Macroporosity and Grain Density of Rubble Pile Asteroid (162173) Ryugu

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Abstract

Rubble pile asteroids such as (162173) Ryugu have large bulk porosities, which are believed to result from void spaces in between the constituent boulders (macroporosity) as well as void spaces within the boulders themselves (microporosity). In general, both macroporosity and microporosity are estimated based on comparisons between the asteroid bulk density and both the bulk and grain density of meteorite analogues, and relatively large macroporosities are usually obtained. Here we use semi-empirical models for the macroporosity of multi-component mixtures to determine Ryugu's macroporosity based on the observed size-frequency distribution of boulders on the surface. We find that Ryugu's macroporosity can be significantly smaller than usually assumed, as the observed size-frequency distribution allows for an efficient packing of boulders, resulting in a macroporosity of \$16 \pm 3°\%. Therefore, { we confirm that} Ryugu's high bulk porosity is a direct consequence of a very large boulder microporosity. Furthermore, using estimates of boulder microporosity of around { 50^\%} as derived from in-situ measurements, the average grain density in boulders is { \$2848 \pm 152\$ kg m\$^{-}{-3}\$, similar to values obtained for CM and the Tagish lake meteorites}. Ryugu's bulk porosity corresponding to the above values is { 58^\%.} { Thus, the macroporosity of rubble pile asteroids may have been systematically overestimated in the past.}

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Key Points: 16

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17	•	Ryugu's large bulk porosity is distributed between intrinsic boulder microporos-
18		ity and macroporosity due to void spaces in-between boulders.
19	•	We use the boulder size-frequency distribution as observed on the surface together
20		with mixing models to estimate Ryugu's macroporosity.
21	•	We find that macroporosity is 16±3 %, indicating that Ryugu's large bulk poros-
22		ity of close to 50 $\%$ is governed by microporosity.

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23 Abstract

Rubble pile asteroids such as (162173) Ryugu have large bulk porosities, which are be-24 lieved to result from void spaces in between the constituent boulders (macroporosity) 25 as well as void spaces within the boulders themselves (microporosity). In general, both 26 macroporosity and microporosity are estimated based on comparisons between the as-27 teroid bulk density and both the bulk and grain density of meteorite analogues, and rel-28 atively large macroporosities are usually obtained. Here we use semi-empirical models 29 for the macroporosity of multi-component mixtures to determine Ryugu's macroporos-30 ity based on the observed size-frequency distribution of boulders on the surface. We find 31 that Ryugu's macroporosity can be significantly smaller than usually assumed, as the 32 observed size-frequency distribution allows for an efficient packing of boulders, result-33 ing in a macroporosity of 16 ± 3 %. Therefore, we confirm that Ryugu's high bulk poros-34 ity is a direct consequence of a very large boulder microporosity. Furthermore, using es-35 timates of boulder microporosity of around 50 % as derived from in-situ measurements, 36 the average grain density in boulders is 2848 ± 152 kg m⁻³, similar to values obtained 37 for CM and the Tagish lake meteorites. Ryugu's bulk porosity corresponding to the above 38 values is 58 %. Thus, the macroporosity of rubble pile asteroids may have been sys-30 tematically overestimated in the past. 40

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Plain Language Summary

The carbonaceous asteroid (162173) Ryugu formed from fragments which re-accreted 42 after its parent body was disrupted by a catastrophic collision. Asteroids of this type 43 are also known as rubble piles and the re-accumulation process is thought to be one of 44 the causes for their large bulk porosity. We have applied mixing models to determine the 45 amount of inter-boulder porosity taking the observed abundance of large and small boul-46 ders on the surface into account. We find that the relative abundances of differently sized 47 boulders allow for a very efficient packing, such that inter-boulder porosity in Ryugu is 48 rather small and only 16 ± 3 %. This implies that a large part of Ryugu's total poros-49 ity must reside inside the boulders themselves. Using estimates of boulder intrinsic poros-50 ity, we furthermore constrain the average density of the boulder's constituent minerals 51 to 2848 ± 152 kg m⁻³, which is consistent with values measured for carbonaceous me-52 teorites as collected on Earth. Thus, inter-boulder porosity of rubble pile asteroids may 53 have been systematically overestimated in the past. 54

55 1 Introduction

Upon arrival of the Hayabusa2 spacecraft the C-complex asteroid (162173) Ryugu 56 was found to be a spinning top-shaped rubble pile (Watanabe et al., 2019) with Cb-type 57 spectrum and very low albedo around 0.045, consistent with thermally metamorphosed 58 CM/CI meteorites (Sugita et al., 2019). Observations further show that a weak 2.7 µm-59 absorption is present, suggesting a small amount of hydrated minerals exist on the sur-60 face (Kitazato et al., 2019). Furthermore, the surface was found to be dominated by blocks 61 and boulders (Sugita et al., 2019; Michikami et al., 2019), and 50% of the surface is cov-62 ered by boulders with diameters exceeding 0.5 m. A bulk density of 1190 ± 20 kg m⁻³ 63 was determined using the SFM20180804 shape model (Watanabe et al., 2019), which al-64 lowed for an estimate of asteroid porosity. Assuming typical grain densities for carbona-65 ceous chondrites (Britt & Consolmagno S.J., 2001; Macke et al., 2011; Flynn et al., 2018), 66 bulk porosity estimates close to 50 % were obtained (Watanabe et al., 2019), which is 67 consistent with the bulk porosity estimates for C-complex asteroids. 68

The bulk porosity inside rubble pile asteroids can be separated into two contribu-69 tions: the first one stems from the intrinsic porosity of rocks and boulders and is termed 70 microporosity, while the second contribution refers to voids in-between particles and is 71 termed macroporosity (Britt et al., 2002). The latter is directly related to the geomet-72 rical arrangement of the constituent blocks, also known as the packing state, which qual-73 itatively describes the arrangement of particles and can vary between random loose and 74 random close packings. Macroporosity of average C-complex asteroids was estimated to 75 be 25-30 % (Britt et al., 2002), which is generally consistent with numerical models of 76 the reassembly of blocks after a catastrophic disruption, which result in macroporosi-77 ties of 20-40 % (Wilson et al., 1999). However, simulations suffer from unrealistically large 78 lower cutoff sizes for the considered boulder population, such that rubble pile asteroids 79 may still exhibit lower macroporosities. 80

