

FORMATION OF RYUGU: APPROACH FROM NUMERICAL SIMULATIONS WITH PHYSICAL PROPERTIES MEASURED IN RYUGU SAMPLES. H. Genda^{1*}, K. Kurosawa², S. Wakita^{3,4}, R. Hyodo⁵, K. Sugiura¹, S. Tanaka⁵, T. Nakamura⁶, H. Yurimoto⁷, T. Noguchi⁸, R. Okazaki⁹, H. Yabuta¹⁰, H. Naraoka⁹, K. Sakamoto⁵, S. Tachibana¹¹, S. Watanabe¹², and Y. Tsuda⁵, ¹Earth-Life Science Institute, Tokyo Institute of Technology, ²Chiba Institute of Technology, ³Massachusetts Institute of Technology, ⁴Purdue University, ⁵Japan Aerospace Exploration Agency, ⁶Tohoku University, ⁷Hokkaido University, ⁸Kyoto University, ⁹Kyushu University, ¹⁰Hiroshima University, ¹¹The University of Tokyo, ¹²Nagoya University, (*genda@elsi.jp)

Introduction: Carbonaceous asteroids are an important source to supply volatiles and organics to the terrestrial planets [e.g., 1,2]. Thus, the origin and evolution of carbonaceous asteroids has been one of major issues in planetary sciences. Hayabusa2 spacecraft visited one of the carbonaceous asteroids, Ryugu [3,4], and brought back Ryugu particles (5.4 g in total [5]) to the Earth. The initial description at JAXA curation and the project-led initial analysis suggest that they are similar to CI-chondrites [5–7], whose parent bodies were thought to form beyond the snow line. Therefore, the potential Ryugu's parent body should be born in mixture of rocky and icy materials. Moreover, the presence of CO₂-bearing water in pyrrhotite [6] indicates that it formed even beyond CO₂ snow line [8], which corresponds to ~ 15 au in the optically thin disk model for the solar nebula [9].

Some particles in the returned samples are large enough for us to measure their physical properties [6,10]. In addition, mineralogic and isotopic studies [6,7] provide important constraints on formation and evolution of Ryugu. Here, we perform a series of numerical simulations by using those measured properties in order to elucidate formation of Ryugu's parent body, its thermal history [11], and formation of Ryugu via catastrophic collision [12]. These simulations are the first attempts where the actual properties measured from a returned asteroid sample have been used. Here we present the highlights for these numerical results [6,11,12].

Thermal Evolution of Ryugu's Parent Body: Orbital calculations [13] and spectroscopic studies [4,14] suggest that the most likely origin of Ryugu is either the Eulalia or Polana families. The size of the parent body can be estimated from the total mass of the Eulalia family [13], and its estimated radius of the rocky part is ~ 50 km.

Ryugu samples are rich in hydrous minerals (e.g., phyllosilicate), but poor in anhydrous minerals (e.g., olivine) [6]. This supports that extensive aqueous alteration occurred in the parent body, and almost all Ryugu materials came from aqueously altered parts in the Ryugu's parent body. Moreover, Mn-Cr dating indicates that carbonate found in the sample was formed at ~ 40°C at 5.2 Myr after CAI formation [7].

Using the thermal properties of the materials measured in Ryugu sample [6,10], we perform numerical simulations for the thermal evolution of the Ryugu's parent body. Fig. 1 shows the time to reach 40°C varies the formation time of Ryugu's parent body and its initial water to rock mass ratio (W/R). Chemical modeling of aqueous alteration indicates that the range of W/R for 0.3–0.9 can reproduce the mineralogy observed in Ryugu samples [6]. The required formation time of the Ryugu parent body should be ~ 1.7 Myr and ~ 2.5 Myr after CAIs for $W/R = 0.9$ and 0.3, respectively [6,11]. As the later formed body has less ²⁶Al, it takes more time to get to 40°C. The further late formed body fails to reach that temperature because the ice melting consumes the heat and takes longer. These formation times are earlier than the estimated time of ~3.5 Myr for CM chondrites [15] and 3.6 ± 0.5 Myr for CI chondrites [16]. When we consider the lower W/R (e.g., ~ 0.1, which was used in [15,16]), the required formation time would be later and become similar to their results.

For these successful cases, ice melted, and hydrous minerals also formed inside the parent body. However, the subsequent temperature increase was limited, so that dehydration of hydrous minerals does not occur. As shown in [11], the cold surface layer (~ 10 km) prevents ice from melting, which allows the survival of the initial mineralogy. Therefore, the least altered lithology rarely found in Ryugu samples might have located at such a surface layer of Ryugu's parent body. A subsequent catastrophic collision to form asteroid Ryugu would mix the materials located in the different depths.

