations with ultra-miniature, ultra-fine-grained organizational patterns. Thus, our strategy for attempting to understand Ryugu is to scour samples of its material for historical evidence—specifically, for remnants left over from various stages in the evolution of our solar system over the past 4.6 billion years, including its earliest phase as a low-temperature molecular cloud, the chemical reactions thought to have accompanied subsequent high-temperature phases, and the complex interplay of heat and water that drove the evolution of the asteroid itself. To observe fine-grained structure as thoroughly as possible given the limited sample volumes at our disposal, we believe it is important to combine existing analytical techniques with the various sample-preparation methods that have been established to date, exploiting both strategies in complementary ways to extract material-science information. Our aim is to establish a new Ryugu dissection science in which various analytical tasks—such as determining quantities and isotope compositions for the various chemical elements present in hydrous and anhydrous minerals and organic matter, as well as identifying mineral textures and the ways in which they are combined—are carried out on Ryugu samples only after carefully selecting the most appropriate analytical instruments and laboratory procedures for each task. By exploiting both bulk analysis of entire samples and two-dimensional in-situ analysis on sub-micron scales, we believe that Ryugu dissection science will successfully identify similarities to other known examples of extraterrestrial matter (including the extensive catalog of meteorites, as well as cosmic dust and samples taken from asteroid Itokawa and comet Wild2) and shed light on the chemical relationships between coexisting minerals and organic matter19).

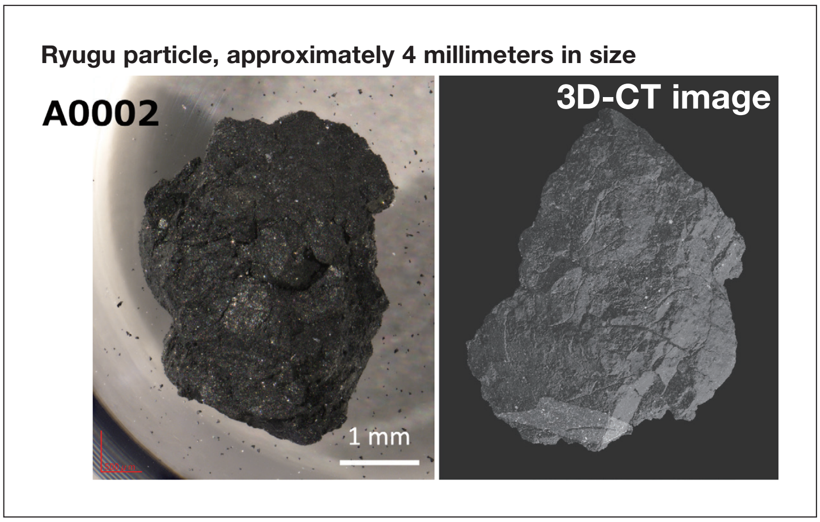


Fig. 3 The largest of the Ryugu samples provided to the Phase-2 Curation Kochi Team (left) and a synchrotron-radiation computed tomography (CT) image captured at SPring-8 (right).
Image credit: JAMSTEC/Phase2 Kochi

Our research team devoted the greatest amount of time to investigating sample-preparation protocols and devising analytical procedures. To ensure that particles with sizes between 0.1 and 0.5 millimeters were not overlooked in our analyses, we used a focused Ion beam (FIB) apparatus to create ultra-thin sections, then explored—at great length—a hybrid form of analysis combining transmission electron microscopy (TEM), ultra-high-resolution secondary ion mass analysis (NanoSIMS), and scanning transmission X-ray microscopy (STXM) using synchrotron radiation. (Our primary analytical instruments are shown in Figure 4.) More specifically, we used FIB to extract sample regions with the greatest material-science value, then mapped the spatial distribution of carbon-containing chemical species in organic matter via STXM, captured element and isotope images via NanoSIMS, and observed atomic-scale organization and crystal structure via TEM, assembling the results of all three analyses to yield a composite picture. In the remainder of this section we briefly describe our use of this methodology to study actual Ryugu samples[20)].

