# Anomalously porous boulders on (162173) Ryugu as primordial materials from its parent body

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## Main text

**Planetesimals, the initial stage of the planetary formation process, are considered to be initially very porous aggregates of dusts[1,2], and subsequent thermal and compaction processes reduce their porosity[3]. The Hayabusa2 spacecraft showed that boulders on the surface of asteroid (162173) Ryugu have an average porosity of 30%-50%[4–6], higher than meteorites but lower than cometary nuclei[7], which are considered to be remnants of the original planetesimals[8]. Here, using high-resolution thermal and optical imaging of Ryugu's surface, we discovered, on the floor of fresh small craters (< 20 m in diameter), boulders with reflectance (~0.015) lower than Ryugu average[6] and porosity > 70%, which is as high as in cometary bodies. The artificial crater formed by Hayabusa2's impact experiment[9] is similar to these craters in size but does not have such high porosity boulders. Thus, we argue that the observed high porosity is intrinsic and not created by subsequent impact comminution and/or cracking. We propose that these boulders are the least processed material on Ryugu and represent remnants of porous planetesimals that did not undergo a high degree of heating and compaction[3]. Our multi-instrumental analysis suggests that fragments of the highly porous boulders are mixed within the surface regolith globally, implying that they might be captured within collected samples by touch-down operations[10,11].**

Hayabusa2 carried out descending operations[10], where thermal infrared camera (TIR) acquired high-resolution images below 500-m altitude, resulting in spatial resolutions better than 45 cm/pixel (Extended Data Fig. 1). To find the low thermal inertia (TI) and high porosity area, which should show higher daytime temperature, we investigated the average temperatures and their standard deviations for each descent sequence (Supplementary Table 1) and searched for regions where the brightness temperature differed by more than 2 standard deviations from the average. As expected, the hot regions are generally located at solar-directed boundaries between the boulders and ground, where self-heating by solar reflection and radiation from the boulder's side wall is strong. Moreover, two isolated hot spots were found (Extended Data Fig. 2).

The most definitive hot spot is a high-temperature boulder assembly (HS1, Fig. 1) located near the centre of a small crater with a diameter of approximately 9 m, catalogued as the ID126 crater located at (4.8°N, 212.4°E) [12]. The size of HS1 is about 40 centimetres and it consists of a few boulders with tens of centimetres in size based on ONC-T (multi-band telescopic camera) images, which might imply breakup of a parent boulder during the cratering process. Based on the image shown in Fig. 1d, the temperature of HS1 corresponds to an apparent TI of 73 ± 25 $\mathrm{Jm^{-2}K^{-1}s^{-0.5}}$, hereafter tiu (see Methods, Extended Data Fig. 3), significantly lower than Ryugu's global average of 200-400 tiu[5,13]. One might attribute the low TI to fine-grained dust deposits[14,15]. Although the presence of dusts with particle sizes of a few hundred micrometres on Ryugu's surface and/or subsurface is indicated by camera images taken during the touch-down operations[11], no such dust layer was found on boulders according to in-situ observations by the MASCOT lander[4,16]. Furthermore, the HS1 boulders show clear outlines and a brightness contrast on the surface (Fig. 1e), thus a thick dust deposit is unlikely. The observed low-TI should therefore stem from the intrinsic insulating and thus porous nature of the boulders. Although a surface dust coating thinner than the camera resolution cannot be ruled out based on the TIR daytime data, it is unlike to play a major role based on local observations at the MASCOT landing site[4,15]. According to the empirical relations between thermal conductivity and porosity (see Methods), the corresponding porosity $\phi$ is taken as 72%–91%.

Furthermore, we found another hot spot (HS2) with potentially low TI comparable with HS1 (Fig. 2). HS2 (~3 m in diameter) is also located at the centre of the crater catalogued as ID69 located at (9.6°N, 149.1°E), whose rim-to-rim diameter is 20 metres[17]. The apparent TI of HS2 is 53 ± 49 tiu. Unfortunately, high-resolution ONC-T images of this crater could not be acquired; thus its detailed morphology is difficult to examine. The question of whether HS2 consists of boulders like HS1 or fine-grained regolith ponds as those found in craters on Eros[18] therefore remains unknown. Under the assumption that HS2 consists of boulders, we estimate $\phi >$ 71%.

Out of seven catalogued craters[17] whose centres are pictured by the TIR images (Extended Data Fig. 1), only the two smallest ones (ID126 and ID69) have central hot spots. For example, crater ID46 does not show any hot spot signature (Extended Data Fig. 4a). Furthermore, global observations from 5 km altitude showed no detectable hot spots in large (and old) craters (Supplementary Fig. 1). An artificial impact crater formed by the small carry-on impactor (SCI) experiment[9] provides useful information for understanding the thermophysical properties of fresh craters. The highest-resolution TIR image (23 cm/pix) showed no detectable hot spot in the SCI crater (Extended Data Figs. 5a-b). Thermal simulations using a local digital elevation model[9] showed that the observed temperatures are consistent with the simulated temperature if a uniform TI of 300 tiu, comparable to the global average, is assumed (Extended Data Figs. 5c-d). We therefore suggest that low-TI material like HS1 and HS2 is not buried in the subsurface of this region or that this material is exposed in patches smaller than the pixel resolution in small quantities relative to more thermophysically common boulders. The absence of a hot spot in the SCI crater also indicates that the low-TI and high-porosity nature of the hot spots is unlikely to be due to single impact comminution and shock-induced cracks.