Catastrophic Collision on Ryugu's Parent Body: The potential Ryugu's parent body was disrupted by a collision to form the Eulalia or Polana families [4]. To perform impact simulations, the equation of state (EOS) is needed. By using the thermo-elastic properties measured in the returned Ryugu samples [6,10], we constructed two types of EOSs for Ryugu because of the large uncertainty in compressibility against rapid compressions [6,12].

To estimate the impactor size for this catastrophic disruption of the Ryugu's parent body, we conducted impact simulations using the three-dimensional smoothed particle hydrodynamics (SPH) code

developed in [17]. The code does not include the material strength, but self-gravity, so that re-accumulation of impact fragments is calculated. To form the largest body with ~ 20 km in radius, which corresponds to asteroid Eulalia (or Polana), we found that the impactor size is ~ 6 km and ~ 8 km in radius for head-on and 45° impacts, respectively, for the typical impact velocity (5 km/s) in the current main asteroid belt (see Fig. 2).

To precisely estimate temperature and pressure increase during this catastrophic collision, we also conducted a series of two-dimensional simulations by using the iSALE code [e.g., 18–20] with the material strength but without self-gravity. Although the process of the re-accumulation of impact fragments is not calculated, high-resolution simulation can provide more precious estimation of temperature and pressure increase during the collision.

As the results, we confirmed that highly shocked region (> 1 GPa and/or > 100 °C) is limited only for the impact-side hemisphere on the Ryugu's parent body, and the location far from the impact site (e.g., opposite hemisphere) is less shocked [12]. This nature does not depend on the constructed Ryugu EOSs, porosity and material strength. From the initial analysis of the returned samples, the constituent materials of Ryugu have unlikely experienced >1 GPa and 90 °C [6], which supports that almost all materials of Ryugu would come from the locations far from the impact point.

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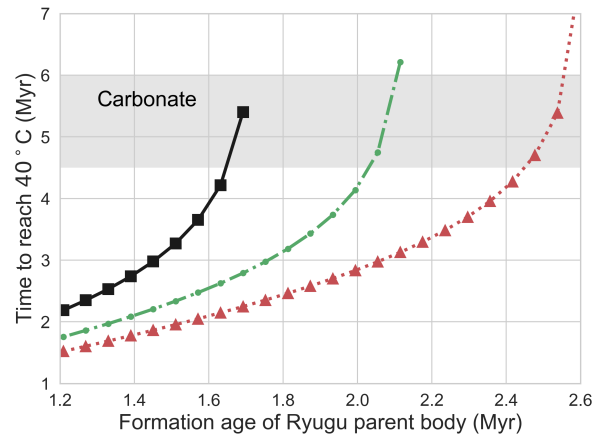


Figure 1. Time to reach 40°C at the center of the Ryugu's parent body as a function of its formation age. Each line represents the result from a different W/R ; black, green, and red for $W/R = 0.9$, 0.6 , and 0.3 , respectively. The shaded region depicts the formation time range of carbonate minerals at $4.5\text{--}6.0$ Myr after CAI formation, which formed at $\sim 40^\circ\text{C}$ [7].

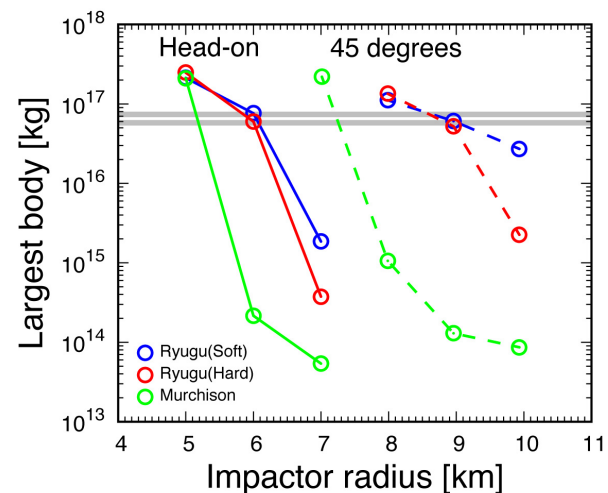


Figure 2. The mass of the largest body after a catastrophic disruption of the Ryugu's parent body (50 km in radius) for the various sizes of impactors. Two impact angles, head-on (solid lines) and 45 degrees (dashed lines) are considered for the constructed EOSs (hard Ryugu, soft Ryugu, and Murchison bulk). Horizontal gray lines correspond to the estimated mass of asteroid Eulalia (or Polana) For the impact velocity, 5 km/s is used for all impact simulations.