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1 **Low thermal conductivity boulder with high porosity identified on C-type asteroid (162173)**  
2 **Ryugu**

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4 Biele, W. Neumann, M. Knapmeyer, E. Kührt, H. Senshu, T. Okada, J. Helbert, A. Maturilli, N.  
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6 Drube, J.-B. Vincent, H. Yano, C. Pilorget, K. D. Matz, N. Schmitz, A. Koncz, S. Schröder, F.  
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7  
8 **C-type asteroids are among the most pristine objects in the solar system, but little is known**  
9 **about their interior structure and surface properties. Telescopic thermal infrared**  
10 **observations have so far been interpreted in terms of a regolith covered surface with low**  
11 **thermal conductivity and particle sizes in the centimeter range. This includes observations**  
12 **of C-type asteroid (162173) Ryugu, for which average grainsizes of 3-30 mm have been**  
13 **derived<sup>1,2,3</sup>. However, upon arrival of the Hayabusa2 spacecraft at Ryugu, a regolith cover**  
14 **of sand- to pebble-sized particles was found to be absent<sup>4,5</sup>. Rather, the surface is largely**  
15 **covered by cobbles and boulders, seemingly incompatible with the infrared observations.**  
16 **Here we report on the first in-situ thermal infrared observations of a boulder on a C-type**  
17 **asteroid. Boulder thermal inertia was found to be much lower than anticipated based on**  
18 **laboratory measurements of meteorites, which implies that the boulder itself exhibits low**  
19 **thermal conductivity. Our results furthermore indicate high boulder porosities as well as a**  
20 **low tensile strength in the few hundred kPa range. This confirms the suspected**  
21 **observational bias in our meteorite collections, as typical samples of common asteroid types**  
22 **would be too frail to survive atmospheric entry.**

23 On October 3rd, 2018, the Hayabusa2 spacecraft<sup>6</sup> delivered the MASCOT<sup>7</sup> lander to the surface  
24 of asteroid (162173) Ryugu, where MASCOT's infrared radiometer MARA<sup>8</sup> obtained surface  
25 brightness temperature measurements for a full day-night cycle. The instrument's field of view  
26 covered a spot of approximately 10 cm in diameter on the surface, which was also observed by  
27 MASCOT's optical camera MasCam<sup>4</sup>. The scene observed by MARA and MasCam<sup>4</sup> is shown in  
28 **Figure 1**, with the footprint of the MARA 8-12  $\mu\text{m}$  broadband sensor indicated in red. MARA is  
29 viewing the top face of a slightly raised ( $\sim 3$  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.

30 Particles with diameters larger than 0.6 mm are resolvable at the bottom of the image (~0.2 mm  
31 per pixel resolution), but only a few separate roundish grains can be identified as loose grains on  
32 this formation. Furthermore, an optically thick cover of fine particles is not observed, and bright  
33 inclusions are visible at multiple locations including the area viewed by MARA. Highly resolved  
34 areas in the MasCam image show that the boulder is composed of a relatively dark matrix with  
35 mostly bright but also darker inclusions at the millimeter scale<sup>4</sup>.

36 Remote spectral observations of Ryugu suggest a composition similar to heated CM (CM2) or CI  
37 meteorites<sup>9</sup>. However, the texture observed in close-up images (compare Fig. 1) shows  
38 millimeter-sized inclusions in at least one location and bright speckles at varying distances. This  
39 seems to be incompatible with a CM2 composition, for which petrographic analysis<sup>10</sup> shows  
40 maximum grain sizes around 0.2 mm. On the other hand, CI meteorites are predominantly  
41 composed of a fine-grained matrix with a mottled appearance, and the texture observed by  
42 MASCOT resembles that of the rare CI2 Tagish Lake meteorite, which possesses up to 2 mm  
43 large calcium aluminum rich inclusions<sup>11</sup>. Thus, CI2 type meteorites appear to be the closest  
44 known Ryugu analogue. However, as Tagish Lake is a rare sample and variations in inclusion  
45 sizes are common for carbonaceous chondrites, it is not feasible to derive a definite meteorite  
46 analogue. Rather, it may be possible that the investigated boulder is not represented in any  
47 meteorite collection on Earth.