Here we investigate the macroporosity of asteroid Ryugu using semi-empirical models for the porosity of multi-component mixtures of non-spherical, cohesive particles (Zou et al., 2011). Such models predict the macroporosity of granular material given the particle size as well as the particle shape distributions applying linear mixing and using the concept of controlling mixtures (Yu & Standish, 1991) to calculate the packing state. In general, polydisperse particle mixtures can have a macroporosity which is considerably

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Figure 1. Top Left: Illustration of particle unmixing for particles with strongly disparate diameters. As small particles are added to a system of larger particles, the larger particles resist being displaced and the packing state does not change. A similar effect occurs for the addition of very large particles. Bottom Left: Illustration of particle mixing for particles with similar diameters. As similar sized particles are added to a system, particles can be displaced thus changing the packing state. Right: Two dimensional illustration of the random packing structure of strongly polydisperse spheres. As compared to monodispersed configurations, porosity is reduced by the filling of void spaces. Macroporosity refers to the porosity generated by the void spaces between particles, while microporosity is caused by void spaces and cracks that formed inside individual particles. Figure adapted from Yu & Zou (1998).

smaller than the canonical ~36 % for a random close packing or ~42 % for a random
loose packing of spherical, monosized particles (Scott, 1960), and values down to 10 %
can be reached (Dullien, 1991).

In binary mixtures, the way particles interact depends on their size ratio, here de-90 fined as the ratio of the respective particles' volume-equivalent diameters. If this ratio 91 is less than 0.154 (Graton & Fraser, 1935), small particles will not affect the packing state 92 and simply fill the gaps between larger ones. In contrast to this unmixing of particles, 93 similar sized particles will mix, creating a new packing structure (also see Yu & Zou (1998) 94 for a discussion of mixing and unmixing effects). Applying these concepts to polydisperse 95 mixtures, particle unmixing will take place for very small and very large particles, as smaller 96 particles start filling the gaps and larger particles completely fill some regions with solid 97 material. The component controlling the porosity of the mixture is then defined by in-98 termediate sized particles, which do not change their packing state by the addition of 99 unmixing components (Yu & Zou, 1998). An illustration of particle mixing and unmix-100 ing is shown in Fig. 1. The semi-empirical models by Yu & Zou (1998) and Zou et al. 101 (2011) can be applied to particle mixtures in loose and dense packing states. They have 102 been shown to reproduce the porosity of mixtures created using the funnel method, in 103 which particles are gently poured into a container, as well as the porosity of mixtures 104 tapped many times to reach maximum compaction. 105

It is important to note that packing is determined by the interplay of the differ-106 ent grain sizes present, and it can be misleading to consider individual grain sizes only. 107 For example, while the addition of a single large block to the mixture can reduce poros-108 ity by displacing smaller particles and filling void spaces, the addition of many large blocks 109 can increase porosity by creating large voids. Similarly, addition of some small particles 110 may reduce porosity, while many small particles can create a large number of small voids, 111 again increasing porosity. Therefore, the porosity finally attained by the mixture depends 112 on the details of the size-frequency distribution of the particles present. 113

In order to apply the theory of multi-component mixtures, the size and shape distributions of boulders need to be known. Here we use the boulder size and shape distributions determined by Michikami et al. (2019), who extend the analysis in Sugita et al. (2019) using images from the Hayabusa2 optical navigation camera (ONC) (Kameda et al., 2017; Suzuki et al., 2018; Tatsumi et al., 2019) which have near global coverage and were acquired at altitudes between 20 km and 6.5 km. These have spatial resolutions down to 0.65 m/pixel, and global counts were performed for boulders with diameters > 2 m and a completeness limit of 5 m. In addition, smaller boulders, cobbles and pebbles with sizes of 0.02 to 9.1 m were studied using close-up images of the sampling areas, where images taken at altitudes from 67 m to 620 m with resolutions down to <0.01 m/pixel are available (Michikami et al., 2019). Overall, size-frequency and shape distributions were determined in the 0.02 to 140 m size range.

By applying the multi-component mixing model to the size distribution of boul-126 ders as observed on the surface, we assume that the same distribution holds in the in-127 terior. This assumption is supported by laboratory experiments on the disruption of mono-128 liths (Michikami et al., 2016), which suggest that boulders on bodies such as Itokawa, 129 Bennu, and Ryugu are relicts of the direct formation of those asteroids by gravitational 130 reaccumulation following the disruption of their parent bodies (Michel & Richardson, 131 2013; Michel et al., 2020) rather than the result of impact events after formation has been 132 completed. Impacts could reshape the size distribution by the production of smaller par-133 ticles after reaccretion has been completed, but the importance of this process may be 134 limited. This is due to the so-called armoring effect (Sugita et al., 2019), by which a large 135 fraction of the impact energy is lost when the projectile contacts the first large boulder, 136 thus producing only few fragments. Another mechanism that could be responsible for 137 a difference between the size-frequency distributions observed on the surface and present 138 in the interior is seismic shaking, and the Brazil Nut Effect could lead to an overrepre-139 sentation of large boulders on the surface (Tancredi et al., 2015; Maurel et al., 2017). How-140 ever, the seismic efficiency of impacts in granular material appears to be low (Yasui et 141 al., 2019; Nishiyama et al., 2020), such that surface modifications are likely localized. Nev-142 ertheless, seismic shaking could have an impact on the global boulder size-frequency dis-143 tribution over geological timescales. Finally, it has been argued that particle size sort-144 ing may take place during rubble pile reaccretion, with larger blocks accreting first and 145 thus in the center (Britt & Consolmagno S.J., 2001). These caveats need to be kept in 146 mind when interpreting the results presented below. 147

A second important input parameter for the multi-component mixing model is the material's packing state, which can vary between a random loose and random close packing. In general, little is known about the packing state of rubble pile asteroids following reaccretion, which depends on many parameters such as the distribution of angu-

-6-

lar momentum in the reaccreting system as well as the size distribution and shape of reac-152 creting fragments. While impact experiments indicate that shattered, elongated parti-153 cles with large deviations from a spherical shape can be produced (Nakamura & Fuji-154 wara, 1991; Durda et al., 2015; Michikami et al., 2016) the results of disruption exper-155 iments need to be interpreted with caution, as the high strain rates imposed during the 156 experiment may not be representative for the destruction of larger blocks. Further, long 157 term seismic shaking could lead to the reduction of pore spaces. Given these unknowns, 158 we will systematically vary the packing state in the analysis below. 159

In the following, we will first introduce the theory of determining asteroid macroporosity from observed size and shape distributions for the rocks and boulders. We will then derive a simple equation relating grain density to macro- and microporosity. Results of the macroporosity calculation and relevant uncertainties will then be used to estimate grain density of Ryugu's constituent material given estimates of boulder microporosity (Grott et al., 2019; Hamm et al., 2020; Okada et al., 2020). Finally, results, assumptions, and implications will be discussed.

