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High Porosity Boulders Identified on C-type Asteroid (162173) Ryugu

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C-type asteroids are among the most pristine objects in the solar system, but little is known 8 about their interior structure and surface properties. Telescopic thermal infrared 9 observations have so far been interpreted in terms of a regolith covered surface with low 10 thermal conductivity and particle sizes in the centimeter range. This includes observations 11 of C-type asteroid (162173) Ryugu, for which average grainsizes of 3-30 mm have been 12 derived^{1,2,3}. However, upon arrival of the Havabusa2 spacecraft at Ryugu, a regolith cover 13 of sand- to pebble-sized particles was found to be absent^{4,5}. Rather, the surface is largely 14 covered by cobbles and boulders, seemingly incompatible with the infrared observations. 15 Here we report on the first in-situ thermal infrared observations of a boulder on a C-type 16 asteroid. Boulder thermal inertia was found to be much lower than anticipated based on 17 laboratory measurements of meteorites, which implies that the boulder itself exhibits low 18 thermal conductivity. Our results furthermore indicate high boulder porosities as well as a 19 low tensile strength in the few hundred kPa range. This confirms the suspected 20 observational bias in our meteorite collections, as typical samples of common asteroid types 21 would be too frail to survive atmospheric entry. 22

On October 3rd, 2018, the Hayabusa2 spacecraft⁶ delivered the MASCOT⁷ lander to the surface of asteroid (162173) Ryugu, where MASCOT's infrared radiometer MARA⁸ obtained surface brightness temperature measurements for a full day-night cycle. The instrument's field of view covered a spot of approximately 10 cm in diameter on the surface, which was also observed by MASCOT's optical camera MasCam⁴. The scene observed by MARA and MasCam⁴ is shown in **Figure 1**, with the footprint of the MARA 8-12 μm broadband sensor indicated in red. MARA is viewing the top face of a slightly raised (~3 cm) boulder in front of MASCOT. The boulder is rough in surface texture at the sub-centimeter scale and generally appears angular to sub-angular. Particles with diameters larger than 0.6 mm are resolvable at the bottom of the image (~0.2 mm per pixel resolution), but only a few separate roundish grains can be identified as loose grains on this formation. Furthermore, an optically thick cover of fine particles is not observed, and bright inclusions are visible at multiple locations including the area viewed by MARA. Highly resolved areas in the MasCam image show that the boulder is composed of a relatively dark matrix with mostly bright but also darker inclusions at the millimeter scale⁴.

- Remote spectral observations of Ryugu suggest a composition similar to heated CM (CM2) or CI 36 meteorites⁹. However, the texture observed in close-up images (compare Fig. 1) shows 37 millimeter-sized inclusions in at least one location and bright speckles at varying distances. This 38 seems to be incompatible with a CM2 composition, for which petrographic analysis¹⁰ shows 39 maximum grain sizes around 0.2 mm. On the other hand, CI meteorites are predominantly 40 composed of a fine-grained matrix with a mottled appearance, and the texture observed by 41 MASCOT resembles that of the rare CI2 Tagish Lake meteorite, which possesses up to 2 mm 42 large calcium aluminum rich inclusions¹¹. Thus, CI2 type meteorites appear to be the closest 43 known Ryugu analogue. However, as Tagish Lake is a rare sample and variations in inclusion 44 sizes are common for carbonaceous chondrites, it is not feasible to derive a definite meteorite 45 analogue. Rather, it may be possible that the investigated boulder is not represented in any 46 meteorite collection on Earth. 47
- Temperatures measured using MARA's 8-12 µm filter are shown as a function of local time in 48 49 Figure 2a along with the best-fitting thermal models taking the illumination conditions at the 50 landing site as well as surface roughness into account (see methods). Diurnal temperatures rise steeply in the morning, but start dropping around 11:07 local time, indicating shadows passing 51 through the radiometer field of view before noon. Maximum temperatures reach 308 K shortly 52 after local noon and the sun sets at 16:39 local time. The complex shape of the davtime 53 54 temperature curve indicates a rough surface, consistent with camera observations. During nighttime, temperatures drop to 201 K. 55
- As daytime data is affected by surface roughness and re-radiation from the environment, only equilibrated nighttime temperatures are used to fit thermophysical models. Best-fitting models (see methods) are indicated in Figure 2a and correspond to a thermal inertia Γ of 282 J m⁻² K⁻¹ s⁻¹ While fitting nighttime data perfectly, the steep increase of temperature during the morning is

underestimated, while midday temperatures are overestimated. Taking surface roughness into account (green solid line in Figure 2a), the quality of the fit to midday temperatures is much improved, but early morning temperatures cannot be fit using this model. The latter are influenced by light reflected from the MASCOT lander, and a local terrain model including reflections would be necessary to improve results. Nevertheless, since only equilibrium nighttime temperatures are used to estimate the thermal inertia Γ, presented results are largely independent of surface roughness and topography.

