FORMATION, EVOLUTION, AND SURFACE MODIFICATION OF THE CARBONACEOUS ASTEROID RYUGU INFERRED FROM PETROLOGICAL AND MINERALOGICAL SIGNATURES OF THE RETURNED SAMPLES

Megumi Matsumoto[1] and Toru Matsumoto[2]

Asteroids are thought to be remnants of planet formation that can provide clues to the origin and evolution of the Solar System. The *Hayabusa2* spacecraft explored the carbonaceous asteroid 162173 Ryugu and brought back surface samples to Earth in late 2020. A mission goal was to investigate the formation and evolution of carbonaceous asteroids and their relationships with carbonaceous chondrite meteorites. The initial analysis of the Ryugu samples was performed with numerous cutting-edge techniques over a one-year period starting in June 2021. Many researchers affiliated with the Japan Association of Mineral Sciences and societies participating with *Elements* magazine have joined in the petrological and mineralogical characterization of the Ryugu samples. The main results of the analysis have recently been published in *Science* (Nakamura et al. 2022) and *Nature Astronomy* (Noguchi et al. 2022). Here, we briefly introduce these two papers discussing the formation and evolution of Ryugu and its surface evolution.

The Formation and Evolution of Ryugu (Nakamura et al. 2022)

Multilateral analyses were performed on 17 millimeter-sized Ryugu particles in laboratories and synchrotron radiation facilities inside and outside of Japan. The analysis revealed the physical and mineralogical properties of the Ryugu samples and provided insights into the formation and evolution of this carbonaceous asteroid.

The Ryugu samples are breccias consisting of tens to several hundreds of micron-sized rock fragments. All these fragments consist almost entirely of fine-grained matrix material. The major components are Mg-rich phyllosilicates (saponite and serpentine), carbonates (dolomite and magnesite), Fe–Ni sulfides (pyrrhotite and pentlandite), magnetite, hydroxyapatite, and organic matter (Fig. 1). The mineralogy and mineral chemistry are most similar to CI chondrites. The major components are the products of low-temperature (<~50 °C) aqueous alteration of primitive planetary materials (e.g., anhydrous silicates, Fe–Ni metal/sulfides, organic matter) that occurred in Ryugu's parent body. X-ray nanoscale computed tomography and cryo-time-of-flight secondary ion mass spectrometry analyses revealed the presence of CO_2-bearing aqueous fluid inclusions inside the pyrrhotite grains. The aqueous fluid is the remnant of ancient water once present in Ryugu's parent body. These findings suggest that Ryugu's parent body formed at a large heliocentric distance (>3–4 AU) from the Sun in the early Solar System.

The Ryugu samples include rock fragments with various degrees of aqueous alteration. Based on chemical equilibrium modeling of the aqueous alteration, most fragments are suggested to have formed under water-rich conditions (water/rock mass ratio: ~0.2–0.9); however, some fragments contain anhydrous and amorphous silicates and are suggested to have formed at a lower water/rock mass ratio of <0.2. The different types of fragments appear to have been derived from different portions (depths) in Ryugu's parent body. This is consistent with remote-sensing observations from the *Hayabusa2* spacecraft, which indicated that Ryugu is a rubble pile formed via the reassembly of fragments of a parent asteroid destroyed by a large-scale impact (Watanabe et al. 2019). Ryugu is suggested to have been a member of the Eulalia or Polana asteroid families in the inner asteroid belt, and the destructive impact occurred after the migration of Ryugu's parent body inward in the Solar System (Sugita et al. 2019). This implies that the parent body size was as large as ~100 km in diameter. Based on this assumption and Ryugu's physical properties, such as its mechanical strength, a numerical simulation of the collision and destruction of Ryugu's parent asteroid was conducted. The results show that a head-on collision of a ~10-km-diameter impactor to a ~100-km-diameter parent body, with an impact speed of 5 km/s, would form a ~50-km-diameter surviving body (similar in size to the Eulalia and Polana asteroids) and numerous smaller bodies. Ryugu would correspond to one of these small bodies. Because most Ryugu samples show no obvious shock features, they likely formed from fragments derived from areas far from the impact site. The overall formation scenario of Ryugu is summarized in Fig. 2.