167 2 Methods

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2.1 Particle Size and Shape Distributions

To estimate Ryugu's macroporosity, the constituent boulder's size and shape dis-169 tributions need to be known. These were determined by Michikami et al. (2019) who fit-170 ted size-frequency data using power laws. Power law exponents between 1.65 and 2.65 171 were obtained, with 2.65 being the best fit for the global dataset. Furthermore, parti-172 cles were generally found to be elongated, and axis ratios for boulders > 2 m are close 173 to 0.7 on average. The size-frequency distribution of boulders on small bodies may bet-174 ter be described by a Weibull distribution than a power law (Schröder et al., 2020), and 175 we have used a cumulative Weibull (Rosin-Rammler) distribution (Rosin, 1933; Weibull, 176 1951; Wingo, 1989; Brown & Wohletz, 1995) to represent the data provided by Michikami 177 et al. (2019). The cumulative size-frequency distribution N(D) is then given by 178

$$N(D) = N_T e^{-3(D/\lambda)^{\beta}/\beta} \tag{1}$$

where D is the mean horizontal diameter, and we determined the fit parameters $\beta =$ 0.09495, $\lambda = 33.78$ m, and $N_T = 5.28 \cdot 10^{14}$ km⁻² by a weighted least-squares approach as a practical means to obtain a good representation of the data. The resulting



Figure 2. Left: Cumulative particle size frequency distribution (SFD) as derived for Ryugu by Michikami et al. (2019). Our Weibull fit to the data (black) is shown along with a power law fit with exponent p = 2.65 (red). Right: Cumulative volume fraction distribution for the SFDs on the left hand side of the figure.

distribution N(D) is shown together with the uncertainty of the data in Fig. 2, where uncertainty comprises the Poisson uncertainty as well as the uncertainty of particle diameters introduced by the limited image resolution. It is worth noting that representing the data using a single power law for the entire size range does not adequately represent the data.

Given the size-frequency distribution N(D) as determined from surface counts of boulders, the normalized cumulative volume distribution V(D) can be calculated by numerical integration. It is given by

$$V(D) = c \left(N_{\text{tot}} D_{\min}^3 - N(D) D^3 + \int_{D_{\min}}^D N(D') 3D'^2 dD' \right)$$
(2)

where N_{tot} is the total number of particles counted per unit area, D_{\min} and D_{\max} are the minimum and maximum particle sizes of the particle size distribution N(D), respectively, and $c \, [\text{m}^{-1}]$ is a normalization factor chosen such that $V(D_{\max}) = 1$.

In addition to the Weibull distribution fit to the data represented by Eq. 1, we will also consider a simple power law to systematically study the influence of the particle size distribution's power law exponent p on the obtained results. The distribution can then be expressed as

$$N(D) = N_{\rm tot} \left(D/D_{\rm min} \right)^{-p} \tag{3}$$

where p = 2.65 represents the best fit to the global dataset (Michikami et al., 2019).

¹⁹⁸ For the power law defined by Eq. 3, Eq. 2 can be integrated analytically and the vol-

¹⁹⁹ ume size distribution is then given by

$$V(D) = \frac{D^{3-p} - D_{\min}^{3-p}}{D_{\max}^{3-p} - D_{\min}^{3-p}}$$
(4)

for $D_{\min} \le D \le D_{\max}$. For $D \ge D_{\max}$, V(D) = 1, whereas for $D \le D_{\min} V(D) = 0$.

Michikami et al. (2019) give the shape of boulders in terms of the maximum dimensions in three mutually orthogonal planes ($a \ge b \ge c$). Here we primarily regard the horizontal axis ratio b/a, with a being the maximum and b the intermediate dimension. As reported by Michikami et al. (2019), shape of particles on Ryugu appears to be largely independent of geographical longitude, whereas some dependence on latitude may indicate boulder migration. Nevertheless, average b/a is only weakly size-dependent and close to 0.7.

In general, particle sphericity is defined as the ratio of the surface area of a sphere (with the same volume as the particle) to the surface area of the particle (Wadell, 1932). However, this is difficult to evaluate in practice, and the Krumbein (Krumbein, 1941) or Riley (Riley, 1941) simplifications are usually applied. Working with two dimensional (image) data, we define sphericity Ψ as

$$\Psi = \sqrt{\frac{D_i}{D_c}} \tag{5}$$

where D_i is the diameter of the largest inscribed circle and D_c is the diameter of the small-213 est circumscribing circle for a given particle (Riley, 1941). Using Eq. 5, the shape pa-214 rameter b/a derived by Michikami et al. (2019) then translates into an average spheric-215 ity of $\Psi = 0.83$. In addition, Michikami et al. (2019) also estimated the third axis, c/a, 216 of 121 arbitrarily selected boulders. The mean axes ratio c/a was found to be 0.44, and 217 the sphericity of a parallelepiped with axis ratios a:b:c of 1:0.71:0.44 is 0.796. On the other 218 hand, sphericity of a triaxial ellipsoid with the same axis ratios is 0.913. Therefore, spheric-219 ity depends not only on axis ratios, but also on particle shape, and we will use $\Psi = 0.85 \pm$ 220 0.06 as an average sphericity rather than the average sphericity derived from the shape 221 data in Michikami et al. (2019) when calculating interparticle forces and initial porosi-222 ties below. 223

224 2.2 Macroporosity

The macroporosity of Ryugu can be calculated from the volume size-frequency dis-225 tribution (Eq. 2) assuming linear mixing models (Yu & Zou, 1998; Zou et al., 2011). In 226 the mixing theory, the macroporosity achieved for a given size distribution will be a func-227 tion of the volume fractions X_i , the initial porosity ϕ_i , as well as the nominal equiva-228 lent volume diameter d_i of particles in each bin. The latter represents the diameter of 229 a volume-equivalent sphere. Further, i = 1, ..., n is the number of size bins used and 230 $d_1 > d_2 > \ldots d_n$ for convenience. Then, the macroporosity ϕ_{Macro} can be expressed 231 as 232

$$\phi_{Macro} = f(X_1, \dots, X_n; d_1, \dots, d_n; \phi_1, \dots, \phi_n).$$
(6)

Note that the equivalent volume diameter d_i of particles is not strictly identical to the mean horizontal diameter as defined by Michikami et al. (2019), but as the observed boulder axis ratios on Ryugu change only little as a function of horizontal diameter, the shape factor relating horizontal diameter to the equivalent volume diameter d_i is close to constant. It can thus be factored out for the mixing model below and has a negligible effect on the Bond number.