We investigated the brightness temperatures of boulders identified in six sets of the TIR and ONC-T images during the touch-down rehearsal (TD1-R3) sequence[10] (Figs. 3a–f, Extended Data Fig. 6). HS1's temperature exceeds that of all other boulders by 10 K (Fig. 4a), which strongly suggests that it has the lowest TI. Approximately 70% of the boulders have TI consistent with the global average of 200-400 tiu (Extended Data Fig. 7b). In addition to the anomalously low TI, HS1 is the darkest among the boulders and regolith. We found a positive correlation between TI and v-band (0.55 μm in wavelength) reflectance (Fig. 4c). Asteroid (101955) Bennu shows the similar correlation[19], and this trend in common in both carbonaceous asteroids may originate from some universal physical/chemical processes in their parent bodies. The trend is discontinuous and three groups appear: the hot spots (HS1 and HS2) with low reflectance, a cluster with intermediate reflectance and TI consistent with Ryugu's global average[6,13], and the bright boulders with high TI (so-called bright/cold spots[5,20]). Visible spectral slopes from 0.55 to 0.86 μm for HS1 and HS2 are contrastive; the former is redder than the clustered boulders and the latter is bluer but consistent with the common boulders (Figs. 4b, 4d). It could be argued that the anomalous properties of the HS1 have an exogeneous origin, for instance from the infall of porous and dark comet-like materials. However, this hypothesis is not likely because on the TI-reflectance, TI-colour, and reflectance-colour diagrams, the regolith lies on a mixing line between the common boulders and HS1. Because of this, we favour the hypothesis that the HS1 material is an original constituent of asteroid Ryugu and small HS1-like boulder fragments are mixed into the regolith. Note that the mixing model in the thermal inertia will be effective if the fragmented regolith grains are comparable in size to or larger than the thermal skin depth of the porous materials (~1 cm); for smaller grain sizes, the thermal inertia of the mixed fragments is dominated by the grain size themselves, and microporosity is less relevant[21].

Global observations by the near-infrared spectrometer NIRS3 revealed weak absorption features of the hydroxyl-related band at 2.72 μm, similar to spectral features of heated and partially dehydrated carbonaceous chondrites[22]. The primary partial dehydration is thought to be caused by radiogenic heating following the formation of hydrous silicates in the parent body, and solar radiative heating of Ryugu's top-surface materials when Ryugu was nearer to the Sun in the past resulted in the additional dehydration[23]. Although there are no NIRS3 data to resolve crater ID126, the ID69 crater data indicate a 2.72-μm absorption band slightly deeper than the surroundings (Figs. 2c-d), whereas the ID46 crater without the hot spot does not show such an increase in the absorption feature (Extended Data Figs. 4c-d). This supports that the ID69 crater including the low-TI materials is fresher and would experience less radiative heating on the surface. On the other hand, the band depth also depends on the porosity itself[24]. The alternative interpretation of the NIRS3 data is that the high porosity nature of HS2 materials in crater ID69 might make the absorption deeper.

Porosity of the hot spot boulders ($\phi > 70\%$) is as high as bulk porosity of comets and trans-Neptunian objects[25], that are thought to preserve the primordial accretion process of dusts or pebbles in the outer protoplanetary disk[8]. We state that the most likely origin of HS1-like materials is the dust aggregation process during the formation of the planetesimal of Ryugu's parent body, in which the highly porous materials are theoretically and experimentally predicted[2,26] (see Methods for other potential processes enhancing the porosity). Furthermore, because our study detected hot spots only in the centres of small fresh craters, we suggest that the porous boulders survived in the subsurface and were excavated by impacts (Figs. 5e-f). Once exposed at the surface, they were selectively disrupted into small fragments by surface activities, such as micro-meteoroid impacts and/or thermal fatigue[27], because of their comparatively lower mechanical strength (Fig. 5c). Concentrations of these fragmented fine grains, which is expected to result in lower thermal inertia than hot spot boulders[21], are not observed by TIR; relatively rapid transportation can therefore be expected to occur on Ryugu's surface (Fig. 5d). One of the most likely processes of the fragment transportation is dust levitation by electric potential differences[28].

The inherent origin of the highly porous materials indicates that they were derived from the uppermost part of a partially consolidated layer on a planetesimal, and are likely to be the most primitive among Ryugu's boulders without a high degree of thermal alteration and compaction in the parent body (Fig. 5a). Indeed, a model of the planetesimal compaction[29] suggests that such highly porous and partially consolidated materials have experienced the temperatures lower than 600 K at the near-surface, whereas the more compact materials were exposed on hotter interior (see Methods and Extended Data Fig. 8). In Hayabusa2's first touch-down and sampling operation, dark and red dust particles consistent with HS1 optical properties were excavated from the surface by the thruster jet[11]. These dust grains have been interpreted as materials that experienced solar radiative heating[11]. Our analysis presents an alternative hypothesis that the excavated dark/red dusts are the fragments of HS1-like boulders, as remnants of less processed planetesimals. Laboratory analysis of the collected samples, in which these primitive materials could be included, will help to reveal the nature of planetesimals as a starting point of the planetary formation process.