48 Temperatures measured using MARA's 8-12  $\mu\text{m}$  filter are shown as a function of local time in  
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  
51 steeply in the morning, but start dropping around 11:07 local time, indicating shadows passing  
52 through the radiometer field of view before noon. Maximum temperatures reach 308 K shortly  
53 after local noon and the sun sets at 16:39 local time. The complex shape of the daytime  
54 temperature curve indicates a rough surface, consistent with camera observations. During  
55 nighttime, temperatures drop to 201 K.

56 As daytime data is affected by surface roughness and re-radiation from the environment, only  
57 equilibrated nighttime temperatures are used to fit thermophysical models. Best-fitting models  
58 (see methods) are indicated in Figure 2a and correspond to a thermal inertia  $\Gamma$  of  $282 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$ .  
59 While fitting nighttime data perfectly, the steep increase of temperature during the morning is

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

67 Admissible thermal inertia values are shown as a function of maximum insolation in Figure 2b,  
68 where the orientation of the surface normal has been systematically varied around its nominal  
69 value. The color bar shows the  $\chi^2$  of the individual fits, and emissivity has been varied between  
70 0.9 and 1. Low  $\Gamma$  corresponds to low emissivity and models with and without re-radiation have  
71 been considered. As a result, admissible thermal inertia values for the boulder in the MARA field  
72 of view were found to be  $282^{+93}_{-35} \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$ . This estimate is similar to telescopically  
73 determined thermal inertia values<sup>1</sup> of 150 to  $300 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$  and values determined by the  
74 thermal infrared imager on the Hayabusa2 spacecraft<sup>5</sup>, which range from 200 to  $500 \text{ J m}^{-2} \text{ K}^{-1}$   
75  $\text{ s}^{-1/2}$ . It therefore seems likely that boulders dominate the thermal emission from Ryugu, which  
76 would be consistent with the high rock abundance determined from orbiter images<sup>5</sup>. Therefore,  
77 contrary to expectation, the low thermal inertia derived for Ryugu does not correspond to a  
78 pebble-sized regolith-covered surface<sup>1,2</sup>. Rather, boulder to block-sized clasts themselves appear  
79 to have thermal inertia lower than that of CM2 Cold Bokkeveld, which has the lowest thermal  
80 inertia ( $600 - 700 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$ ) of a meteorite measured so far.

81 While thin layers of fine material could in principle mask the thermal signature of competent  
82 rock, the boulder observed by MARA appears to be free from an optically thick, dusty layer.  
83 Furthermore, the presence of a fine dust layer can be ruled out by considering a two layer  
84 thermal model. Results of the calculations (see methods) are shown in Figure 3, where dust with  
85 a thermal inertia of  $25 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$  was assumed to cover a boulder with a thermal inertia of  
86  $700 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$ . As is evident, the model is incompatible with the observed nighttime cooling  
87 rates, and the boulder observed by MARA itself must exhibit very low bulk thermal conductivity  
88 to fit the data. However, it cannot be ruled out that the low conductivity zone is limited to a

89 highly porous outer layer. Such a layer may for example be generated by cracking due to thermal  
90 fatigue<sup>12,13,14</sup> and could extend to a few thermal skin depths.

91 Given the above estimate of thermal inertia, thermal conductivity can be derived for a given bulk  
92 density and heat capacity (see methods). Furthermore, since thermal conductivity  $k$  of porous  
93 material depends more on porosity  $\phi$ , and thus the total area of inter-grain contacts, than on the  
94 conductivity of the grains themselves<sup>3</sup>, the porosity of the investigated boulder could in principle  
95 be estimated if the functional dependence of  $k(\phi)$  were known. However, while models for H and  
96 L chondrites indicate that porosity and thus thermal conductivity is governed by dehydration- or  
97 shock-induced cracks<sup>15,16,17</sup>, thermal conductivity data on CI chondrites are absent. Nevertheless,  
98 since cracks are abundant in CI types<sup>18</sup>, it stands to reason that a similar mechanism would  
99 reduce thermal conductivity in these types and models derived for H and L chondrites should be  
100 applicable to CI types, too.