The above formulation holds if particle sphericity is independent of particle size, 239 which is the assumption made in the following. However, we note for completeness that 240 the method to estimate macroporosity used here can be generalized to arbitrary sphericity-241 size relations $\Psi(d)$ by introducing the equivalent packing diameter d_p , which then ac-242 counts for particle shape effects, i.e., mixing of particles that have different sphericities 243 at different sizes. Then, the equivalent volume diameter d in Eq. 6 needs to be replaced 244 by the equivalent packing diameter d_p , which is related to the observed equivalent vol-245 ume diameter d through sphericity $\Psi(d)$ by (Yu & Zou, 1998) by the empirical relation 246

$$\frac{d}{d_p} = \Psi(d)^{2.785} e^{2.946(1-\Psi(d))} \tag{7}$$

247 248 The dimensionless specific volume describing the packing state for each bin is defined as (Zou et al., 2011)

$$V_j = \frac{1}{1 - \phi_j} \tag{8}$$

and the macroporosity finally attained by the mixture will be governed by the interaction of all differently sized particles. However, there will be one intermediate-sized bin

-10-

i that controls the packing structure (see Yu & Zou (1998), also compare Fig. 1). While the size-bin number i of the controlling component is not known a priori, the specific vol-

253 ume \tilde{V}_i of a particular packing can in general be expressed as

$$\tilde{V}_i = \sum_{j=1}^{i-1} [V_j - (V_j - 1)g(d_i, d_j)] X_j + V_i X_i + \sum_{j=i+1}^n [V_j (1 - f(d_i, d_j)] X_j$$
(9)

where small particles have indices $j = 1 \dots i - 1$ and large particles have indices $j = 1 \dots i - 1$

i+1...n. The functions $f(d_i, d_j)$ and $g(d_i, d_j)$ are referred to as interaction functions

between components i and j and were derived experimentally (Yu et al. (1997), Zou et

al. (2011). They are given by

$$f(d_i, d_j) = f(r_{ij}) = (1 - r_{ij})^{3.33} + 2.81r_{ij}(1 - r_{ij})^{2.77}$$
 and (10)

$$g(d_i, d_j) = g(r_{ij}) = (1 - r_{ij})^{1.97} + 0.36r_{ij}(1 - r_{ij})^{3.67}$$
 (11)

and depend on the equivalent packing diameter size ratios r_{ij} between small and large particles of the two components. Parameters r_{ij} can be expressed as (Zou et al., 2011)

$$r_{ij} = (1 - x_{ij})R_{ij}^k + x_{ij}R_{ij}$$
(12)

where $R_{ij} = d_j/d_i$ is the small-to-large size ratio and i < j. The empirical parameter

k is 0.451 (Zou & Yu, 1996), and x_{ij} depends on the type of particle-particle interaction

(Zou et al., 2011). It is given by

$$x_{ij} = \begin{cases} 1 & d_j > d_{cri} \\ 0 & d_i < d_{cri} \\ 1 - 1.543 \cdot e^{-0.697d_i/d_{cri}} & d_j \le d_{cri} \le d_i \end{cases}$$
(13)

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In the above equation, the critical particle diameter d_{cri} divides fine and coarse particles, i.e., it is the particle diameter below which cohesion between particles starts to influence particle interactions. Under Earth gravity conditions, d_{cri} is close to 150 µm (Zou et al., 2011), but under micro-gravity conditions, cohesion can be relevant even for decimeter-sizes boulders (Scheeres et al., 2010; Kiuchi & Nakamura, 2015; Zou et al., 2011). Here, we define the critical diameter based on the Bond number *B*, i.e., the ratio between interparticle forces and the weight of a particle (Scheeres et al., 2010).

We define the Bond number assuming a cleanliness factor equal to unity and a particle separation of $1.5 \cdot 10^{-10}$ m (Scheeres et al., 2010). Furthermore, we calculate the co-



Figure 3. Bond number, i.e., the ratio between interparticle forces and particle weight, as a function of particle diameter, assuming parameters as appropriate for Ryugu. The diameter corresponding to a critical Bond number of $B_{cri} = 0.1$ is indicated.

hesive force for equally sized particles and include effects of particle sphericity Ψ and roundness Ω (Powers, 1953) by adding these as multiplicative factors (Wood, 2020). The Bond number is then given by

$$B(d) = \frac{1.1 \cdot 10^{17} A \Psi \Omega}{\rho g (d/2)^2}$$
(14)

where d is particle diameter, $q = 0.9825 \cdot 10^{-4} \text{ m s}^{-2}$ is volume averaged gravity of 276 Ryugu (Yamamoto et al., 2020), and $A = 4.1 \cdot 10^{-20}$ J is the Hamaker constant for 277 olivine in high vacuum (Perko et al., 2001). While olivine is certainly not the most com-278 mon mineral in carbonaceous material, we consider its Hamaker constant to be a more 279 appropriate choice than, e.g., the widely used Hamaker constant for amorphous SiO₂. 280 In any case, the Hamaker constant needs to be regarded as highly uncertain. This also 281 implies that the exact choice of parameters like boulder density, sphericity, and round-282 ness has little influence on the results presented below. We choose boulder bulk density 283 $\rho = 1420 \text{ kg m}^{-3}$ to match a macroporosity of 16 % and a bulk density of 1190 kg m⁻³ 284 (Watanabe et al., 2019) for consistency, where ρ was determined using an iterative ap-285 proach. Furthermore, we choose a particle roundness Ω of 0.24, as appropriate for an-286 gular to subangular particles (Powers, 1953). 287

The resulting Bond number for parameters appropriate for Ryugu is shown in Fig. 3 as a function of particle diameter. The critical diameter d_{cri} corresponding to a critical Bond number $B_{cri} = 0.1$ is indicated in blue and has been calculated using Eq. 14. We use $B_{cri} = 0.1$ as a baseline, i.e., we assume that cohesion starts to have a notice²⁹² able effect on porosity once the interparticle forces exceed 10 % of the particle weight. ²⁹³ For Ryugu, $B_{cri} = 0.1$ corresponds to $d_{cri} = 0.52$ m, but the influence of varying B_{cri} ²⁹⁴ over a large range will also be discussed.