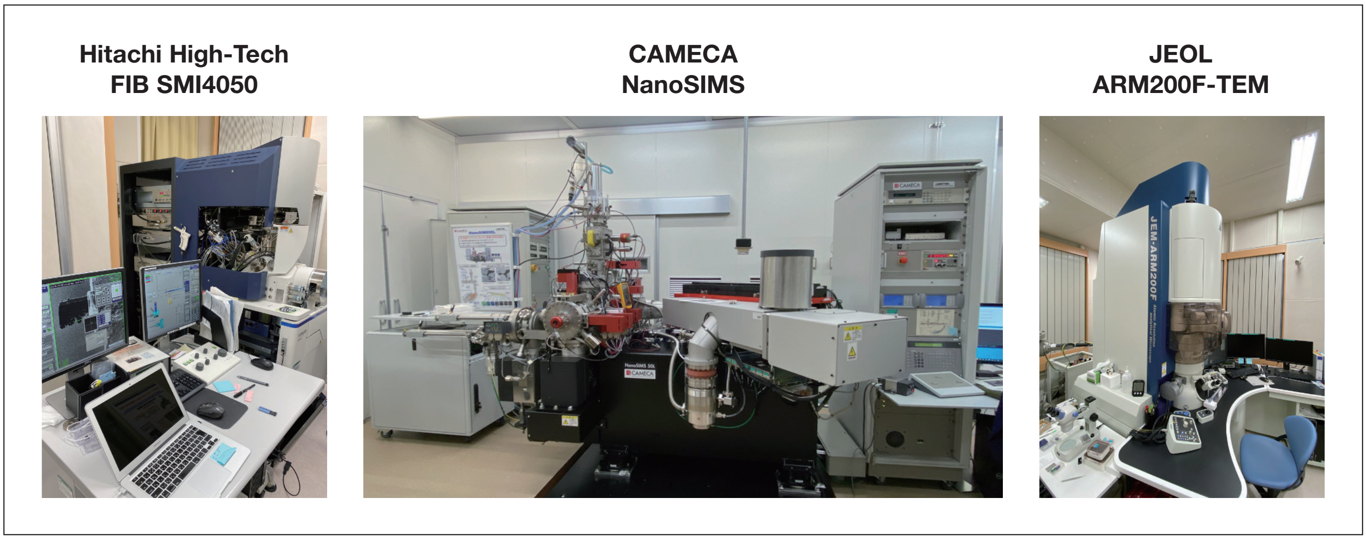


Fig. 4 Laboratory instruments at the JAMSTEC Kochi Core Center: focused Ion beam system (FIB), nanoscale scanning secondary ion mass analyzer (NanoSIMS), and transmission electron microscope (TEM). The FIB system, which plays a key role in sample preparation, has proven particularly essential for Ryugu research.
Image credit: JAMSTEC/Phase2 Kochi

Our "Phase-2 Curation Kochi Team" was first allocated a set of 8 Ryugu sample particles (1-4 millimeters in size) with a total mass of around 50 milligrams. Starting in mid-June 2021, we captured X-ray CT images using the BL20XU beamline at SPring-8, Japan's large-scale synchrotron-radiation facility; these images indicated the shape and internal structure of each particle, which we used to determine which particle regions were optimal for various types of analysis. We then shipped the Ryugu particles to various research institutions in Japan and overseas, taking care to ensure no exposure to the Earth's atmosphere during shipping. In arranging international shipping for precious Ryugu samples, we were assisted by the Embassy of the United Kingdom in Tokyo, as well as by Japan's Ministry of Foreign Affairs and Ministry of Education, Culture, Sports, Science and Technology, who helped to ensure safe and speedy delivery of samples to the Open University in the U.K. and to UCLA in the U.S.

The conclusions of our analysis of the elemental composition of Ryugu particles were consistent with results reported by previous research studies21,22), again confirming the basic picture that Ryugu consists of primordial matter whose elemental composition reflects that of the overall solar system. Although there is some variation from particle to particle, we see many minerals whose formation is believed to have involved water (Figure 5). This suggests that, in the past, ice existed on Ryugu, and the water produced by the melting of this ice reacted with the minerals present in the original composition of the asteroid to yield the minerals that comprise it today.

