POROUS BOULDERS ON (162173) RYUGU: COMPACTION MODELING AND IMPLICATIONS FOR PARENT BODY'S RADIUS, ACCRETION TIME, AND INTERIOR POROSITY DISTRIBUTION.

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Introduction: Observations of the C-type NEA (162173) Ryugu by Hayabusa II demonstrated that this asteroid is a low-density rubble pile whose surface is dominated by large boulders. MASCOT's[1] measurements during its operational phase on the surface of the rubble pile NEA (162173) Ryugu provided boulder brightness temperatures that allowed estimating thermal inertia[2]. The latter was interpreted in order to estimate boulder thermal conductivity k and porosity ϕ[2]. Thermal properties of boulders indicate high intrinsic porosities[2], consistent with the overall low bulk density of the asteroid[3], resulting in values of k = 0.06-0.16 $Wm^{-1}K^{-1}$ at 230 K, $\phi \approx$ 28-55 % for different models of $k(\phi)$.

While the bulk porosity of a rubble pile asteroid is due to the contributions of the micro-porosity (the intrinsic boulder porosity) and the macro-porosity (the voids in-between boulders), the porosity of a single boulder is a local micro-porosity value. It is a result of processes that were initiated during the thermal evolution of a parent body from which the boulder originated prior to its re-accretion onto Ryugu.

We calculated the evolution of temperature and porosity for planetesimals in order to identify potential parent bodies for Ryugu's material and likely burial depths for the boulders observed at the surface. By varying planetesimal properties that have strong influence on temperature and porosity, we constrained a field within the (t_0,R)-diagram appropriate for bodies that could have produced such material.

Methods: The calculations were performed using a 1D finite differences thermal evolution model for planetesimals[4]. It considers heating by ^{26}Al and evolution of the interior temperature as well as compaction of an initially unconsolidated body due to hot pressing. An ice-rich initial composition that leads to a material dominated by phyllosilicates upon aqueous alteration was assumed consistent with spectral observations that suggest a composition close to CI or CM chondrites[5,6]. Using creep laws for major components antigorite and olivine, the bulk strain rate was considered as a volume fraction weighted arithmetic mean of strain rates of both species for the modelling of compaction. Material properties adopted 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], which is close to values assumed to be representative for CI and CM parent bodies[8].

A minimum requirement on the mass of a parent body is the mass of Ryugu and a minimum requirement on its initial porosity ϕ_0 is the boulder microporosity of 28-55 %. The thermal evolution and gradual reduction of ϕ upon heating of such an object is calculated. Apart from that, the parent body mass (i.e., its size) and accretion time are free parameters.

Results: A sample aqueous alteration 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]). Thus, in a first-order approximation, only the melting temperature of water ice must be surpassed for reproducing conditions for the formation of phyllosilicates. Such temperatures can be obtained for a variety of accretion times and planetesimal sizes. However, rapid decay of ^{26}Al limits the accretion times of kilometer-sized objects to t_0 < 1.5 Myr after CAIs. A weaker cooling of larger bodies allows for later accretion times with an increasing size. On the other hand, a very early accretion is less likely for planetesimals with radii larger than approximately 10 km. At least partial melting in the interior of such bodies would erase traces of aqueous alteration contradicting Ryugu's observed composition.

Another important implication arises from the planetesimal size with regard to the evolution of porosity. Since compaction is driven by both the temperature T and pressure P, different (P, T) conditions over extended time periods of different length can produce the same porosity. Consequently, models produce material with $\phi \approx$ 28-55 % in planetesimals of considerably different sizes and

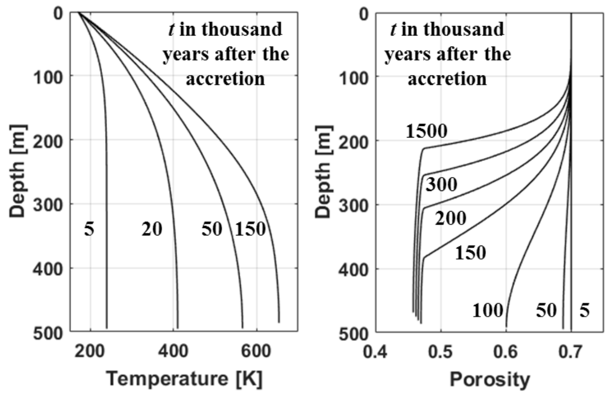

Fig. 1: Time snapshots of temperature- and porosity-depth profiles for a calculation with R = 0.5 km, t_0 = 0 Myr rel. to CAIs, and ϕ_0 = 70%.

accretion times at different depths, i.e., in the deep interior of kilometer-sized early accreting bodies and in very shallow layers of 10-100 kilometer sized late accreting bodies.

The temperature- and porosity-depth profiles at different times are shown in Fig. 1 for a selected case with R = 0.5 km, t_0 = 0 Myr rel. to CAIs, and ϕ_0 = 70%. Conditions for aqueous alteration are established early and 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 throughout the deeper interior at temperatures that are similar to peak temperatures of CM chondrites[9], but not in the outer part. By contrast, in larger planetesimals with R > 10 km, material with a porosity of 28-55 % is confined to rather thin layers in the shallow subsurface where the porosity profile shows a strong gradient between ϕ_0 (surface) and ϕ = 0 (interior)[4,10] . Such layers experience compaction typically at temperatures that are considerably smaller than CM peak temperatures.

Summary and Conclusions: Assuming initial porosities[11] of the order of 70%, Ryugu's precursor needs to have had a sufficient size to reduce the micro-porosity to values below 55% by compaction, while simultaneously avoiding porosities to drop below 28%. This can be achieved in the deeper interior of small kilometer-sized bodies which accreted early while ^{26}Al was still active. Alternatively, such material could have been produced in thin subsurface layers of larger (R > 10 km) parent bodies which accreted later. The main mechanism for porosity reduction is hot pressing, while other mechanisms that could have influenced the porosity require either considerably higher pressures (cold pressing[12]) or are rather inefficient (aqueous alteration, dehydration[10]). 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[4,10]. Both compaction by hot pressing and aqueous alteration could have occurred either in the precursors or in the re-accreted "secondary" parent body provided early destruction and re-accretion[10]. Such a re-accretion event must have occurred relatively late with a smaller concentration of ^{26}Al, therefore, the secondary parent body must have been definitely larger than several kilometers, if it existed in the first place. The calculated heating of small Ryugu-sized precursors is consistent with the alteration temperatures of CI and CM chondrites[13,14,15] but its rapid cooling is inconsistent with CI/CM carbonate formation ages[15], 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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