## References

1. Okuzumi, S., Tanaka, H., Kobayashi, H. & Wada, K. Rapid coagulation of porous dust aggregates outside the snow line: A pathway to successful icy planetesimal formation. *Astrophys. J.* **752**, 106 (2012).
2. Kataoka, A., Tanaka, H., Okuzumi, S. & Wada, K. Fluffy dust forms icy planetesimals by static compression. *Astron. Astrophys.* **557**, L4 (2013).
3. Neumann, W., Breuer, D. & Spohn, T. Modelling of compaction in planetesimals. *Astron. Astrophys.* **567**, A120 (2014).
4. Grott, M. *et al.* Low thermal conductivity boulder with high porosity identified on C-type asteroid (162173) Ryugu. *Nat. Astron.* **3**, 971–976 (2019).
5. Okada, T. *et al.* Highly porous nature of a primitive asteroid revealed by thermal imaging. *Nature* **579**, 518–522 (2020).
6. Sugita, S. *et al.* The geomorphology, color, and thermal properties of Ryugu: Implications for parent-body processes. *Science* **364**, 252 (2019).
7. Groussin, O. *et al.* The thermal, mechanical, structural, and dielectric properties of cometary nuclei after Rosetta. *Space Sci. Rev.* **215**, 29 (2019).
8. Weissman, P., Morbidelli, A., Davidsson, B. & Blum, J. Origin and Evolution of Cometary Nuclei. *Space Sci. Rev.* **216**, 1–40 (2020).
9. Arakawa, M. *et al.* An artificial impact on the asteroid (162173) Ryugu formed a crater in the gravity-dominated regime. *Science* **368**, 67–71 (2020).
10. Tsuda, Y. *et al.* Hayabusa2 mission status: Landing, roving and cratering on asteroid Ryugu. *Acta Astronaut.* **171**, 42–54 (2020).
11. Morota, T. *et al.* Sample collection from asteroid (162173) Ryugu by Hayabusa2: Implications for surface evolution. *Science* **368**, 654–659 (2020).
12. Cho, Y. *et al.* Geologic history and crater morphology of asteroid (162173) Ryugu. Preprint at https://doi.org/10.1002/essoar.10506689.2 (2021).
13. Shimaki, Y. *et al.* Thermophysical properties of the surface of asteroid 162173 Ryugu: Infrared observations and thermal inertia mapping. *Icarus* **348**, 113835 (2020).
14. Sakatani, N. *et al.* Thermal conductivity model for powdered materials under vacuum based on experimental studies. *AIP Adv.* **7**, 015310 (2017).
15. Biele, J. *et al.* Effects of dust layers on thermal emission from airless bodies. *Prog. Earth Planet. Sci.* **6**, 48 (2019).

16. Jaumann, R. *et al.* Images from the surface of asteroid Ryugu show rocks similar to carbonaceous chondrite meteorites. *Science* **365**, 817–820 (2019).
17. Noguchi, R. *et al.* Crater depth-to-diameter ratios on asteroid 162173 Ryugu. *Icarus* **354**, 114016 (2021).
18. Roberts, J. H. *et al.* Origin and flatness of ponds on asteroid 433 Eros. *Meteorit. Planet. Sci.* **49**, 1735–1748 (2014).
19. Rozitis, B. *et al.* Asteroid (101955) Bennu's weak boulders and thermally anomalous equator. *Sci. Adv.* **6**, eabc3699 (2020).
20. Tatsumi, E. *et al.* Collisional history of Ryugu's parent body from bright surface boulders. *Nat. Astron.* **5**, 39–45 (2020).
21. Ryan, A. J., Pino Muñoz, D., Bernacki, M. & Delbo, M. Full-Field Modeling of Heat Transfer in Asteroid Regolith: Radiative Thermal Conductivity of Polydisperse Particulates. *J. Geophys. Res. Planets* **125**, e2019JE006100 (2020).
22. Kitazato, K. *et al.* The surface composition of asteroid 162173 Ryugu from Hayabusa2 near-infrared spectroscopy. *Science* **364**, 272–275 (2019).
23. Kitazato, K. *et al.* Thermally altered subsurface materials of asteroid 162173 Ryugu. *Nat. Astron.* **5**, 246–250 (2021).
24. Potin, S., Beck, P., Schmitt, B. & Moynier, F. Some things special about NEAs: Geometric and environmental effects on the optical signatures of hydration. *Icarus* **333**, 415–428 (2019).
25. Carry, B. Density of asteroids. *Planet. Space Sci.* **73**, 98–118 (2012).
26. Blum, J. Dust Evolution in Protoplanetary Discs and the Formation of Planetesimals: What Have We Learned from Laboratory Experiments? *Space Sci. Rev.* **214**, 52 (2018).
27. Delbo, M. *et al.* Thermal fatigue as the origin of regolith on small asteroids. *Nature* **508**, 233–236 (2014).
28. Hartzell, C. M. & Scheeres, D. J. Dynamics of levitating dust particles near asteroids and the Moon. *J. Geophys. Res. Planets* **118**, 116–125 (2013).
29. Neumann, W. *et al.* Microporosity and parent body of the rubble-pile NEA (162173) Ryugu. *Icarus* **358**, 114166 (2021).

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## Competing Interests

The authors declare no competing interests.

## Main figure legends

**Fig. 1 | Hot spot HS1 within the ID126 crater.** **a**, TIR image of the ID126 crater (hyb2_tir_20181015_133900_l2). The black dashed and red solid circles show the crater rim and hot spot HS1. **b**, ONC-T image of the ID126 crater (hyb2_onc_20181025_025356_twf_l2b). **c**, Mosaic image created from two ONC-T images acquired during TD1-R1A (hyb2_onc_20181015_133833_tvf_l2b) and TD1-R3 (hyb2_onc_20181025_022806_tvf_l2b). **d**, Close-up TIR image (hyb2_tir_20181025_022832_l2) of HS1. **e**, Close-up ONC-T image (hyb2_onc_20181025_022806_tvf_l2b). The hot spot corresponds to the region enclosed by the red ellipse, which consists of 10-cm-sized boulders, whose outlines are indicated by white lines. See also Fig. 3e for a composite of the TIR and ONC images.

**Fig. 2 | Hot spot HS2 observed by TIR and NIRS3 observation. a**, TIR image of the ID69 crater (9.6°N, 149.1°E) with hot spot HS2 (hyb2_tir_20180921_034132_l2). **b**, ONC-T image of the ID69 crater (hyb2_onc_20190221_154026_tvf_l2b). This image was acquired after the solar conjunction in December 2019, whereas the TIR image in **a** was collected previously, thus the shadow direction is different in each image. **c**, NIRS3 footprint around the ID69 crater on 31 October 2018. The blue and yellow rectangles denote the NIRS3 spot sizes inside and outside the crater, respectively. **d**, NIRS3 spectra of the crater including HS2 normalized to the spectra outside of the ID69 crater. A relatively stronger 2.72-μm absorption feature marked with the vertical blue dashed line is found in the crater. Error bars are calculated from equation (8) in Methods.