To evaluate Eq. 9, we first discretize the size range between $D_{\min} = 0.02$ m and 295 $D_{\rm max} = 140$ m into $\log(D_{\rm max}/D_{\rm min})/\log(q)$ logarithmically spaced bins. We use a size 296 factor of q = 1.05 from one bin to the next, resulting in a total of 182 size bins, which 297 turned out to be sufficient. Volume fractions X_i in each size-bin were calculated accord-298 ing to the Weibull or power law representation of the size-frequency distribution as needed. 299 Furthermore, initial specific volumes V_i and therefore initial porosities ϕ_i need to be pre-300 scribed. While initial porosities of coarse monosized spherical particles generally vary 301 between 0.42 for loose random packing and 0.36 for dense random packing (Scott, 1960), 302 cohesive forces between small particles can considerably increase porosities (Scheeres et 303 al., 2010; Kiuchi & Nakamura, 2015). We use the empirical relation (Kiuchi & Nakamura, 304 2015; Kiuchi & Nakamura, 2015b) 305

$$\phi_i = \phi_0 + (1 - \phi_0)e^{-\alpha B(d_i)^{-\gamma}} \tag{15}$$

to determine initial porosity, where ϕ_0 is the porosity of the non-cohesive particles and 306 describes the packing state. Note that we here implicitly assume initial porosities as ap-307 propriate for spherical particles, as for the relevant range of observed sphericities the in-308 fluence of deviations from an ideal spherical shape on initial porosity is negligible (Zou 309 & Yu, 1996). Particle shape enters Eq. 15 in the Bond number $B(d_i)$ only, and it is a 310 secondary effect in the analysis presented for Ryugu below. The constants $\alpha = 2.414$ 311 and $\gamma = 0.1985$ have been derived from a new fit to the data of Kiuchi & Nakamura 312 (2015). Finally, the specific volume occupied by the mixture is obtained by calculating 313 the maximum of all specific volumes for the different controlling mixture sizes and 314

$$V = \max\{\tilde{V}_1, \dots, \tilde{V}_n\}$$
(16)

315 Mixture macroporosity is then given by $\phi_{Macro} = 1 - 1/V$.

In summary, the following steps need to be performed to determine the macroporosity of a granular mixture using the model above: First, volume fractions in the individual size-bins need to be calculated from the given size-frequency distribution (Eq. 8, 9). Then, initial porosity in each size-bin needs to be determined. This will primarily depend on the packing state. Further, it also depends on particle roundness and shape, which influence cohesion (Eq. 14, 15) as well as the geometrical packing properties (not considered here). Finally, the macroporosity is determined by examining all possible particle interactions (Eq. 16).

324

2.3 Average Grain Density

While the main goal of the present paper is a determination of the macro-porosity of rubble-pile asteroid Ryugu, additional information on the asteroid's average grain density can be derived. As macroporosity ϕ_{Macro} , microporosity ϕ_{Micro} , and bulk density ρ_{Bulk} are related by

$$\phi_{\text{Macro}} = 1 - \frac{1 - \phi_{\text{Bulk}}}{1 - \phi_{\text{Micro}}} \tag{17}$$

information on grain density ρ_{Grain} can be extracted from

$$\phi_{\rm Bulk} = 1 - \frac{\rho_{\rm Bulk}}{\rho_{\rm Grain}} \tag{18}$$

Eq. 18 requires the macroporosity, microporosity, and bulk density to be known. 330 While the bulk density of Ryugu was estimated to be 1190 ± 20 kg m⁻³ (Watanabe et 331 al., 2019), the boulders' microporosity cannot currently be unambiguously constrained 332 due to the difficulties associated with extrapolating meteorite thermal conductivities to 333 porosities in excess of 20 % (Grott et al., 2019; Macke et al., 2011). However, end-member 334 models (Flynn et al., 2018; Henke et al., 2016) suggest microporosities ϕ_{Micro} of either 335 $32\,\pm\,2$ % or $50\,\pm\,2$ % for Ryugu's dark and rugged boulders (Hamm et al., 2020) which 336 comprise the vast majority of all boulders observed on the surface (Sugita et al., 2019; 337 Okada et al., 2020). We will use Monte-Carlo simulations to propagate these uncertain-338 ties to the determination of Ryugu's grain density, while simultaneously taking the un-339 certainty associated with Ryugu's macroporosity as derived from the linear mixing the-340 ory (Sec. 2.2) into account. 341

342 3 Results

Given the parameterization of the size-frequency distribution (Eq. 1) for the boulders observed on the surface of Ryugu, and assuming the distribution also applies to the interior, we have first calculated the corresponding volume frequency distribution using Eq. 2. Given roundness Ω , Hamaker constant A, particle bulk density ρ , and volume average gravity g (see Eq. 14), we then varied the initial porosity ϕ_i in each size bin (Eq.



Figure 4. Left: Histogram of macroporosities ϕ_M obtained using Monte-Carlo simulations. Right: Ryugu grain densities derived from a second set of Monte-Carlo calculations (see text for details). The two distinct distributions result from the uncertainty of microporosity for Ryugu's boulders (Grott et al., 2019; Hamm et al., 2020), and two end-member models for the microporosity have been assumed.