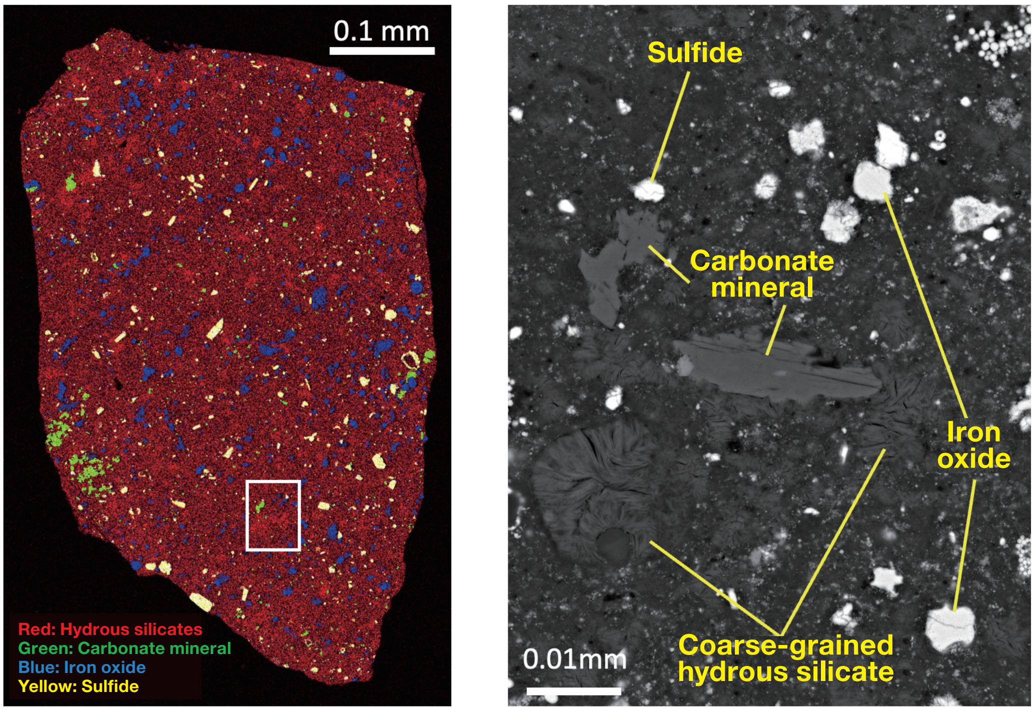


Fig. 5 Electron microscope image of Ryugu sample, indicating that the sample is composed of minerals containing water in the form of hydroxyl groups or minerals whose formation involved water.
Image credit: JAMSTEC/Phase2 Kochi

Using NanoSIMS to analyze the status of more fine-grained matter revealed that, for hydrogen and nitrogen, Ryugu samples contain a greater abundance of heavy isotopes than we observe on Earth. This result not only agrees well with evidence from cosmic dust, but also reveals a tendency toward isotope-abundance values close to those observed for comets (Figure 6)—suggesting that the material-science properties of Ryugu particles have remained largely unchanged since their formation, and thus that Ryugu particles have been relatively unaffected by heat. These particles most likely formed at the outer edges of the solar system before migrating to their current locations.