**Fig. 3 | TIR temperature images overlain on the ONC-T images acquired during the TD1-R3 sequence.** We examined these six regions (region A to F) where ONC-T images covered the field of view of TIR images in this descent sequence. Centre latitude and longitude of these images based on LIDAR-derived trajectory are (4.5°N, 235.9°E), (4.5°N, 224.8°E), (4.8°N, 215.5°E), (4.9°N, 213.8°E), (4.9°N, 212.2°E), and (4.8°N, 210.5°E), for region A to F, respectively (see also Extended Data Fig. 1d). White circles and squares indicate regions where the temperature, v-band (550 μm in wavelength) reflectance factor at standard geometric conditions ([$i$, $e$, $\alpha$] = [30°, 0°, 30°], where $i$, $e$, and $\alpha$ are incident, emission, and solar phase angles, respectively), and v-band to x-band (860 μm) slope were measured for the boulders and regolith (region mainly with grains unresolved from images with resolutions of 26 to 4.4 mm/pix in Figs. 3a-f), respectively, as shown in Fig. 4. The red arrow indicates the hot spot HS1, and the blue arrow indicates cold and bright spot CS1[5,20]. Note that the hot spot HS2 was imaged in the other decent sequence (MNRV), they are not shown here but in Extended Data Fig. 6g.

**Fig. 4 | Thermal and optical properties of boulders and regolith on Ryugu.** Correlation between temperature and v-band reflectance (**a**), v-to-x slope and reflectance (**b**), thermal inertia and reflectance (**c**), and thermal inertia and v-to-x slope (**d**). Black and blue points represent boulders and regolith, respectively. Error bards for each point represent the standard deviation in the counted area. The red square represents hot spot HS1, and the red circle hot spot HS2. Because the multi-band imaging sequence is spatially discrete, the number of boulders with spectral information is limited. Gray (boulders) and blue (regolith) clouds show 95% (2σ) probability regions assuming 2D Gaussian distributions, except for the two brightest boulders. Red lines in **b-d**, connecting the HS1 and centre of the boulder distribution, indicate mixing lines between HS1 and abundant boulders, along which the regolith-rich regions are mapped. These mixing lines imply that fragments from the HS1-like materials are included in the regolith.

**Fig. 5 | Formation process and surface behaviour of the hot spot boulders. a**, Layered or gradual porosity forms in the parent body owing to the thermal evolution and compaction process (Methods and Extended Data Fig. 8). **b**, Its catastrophic disruption and subsequent accumulation of the fragments form a precursor of Ryugu. **c**, On the asteroid surface, highly porous hot spot materials are selectively fragmented by micrometeorite impacts and/or thermal fatigue owing to weak mechanical strength. **d**, The fragmented grains are transported horizontally and mixed into the regolith and/or released into space by dust levitation. **e, f**, Surviving porous boulders in the subsurface are exposed by crater formation. The absence of a hot spot in the SCI crater indicates a heterogeneous distribution of the large and porous boulders in the subsurface.

# Methods

## *Thermal simulation and thermal inertia estimate*

We have developed a thermal simulation code using a given shape model that can output the one-rotation temperature history for all facets at arbitrary spin parameters and asteroid position in equatorial coordinates relative to the Sun[5,13,30]. This model solves the one-dimensional heat conduction equation for each facet of the shape model, including the effect of solar isolation from the surrounding topography, input of thermal radiation and solar reflection from the other facets (so-called self-heating). The albedo is uniformly set to 0.0146 (bond albedo[31]) and the emissivity is 1.0 for compatibility with the brightness temperature (equivalent blackbody temperature) data. The spin parameters are based on the public version of SPICE PCK kernel (hyb2_ryugu_shape_v20190328.tpc, https://www.darts.isas.jaxa.jp/pub/hayabusa2/spice_bundle/spice_kernels/), the rotational period is 7.6326 h and the ecliptic longitude and latitude of the spin axis are 179.091° and −87.428°, respectively.

We performed simulations using two different shape models. One is a global shape model, named SHAPE_SPC_3M_v20190328 based on stereo-photoclinometry (SPC) [17], to derive the apparent thermal inertia of the boulders and regolith in regions A to F (Fig. 3). For efficiency, we cut out regional data (rectangular regions in longitude-latitude coordinates) including the region of interest from the global model. The facet size of the global shape model is roughly 1 m, which is larger than the pixel resolution of the TIR image in the descent sequence described in this paper (<45 cm). The other shape model is the local digital elevation model around the SCI crater constructed using high-resolution ONC-T images[9]. The facet size used for the thermal simulation is approximately 20 cm, which is comparable with the spatial resolution of the TIR image in Extended Data Fig. 5.

Thermal inertia (TI) is typically estimated from diurnal temperature profiles[32]. Nighttime cooling curves are especially sensitive to the TI and layered structure of the top surface[15]. Because the number of high-resolution images and range of local-time observations for a single target region is limited, we could not examine the entire diurnal temperature history of the boulders and regolith. TI must be estimated by comparing the observed temperature with simulated temperatures at given times. We created simulated images by rendering of the three-dimensional temperature data[33] with TI ranging from 20 to 1000 Jm$^{-2}$K$^{-1}$s$^{-0.5}$ (hereafter tiu). The spacecraft position relative to Ryugu's fixed frame at the observation epoch was derived from improved trajectory data using the post-evaluated trajectory after the operation and altitude information of the laser altimeter (LIDAR)[34]. From the simulated temperature images, we averaged the pixel values within latitude and longitude ranges for each region and then compared these with the observed temperatures of the respective boulders and regolith. The apparent TI, $\Gamma$, was determined by linear interpolation of the calculated temperature as:

$$\Gamma = \frac{\Gamma_{i+1}-\Gamma_i}{T_{i+1}-T_i}(T_{obs}-T_i)+\Gamma_i \qquad (1)$$