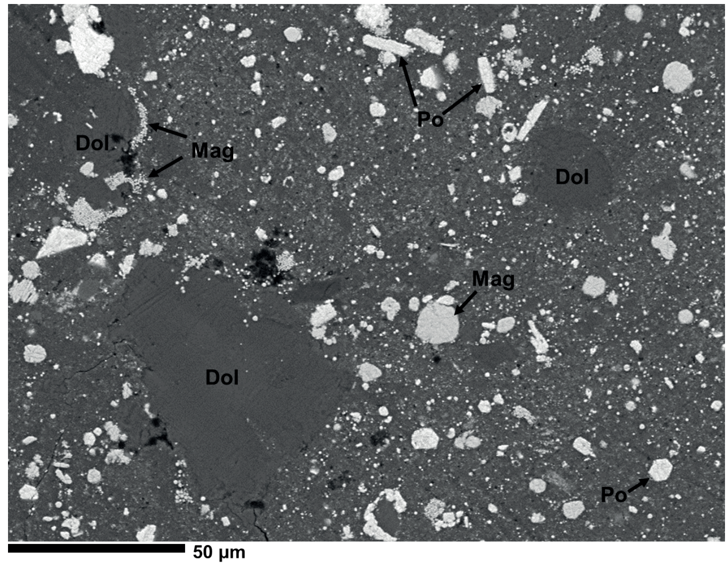

Figure 1 Back-scattered electron scanning electron microscope (SEM) image of a typical petrologic texture of a Ryugu sample. Dolomite (Dol), pyrrhotite (Po), and magnetite (Mag) are embedded in a fine-grained Mg-rich phyllosilicate matrix.

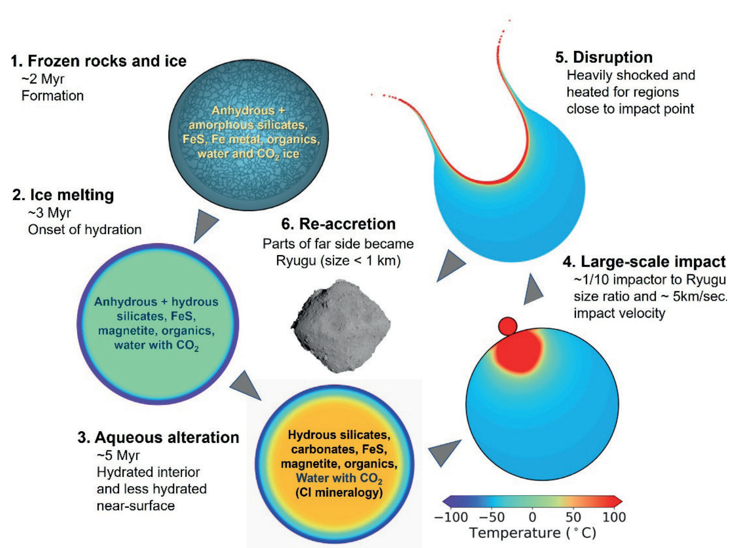

Figure 2 Schematic illustration of the early history of Ryugu's parent asteroid.

1 Department of Earth and Planetary Materials Sciences, Tohoku University
E-mail: m_matsumoto@tohoku.ac.jp

2 The Hakubi Center for Advanced Research, Kyoto University
E-mail: matsumoto.toru.2z@kyoto-u.ac.jp

The surface evolution of Ryugu (Noguchi et al. 2022)

Airless surfaces of small bodies gradually alter in composition, structure, and optical properties through a collective process referred to as space weathering. Solar wind irradiation and high-velocity micrometeoroid bombardment are the main causes of space weathering. Thus far, space weathering of carbonaceous bodies has been poorly understood. The Ryugu samples show surface modifications of the phyllosilicate-rich matrix in ~6% of the fine grains from the first touch-down site and ~7% from the second touch-down site. Several distinct surface modifications are observed in scanning electron microscope (SEM) and (scanning) transmission electron microscope (S)TEM analyses, including smooth layers, frothy layers, melt splashes, and their combinations (Fig. 3).

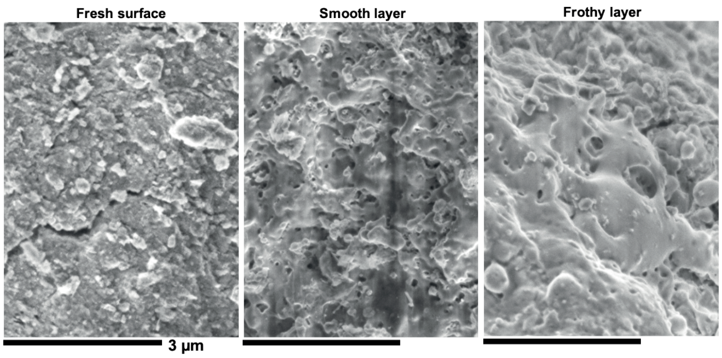

Figure 3 Secondary electron SEM images of the phyllosilicate surfaces of Ryugu grains. Scale bars indicate 3 µm. These images were obtained using field emission SEM at Kyoto University.