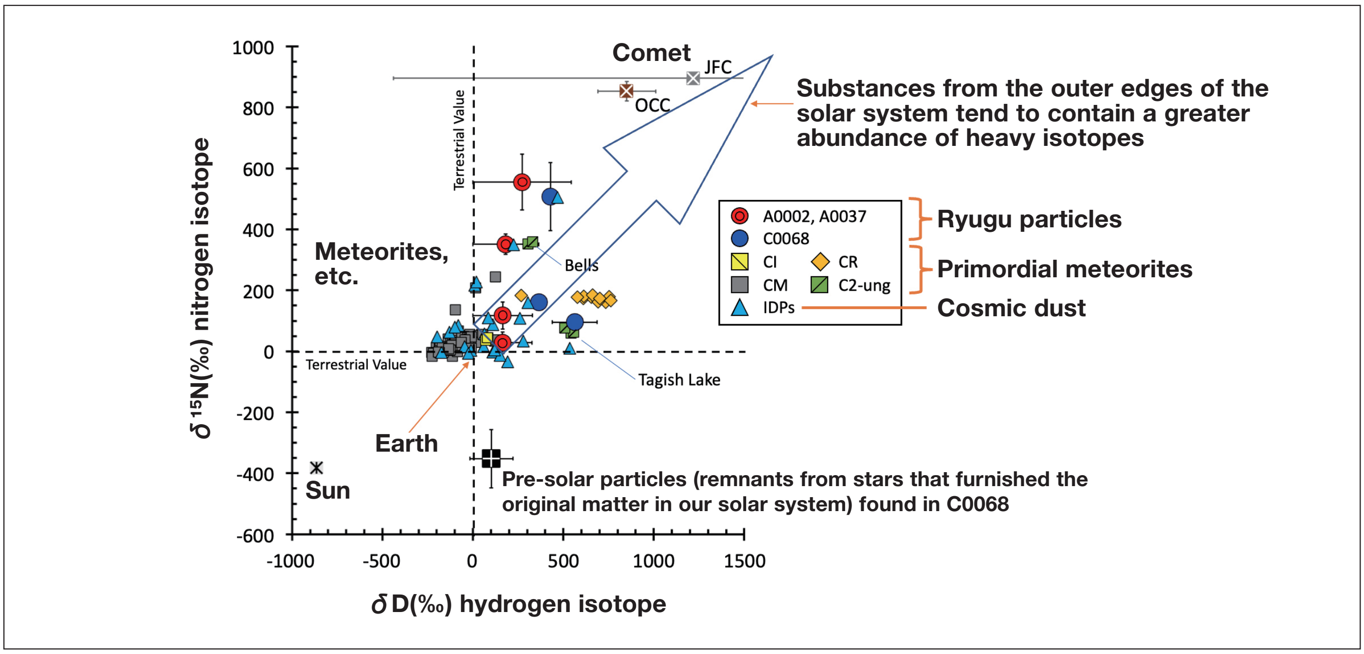


Fig. 6 Correlations between the isotope ratios of hydrogen and nitrogen suggest that Ryugu particles formed at the outer edges of the solar system.
Image credit: JAMSTEC/Phase2 Kochi

Combining the results of STXM and TEM analyses, we find that organic matter containing abundant aliphatic hydrocarbons consists of coarse-grained hydrous silicate minerals interspersed with various organizational patterns in complicated configurations (Figure 7). This observation furnishes direct evidence that organic matter reacted with minerals in the presence of water. Other research studies have reported that organic matter containing abundant aliphatic hydrocarbons decomposes at temperatures above 30 °C, and the existence of such substances on Ryugu thus suggests that the asteroid has never experienced temperatures above 30 °C. Determining precisely which varieties of organic matter are contained in specific sample regions is a topic for future work.