where $\Gamma_i$ is TI chosen in the simulation (20, 50, 100, 200 tiu …), $T_i$ is the simulated temperature and $T_{obs}$ is the mean observed temperature of the boulders or regolith. Using the standard deviations of $T_i$ and $T_{obs}$ within the averaged regions, the uncertainty of the estimated TI is calculated according to the error propagation via above the equation. Extended Data Figs. 3a and 3b show how to determine the apparent TI of HS1, yielding TI = 73 ± 25 tiu. The ID69 crater is topographically resolved in the global shape model. The simulated temperatures were then averaged within the hot spot region and compared with the observed temperature of HS2 (Extended Data Figs. 3c, 3d). The apparent TI of HS2 is 53 ± 49 tiu. The larger error of HS2 can be attributed to the heterogeneous temperature distributions in both the observations and simulation. Extended Data Fig. 7b shows a histogram of the TI for the boulders in regions A–F (Figs. 3, 4) and HS2 hot spot.

### *Possible uncertainties in thermal inertia*

During the touch-down rehearsal (TD1-R3) sequence on 25 October 2018, the local solar incident angle of the observed region was lower than those in the other sequences (Supplementary Table 1). It is reasonable to focus on the TD1-R3 data to minimise the disturbance of the apparent temperature caused by the roughness effect, which is effective at higher solar phase angle[13], and by the uncertainty of local slope of boulder's surfaces, which is not reproduced in the global shape model.

Fig. 4a indicates a negative correlation between temperature and reflectance. Brighter materials generally have lower temperatures owing to less absorption of the solar energy. However, because the reflectance factor ranges from 0.015 to 0.029 and the radiative equilibrium temperature is related to 1/4th power of the absorption coefficient given by 1 minus reflectance, the relative difference of the reflectance affects the temperature by only 0.4%. In a similar way, although dark materials might have higher infrared emissivity, emissivity does not substantially contribute the temperature difference. The variation of brightness temperature shown in Fig. 4a is therefore less affected by the reflectance and emissivity, and rather is due to true differences in thermal inertia.

Additional TI uncertainties arise from the local topography, which are not represented in the global shape model. The first is the local slope relative to the Sun, the second is crater topography, and the third is the surface roughness; both affect the simulated temperature. In the case of maximum solar illumination, the highest temperature of HS1 might be explained even by the higher thermal inertia. For example, the average solar incident angle $i = 24°$ is derived from the global shape model for region E, including HS1, at the observation epoch (25 October 2018, 02:28:32 UT). The radiative equilibrium temperature $T_{eq}$, or temperature with $\Gamma = 0$ tiu, is given by:

$$\varepsilon \sigma T_{eq}^4 = (1 - A) S \left(\frac{R}{1\mathrm{AU}}\right)^{-2} \cos i, \qquad (2)$$

where $\varepsilon$ is the emissivity, $\sigma$ is the Stefan-Boltzmann constant, $A$ is the albedo, $S$ is the solar constant, and $R$ is the distance of Ryugu from the Sun. If this region, or HS1 boulders, directly faced the Sun ($i = 0°$), $T_{eq} = 357$ K is estimated, whereas $T_{eq} = 349$ K for $i = 24°$. The effect of the solar illumination angle is therefore 8 K at a maximum and decreases when $\Gamma > 0$ tiu. The offset of 8 K in the simulation leads to higher TI of 130 tiu for the HS1 boulders, although this is an overestimate.

Furthermore, crater ID126 is not resolved in the global shape model and its detailed topography including the crater depth is unknown, so that the self-heating by the crater topography acts as an error source. To evaluate this effect, we performed thermal calculation without the self-heating using the local DEM of the SCI crater (Supplementary Fig. 2a). A differential image between the simulations with and without the self-heating shows that there are some regions with very strong self-heating effect up to by 50 K. However, they correspond to the bases of boulders or low temperature regions where direct solar energy input is relatively low. On the floor of the crater, the temperature enhancement by the self-heating is about 10-15 K, but local enhancement of the central temperature does not appear. If the hot spots were due to self-heating effect and had similar thermal inertia to others in the craters, we expect that other boulders (and regolith) have the temperatures as high as the hot spots. But this is not the case from the TIR observations. Therefore, the hot spots should have lower thermal inertia than others. We should also note that the SCI crater has a depth-to-diameter ratio about 0.15[9], which is higher than small (< 20 m) natural craters on Ryugu (< 0.09)[17]. The self-heating is more effective for craters with higher depth-to-diameter ratio, so that the effect of the self-heating of the natural craters including ID69 and ID126 is lower than that of the SCI crater. In fact, the similar evaluation of the self-heating for ID69 craters (Supplementary Fig. 2b) showed that the self-heating contribution is about 5 K, which is less than observed temperature enhancement for the HS1 and HS2 hot spots (10 K and 20 K, respectively). Therefore, it is difficult to reproduce the hot spots by the self-heating effect of the crater topography.

Surface roughness, whose typical scale is smaller than the facet sizes and TIR pixel resolution, reduces the apparent temperature of low-latitude regions[13]. The flat diurnal temperature profiles of Ryugu's surface[5] can be explained by a randomly rough surface model[35], which produces the lower temperature around noon and higher temperatures around dawn and dusk regions at low latitudes than the flat surface model[13]. Small shadows can be seen in the highest-resolution ONC image of HS1 (Fig. 1f), which reduce the apparent temperature. Thus, in contrast with the solar illumination condition and crater-related self-heating effect discussed above, TI values estimated using the model that does not account for roughness are upper limits. Similarly, high TI values are expected when using images with high solar phase angles and high emission angles. In fact, images in the TD1-R1A and TD1-L08E1 sequences yield higher TI for HS1 than TD1-R3. Nevertheless, the apparent TIs are less than 136 tiu (see Supplementary Information and Supplementary Fig. 3). Because the temperatures of the hot spots are effectively higher than the other randomly selected boulders with various solar incident angles and HS1 and HS2 are seen as hot spots in all of the TIR data obtained with different solar illumination and viewing geometries (Extended Data Figs. 2), the TI of HS1 and HS2 is expected to be significantly lower than the other boulders.