- Admissible thermal inertia values are shown as a function of maximum insolation in Figure 2b, 67 where the orientation of the surface normal has been systematically varied around its nominal 68 value. The color bar shows the χ^2 of the individual fits, and emissivity has been varied between 69 0.9 and 1. Low Γ corresponds to low emissivity and models with and without re-radiation have 70 been considered. As a result, admissible thermal inertia values for the boulder in the MARA field 71 of view were found to be 282^{+93}_{-35} J m⁻² K⁻¹ s^{-1/2}. This estimate is similar to telescopically 72 determined thermal inertia values¹ of 150 to 300 J $m^{-2} K^{-1} s^{-1/2}$ and values determined by the 73 thermal infrared imager on the Hayabusa2 spacecraft⁵, which range from 200 to 500 J m⁻² K⁻¹ 74 $s^{-1/2}$. It therefore seems likely that boulders dominate the thermal emission from Ryugu, which 75 would be consistent with the high rock abundance determined from orbiter images⁵. Therefore, 76 contrary to expectation, the low thermal inertia derived for Ryugu does not correspond to a 77 pebble-sized regolith-covered surface^{1,2}. Rather, boulder to block-sized clasts themselves appear 78 to have thermal inertia lower than that of CM2 Cold Bokkeveld, which has the lowest thermal 79 inertia (600 - 700 J m⁻² K⁻¹ s^{-1/2}) of a meteorite measured so far. 80
- While thin layers of fine material could in principle mask the thermal signature of competent 81 rock, the boulder observed by MARA appears to be free from an optically thick, dusty layer. 82 Furthermore, the presence of a fine dust layer can be ruled out by considering a two layer 83 thermal model. Results of the calculations (see methods) are shown in Figure 3, where dust with 84 a thermal inertia of 25 J m^{-2} K⁻¹ s^{-1/2} was assumed to cover a boulder with a thermal inertia of 85 700 J m^{$^{-2}$} K^{$^{-1}$} s^{$^{-1/2}$}. As is evident, the model is incompatible with the observed nighttime cooling 86 rates, and the boulder observed by MARA itself must exhibit very low bulk thermal conductivity 87 to fit the data. However, it cannot be ruled out that the low conductivity zone is limited to a 88

highly porous outer layer. Such a layer may for example be generated by cracking due to thermal
 fatigue^{12,13,14} and could extend to a few thermal skin depths.

Given the above estimate of thermal inertia, thermal conductivity can be derived for a given bulk 91 density and heat capacity (see methods). Furthermore, since thermal conductivity k of porous 92 material depends more on porosity ϕ , and thus the total area of inter-grain contacts, than on the 93 conductivity of the grains themselves³, the porosity of the investigated boulder could in principle 94 be estimated if the functional dependence of $k(\phi)$ were known. However, while models for H and 95 L chondrites indicate that porosity and thus thermal conductivity is governed by dehydration- or 96 shock-induced cracks^{15,16,17}, thermal conductivity data on CI chondrites are absent. Nevertheless, 97 since cracks are abundant in CI types¹⁸, it stands to reason that a similar mechanism would 98 reduce thermal conductivity in these types and models derived for H and L chondrites should be 99 applicable to CI types, too. 100

Two models^{16,17} for thermal conductivity as a function of porosity are shown in Figure 4a. 101 Available data for H, L, and CM chondrites are shown together with the thermal conductivities 102 extrapolated for Ryugu. The first model¹⁶ results in $28 < \phi < 34\%$, typical for CM and CI 103 chondrites, which have class average porosities of 22.2% and 34.9%, respectively¹⁷. The second 104 model¹⁷ yields $41 < \phi < 55\%$. Other models applicable to partially-sintered granular material¹⁶ 105 yield intermediate results. Corresponding thermal conductivities are 0.06 - 0.13 and 0.09 - 0.16106 W m^{-1} K⁻¹, respectively, and thus much lower than measurements reported for the thermal 107 conductivities of meteorites. Measurements on CI chondrites are missing entirely, but since CI 108 chondrites are those meteorites with highest porosities¹⁷, low conductivities could be expected. 109