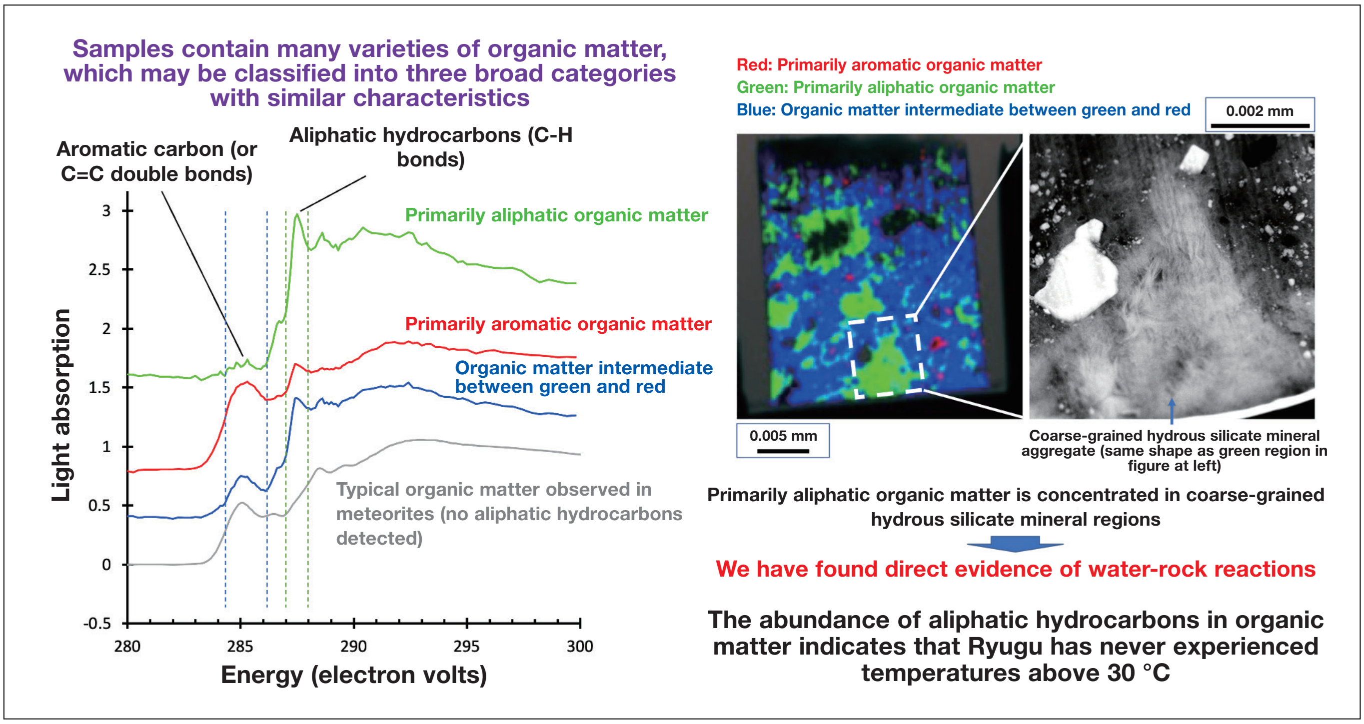


Fig. 7 Left: STXM analysis reveals that the many varieties of organic matter contained in Ryugu particles may be classified into three broad categories, each with distinct characteristics. Right: A color map indicates how the three types of organic matter are distributed across a square region (side length: 0.02 mm) of a Ryugu particle sample, while a TEM image of the subregion delineated by white dashed lines shows that organic matter containing aliphatic carbons is densely concentrated within coarse-grained hydrous silicate mineral domains.
Image credit: JAMSTEC/Phase2 Kochi

3. Conclusions

Material samples from asteroid Ryugu have now been analyzed by eight research teams—including our team—working in parallel and reporting results in a lengthy and growing series of publications[20-27)]. For further details we encourage readers to consult the individual articles in this series, which demonstrate the unparalleled scientific value of Ryugu samples as specimens in the field of Earth and space science.

The question of how organic matter and water were originally transported to our Earth remains a subject of vigorous ongoing debate. One possibility is that the coarse-grained hydrous silicate minerals in Ryugu samples constituted one source of organic matter and water. Indeed, organic matter contained in coarse-grained hydrous silicate minerals is believed to be more resistant to decomposition than organic matter contained in fine-grained hydrous silicate minerals; perhaps organic matter transported in this way was entirely unchanged upon arriving on Earth. On the other hand, asteroids such as Ryugu cannot have been the only sources of water on Earth, as we see from the greater abundance of heavy hydrogen isotopes in Ryugu particles compared to Earth matter. Meanwhile, particles sampled from asteroid Itokawa have been found to contain silicate minerals composed of light hydrogen isotopes originating from the solar wind; thus, perhaps the Earth's water formed as a blend of components with distinct hydrogen isotope compositions. Our findings in this study allow us to state the following hypothesis: The microscopic particles that comprise asteroid Ryugu were originally created at the outer edges of the solar system and contained copious quantities of water and organic matter. This primordial asteroid eventually migrated toward the center of the solar system, bringing water and organic matter to Earth. We expect that further analysis of Ryugu particles, together with insights gleaned from asteroid Bennu (NASA's OSIRIS-REx mission), will allow us to validate this hypothesis.

Needless to say, our scientific purview is not limited to the analysis of extraterrestrial substances such as meteorites and asteroid samples from Hayabusa and Hayabusa 2. One alternative way to study the cosmos—and a focus of vigorous current research efforts—is to observe more distant stars and regions of space using instruments such as space telescopes launched into Earth-orbiting trajectories (including the U.S. Hubble and James Webb telescopes and Japan's Akari and Hinode projects) and large-scale radio telescopes such as the ALMA observatory. Because these techniques are capable of observing the complex organic molecules that form the constituent elements of life as we know it, they are gradually shedding light on the formation and diversity of organic molecules in our universe. Going forward, we are hopeful that the complementary approaches of observing celestial bodies and studying planetary matter—in combination with material-science insights spanning vastly different temporal and spatial scales—will lead to deeper understanding, not only of our Earth and solar system but of the universe itself.

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