### ***Porosity from thermal inertia***

The thermal inertia $\Gamma$ is related to thermal conductivity and porosity according to:

$$\Gamma = \sqrt{k\rho_s(1-\phi)c}, \qquad (3)$$

where $k$ is thermal conductivity, $\phi$ is boulder porosity, $\rho_s$ is the material grain density, and $c$ is specific heat. Two empirical models were proposed for the relationship between $k$ and $\phi$ on Ryugu based on the $k$ data for chondritic meteorites[4]. Recent experimental studies using analogous porous rocks[36,37] and analytical studies of Ryugu's macroporosity[38] prefer the empirical model described as[4,39]:

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

(solid curve in Extended Data Fig. 7a). With a grain density[38] of $\rho_s = 2751$ kg m$^{-3}$ and specific heat[40] as a function of the observed temperature $T$,

$$c(T) = -23.173 + 2.127T + 1.5009 \cdot 10^2 T^2 - 7.3699 \cdot 10^{-5} T^3 + 9.6552 \cdot 10^{-8} T^4, \tag{5}$$

we calculated $\phi$ from the TI data. The resulting porosities are $86.3^{+4.3}_{-4.2}\%$ and $90.0^{+9.2}_{-8.4}\%$ for the hot spots of HS1 ($\Gamma = 73 \pm 25$ tiu) and HS2 ($\Gamma = 53 \pm 49$ tiu), respectively.

However, we note that the porosities of the measured meteorites and analogues are less than 50%, thus the estimated porosities are extrapolated values. Alternatively, micrometre-sized $SiO_2$ grain aggregates[41] cover a higher porosity range (40%–90%). An preferred empirical relation between thermal conductivity and porosity is given as[42]:

$$k = 3.3[\exp(-50\phi) + \exp(-4.4 - 23.5\phi)]^{1/4}, \tag{6}$$

(dashed curve in Extended Data Fig. 7a). Applying this equation to the thermal conductivity, we derived porosities of $78.3^{+7.2}_{-5.9}\%$ and $84.2^{+15.6}_{-12.5}\%$ for HS1 and HS2, respectively. Compression tests on the aggregates[43] showed that the highest porosity aggregate ($\phi = 85\%$) is mechanically stable with a uniaxial compressional strength of approximately 500 Pa. Such fluffy aggregates might be also possible candidates of the hot spot materials on Ryugu as a remnant of the less-processed near-surface layer of planetesimals. We note that the thermal conductivity of dust aggregates[41] will be lower than that of rocks with the same porosity, because of the higher cohesion of the consolidated rock, with the grains likely held together by some sort of cement or sintered neck rather than just electrostatic forces alone. The enhanced grain-to-grain heat exchange hence increases thermal conductivity in consolidated rocks. Therefore, the porosities from this empirical equation may be underestimated. To derive an accurate porosity-conductivity relationship for the highly-porous consolidated materials, measurements of thermophysical properties for the extremely porous and consolidated materials will be required by experimental studies.

Extended Data Fig. 7c shows a histogram of the boulder porosity based on this equation, which indicates that boulders with a porosity between 30% and 60% are dominant and small fractions of higher and lower porosity materials exist on Ryugu.

### ***ONC-T spectral analysis***

ONC-T multi-band imaging was conducted during the descent operations from an altitude of approximately 500 m, according to the pre-registered timeline sequence. The acquired digital images were calibrated into radiance factors[44]. A photometric correction using the Ryugu photometric model[45] yielded the reflectance factor in the standard geometric condition with solar incident, emission and phase angles of 30°, 0° and 30°, respectively (left panels in Extended Data Fig. 6). We used the SPC-based shape model and LIDAR-derived trajectory, as in the case for the TIR data analysis. Note that the shape model resolution is substantially lower than the image resolution. We selected the boulder with the facet towards cameras to avoid errors introduced by the photometric correction. The spectral slope from the v-band (0.55 µm in wavelength) to x-band (0.86 µm) is defined as:

$$S_{vx} = \frac{1 - R_x/R_v}{\lambda_v - \lambda_x}, \qquad (7)$$

where $R_v$ and $R_x$ are the reflectance factors and $\lambda_v$ and $\lambda_x$ are the effective wavelengths for the v-band and x-band, respectively. Owing to the delay induced by rotating the filter wheel in the multi-band images, the field-of-view (FOV) of ONC-T slightly drifts, which results in a small overlap between different band images. The regions with spectral information are thus limited, and the spectral information of some boulders and regolith cannot be measured (right panels in Extended Data Fig. 6).

We used multi-band images acquired during the descent sequence in TD1-R3 for regions A and B, whereas no high-resolution multi-band data with boulder resolution were available for regions D and F. An image set of region C was obtained during the TD1-L08E1 operation on 21 February 2019 (Extended Data Fig. 6c). Multi-band images were acquired for region E, including the ID126 crater, during the ascent phase of TD1-R3 at an altitude of approximately 230 m (Extended Data

Fig. 6e). Unfortunately, the v-band image did not cover the ID126 crater; thus, b-band (0.48 μm) and x-band images were used for the spectral analysis of region E and b-to-x slope is used rather than v-to-x slope. This is reasonable because Ryugu's visible spectra are featureless from the b-band to x-band, including the v-band[6].

Visible spectral shape changes (e.g., object size with respect to the FOV) are a known issue and depend on the spacecraft altitude[20]. Objects appear redder at low altitude and attribute the broad element of the scattering function[44], which is enhanced at lower altitudes and longer and shorter wavelengths. To correct the observation altitude difference between regions A, B, C, E and ID69, we factored those regional spectra to match with the same regional spectra observed in Box-A obtained on 10 July 2018 at an altitude of 20 km. The offsets in the v-x slopes range from 0.08 to 0.13 $\mu m^{-1}$ depending on the regions, and the corrected v-x slope values are shown in Figs. 4b, 4d and Extended Data Fig. 6.