101 Two models<sup>16,17</sup> for thermal conductivity as a function of porosity are shown in Figure 4a.  
102 Available data for H, L, and CM chondrites are shown together with the thermal conductivities  
103 extrapolated for Ryugu. The first model<sup>16</sup> results in  $28 < \phi < 34\%$ , typical for CM and CI  
104 chondrites, which have class average porosities of 22.2% and 34.9%, respectively<sup>17</sup>. The second  
105 model<sup>17</sup> yields  $41 < \phi < 55\%$ . Other models applicable to partially-sintered granular material<sup>16</sup>  
106 yield intermediate results. Corresponding thermal conductivities are 0.06 - 0.13 and 0.09 - 0.16  
107  $\text{W m}^{-1} \text{K}^{-1}$ , respectively, and thus much lower than measurements reported for the thermal  
108 conductivities of meteorites. Measurements on CI chondrites are missing entirely, but since CI  
109 chondrites are those meteorites with highest porosities<sup>17</sup>, low conductivities could be expected.

110 Pores in the boulder would be observable in nighttime images, as the illumination provided by  
111 the MasCAM LED array covers a variety of directions. However, no such pores are observed,  
112 indicating that potential pores must be smaller than 1 mm. The radiative contribution to the total  
113 heat transport inside the boulder can now be estimated by considering radiative heat exchange  
114 between parallel planes<sup>3</sup>, and for pores smaller than 1 mm this results in a minor contribution to  
115 the overall thermal conductivity. The latter must therefore be governed by solid conduction  
116 through grain contacts. Given porosity and thermal conductivity, the amount of contacts can be  
117 estimated, which in turn can be converted to an estimate of tensile strength (see methods). Given  
118 the values derived above and assuming a Young's modulus representative for carbonaceous

119 chondrites, tensile strength of the boulder is estimated to be 200 to 280 kPa and thus  
120 considerably lower than measurements on meteorite samples<sup>17</sup>, which generally show tensile  
121 strengths of the order of one to a few MPa<sup>19</sup>. This low tensile strength indicates an observational  
122 bias, namely that any hypothetical meteoroid originating from the boulder observed by  
123 MASCOT would likely break up during atmospheric entry and would thus be absent in our  
124 meteorite collections.

125 Thermal conductivity values derived above can be compared to estimates for other minor bodies,  
126 and corresponding data are shown in Figure 4b, where thermal conductivity is given as a  
127 function of temperature for asteroids (162173) Ryugu<sup>1</sup>, (101955) Bennu<sup>20</sup>, and the average  
128 estimated for small near Earth asteroids<sup>21</sup>. Values are compatible within error bars and similar to  
129 values derived for comets 67P/Churyumov–Gerasimenko<sup>22</sup>, 9P/Tempel 1<sup>23,24</sup>, and 103P/Hartley  
130 2<sup>23</sup> when heat capacity is properly scaled for temperature and appropriate densities are assumed  
131 (see methods section). On the other hand, estimates for S-type asteroid (25143) Itokawa<sup>25,26</sup> are  
132 larger by a factor of three, indicating that thermal properties of C-type asteroids are more similar  
133 to those of comets than those of S-type asteroids. It is also worth noting that no cubic  
134 dependence of thermal conductivity on temperature is observed in Figure 4b, which could  
135 indicate that radiative heat transfer through large pores is negligible in the bodies considered  
136 here.