Pores in the boulder would be observable in nighttime images, as the illumination provided by 110 the MasCAM LED array covers a variety of directions. However, no such pores are observed, 111 indicating that potential pores must be smaller than 1 mm. The radiative contribution to the total 112 heat transport inside the boulder can now be estimated by considering radiative heat exchange 113 between parallel planes³, and for pores smaller than 1 mm this results in a minor contribution to 114 the overall thermal conductivity. The latter must therefore be governed by solid conduction 115 through grain contacts. Given porosity and thermal conductivity, the amount of contacts can be 116 estimated, which in turn can be converted to an estimate of tensile strength (see methods). Given 117 the values derived above and assuming a Young's modulus representative for carbonaceous 118

chondrites, tensile strength of the boulder is estimated to be 200 to 280 kPa and thus considerably lower than measurements on meteorite samples¹⁷, which generally show tensile strengths of the order of one to a few MPa¹⁹. This low tensile strength indicates an observational bias, namely that any hypothetical meteoroid originating from the boulder observed by MASCOT would likely break up during atmospheric entry and would thus be absent in our meteorite collections.

125 Thermal conductivity values derived above can be compared to estimates for other minor bodies, and corresponding data are shown in Figure 4b, where thermal conductivity is given as a 126 function of temperature for asteroids (162173) Ryugu¹, (101955) Bennu²⁰, and the average 127 estimated for small near Earth asteroids²¹. Values are compatible within error bars and similar to 128 values derived for comets 67P/Churyumov-Gerasimenko²², 9P/Tempel 1^{23,24}, and 103P/Hartley 129 2^{23} when heat capacity is properly scaled for temperature and appropriate densities are assumed 130 (see methods section). On the other hand, estimates for S-type asteroid (25143) Itokawa^{25,26} are 131 larger by a factor of three, indicating that thermal properties of C-type asteroids are more similar 132 to those of comets than those of S-type asteroids. It is also worth noting that no cubic 133 dependence of thermal conductivity on temperature is observed in Figure 4b, which could 134 135 indicate that radiative heat transfer through large pores is negligible in the bodies considered here. 136

The high porosities derived here have important implications for Ryugu's parent body. 137 Assuming initial porosities²⁷ of the order of 70%, the Ryugu precursor needs to have been large 138 enough to reduce intrinsic (micro-) porosity to values below 55% by compaction and aqueous 139 alteration, while simultaneously avoiding porosities to drop below 28%. This implies that the 140 material we observe on Ryugu's surface today was either produced in the outer layers of a larger 141 (50-100 km sized) parent body, or the interior of a smaller, kilometer-sized body. The latter 142 would be feasible provided accretion occurred while ²⁶Al was still active, in which case aqueous 143 alteration and hot pressing of the precursor material would be efficient. In this way, porosities of 144 45% can be achieved starting from initial porosities of 70% even on small, kilometer-sized 145 objects, provided that a water ice dominated primordial composition similar to that of CI/CM 146 chondrites is assumed^{28,29}. 147

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M.G. coordinated and wrote the paper, J.K. and M.G. evaluated the instrument calibration, M.H., 241 K.O., S.M., J.-B.V., M.S. and I.P. computed illumination and thermal models, N.S., S.S., A.K. 242 and F.T. contributed to camera development, K.O. and K.D.M. localized the MARA FoV in 243 camera images, W.N., P.M., S.T., J.B., M.D., and M.K. provided the discussion on material 244 parameters, H.S., T.O., E.K., J.B., H.Y., R.J., N.M., C.P., L.D., N.S., S.T., T.A., and S.S. added 245 to the science discussion, J.H. and A.M. contributed to the radiometer development, C.K., T.-246 M.H., and A.M.-S. contributed to data acquisition. A.H. contributed to instrument 247 248 characterization. All authors have read and approved the final manuscript.

