

THERMAL EVOLUTION MODELS FOR A PARENT BODY OF RYUGU. S. Wakita^{1,2*}, H. Genda³, T. Nakamura⁴, H. Yurimoto⁵, T. Noguchi⁶, R. Okazaki⁷, H. Yabuta⁸, H. Naraoka⁷, K. Sakamoto⁹, S. Tachibana¹⁰, S. Watanabe¹¹, Y. Tsuda⁹, ¹Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA, ²Department of Earth, Atmospheric, and Planetary Sciences, Purdue Univ., West Lafayette, IN, USA, ³Earth-Life Science Institute, Tokyo Institute of Technology, Tokyo, Japan, ⁴Department of Earth Science, Tohoku Univ., Sendai, Japan, ⁵Hokkaido Univ., Sapporo, Japan, ⁶Kyoto Univ., Kyoto, Japan, ⁷Kyushu Univ., Fukuoka, Japan, ⁸Hiroshima Univ., Higashi-Hiroshima, Japan, ⁹ISAS/JAXA, Sagami-hara, Japan, ¹⁰Univ. Tokyo, Tokyo, Japan, ¹¹Nagoya Univ., Nagoya, Japan (*shigeru@mit.edu).

Introduction: Sample return mission, Hayabusa 2 spacecraft visited the carbonaceous asteroid Ryugu [1, 2] and brought back Ryugu particles to the Earth. The initial analysis of Ryugu samples suggested that they are similar to CI-chondrites [3-5]. As Ryugu particles are large enough, it enables us to measure their thermal properties [6]. In addition, mineralogic and isotopic studies provide important information to estimate the parent body of Ryugu in the early solar system: Phyllosilicates are major minerals in the Ryugu samples without dehydration and the peak metamorphic temperature is less than 100 °C [4]. The carbonate formed at ~5.2 Myr after CAIs with a temperature of ~40 °C [5]. Here we explore the possible Ryugu parent body as an ice-rock mixture body using the thermal evolution models and find that its formation age is around 2 Myr after CAIs to satisfy the analysis data of Ryugu samples.

Methods: We numerically solve the heat conduction equation for a spherical body. Since the Ryugu sample are similar to CI chondrites [3-5], we assume that the parent body is an ice-rock mixture body. The spectroscopic study suggested that Ryugu is similar to the Eulalia or Polana family, suggesting that Ryugu has originated from the same parent asteroid as Eulalia or Polana [2, 7]. While the current size of Eulalia is ~50 km in diameter, it is estimated that the original total size of the Eulalia family was 100 km [8]. We assume that the Ryugu parent body originally has a rocky component of 50 km in radius. We take initial water to rock mass ratios (W/R) as a parameter from 0.3 to 0.9, which is verified by the chemical modeling of Ryugu [9]; the total radius of the parent body ranges from 60 km to 70 km. We use the physical properties of Ryugu samples, which are the thermal diffusivity, the heat capacity, and the density [4, 6], as the rock in the models. We use those properties of ice and water as the same as in [10]. The decay heat of ²⁶Al is the main heat source in our model. The initial abundance of ²⁶Al/²⁷Al at the CAI formation (5.25×10^{-5} [11]) was used for simulation; the parent body formed at 1.7 Myr after CAIs corresponds to have ²⁶Al/²⁷Al

ratio of 1.02×10^{-5} . We also consider the latent heat of the water-ice and the reaction heat of aqueous alteration [10]. Note that we assume aqueous alteration occurs at 20 °C. We fix the initial temperature of the parent body as 70 K (-200 °C), which may correspond to the disk temperature at ~15 au [12].

Results: To form secondary minerals at ~5 Myr after CAIs with a temperature of 40 °C, the required formation time of the Ryugu parent body varies depending on W/R. We found that the water-rich parent body (W/R = 0.9) should have formed at ~1.7 Myr to have aqueous alteration and reach 40 °C at ~5 Myr [13]. On the contrary, the water-poor body (W/R = 0.3) could form at ~2.5 Myr to be a Ryugu parent body. As such, the formation time of the Ryugu parent body would shift according to the initial water/rock ratio.