- ³⁴⁸ 15) using a Gaussian distribution for ϕ_0 centered around 39.5 % with standard devi-³⁴⁹ ation of 3 %. In addition, particle sphericity was varied using a Gaussian distribution ³⁵⁰ centered around 0.85 with standard deviation of 0.06, and 10⁶ draws from these distri-³⁵¹ butions were used in a Monte-Carlo simulation to calculate the resulting macroporos-³⁵² ity according to Eq. 16.
- Results of the calculation are shown in the left hand panel of Fig. 4, where a histogram of the obtained macroporosities ϕ_M is shown. The range of macroporosities obtained in the calculations is $\phi_M = 16.2 \pm 2.6$ % (1-sigma), and thus considerably smaller than porosities of monodisperse packings. This is not surprising given the broad particle size distribution observed on the surface of Ryugu.
- Given the range of macroporosities derived above as well as estimates for the boul-358 der microporosities derived from in-situ thermal inertia measurements (Grott et al., 2017, 359 2019; Hamm et al., 2020), we calculated the range of grain densities compatible with the 360 observed bulk porosity of Ryugu (Watanabe et al., 2019) using Eq. 17 and 18. We ap-361 plied two endmember models for the microporosity ϕ_{Micro} : for the first model (Flynn 362 et al., 2018) we use $\phi_{Micro} = 50 \pm 2$ %, while for the second model (Henke et al., 2016) 363 $\phi_{Micro} = 32 \pm 2$ % (Hamm et al., 2020). In the 10⁶ Monte-Carlo simulations performed, 364 we varied microporosity using Gaussian distributions centered around 50 % and 32 %365



Figure 5. Left: Macroporosity ϕ_{Macro} (porosity caused by void spaces in-between particles) as a function of the power law exponent of the underlying size-frequency distribution and critical Bond number B_{cri} . For comparison, results obtained neglecting cohesion between particles are also shown. Right: Macroporosity ϕ_{Macro} as a function of lower cutoff size D_{min} for three different power law exponents p. For reference, the power law exponent for Ryugu as derived from the observed surface boulder size-frequency distribution is p = 2.65 on average (Michikami et al., 2019).

with standard deviations of 2 %, respectively. Furthermore, we varied bulk density using a Gaussian distribution centered around 1190 kg m⁻³ with a standard deviation of 20 kg m⁻³ (Watanabe et al., 2019) and macroporosity using a Gaussian distribution centered around 16.2% with a standard deviation of 2.6 %.

Results of the calculation are shown in the right hand panel of Fig. 4, where the 370 resulting histograms for the grain densities ρ_{Grain} are shown for the two endmember mod-371 els. Owing to the two different models used to estimate boulder microporosity, two sep-372 arate peaks are obtained for the distribution of grain densities. For the model of Flynn 373 et al. (2018), we find grain densities of $\rho_{Grain} = 2848 \pm 152$ kg m⁻³, whereas the model 374 of Henke et al. (2016) results in $\rho_{Grain} = 2093 \pm 96$ kg m⁻³. As expected, higher mi-375 croporosities (Flynn et al., 2018) yield larger grain densities and vice versa to satisfy the 376 constraint posed by Ryugu's bulk density. 377

Results of a systematic study of the influence of critical Bond number B_{cri} and lower diameter cutoff sizes D_{\min} on the obtained macroporosities ϕ_{Macro} are shown in Fig. 5. Here, the size-frequency distribution of boulders has been approximated by a power law with exponent p to facilitate a comparison of Ryugu with other rubble pile asteroids. For

-16-

smaller power law exponents, the size-frequency distribution is shallower as compared to distributions with larger p, and as a result, such distributions represent surfaces with a higher ratio of large particles.

In general, the macroporosities ϕ_{Macro} obtained using the above mixing theory show 385 a distinct minimum at intermediate power law exponents p, whereas distributions which 386 have too many small or too many large particles result in unfavorable mixing and larger 387 ϕ_{Macro} are obtained. This minimum around p = 2.5 is known as the Fuller parabola 388 in the engineering literature and has long been known as the optimum packing size dis-389 tribution for spherical particles (Fuller & Thompson, 1907). Results obtained varying 390 the critical Bond number are shown in the left panel of Fig. 5, where the critical Bond 391 number parametrizes the particle size below which interparticle forces result in signif-392 icant cohesion. As expected, low critical Bond numbers, corresponding to larger contri-393 butions from cohesive particles, result in larger macroporosities. However, the overall ef-394 fect is small and in the few percent range. The low critical Bond number of 0.1 adopted 395 above therefore results in a conservative upper limit on macroporosity. It is also worth 396 noting that results obtained using a power law distribution with p = 2.65, which over-397 estimates the fraction of small particles, are lower than those obtained using the Weibull 398 representation of the data by 4-5 %, such that results obtained using global power law 399 fits must be interpreted with caution. For comparison, results obtained neglecting co-400 hesion are also shown in the left panel of Fig. 5, and macroporosity approaches a limit 401 of 39.5 % (compare Eq. 15) for large p (not shown). 402

The influence of varying the lower cutoff diameter D_{\min} of the size-frequency dis-403 tribution on the obtained macroporosity ϕ_{Macro} is shown in the right panel of Fig. 5, 404 where ϕ_{Macro} is shown as a function of D_{\min} for three power law exponents p. In the 405 calculations, a critical Bond number of $B_{cri} = 0.1$ has been assumed. While the min-406 imum macroporosity that can be achieved by the packing is close to constant for small 407 D_{min} , predicted macroporosity drastically increases for cutoff diameters larger than a 408 few decimeters. In this case, unfavorable mixing is a result of the sparsity of smaller rocks 409 to fill the gaps between larger blocks. These results indicate that image data with cen-410 timeter resolution are necessary to properly characterize the packing state of rubble pile 411 asteroids, and that results presented above are largely independent of the cutoff size of 412 $D_{\min} = 0.02$ m imposed by the image data available for Ryugu. 413

414 4 Discussion and Conclusions

In the present paper, we have used semi-empirical models for the porosity of multi-415 component mixtures to estimate the macroporosity of Cb-type asteroid (162173) Ryugu 416 based on the observed size-frequency distribution of boulders on the asteroid's surface 417 and the assumption that the surface distribution of boulders is representative for the bulk 418 asteroid. Using the concept of controlling mixtures (Yu & Standish, 1991; Yu & Zou, 1998; 419 Zou et al., 2011), we estimated the macroporosity of Ryugu to be $\phi_M = 16.2 \pm 2.6$ %. 420 Based on estimates of boulder microporosity, we furthermore constrained the average grain 421 density of Ryugu's boulders to $\rho_{Grain} = 2848 \pm 152 \text{ kg m}^{-3}$ or $\rho_{Grain} = 2093 \pm 96 \text{ kg}$ 422 m^{-3} , depending on the microporosity model used. 423