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276 **Figure Legends:**

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Figure 1: MasCam Image of the boulder observed by MASCOT indicating the MARA field 277 of view (red shaded area). a) The location in daylight (local time 9:20) with the yellow arrow 278 indicating the approximate direction of illumination with sun elevation and azimuth at 40.2° and 279 280 67.2°. The image suggests that MASCOT is located in front of an angular to sub-angular formation whose edges are outlined by the yellow dotted line. The yellow dashed line indicates 281 the edge of an elevated part of the boulder (compare the nighttime image on the right). The front 282 face of the formation orientated towards MARA is approximately 3 cm above the plane 283 MASCOT is located on. b) The same location at night (local time 23:18) illuminated by the 284 camera's red LED. Only the foreground is visible due to the limited illumination provided. The 285 images are distorted with pixel resolutions varying between approximately 0.2 mm at the bottom 286

and 3 mm near the horizon. Note that due to a minor relocation of MASCOT the scene in panelb) is slightly shifted towards the left with respect to panel a).

Figure 2: Observed and modeled surface temperatures and derived thermal inertia. a) 289 Variation of surface temperature observed in-situ at geographical coordinates of 22.22 ± 0.05 °S, 290 $317.26 \pm 0.07^{\circ}$ E. Temperature is shown as a function of time as derived from the MARA 8-12 291 μ m filter and using a surface emissivity of $\varepsilon = 1$. Error bars indicate 2σ confidence limits and 292 uncertainties are below 0.5 K and 1.5 K during daytime and nighttime, respectively. Data are 293 shown together with best fitting thermal models. While the model shown as a dashed red line 294 assumes a flat surface, midday temperatures are reduced by surface roughness effects for the 295 model shown in green. The steep rise of morning temperatures is caused by reflections from the 296 MASCOT lander (not modeled). Best fitting models correspond to a thermal inertia of 282 J m⁻² 297 $K^{-1} s^{-1/2}$ and a crater density of 0.34 (see methods). b) Retrieved thermal inertia as a function of 298 the maximum insolation for the respective surface orientation. Emissivity has been varied 299 between $\varepsilon = 0.9$ and 1. The χ^2 value of the individual fits is shown in color and admissible 300 thermal inertia values were found to be 282^{+93}_{-35} J m⁻² K⁻¹ s^{-1/2}. 301

Figure 3: Modeled temperatures for a dust covered surface. Variation of surface temperature 302 as a function of time as derived from the MARA 8-12 µm filter and using a surface emissivity of 303 ε = 1. Error bars indicate 2 σ confidence limits and uncertainties are below 0.5 K and 1.5 K 304 during daytime and nighttime, respectively. Data are shown together with the results of a two 305 layer thermal model, which assumes best fitting illumination conditions as well as a thin dust 306 layer covering the underlying boulder. Dust thermal inertia is assumed to be 25 J m⁻² K⁻¹ s^{-1/2}. 307 Results for four different dust thicknesses assuming a boulder thermal inertia of 700 J m⁻² K⁻¹ s⁻ 308 $^{1/2}$ are shown. 309

Figure 4: Derived thermal conductivity and boulder porosity. a) Thermal conductivity as a function of porosity. Data for H, L, and CM chondrites is shown together with two models fitting the data for porosities below 20%. For the low thermal conductivities determined from MARA measurements, models have to be extrapolated to high porosities. Depending on the model used, porosities between 28-34% and 41-55% are obtained. b) Thermal conductivity as a function of temperature as derived for different small bodies. For the boulder in the MARA field of view, a

grain density of 2420 kg m⁻³ has been assumed. Heat capacity¹ was evaluated at 230 K, 316 corresponding to the average observed nighttime temperature. In addition, conductivity values as 317 derived from disc integrated measurements of Ryugu, disc integrated measurements of asteroid 318 Bennu²⁰, as well as the estimated average thermal conductivity for near Earth asteroids (NEA)²¹ 319 are shown. As a comparison, conductivity derived from in-situ observations of comet 320 67P/Churyumov-Gerasimenko²² as well as values derived from spacecraft observations of 321 comets 9P/Tempel 1^{23,24} and 103P/Hartley 2²³ are given. In contrast, the conductivity derived 322 from disc integrated measurements of asteroid Itokawa²⁶ is also shown. 323

