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Thermal Evolution Modeling of Ryugu and its Precursors

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Abstract

The evolution of the temperature and porosity in potential parent bodies of Ryugu was calculated and compared with the measurements of MASCOT and properties of CI and CM chondrites. Key properties of the parent body were estimated.

1. Introduction

During MASCOT's[1] operational phase on the surface of the rubble pile NEA (162173) Ryugu, brightness temperatures of a single boulder were measured and its thermal inertia was estimated[2]. The observed thermal inertia was interpreted in order to estimate the thermal conductivity k and porosity ϕ of the boulder[3] resulting in values of k = 0.06-0.16 $Wm^{-1}K^{-1}$ at 230 K, $\phi \approx$ 30-55 % for different models of $k(\phi)$. The porosity of the boulders is a result of processes that occurred during the thermal evolution of the parent bodies, during their destruction, and during the re-accretion of the rubble that eventually formed Ryugu. Spectral observations suggest presence of phyllosilicates and a composition close to CI or CM chondrites[4,5] indicating an origin beyond the frost line.

In the present study, we calculate the interior evolution of a potential parent body for Ryugu and compare resulting compositions with the properties of CI and CM chondrites. We estimate key properties of the parent body, such as accretion time t_0 and size, and trace the evolution of porosity.

2. Methods

The calculations were performed using a 1D finite differences thermal evolution model for ^{26}Al-heated planetesimals[6]. Such models consider heating of small bodies after accretion and the evolution of the temperature in their interiors. In particular, compaction due to hot pressing of an initially unconsolidated interior is included. An ice-rich initial composition that leads to a material dominated by phyllosilicates upon aqueous alteration (similar to CI and CM chondrites) was assumed. Creep laws for major components antigorite and olivine after aqueous alteration were implemented. The strain rate was calculated as a volume fraction weighted arithmetic mean of strain rates of antigorite and olivine. Material properties (thermal conductivity, density, heat capacity, etc.) correspond to the composition assumed and are adjusted with temperature and porosity. The initial temperature of 170 K corresponds to an accretion at ≈2.7 AU[7], appropriate for a H_2O-rich composition and close to values assumed to be representative for the CI and CM parent bodies[8]. A comparison of the measured bulk density (≈1186 kg m^{-3}) with grain densities of carbonaceous chondrites[9] indicates a present average porosity ϕ_{av} of 50-70%. Since Ryugu is a rubble pile, a major part of the evolution of its material occurred on the precursor bodies. Therefore, the evolution of these precursors that had at least as massive must be calculated. Adopting a lower bound on the mass, a body with Ryugu's mass and with a high initial porosity ϕ_0 after accretion is considered. The thermal evolution and gradual reduction of ϕ upon heating of such an object is calculated. A high initial porosity of 60-80% implies a larger initial radius and shrinking due to compaction.

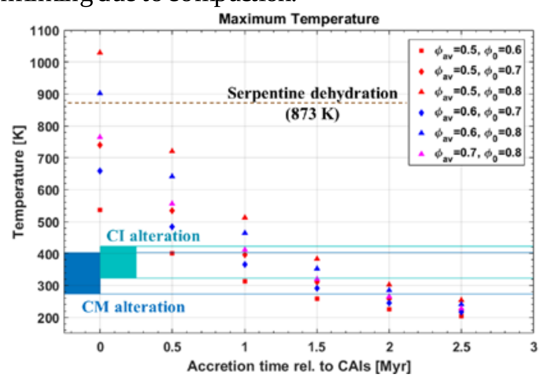

Fig. 1: Maximum temperature for different combinations of ϕ_{av} and ϕ_0 as a function of the accretion time t_0 rel. to CAIs compared with CI and CM alteration temperatures[10,11].

3. Results

Since the chemical reaction of olivine and water to serpentine, talc, magnetite and hydrogen is quasi-instantaneous on a geological time scale (≈ 200 years at 273 K[7]), only the melting temperature of water ice must be achieved for reproducing conditions for the formation of phyllosilicates. For a test whether Ryugu can be a CI/CM parent body, their alteration temperatures of 273 K to >400 K[10,11] and carbonate formation temperatures at respective times of 3.5-4.8 Myr after CAIs must be reproduced in the interior.