137 The high porosities derived here have important implications for Ryugu’s parent body.  
138 Assuming initial porosities<sup>27</sup> of the order of 70%, the Ryugu precursor needs to have been large  
139 enough to reduce intrinsic (micro-) porosity to values below 55% by compaction and aqueous  
140 alteration, while simultaneously avoiding porosities to drop below 28%. This implies that the  
141 material we observe on Ryugu’s surface today was either produced in the outer layers of a larger  
142 (50-100 km sized) parent body, or the interior of a smaller, kilometer-sized body. The latter  
143 would be feasible provided accretion occurred while <sup>26</sup>Al was still active, in which case aqueous  
144 alteration and hot pressing of the precursor material would be efficient. In this way, porosities of  
145 45% can be achieved starting from initial porosities of 70% even on small, kilometer-sized  
146 objects, provided that a water ice dominated primordial composition similar to that of CI/CM  
147 chondrites is assumed<sup>28,29</sup>.

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231

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239

240 **Author contributions**

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

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275

276 **Figure Legends:**

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

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

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

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

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

316 grain density of  $2420 \text{ kg m}^{-3}$  has been assumed. Heat capacity<sup>1</sup> was evaluated at 230 K,  
317 corresponding to the average observed nighttime temperature. In addition, conductivity values as  
318 derived from disc integrated measurements of Ryugu, disc integrated measurements of asteroid  
319 Bennu<sup>20</sup>, as well as the estimated average thermal conductivity for near Earth asteroids (NEA)<sup>21</sup>  
320 are shown. As a comparison, conductivity derived from in-situ observations of comet  
321 67P/Churyumov–Gerasimenko<sup>22</sup> as well as values derived from spacecraft observations of  
322 comets 9P/Tempel 1<sup>23,24</sup> and 103P/Hartley 2<sup>23</sup> are given. In contrast, the conductivity derived  
323 from disc integrated measurements of asteroid Itokawa<sup>26</sup> is also shown.

## 324 **Methods**

325 **Asteroid Thermophysical Model.** To estimate thermophysical properties from the brightness  
326 temperatures observed, a thermophysical model of the Ryugu boulder was constructed assuming  
327 a single, flat surface in the MARA field of view. A specific heat  $c_p$  of  $600 \text{ J kg}^{-1} \text{ K}^{-1}$  and density  
328  $\rho$  of  $1270 \text{ kg m}^{-3}$  have been assumed for the boulder, consistent with pre-encounter estimates<sup>1</sup>.  
329 Parameters have been assumed to be constant and independent of temperature, as more  
330 complicated models did not improve the quality of the fit. Thermal conductivity  $k$  was treated as  
331 a free fitting parameter, and results are reported in terms of surface thermal inertia

$$\Gamma = \sqrt{k\rho c_p} \quad (1)$$

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

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

352 Given insolation  $I$  and thermal inertia  $\Gamma$ , the 1D heat equation is solved<sup>30</sup> using

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

353 as the upper boundary condition. Here,  $T$  is surface temperature,  $\Gamma$  thermal inertia,  $P$  rotation  
 354 period,  $A$  bond albedo,  $\sigma$  the Stephan-Boltzmann constant,  $z$  depth normalized to the diurnal skin  
 355 depth<sup>31</sup>,  $\varepsilon$  emissivity, and  $f$  the view factor to the surrounding environment. In the calculations,  
 356 an albedo of  $A = 0.0146$  is assumed while emissivity was varied between 0.9 and 1. The  
 357 rotation period of Ryugu is 7.6326 h.