The original location of the Ryugu sample would be a few to tens km beneath the surface of the Ryugu parent body. Figure 1 shows the temperature profile of the Ryugu parent body, a 70 km radius body with W/R = 0.9 formed at 1.7 Myr after CAIs. As it does not exceed 50 °C, it is appropriate for the Ryugu parent body. While the anhydrous crust in this body is 13 km from the surface, it still has a hydrous rock of 57 km in radius. Thus, the majority of this body can be Ryugu particles. For the case of W/R = 0.3, the parent body of 60 km in radius formed at 2.5 Myr after CAIs also satisfies the requirement from carbonate [5]. Since the anhydrous crust (7 km from the surface) has never experienced aqueous alteration, they might have resulted in less altered Ryugu particles. The other parts (53 km from the center) having hydrous rock would reach a peak temperature up to 150 °C. While they still avoid temperature for dehydration (~500 °C), it exceeds 100 °C which might be unsuitable for Ryugu samples [4]. However, if we consider the circulation of water in a rocky body as a permeable flow [14, 15], the maximum temperature in our model could become lower. Regardless of W/R, the part that reaches 40 °C is about 50 km from the center of the body if it satisfies the requirement from carbonate.

Discussions: We here discuss the sensitivity of model results on assumptions we made. As the Ryugu particles indicate the presence of CO₂ bearing water, its parent body is expected to be formed beyond the CO₂ snow line [4]. Thus, we take the initial temperature of 70 K in our model, based on the condensation temperature of CO₂ ice in the solar nebula [16]. If the Ryugu parent body was located much closer to the Sun, the initial temperature could be higher. When we consider the case of the initial temperature of 150 K, it would make the required formation time 0.3 Myr earlier. The variation in choice of initial temperature would be minor than that of W/R. We consider the reaction heat from the chemical reactions; aqueous alteration forming serpentine and saponite from olivine and water [10]. However, the mineralogy in Ryugu particles is diverse, and the formations of magnesite, pyrrhotite, and dolomite are also precipitated from the aqueous solution [4]. The reaction heat due to the formation of these minerals might change our results. As the phyllosilicate is dominant in the Ryugu particles, our assumption of serpentinization can be acceptable.

In the case of a water-rich parent body, the rocky core might be formed after the melting of water ice [8]. The formation of the rocky core might cause dehydration at a higher temperature, but the dehydrated minerals are absent in the Ryugu particles [4]. We have tested this scenario by considering the rocky core formed at 5 Myr with an initial temperature of 20 °C. We found that it could reach up to 70 °C. Even if the rocky core formation occurs at 4 Myr, the peak temperature would be 150 °C. These temperatures are well below the temperature for dehydration (500 °C). Moreover, the remnant water could exist in the rocky core. Since it might trigger the hydrous circulation and make the temperature much lower [14, 15], our current results are the upper value. Thus, dehydration is unlikely in any case. Note that those conditions also depend on the initial water/rock ratio. The secondary minerals in Ryugu particles suggest that the chemical composition of the aqueous solution changed during the aqueous alteration [4]. This may indicate that the water/rock ratio also varied during its aqueous processing. If further analyses constrain the initial water/rock ratio, we can also limit the Ryugu parent body. Overall, the ice-rock mixture body formed at 1.7–2.5 Myr after CAIs with 60–70 km in the radius is a likely candidate for the Ryugu parent body.

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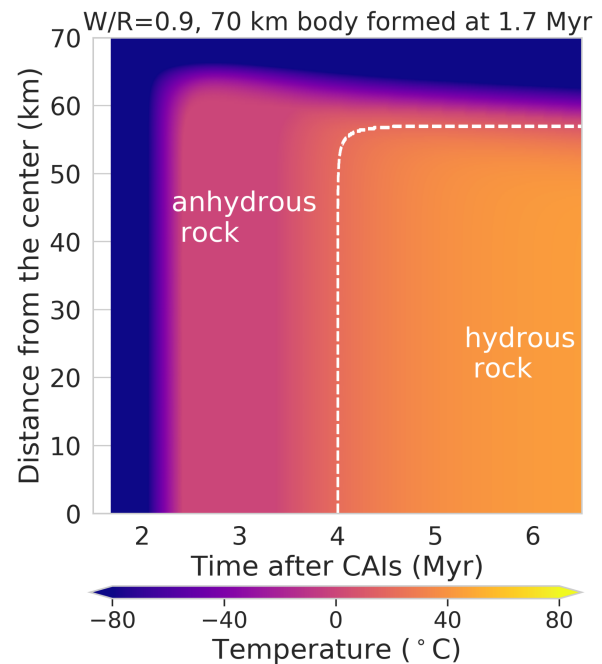


Figure 1. Temperature profile of 70 km-radius-body with W/R = 0.9. Color indicates the temperature at each location and time. A white dashed line depicts the material boundary between anhydrous and hydrous material.