The maximum temperatures obtained for a number of models satisfy the CI/CM alteration temperature range (Fig. 1). These are mostly early accreting bodies, consistent with the short half-life of ^{26}Al. A stronger heating of bodies with a higher ϕ is consistent with progressively low values of k at high porosity. For early formation times the CI/CM alteration temperatures are exceeded and for $t_0 \approx 0$ Myr rel. to CAIs dehydration of serpentine is possible.

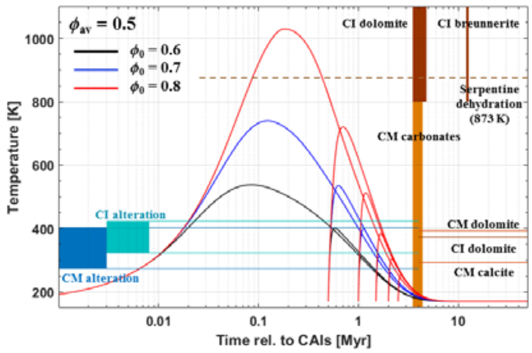

Fig. 2: Thermal evolution at the center for $\phi_{av} = 0.5$, different values of ϕ_0 and a varying t_0, CI and CM alteration temperature, and carbonate formation times and temperatures.

Fig. 2 shows the evolution of the central temperature for selected models with accretion times of ≤2.5 Myr rel. to CAIs and for different combinations of ϕ_{av} and the initial porosity. For the cases considered, the water ice melts early, at 7-80 thousand years after accretion. However, those models that reach CI and CM alteration temperatures do not reproduce the carbonate formation ages, excluding a Ryugu-sized planetesimal as a CI or CM parent body. Nevertheless, mineralogies similar to CI and CM chondrites are produced.

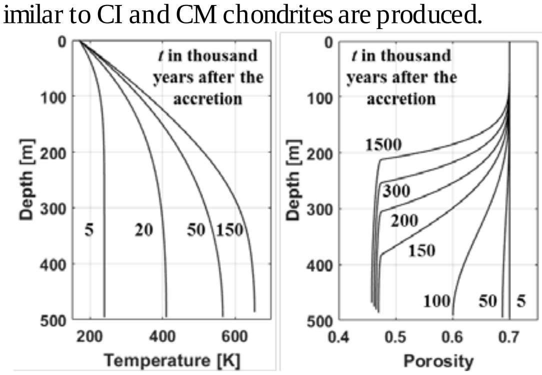

Fig. 3: Time snapshots of temperature- and porosity-depth profiles for a calculation with $\phi_{av} = 0.6$, $\phi_0 = 0.7$, and $t_0 = 0$ Myr rel. to CAIs.

The temperature- and porosity-depth profiles at different times are shown in Fig. 3 for a selected case. The conditions for aqueous alteration persist for up to 2 Myr. Due to a quasi-constant temperature of >273 K throughout the interior, most of the material is altered except in a thin surface layer of ≈ 50 m. The porosity is reduced in the interior, but not in the outer part. These processes are fast compared to the collisional lifetime, which is likely of the order of tens of Myr for bodies of a comparable size[12]. Therefore, aqueous alteration and compaction can take place long before the body is destroyed by collisions and re-accretes.

4. Summary and Conclusions

Compaction from an initial porosity of 60-80% to values of ≈45% in the interior agrees with porosities estimated for boulders on the surface of Ryugu indicating that this body could have formed from one or more Ryugu-sized precursors which accreted early while ^{26}Al was still active. The main mechanism for porosity reduction would then be hot pressing, while other mechanisms that could have influenced the porosity require either considerably higher pressures (cold pressing[13]) or are rather inefficient (aqueous alteration, dehydration[6]). Compaction by hot pressing and aqueous alteration could have occurred either in the precursors or in the re-accreted parent body provided early destruction and re-accretion[14]. In this way, porosities down to 45 % can be achieved even on small, kilometer-sized bodies if a water ice rich primordial composition similar to those of CI and CM chondrites is assumed[6,14]. The rapid cooling of small Ryugu-sized precursors is inconsistent with CI/CM carbonate formation ages (Fig. 2), which implies that a Ryugu-sized precursor can be ruled out as a parent body for these meteorite groups. However, carbonate formation ages can be reproduced for larger objects, which take longer to cool. Re-accretion of a small part of such a body provides another formation scenario for Ryugu, which would then be a fragment of a CI or CM parent body.

References

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