324 Methods

Asteroid Thermophysical Model. To estimate thermophysical properties from the brightness temperatures observed, a thermophysical model of the Ryugu boulder was constructed assuming a single, flat surface in the MARA field of view. A specific heat c_p of 600 J kg⁻¹ K⁻¹ and density ρ of 1270 kg m⁻³ have been assumed for the boulder, consistent with pre-encounter estimates¹. Parameters have been assumed to be constant and independent of temperature, as more complicated models did not improve the quality of the fit. Thermal conductivity *k* was treated as a free fitting parameter, and results are reported in terms of surface thermal inertia

$$\Gamma = \sqrt{k\rho c_p} \tag{1}$$

Insolation of the surface in the field of view was varied around the average surface normal 332 333 which, according to the Ryugu shape model, points towards longitude 314.207°E and latitude 34.599°S in the asteroid fixed frame at the landing site. In a local frame, elevation and azimuth 334 of the normal vector have been varied by 25° and 360° around this surface normal, respectively. 335 This accounts for the unknown orientation of the surface in the MARA field of view and covers 336 all plausible illumination conditions. Results are reported in terms of the maximum insolation 337 corresponding to the respective surface normal. Furthermore, the times of sunrise and sunset 338 have been adapted to fit MARA observations, which indicate that sunrise is delayed by 37 min 339 with respect to the nominal insolation. In addition, the sun sets 21 min earlier than predicted by 340 the illumination model and insolation has been adapted accordingly. This is consistent with the 341 terrain at the landing site, which shows that MASCOT is situated in a local depression. 342

Re-radiation from the environment onto the surface observed by MARA was taken into account 343 using a local terrain model. View factors f from the surrounding topography to the surface have 344 been estimated from the model and were found to amount to 0.048 ± 0.007 for facets within 1 345 meter of the MASCOT landing site (see supplementary Figures 1 and 2). No facet showed 346 f > 0.08. In the thermophysical modeling, f has been varied between 0 and 0.08 to provide a 347 conservative upper limit. The incident flux was then derived assuming that the surrounding 348 terrain has temperatures T_{obs} corresponding to those on the surface of the boulder observed by 349 MARA. As thermal re-radiation decreases the estimated thermal inertia, f = 0.08 results in an 350 upper limit for the derived thermal inertia. 351



Given insolation I and thermal inertia Γ , the 1D heat equation is solved³⁰ using

$$-\Gamma \sqrt{\frac{\pi}{P}} \frac{\partial T}{\partial z} = (1 - A)I - \sigma \varepsilon T^4 + f \sigma \varepsilon T_{obs}^4$$
(2)

as the upper boundary condition. Here, T is surface temperature, Γ thermal inertia, P rotation 353 period, A bond albedo, σ the Stephan-Boltzmann constant, z depth normalized to the diurnal skin 354 depth³¹, ε emissivity, and f the view factor to the surrounding environment. In the calculations, 355 an albedo of A = 0.0146 is assumed while emissivity was varied between 0.9 and 1. The 356 rotation period of Ryugu is 7.6326 h. 357

Data Fitting. To avoid complications caused by inhomogeneous temperatures in the MARA 358 field of view due to the changing illumination conditions and re-radiation from the surroundings, 359 only equilibrated nighttime data were used to fit thermophysical models³² and invert for 360 thermophysical parameters. To fit the data, a suite of models was computed by systematically 361 varying thermal inertia and the orientation of the surface normal in a grid search approach. In the 362 models, thermal inertia was varied in steps of 1 J $m^{-2} s^{-1/2} K^{-1}$ between 170 and 410, elevation of 363 the target surface normal was varied in steps of 5° between 90° and 65°, and azimuth of the 364 target surface normal was varied in steps of 10° between 0° and 360°. For each model, the χ^2 365 value between model and data was computed and models resulting in a χ^2 larger than a critical 366 value were discarded. Here we choose a critical χ^2_{crit} corresponding to a 2σ confidence interval³⁰ 367

$$0.05 = \int_{\chi^2_{crit}}^{\infty} f(\chi^2, \nu) d\chi^2$$

where $f(\chi^2, \nu)$ is the χ^2 -distribution and ν is equal to the number of data points minus the number of fitting parameters. We obtain a critical χ^2_{crit} of 587.8 for the 534 data points obtained between 17:15 and 07:16 local time used in the fitting. The minimum χ^2_{min} obtained for the best fit was found to be $\chi^2_{min} = 66$.