### *NIRS3 spectral analysis*

We use calibrated NIRS3 reflectance spectra acquired on 31 October 2018 to spectrally characterize the ID69 crater where one hot spot was detected. The observation resolution for the six extracted spectra is ~8 m/pixel, which is close to the diameter size of the crater but larger than the identified hot spot HS2. We also extracted 14 spectra acquired on the same observation day under the same conditions in the crater vicinity to compare the spectral properties between the hot spot and crater surroundings. Other NIRS3 observations with sufficiently high resolution are not available for the characterization of this small hot spot. The crater where HS1 was detected cannot be characterized in the near-infrared because it is too small and no high-resolution NIRS3 observations of this crater are available. The successive calibration steps to convert the raw data to reflectance are detailed in previous studies[22,46]. The reflectance factor is corrected to the standard viewing geometry with incidence, emergence and phase angles of 30°, 0° and 30°, respectively.

We computed an average spectrum for the hot spot using the spectra that fall on the crater (blue boxes in Fig. 2c) and an average spectrum for the hot spot vicinity using the spectra that fall just outside of the ID69 crater (orange boxes in Fig. 2c). We computed error bars on the average spectra by evaluating the standard deviation amongst the spectra on and off of the hot spot. Very slight differences are observed in the spectra between those that include or exclude the hot spot. To highlight the potential subtle spectral differences, we normalized the average spectra of the hot spot with the average spectra in the crater vicinity. The error bars on the normalized spectrum are calculated from the law of propagation of error:

$$\frac{(\bar{R}_{on} \pm \sigma_{on})}{(\bar{R}_{off} \pm \sigma_{off})} = \frac{\bar{R}_{on}}{\bar{R}_{off}} \pm \sqrt{\left(\frac{\sigma_{on}}{\bar{R}_{off}}\right)^2 + \left(\frac{\bar{R}_{on}}{\bar{R}_{off}^2}\sigma_{off}\right)^2}, \qquad (8)$$

where $\bar{R}_{on}$ is the average spectra on the ID69 crater including the hot spot, $\bar{R}_{off}$ corresponds to the surrounding area off of the hot spot, and $\sigma_{on}$ and $\sigma_{off}$ are the corresponding standard deviations, respectively. The ratioed spectra are shown in Fig. 2d. We were able to highlight an increase of band depth at 2.72 μm of a few percent for the spectra on the hot spot. An increase of the absorption strength at 2.72 μm has been observed in numerous craters and might be globally attributed to similar material to the hot spot, which is too small to be resolved in the TIR images[47].

For comparison, we performed the same analysis on the ID46 crater. We used the calibrated NIRS3 spectra acquired on 30 October 2018 with a resolution of 12 m/pixel, which is smaller than the crater size. We extracted nine spectra inside the crater, where no hot spot has been detected with thermal and visible images, and 47 spectra outside of the crater that were acquired on the same day to perform a spectral comparison. We used these observations for comparison with the ID69 crater because they were acquired at similar times and with similar footprints. In Extended Data Fig. 4d, we show the spectral ratio of the average spectra inside the crater by the average spectra outside of the ID46 crater. With spectra of similar resolution for this crater, we do not observe the same trend as in the ID69 crater. Specifically, no significant increase of the absorption feature at 2.72 μm is observed.

### ***Possible origins of the highly-porous consolidated materials***

There are several possibilities to explain the formation of consolidated materials with extremely high porosity of the hot spots ($\phi > 70\%$). Thermal fatigue (fracturing by thermal cycling)[27] is a potential mechanism to enhance the rock's porosity. In this case, however, since most of the boulders at least adjacent to HS1 and HS2 should have experienced a similar thermal cycling, the very limited number of the hot spots on Ryugu cannot be explained. A highly porous structure that was attributed to the removal of water-ice that once filled pore space was identified in a carbonaceous chondrite Acfer 094[48]. But, its porosity is approximately 40%, less than that of hot spots. Because the SCI crater does not show any hot spot, a single cratering event, or impact, is unlikely. On the other hand, the Ryugu's materials have experienced many precursor impact processes including the micrometeorite impacts, the more energetic catastrophic disruption of the parent body, and impacts of S-type materials[20]. During these numerous impact processes, brecciation of the materials may occur and somewhat enhance the porosity. In fact, many boulders on Ryugu's surface showed the morphological features consistent with breccia[6] and most of the carbonaceous chondrites show brecciated structures[49]. However, it is unknown if highly porous breccia can be formed during these energetic impacts, because we do not have natural brecciated samples, including the chondritic meteorites and lunar brecciated rocks, with such a high porosity[50–52].

Although all of these potential processes might contribute partially to the high porosity observed, the dust aggregation process through slow velocity impacts of dusts and/or pebbles in the early solar nebula is predicted to result in such highly porous materials[2,26]. The consolidation of the dust aggregates would occur during the thermal evolution of the parent body (see below). In any case, the highly porous materials should have experienced a different history from the other abundant materials on Ryugu.

### *Thermal evolution of the parent body*

The porous nature of the boulders on Ryugu would have originated from some partial compaction processes of an initially porous and unconsolidated planetesimal, in which highly porous materials (porosity > 60%) like the hot spots, intermediately porous materials (30% < porosity < 60%) like the common boulders on Ryugu and compact materials (porosity < 30%) like the cold spots formed. All of the boulders would need to be partially consolidated in the planetesimal to survive after the catastrophic disruption. The main consolidation mechanism would be hot pressing, i.e., sintering and creep processes of dust grains in the planetesimals, which strongly depend on temperature and pressure. Additional cementation process would be caused by the mineral dissolution and reprecipitation onto the necks between grains. We investigated the thermal evolution of porous planetesimals by applying the methodology by Neumann et al.[29] (see also Neumann and Kruse[53] and Neumann et al.[54] for model applications to water-rich objects).