358 **Data Fitting.** To avoid complications caused by inhomogeneous temperatures in the MARA  
 359 field of view due to the changing illumination conditions and re-radiation from the surroundings,  
 360 only equilibrated nighttime data were used to fit thermophysical models<sup>32</sup> and invert for  
 361 thermophysical parameters. To fit the data, a suite of models was computed by systematically  
 362 varying thermal inertia and the orientation of the surface normal in a grid search approach. In the  
 363 models, thermal inertia was varied in steps of  $1 \text{ J m}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}$  between 170 and 410, elevation of  
 364 the target surface normal was varied in steps of  $5^\circ$  between  $90^\circ$  and  $65^\circ$ , and azimuth of the  
 365 target surface normal was varied in steps of  $10^\circ$  between  $0^\circ$  and  $360^\circ$ . For each model, the  $\chi^2$   
 366 value between model and data was computed and models resulting in a  $\chi^2$  larger than a critical  
 367 value were discarded. Here we choose a critical  $\chi_{crit}^2$  corresponding to a  $2\sigma$  confidence interval<sup>30</sup>

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

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

372 This procedure was repeated by varying surface emissivity and assuming values of  $\varepsilon = 0.9, 0.95$   
373 and 1. Furthermore, models with view factors to the surroundings of  $f = 0$  and 0.08 have been  
374 computed to study the effect of re-radiation, which was found to have only a small influence on  
375 nighttime temperatures. The stated uncertainty for the thermal inertia was then derived from the  
376 lowest and highest admissible values of all simulations. The best-fitting model has an emissivity  
377 of  $\varepsilon = 1$ . For consistency, the emissivity used for both the thermophysical models and the  
378 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  $\varphi$ , the  
380 angle between surface normal and observation direction  $\delta$ , as well as the angle between  
381 projections of the sun vector and the observation direction onto the surface  $\psi$ . These need to be  
382 taken into account when calculating fluxes received by the instrument. Here, the rough surface is  
383 modeled as a surface covered by spherical-section craters<sup>33,34</sup>, assuming lateral heat transport to  
384 be negligible. Using this model, a factor  $c_r(\varphi, \delta, \psi, t, \lambda)$  is calculated for each time  $t$  and  
385 observed wavelength  $\lambda$  relating the flux emitted by a flat surface  $F$  to the flux emitted by the  
386 rough surface  $F_r = c_r(\varphi, \delta, \psi, t, \lambda)F$ . This model is scale-independent<sup>33</sup>, leaving the crater  
387 density on the surface and the opening angle of the craters as free parameters. The latter is kept  
388 constant at  $180^\circ$ , corresponding to a surface covered by hemispherical depressions. The model  
389 also depends on parameters such as albedo and heliocentric distance, which are all kept constant  
390 to be consistent with the thermophysical model described above.  $c_r$  was calculated at  $\lambda =$   
391  $10 \mu m$ .

392 **Two Layer Model.** To estimate the possible influence of a low conductivity dust layer on the  
393 modeling results, a two layer regolith model assuming geometry parameters corresponding to  
394 those of the best fitting one-layer model was calculated. In the model, the dust layer is treated in  
395 the continuum approximation, i.e., it is assumed that thermal transport properties inside the layer  
396 can be treated using the theory of porous media<sup>3</sup>. This approximation breaks down if thin layers  
397 of dust are present, in which case radiative heat transport inside the dust layer would need to be

398 treated explicitly. Here we assume that the dust layer has a thermal inertia of  $25 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$ .  
 399 This corresponds to typical particle sizes of  $\sim 10 \text{ }\mu\text{m}$  at porosities of 80%<sup>3</sup>. Therefore, our model  
 400 assumptions are valid for layer thicknesses in excess of  $50 \text{ }\mu\text{m}$ .

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  $700 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$ , 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  $\phi$  for the  
 407 boulder observed by MARA are calculated by solving

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

408 for a given functional dependence for  $k(\phi)$ . Here,  $\Gamma$  is thermal inertia,  $c_p$  is specific heat,  $\rho_s$  is  
 409 grain density, and  $\phi$  is porosity. For the grain density  $\rho_s$ , the average density of CI chondrites<sup>17,35</sup>  
 410  $\rho_s = 2420 \text{ kg m}^{-3}$  has been assumed. Heat capacity was determined by evaluating<sup>1</sup>  $c_p(T)$  at  $T =$   
 411  $230 \text{ K}$ . For the functional dependence of  $k(\phi)$ , two models have been considered. Both are based  
 412 on empirical fits to available thermal conductivity data for chondritic meteorites, and the first  
 413 relation<sup>17</sup> is

