EARLY HISTORY OF RYUGU'S PARENT ASTEROID: EVIDENCE FROM RETURN SAMPLE.

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Introduction: Near-Earth Cb-type asteroid (162173) Ryugu is a rubble pile asteroid made of fragments of the original parent asteroid [1-5]. It is possible that the fragments from various depths of the original asteroid are on the surface of the present-day Ryugu. Therefore, samples collected from Ryugu are expected to retain formation and evolution history of the interior of Ryugu's parent asteroid.

In this study, we will focus on understanding the early history of Ryugu's parent asteroid. For this purpose, we need to understand: 1) when and where in the solar nebula Ryugu's parent asteroid formed, 2) the original mineralogy and the abundance and composition of water-rich ice in the accreted materials, 3) how these materials chemically and mineralogically evolved, and 4) how the parent body was destroyed by a catastrophic collision.

Samples and Experiments: We analyzed sixteen coarse Ryugu particles 1 ~ 8 mm in size (pictures shown in [6]): six from the 1st touch down site and ten from the 2nd touch down site.

We measured reflectance spectra of UV [7], visible [8], near infrared [9], mid to far infrared [10, 11] wavelength range. In addition, we used infrared nano-spectroscopy (AFM-IR) to image fine structures of organics and phyllosilicates [12, 13]. We performed X-ray [14] and infrared [15] tomography in micron- to nano-scale to understand the internal 3D structure of individual samples. Fe valence state and magnetic structure were investigated by Mössbauer spectroscopy [16] and electron holography [17], respectively. Muon measurement [18] and synchrotron XRF tomography [19, 20] were performed to see bulk abundance and 3D distributions of major- and minor-elements. Physical and thermal properties were measured [21, 22] to understand the response to shock and heating.

Individual Ryugu coarse samples were cut by Xe-FIB or wire-saw to expose particular objects or textures to be exposed on the surface based on 3D structure and element distribution [23]. FE-SEM/EDS and FE-EPMA/WDS analysis were made on polished sections [24]. TEM observation was made to see microstructures and to compare with carbonaceous chondrites [25, 26, 27, 28]. Mineralogical comparisons were also made between Ryugu samples and AMMs [29] and IDPs [28]. TOF-SIMS analysis was carried out to analyze fluid inclusions in a pyrrhotite single crystal [30].

Based on the obtained mineralogical properties, we performed chemical modeling of aqueous alteration of Ryugu's parent asteroid [31]. Numerical simulations [32, 33, 34] to reproduce thermal history and impact-induced destruction of the Ryugu's parent asteroid were also carried out using mineralogical and physical properties of the Ryugu samples. The results of all analyses and simulations are described in [35] and a summary is shown below.

Results and discussion: Based on the presence of CO_2-bearing water in fluid inclusions in the pyrrhotite crystal [30], Ryugu's parent asteroid formed outside the CO_2 and H_2O snowlines. Remanent magnetization was detected [17], implying that the solar nebula might have still been present when the carrier phase of the magnetic field, i. e., small magnetite, formed in Ryugu's parent asteroid.

Muon analysis of ten Ryugu samples revealed the abundances of C, N, Na, Mg, S, and Fe, relative to Si, to be close to CI chondrites, while O is deficient compared to CI chondrites [18]. X-ray CT analysis showed that all sixteen Ryugu particles are composed of fine-grained material, with no chondrules and CAIs larger than 100 μm in size. FE-EPMA observation showed that Ryugu samples are breccias, consisting of many small rock fragments of different compositions, lithologies, and histories. The most common lithology includes Mg-rich saponite and serpentine, dolomite, magnesite, hydroxyapatite, pyrrhotite, and magnetite as main constituents. The mineralogy of this major lithology supports the classification of Ryugu samples as CI chondrites [36], which experienced extensive aqueous alteration in Ryugu's parent asteroid.

In contrast, some fragments show a different lithology, containing a higher abundance of anhydrous silicates (olivine + low-Ca pyroxene), Ca carbonate, phosphides, together with pyrrhotite, magnetite, and poorly-crystalline phyllosilicates [24, 26]. These fragments experienced a lesser degree of aqueous alteration. According to the chemical modeling of aqueous alteration [31], the mineral composition of this less-altered lithology formed at a low water/rock mass ratio of < 0.3, probably at shallow depths within the parent asteroid [34], while the dominant more-altered major lithology was produced at a higher water/rock ratio of 0.3–1.0 in the interior of the asteroid.

Mechanical and thermal properties are similar, but not identical, to CI and CM carbonaceous chondrites [21, 22]. Numerical simulations of the thermal history of Ryugu's parent asteroid revealed temperature distribution and its changes with time [34], and those of and impact disruption processes show pressure and temperature distribution upon impact and size distribution of broken fragments [33].

Based on evidence derived from analyses and simulations stated above and isotopic analysis [37], we infer the early history of Ryugu's parent asteroid as follows. It formed at 1.5–2.5 Myr after CAI formation with a water ice/rock ratio of 0.3–1.0 in a cold region of the solar nebula. Water ice melted 3 Myr after CAIs and aqueous alteration occurred and gradually changed the initial anhydrous mineralogy to a largely hydrous mineralogy. Approximately 5 Myr after CAIs, Ryugu material at all depths experienced the highest temperature (< ~100°C), and aqueous alteration continued. A catastrophic impact disrupted Ryugu's parent asteroid at ~1 Gyr ago [2], and some fragments originating far from the impact point were reassembled to form present-day Ryugu.

Acknowledgments: We thank Toyo Cooperation for the use of pFIB system for sample preparation.

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