This procedure was repeated by varying surface emissivity and assuming values of $\varepsilon = 0.9$, 0.95 and 1. Furthermore, models with view factors to the surroundings of f = 0 and 0.08 have been computed to study the effect of re-radiation, which was found to have only a small influence on nighttime temperatures. The stated uncertainty for the thermal inertia was then derived from the lowest and highest admissible values of all simulations. The best-fitting model has an emissivity of $\varepsilon = 1$. For consistency, the emissivity used for both the thermophysical models and the derivation of surface temperature from the observed flux was identical in all cases.

379 **Surface Roughness.** For a rough surface, observed flux depends on the solar zenith angle φ , the angle between surface normal and observation direction δ , as well as the angle between 380 projections of the sun vector and the observation direction onto the surface ψ . These need to be 381 taken into account when calculating fluxes received by the instrument. Here, the rough surface is 382 modeled as a surface covered by spherical-section craters^{33,34}, assuming lateral heat transport to 383 be negligible. Using this model, a factor $c_r(\varphi, \delta, \psi, t, \lambda)$ is calculated for each time t and 384 observed wavelength λ relating the flux emitted by a flat surface F to the flux emitted by the 385 rough surface $F_r = c_r(\varphi, \delta, \psi, t, \lambda)F$. This model is scale-independent³³, leaving the crater 386 density on the surface and the opening angle of the craters as free parameters. The latter is kept 387 constant at 180°, corresponding to a surface covered by hemispherical depressions. The model 388 also depends on parameters such as albedo and heliocentric distance, which are all kept constant 389 to be consistent with the thermophysical model described above. c_r was calculated at $\lambda =$ 390 10 µm. 391

Two Layer Model. To estimate the possible influence of a low conductivity dust layer on the modeling results, a two layer regolith model assuming geometry parameters corresponding to those of the best fitting one-layer model was calculated. In the model, the dust layer is treated in the continuum approximation, i.e., it is assumed that thermal transport properties inside the layer can be treated using the theory of porous media³. This approximation breaks down if thin layers of dust are present, in which case radiative heat transport inside the dust layer would need to be

- treated explicitly. Here we assume that the dust layer has a thermal inertia of 25 J m⁻² K⁻¹ s^{-1/2}. This corresponds to typical particle sizes of ~10 μ m at porosities of 80%³. Therefore, our model assumptions are valid for layer thicknesses in excess of 50 μ m.
- 401 Models have then been calculated varying the thermal inertia of the bottom layer along with the 402 top layer thickness. Even thin dust layers appreciably distort the temperature curves, and using 403 bottom layer thermal inertias between 250 and 700 J m⁻² K⁻¹ s^{-1/2}, nighttime cooling curves 404 could only be fitted within the errorbars for thermal inertias close to the values reported above. 405 This indicates that the thermophysical properties of the boulder itself govern thermal emission.
- 406 **Thermal Conductivity and Porosity Estimate.** Thermal conductivity k and porosity ϕ for the 407 boulder observed by MARA are calculated by solving

$$k = \frac{\Gamma^2}{c_p \varrho_s (1 - \phi)} \tag{3}$$

for a given functional dependence for $k(\phi)$. Here, Γ is thermal inertia, c_p is specific heat, ρ_s is grain density, and ϕ is porosity. For the grain density ρ_s , the average density of CI chondrites^{17,35} $\rho_s = 2420 \text{ kg m}^{-3}$ has been assumed. Heat capacity was determined by evaluating¹ $c_p(T)$ at T =230 K. For the functional dependence of $k(\phi)$, two models have been considered. Both are based on empirical fits to available thermal conductivity data for chondritic meteorites, and the first relation¹⁷ is

$$k(\phi) = \frac{0.11(1-\phi)}{\phi}$$
(4)

414 while the second relation¹⁶ is

$$k(\phi) = 4.3e^{-\phi/0.08} \tag{5}$$

Both formulations fit the experimental data equally well, but diverge at porosities larger than 20%.