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

414 while the second relation<sup>16</sup> is

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

415 Both formulations fit the experimental data equally well, but diverge at porosities larger than  
 416 20%.

417 To compare the thermal conductivity estimates for meteorites with those for comets, cometary  
 418 thermal inertia estimates have been converted to an estimate of thermal conductivity assuming a  
 419 cometary bulk density of  $300 \text{ kg m}^{-3}$  as derived from spacecraft observations<sup>23</sup> of the Deep



420 Impact experiment on 9P/Tempel 1. For the heat capacity, a value of  $1000 \text{ J kg}^{-1} \text{ K}^{-1}$  was used<sup>23</sup>.  
 421 For the computation of thermal conductivities for (101955) Bennu, (25143) Itokawa, and average  
 422 NEA, heat capacity<sup>1</sup> was evaluated at a temperature of 340 K, while for the disc-averaged  
 423 measurement of (162173) Ryugu a temperature of 277 K has been assumed. Assumed bulk  
 424 densities for (162173) Ryugu<sup>1</sup>, average NEA<sup>21</sup>, (25143) Itokawa<sup>25</sup>, and (101955) Bennu were  
 425  $1270 \text{ kg m}^{-3}$ ,  $1950 \text{ kg m}^{-3}$ ,  $1950 \text{ kg m}^{-3}$ ,  $1270 \text{ kg m}^{-3}$ , respectively.

426 **Strength Estimate.** To estimate mechanical tensile strength given thermal conductivity  $k$  and  
 427 porosity  $\phi$ , the amount of inter-grain contacts is estimated neglecting radiative heat transport  
 428 using<sup>3</sup>

$$k = \frac{4}{\pi^2} k_s (1 - \phi) CH \quad (6)$$

429 where the grain thermal conductivity  $k_s$  has been assumed to be  $2.95 \text{ W m}^{-1} \text{ K}^{-1}$  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

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

432 was used, where

$$f = 0.07318 + 2.193\phi - 3.357\phi^2 + 3.194\phi^3 \quad (8)$$

433 Given  $k$ ,  $k_s$ ,  $\phi$ ,  $C$  and  $H$  can then be calculated. For a random packing of identical, isotropic and  
 434 homogeneous spheres with shear modulus  $\mu$  and Poisson's ratio  $\nu$ , the bulk elastic parameters  
 435 can then be related to those in a porous medium following the approach of Digby<sup>36</sup>: in Hertzian  
 436 contact theory, two identical spheres have a circular contact area of radius  $r_c$ , depending on the  
 437 confining pressure and the Young's modulus of the sphere material. In extension of the Hertz  
 438 contact model, Digby assumes that the contact area between two spheres contains a small,  
 439 concentric area of radius  $r < r_c$  where the spheres are firmly bonded, i.e., remain in contact even  
 440 without confining pressure. He obtains the effective Lamé parameters of the packing

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

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

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

$$E = \mu \frac{3\lambda + 2\mu}{\lambda + \mu} \quad (11)$$

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

$$E = 2\mu(1 + \nu) \quad (12)$$

444 between shear modulus, Lamé parameter  $\lambda$  and Young's modulus  $E$ , we obtain the effective  
 445 Young's modulus

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

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

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

450 and the obtained (reduced) Young's modulus is then converted into an estimate of tensile  
 451 strength  $\sigma_t$  using the empirical relation<sup>37</sup>

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

452 The Young's modulus  $E$  of ordinary chondrites is usually reported<sup>17</sup> to be of the order of tens of  
453 GPa, while values for carbonaceous chondrites are usually much lower<sup>38,39</sup>, ranging from a few  
454 to about 10 GPa. Here we assume 10 GPa to be representative for the Ryugu boulder, pointing  
455 out that this likely places an upper limit on the derived tensile strength.

456

### 457 **Data Availability**

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

460

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