Boulder shape can affect the above mixing model by changing interparticle cohe-424 sion, by changing the geometrical arrangement between different particle sizes, and by 425 changing the initial porosity in each individual size-bin. In the modeling, we have taken 426 the influence of shape on particle cohesion explicitly into account, while we neglected its 427 influence on geometrical interactions and initial porosity. This is justified because for the 428 case of Ryugu the majority of particles has axis ratios b/a in excess of 0.5 (Michikami 429 et al., 2019), corresponding to sphericities larger than 0.7. For such particles, initial poros-430 ity is nearly independent of shape and equal to the value appropriate for spherical par-431 ticles (Zou & Yu, 1996). It is also worth noting that for Ryugu all of the above are sec-432 ondary effects when compared to the unknown packing state, which we address by con-433 sidering the entire range stretching from a random loose to a random close packing. 434

For the case of Ryugu, the primary factor determining macroporosity is the boul-435 der size-frequency distribution, and while the applied model takes cohesion between par-436 ticles into account, disregarding cohesion results in only a slight modification of the ob-437 tained macroporosity ϕ_M . Switching off cohesion in the model by assuming a critical bond 438 number of 10^5 results in a macroporosity of 16.1 %, only 0.1 % smaller than the value 439 presented above. This is a direct consequence of the low volume fraction of small cohe-440 sive particles on Ryugu, which directly follows from the given boulder size-frequency dis-441 tribution. This also implies that the results presented here are robust with respect to 442 the exact choice of parameters like boulder density, roundness, and sphericity, which en-443 ter the calculation of the Bond number. It is also worth noting that the power law rep-444 resentation of the data significantly overestimates the influence of cohesion on macro-445

⁴⁴⁶ porosity when compared to the Weibull fit by overestimating the volume fraction of small⁴⁴⁷ particles.

The cratering experiment performed by Hayabusa2's small carry-on impactor re-448 sulted in the formation of a crater in the gravity-dominated regime (Arakawa et al., 2020), 449 indicating that particle cohesion played a minor role in the crater formation process. On 450 the other hand, particles with diameters of 0.2 m were observed in the SCI crater wall, 451 which, according to Eq. 14, have Bond numbers close to unity and should therefore in-452 teract cohesively. This apparent discrepancy is resolved by the fact that small particles 453 appear not to be volumetrically dominant inside Ryugu. This is indicated by the shal-454 low particle size distribution for particles smaller than 1 m on the surface (Sugita et al., 455 2019; Michikami et al., 2019) and inside the artificial crater (Arakawa et al. (2020), Fig. 456 S5), where the particle size distribution shows a power law exponent $p \sim 2$ (also com-457 pare the volume-size distribution on the right hand side of Fig. 2). Therefore, results of 458 the cratering experiment confirm that cohesion has a small influence on Ryugu's pack-459 ing state. However, cohesion may become significant for rubble pile asteroids with a steep 460 particle size distribution, e.g., power-laws with p > 3, where - in contrast to Ryugu -461 the mixture is dominated by a high volume fraction of very small particles. 462

Although a full analysis using empirical fits of the cumulative boulder size-frequency 463 distribution of other small bodies has not been performed here, macroporosity results 464 can be qualitatively compared by considering the power law exponents of their respec-465 tive size distributions and assuming similar size cutoffs D_{\min} and D_{\max} . The former have 466 been widely used to describe size distributions in the literature, and values of $p = 2.9 \pm$ 467 0.3 and $p = 3.52 \pm 0.20$ have been obtained for Bennu (Lauretta et al., 2019) and Itokawa 468 (Michikami et al., 2008; Mazrouei et al., 2014; Michikami et al., 2019), respectively. As-469 suming $B_{cri} = 0.1$ as above, these correspond to macroporosities between 10 and 38 % 470 for Bennu and 43 to 52 % for Itokawa. Assuming average grain densities of 2600 kg m⁻³, 471 Bennu's low bulk density of 1190 ± 13 kg m⁻³ (Lauretta et al., 2019) implies a bulk poros-472 ity of 54 %, indicating significant microporosity. For Itokawa, average grain density has 473 been estimated based on the modal abundance of minerals in the returned samples, and 474 densities of 3400 kg m^{-3} have been obtained (Tsuchiyama et al., 2011, 2014). This im-475 plies a bulk porosity of 39 ± 6 % (Abe et al., 2006; Fujiwara et al., 2006; Tsuchiyama 476 et al., 2011), consistent with the results obtained from the mixing theory. For Eros, the 477 power law exponent of $p = 3.31 \pm 0.06$ (Thomas et al., 2001) implies macroporosities 478

-19-

of 40 - 45 %, which is larger than the inferred bulk porosity of Eros. The latter is estimated to be 21-33 % (Yeomans et al., 2000; Wilkison et al., 2002), indicating that macroporosities derived using the presented mixing model are incompatible with the observations. However, although Eros is a heavily fractured body, there is little evidence that
it was ever catastrophically disrupted and later reaccumulated into a rubble pile (Wilkison et al., 2002), such that the theory presented here can probably not be be applied.

Results for Ryugu have been obtained assuming minimum and maximum particle 485 sizes of 0.02 m and 140 m, respectively, and these results are robust with respect to the 486 cut-off at small particle sizes D_{\min} . Only shifting the cut-off D_{\min} to values larger than 487 0.30 m has a noticeable effect on the macroporosity. The upper cut-off size $D_{\rm max}$ was 488 chosen to correspond to the Otohime boulder, which is the largest boulder observed on 489 Ryugu's surface. However, boulders larger than Otohime could potentially reside in Ryugu's 490 interior, which would decrease the obtained macroporosity through a filling of void spaces. 491 Reasonable upper limits on monolith sizes are 200 m, as derived from observations of fast 492 rotators in the asteroid population (Pravec & Harris, 2000) and the catastrophic disrup-493 tion threshold (Benz & Asphaug, 1999; Jutzi et al., 2010). Assuming $D_{\text{max}} = 200 \text{ m}$ 494 reduces ϕ_{Macro} to 15 %. 495

One way to increase macroporosity in the above models would be an increased ini-496 tial porosity in each size bin, which may for example be caused by mechanical interlock-497 ing of particles due to particle angularity. For a random loose packing, non-cohesive ini-498 tial porosity can increase from ~ 42 % for smooth frictionless particles to ~ 44 % for very 499 rough particles (Onoda & Liniger, 1990; Jerkins et al., 2008). In the frame of the applied 500 mixing model, this effect is taken into account in the chosen initial porosity (Eq. 15), 501 and shifting the applied Gaussian distribution in the performed Monte-Carlo simulations 502 by 2 % results in slightly increased macroporosities of 18.0 ± 3 %. Therefore, while rough-503 ness and particle interlocking can increase macroporosity, this is likely not a significant 504 effect. 505