To compare the thermal conductivity estimates for meteorites with those for comets, cometary thermal inertia estimates have been converted to an estimate of thermal conductivity assuming a cometary bulk density of 300 kg m⁻³ as derived from spacecraft observations²³ of the Deep Impact experiment on 9P/Tempel 1. For the heat capacity, a value of 1000 J kg⁻¹ K⁻¹ was used²³.
For the computation of thermal conductivities for (101955) Bennu, (25143) Itokawa, and average
NEA, heat capacity¹ was evaluated at a temperature of 340 K, while for the disc-averaged
measurement of (162173) Ryugu a temperature of 277 K has been assumed. Assumed bulk
densities for (162173) Ryugu¹, average NEA²¹, (25143) Itokawa²⁵, and (101955) Bennu were
1270 kg m⁻³, 1950 kg m⁻³, 1950 kg m⁻³, 1270 kg m⁻³, respectively.

426 **Strength Estimate.** To estimate mechanical tensile strength given thermal conductivity k and 427 porosity ϕ , the amount of inter-grain contacts is estimated neglecting radiative heat transport 428 using³

$$k = \frac{4}{\pi^2} k_s (1 - \phi) C H \tag{6}$$

429 where the grain thermal conductivity k_s has been assumed to be 2.95 W m⁻¹ K⁻¹ as appropriate for 430 serpentine. Here, $H = r_c/R$ is the Hertz factor with r_c being the contact radius and R the radius of 431 interacting spheres. For the coordination number C, the relation

$$C = \frac{2.812(1-\phi)^{-1/3}}{f^2(1+f^2)}$$
(7)

432 was used, where

$$f = 0.07318 + 2.193\phi - 3.357\phi^2 + 3.194\phi^3 \tag{8}$$

Given k, k_s , ϕ , C and H can then be calculated. For a random packing of identical, isotropic and 433 homogeneous spheres with shear modulus μ and Poisson's ratio ν , the bulk elastic parameters 434 can then be related to those in a porous medium following the approach of Digby³⁶: in Hertzian 435 contact theory, two identical spheres have a circular contact area of radius r_c , depending on the 436 confining pressure and the Young's modulus of the sphere material. In extension of the Hertz 437 contact model, Digby assumes that the contact area between two spheres contains a small, 438 concentric area of radius $r < r_c$ where the spheres are firmly bonded, i.e., remain in contact even 439 without confining pressure. He obtains the effective Lamé parameters of the packing 440

$$\lambda_{Digby} = \frac{\mu C (1 - \phi)}{5\pi R} \left[\frac{r_c}{1 - \nu} - \frac{2r}{2 - \nu} \right]$$
(9)

$$\mu_{Digby} = \frac{1}{2} \frac{\mu C (1 - \phi)}{5\pi R} \left[\frac{2r_c}{1 - \nu} + \frac{6r}{2 - \nu} \right]$$
(10)

441 We take the adhesive region as a model for a sintering neck between two particles and consider 442 the case without confining pressure, where $r \equiv r_c$. Using the relation

$$E = \mu \frac{3\lambda + 2\mu}{\lambda + \mu} \tag{11}$$

between Lamé-parameters and Young's modulus, and the relation

$$E = 2\mu(1+\nu) \tag{12}$$

between shear modulus, Lamé parameter λ and Young's modulus *E*, we obtain the effective Young's modulus

$$E_{Digby} = \frac{1}{2\pi} \frac{r_c}{R} C(1-\phi) \frac{1}{1-\nu^2} \frac{5-4\nu}{5-3\nu} E$$
(13)

of the conglomerate of sintered spheres in relation to the Young's modulus of the matrix material. Since $0 \le v \le 1/2$ usually holds for Poisson's ratio, the dependence of E_{Digby} on vamounts to a factor between 0.988 and 8/7, or to 256/255 \approx 1.004 if the matrix material is Poissonian. Therefore, we finally obtain

$$E_{Digby} \cong \frac{1}{2\pi} HC(1-\phi)E = \frac{\pi}{8} \frac{k}{k_s}E$$
(14)

450 and the obtained (reduced) Young's modulus is then converted into an estimate of tensile 451 strength σ_t using the empirical relation³⁷

$$\sigma_t = \frac{E_{Digby}}{500} = \frac{\pi}{4000} \frac{k}{k_s} E$$
(15)

The Young's modulus *E* of ordinary chondrites is usually reported¹⁷ to be of the order of tens of GPa, while values for carbonaceous chondrites are usually much lower^{38,39}, ranging from a few to about 10 GPa. Here we assume 10 GPa to be representative for the Ryugu boulder, pointing out that this likely places an upper limit on the derived tensile strength.

456

457 Data Availability

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

460

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