The smooth layers are continuous smooth sheets with completely amorphous structures. The iron is more reduced in the smooth layers than in the matrix. Ion irradiation experiments simulating solar wind exposure produced surface structures similar to those of the smooth layers. Solar wind irradiation therefore likely played a key role in forming the smooth layers. The frothy layers are composed of silicate glass containing abundant vesicles and submicroscopic iron sulfides. The internal structure suggests the melting of silicate and Fe–Ni sulfides and their immiscible separation, indicating that these structures formed by heating through micrometeorite bombardments. The depletion of structural –OH has been identified in both layers, suggesting that structural –OH in phyllosilicates is removed through dehydroxylation as space weathering proceeds. Approximately 40% of C-type asteroids do not show the 2.7-µm band features in their reflectance spectra; this is related to water absorption. Based on the analysis of the Ryugu samples, the absence of the 2.7-µm absorption band can be partly explained by surface dehydration resulting from space weathering, suggesting that asteroids showing apparently dry surfaces may have water-rich regions in their interiors.

REFERENCES

Nakamura T and 220 coauthors (2022) Formation and evolution of carbonaceous asteroid Ryugu: direct evidence from returned samples. Science 379: eabn8671, doi: http://doi.org/10.1126/science.abn867

Noguchi T and 138 coauthors (2022) A dehydrated space-weathered skin cloaking the hydrated interior of Ryugu. Nature Astronomy 7: 170-181, doi: 10.1038/s41550-022-01841-6

Sugita S and 119 coauthors (2019) The geomorphology, color, and thermal properties of Ryugu: implications for parent-body processes. Science 364: eaaw0422, doi: 10.1126/science.aaw0422

Watanabe S and 87 coauthors (2019) Hayabusa2 arrives at the carbonaceous asteroid 162173 Ryugu—a spinning top–shaped rubble pile. Science 364: 268-272, doi: 10.1126/science.aav8032

SEM 2023 ANNUAL MEETING IN MADRID

The 40th Annual Meeting of the Spanish Mineralogical Society (SEM) will be held in Madrid on June 16, 2023. It will be organized and coordinated by Nuria Sánchez Pastor and Rubén Piña García (Complutense University of Madrid).

The program for the SEM 2023 meeting includes the following.

- Two plenary lectures: "Mineral evolution: the perspective of time in mineralogy" by Dr. José María Fernández Barrenechea and "The power of crystals: origin and impact on our culture" by Juan Manuel García-Ruiz.
- A poster session. Presentations in the fields of clays, mineralogy, petrology, and geochemistry may be submitted. The main objective is to hold a high-quality scientific session that can become a platform for debate, the exchange of ideas, and the establishment of new scientific collaborations.
- General assembly of the Spanish Mineralogical Society.
- Closing dinner.

For updated information, visit https://sem2023madrid.com/.

EMU MEDAL

The Spanish Society of Mineralogy calls upon its members for nominations for the European Mineralogical Union (EMU) Research Excellence Medal 2023. This medal is presented to an early-career scientist who has made significant contributions to research in mineralogy and whose professional and societal activities contribute to strengthening scientific links in Europe. Early-career scientist nominees are expected to have completed their PhDs within 15 years (or equivalent once accounting for career breaks) of the closing date for nominations.

The deadline for applications is June 1, 2023. Please submit the nomination cover page and all other documents (which can be found at http://eurominunion.org/wp-content/uploads/2018/11/cover-page-EMU-award-interactive.pdf) to the Chair of the Medal Committee, Dr. István János Kovács (kovacs.istvan.janos@mfgi.hu).

The award ceremony will be held before the Medal talk given during an international meeting of relevance to Mineralogical Sciences selected according to the winner's expertise. EMU will provide partial support for the travel expenses. Additionally, the *European Journal of Mineralogy* (*EJM*) offers to the recipient/recipients of the medal the possibility to publish, as first author, one open-access article free of charge, which must be submitted no later than three years after the date of the announcement of the attribution of the Medal is made.