While the obtained macroporosity may appear to be relatively low, a significant reduction with respect to the porosity of random close packings of monodisperse spheres can be expected. Even binary mixtures of particles can be arranged in packing states with porosities of 15-20 % (Yu & Standish, 1991; Yu et al., 1992), such that it should not be surprising to achieve similar packing densities with the broad size distributions

-20-

used here. Ternary mixtures can achieve $\phi_{Macro} < 10 \%$ (Yu & Standish, 1991), and 511 while most common loose or compact granular materials have macroporosities between 512 30 % and 50 %, almost any degree of macroporosity between 10 and 90 % can be ob-513 tained for polydisperse angular particles (Dullien, 1991). Experimentally, macroporosi-514 ties down to 10 % have been produced in the lab (Latham et al., 2002). Therefore, the 515 macroporosity of Ryugu obtained here falls within a reasonable range, and Ryugu's high 516 bulk porosity is a direct consequence of the very large microporosity of Ryugu's boul-517 ders. 518

The average grain densities obtained here are much lower than typical grain den-519 sities of ordinary chondrites, which range from 3520 to 3710 kg m⁻³ (Flynn et al., 2018), 520 and also lower than those of most carbonaceous chondrites, which typically have grain 521 densities in excess of 3360 kg m⁻³ (Flynn et al., 2018). Only the CM and CI sub-classes 522 show lower grain densities, and $\rho_{CM,Grain} = 2960 \pm 40 \text{ kg m}^{-3}$ while $\rho_{CI,Grain} = 2420$ 523 kg m⁻³ (Consolmagno et al., 2008; Macke et al., 2011; Flynn et al., 2018). The Tagish 524 Lake meteorite, an ungrouped carbonaceous chondrite, exhibits similar grain densities 525 in the range between 2430 and 2840 kg m⁻³ (Ralchenko et al., 2014). While the larger 526 grain densities of 2848 ± 152 kg m⁻³ are consistent with the CM and Tagish Lake re-527 sults, the lower densities of 2093 ± 95 kg m⁻³ are inconsistent with those of known me-528 teorite samples. 529

Estimates of grain densities discussed above indicate that extrapolating boulder 530 porosities as a function of thermal conductivity using the model by Flynn et al. (2018) 531 is preferred to extrapolations using the model by Henke et al. (2016). In addition, lab-532 oratory measurements of thermal conductivity (Hamm et al., 2019) using the UTPS Tag-533 ish Lake meteorite simulant (Miyamoto et al., 2018) provide further evidence of high boul-534 der microporosity. The UTPS simulant has a grain density of 2813 kg m⁻³ and a poros-535 ity of 47.5 %, while thermal conductivity was determined to be similar to that of Ryugu's 536 rugged boulders (Hamm et al., 2019). It therefore seems likely that boulder porosity on 537 Ryugu falls within the high range determined by Grott et al. (2019), but more labora-538 tory measurements of thermal conductivity at high porosity are needed to confirm these 539 results and reduce uncertainties. If grain densities are indeed of the order of 2850 kg 540 m^{-3} , Ryugu's bulk porosity is estimated to be 58 % (cf. Eq. 18). 541

-21-

It is noted that close-up images have revealed that many boulders on Ryugu and 542 Bennu exhibit morphologic properties consistent with a brecciated structure (Sugita et 543 al., 2019; Walsh et al., 2019). Breccia would have much larger microporosities than pris-544 tine rocks, consistent with the large microporosities preferred here. Furthermore, the pres-545 ence of breccia on Ryugu and Bennu is consistent with the fact that many carbonaceous 546 chondrites and, in particular, all CM and CI meteorites found on Earth are known to 547 be brecciated (Bischoff et al., 2006). However, it remains to be investigated if breccia-548 tion is the main mechanism providing microporosity, or whether the boulder's highly porous 549 structure is a result of the formation mechanisms acting in Ryugu's parent body (Neu-550 mann et al., 2014, 2015). 551

If microporosity in typical carbonaceous asteroids is as high as predicted here for 552 Ryugu, macroporosities of rubble pile asteroids may have been systematically overesti-553 mated in the past (e.g., Consolmagno et al., 2008). Macroporosities have been estimated 554 based on measurements of asteroid bulk density and porosities of meteorite samples, the 555 latter of which could have been underestimated compared to values for actual carbona-556 ceous material on asteroids derived from in-situ measurements (Grott et al., 2017, 2019). 557 This bias could be the result of filtering by the Earth's atmosphere, as only the strongest, 558 densest carbonaceous meteoroids would survive atmospheric entry, while weaker sam-559 ples would break up (Popova et al., 2011). This could explain the absence of high poros-560 ity samples in our meteorite collections, where the most porous sample reported to date 561 is the Tagish Lake meteorite, which shows porosities in the range from 26 to 36~% (Ralchenko 562 et al., 2014). The samples to be returned from Ryugu by the Hayabusa2 mission will pro-563 vide crucial information on this issue. 564

Results presented here assume that the size-frequency distribution observed on the 565 surface of Ryugu is representative for the entire asteroid, but as discussed in Sec. 1, the 566 reaccretion process itself as well as post accretion surface modifications could influence 567 the observed size-frequency distribution. For example, meteorite impacts could increase 568 the number of small boulders on the surface and the observed size-frequency distribu-569 tion would be steeper than the distribution in the interior. Therefore, macroporosity would 570 have been overestimated in the presented model, as the interior distribution would move 571 closer to the Fuller minimum (Fuller & Thompson, 1907). Conversely, the Brazil Nut 572 Effect could bias the slope of the surface size-frequency distribution towards smaller val-573 ues, implying that macroporosity would have been underestimated. This topic can be 574

-22-

addressed once average grain density and possibly also microporosity have been deter-

⁵⁷⁶ mined from the returned samples, as has been done for Itokawa (Tsuchiyama et al., 2011).

577 Then, Ryugu's macroporosity can be derived given the measured bulk density (Watan-

- abe et al., 2019). Any significant deviation from the macroporosity value calculated here
- will indicate a non-homogeneous boulder size distribution in the bulk volume of the as-
- 580 teroid.

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