We simulated the thermal history and resulting final porosity distribution in the planetesimals to find a parent body that reproduces the porosity population measured on Ryugu (Extended Data Fig. 7c) by solving the one-dimensional heat conduction equation. A homogeneous initial porosity of 90% is assumed, while Neumann et al.[29] investigated the evolution of planetesimals with an initial porosity ranging from 50% to 80%. The other assumed parameters are exactly the same as those in Neumann et al.[29] The initial composition is olivine and water ice with mass fractions of 80% and 20%, respectively. Hydration of a part of the olivine is assumed after reaching 274 K (melting point of ice) as a quasi-instantaneous process that results in a serpentine fraction of 84%. The compaction of a two-component mixture of serpentine and olivine is simulated according to theoretical and experimental results of hot pressing. The porosity $\phi$ is calculated as:

$$\frac{\partial \log(1-\phi)}{\partial t} = \dot{\varepsilon} = \nu_{se}\dot{\varepsilon}_{se} + \nu_{ol}\dot{\varepsilon}_{ol}, \qquad (9)$$

with bulk strain rate $\dot{\varepsilon}$ and volume fraction $\nu_{se}$ and $\nu_{ol}$ and strain rates $\dot{\varepsilon}_{se}$ and $\dot{\varepsilon}_{ol}$ of serpentine and olivine, respectively. The strain rates are given by creep laws for minerals involved. For serpentine[55]:

$$\dot{\varepsilon}_{se} = \exp(\alpha\chi)\, 4 \cdot 10^{-22}\sigma^{2} \exp\left(-\frac{27}{RT}\left(1-\frac{\sigma}{2.7\cdot 10^{9}}\right)\right), \qquad (10)$$

with an effective stress $\sigma$ in Pa, gas constant $R = 0.008314$ kJ K$^{-1}$mol$^{-1}$, and temperature $T$. For olivine[56],

$$\dot{\varepsilon}_{ol} = \exp(\alpha\chi)\, 1.26 \cdot 10^{-18}\sigma^{1.5} b^{-1.4} \exp\left(-\frac{356}{RT}\right), \qquad (11)$$

with a particle grain diameter $b = 1$ μm (typical for matrix grain sizes of CI and CM chondrites[57,58]). The exponential term exp(αχ) accounts for the enhancement of the strain rate in presence of liquid water (this approach is analogous to the strain rate enhancement in presence of silicate melt[59]). Here, $\alpha = 26$ is an empirical constant and $\chi = 0.1$ is the free water volume fraction assumed after the melting of a CM like initial ice volume fraction of 0.2 in the initial ice-dust mixture and consumption of a half of the water for the silicate hydration. Thermal conductivity is given as an exponential function of porosity, in which the compaction by hot pressing enhances the thermal conductivity.

Extended Data Figs. 8a–d show examples of the potential parent body with a reference radius (determined from the total mass assuming zero porosity) of $R$ = 2–5 km and accretion time of $t_0 = 2.2$ Myr after CAI (calcium-aluminum-rich inclusions) formation. The final porosity fraction (right panels for each result) for $R = 3$ km (Extended Data Fig. 8b) is most consistent with that of the boulders on Ryugu, i.e., high abundance of boulders with porosities between 30% and 60% and small fraction of higher and lower porosities, corresponding to the hot and cold spots, respectively. Furthermore, the peak temperatures of the abundant materials ($30\% < \phi < 60\%$, left panels in Extended Data Fig. 8) range from 600 to 800 K, which is consistent with the estimated hydration temperature range (573–973 K) from the hydroxyl-band features in the SCI crater, as well as on the global scale[23], and are mostly homogeneous (~800 K), which is consistent with the globally uniform visible and infrared spectra on Ryugu[6,22]. The materials with $\phi > 60\%$, including the hot spots, would have experienced lower temperatures and were less dehydrated. Indeed, the near-infrared observation of the ID69 crater, where HS2 is located near the centre, shows a slightly stronger hydroxyl-band absorption than the surroundings by a few percent (Fig. 2d). This deeper absorption can be explained as the freshness of the ID69 crater to have avoided the solar radiative heating in the past, but this absorption feature might be partially attributed to the less dehydrated nature of HS2 resulted from the low peak temperature in the parent body. Because the NIRS3 spot sizes (~8 m) are larger than the HS2 size (~ 3 m), the observed spectra are the mixture of those of the hot spot and its surroundings. The strong hydroxyl-band absorption would therefore be somewhat weakened for the hot spot.

On the other hand, numerical and observational studies on planetary growth suggest the formation of larger planetesimals of typically 100-km size[1,60,61]. The larger bodies (e.g., 20–100 km) might also allow porous materials to form in the near-surface layer as the origin of Ryugu's boulders. However, those bodies would be dominated by low-porosity material with $\phi < 60\%$ (Extended Data Figs. 8e–j) and produce a very small fraction of higher-porosity consolidated materials. Because of the depleted radioactive heat source, bodies that accreted at a later time, e.g., $t_0 \geq 3$ Myr, had overall peak temperatures of $\leq 500$ K ($R = 20$ km) and $\leq$ 600 K ($R = 100$ km), which are lower than the hydration temperature of the Ryugu material[23]. Large parent bodies would be therefore unlikely to produce the boulder porosity distribution found on Ryugu. It should be noted that the preferred parent body with $R = 3$ km and $t_0 = 2.2$ Myr would not be a unique solution to produce Ryugu’s boulder porosity distribution because the calculation results strongly depend on the many parameters, including initial porosity (here 90%) and composition.

## Data availability

All images and essential data used in this study are available at the JAXA Data Archives and Transmission System (DARTS) at http://www.darts.isas.jaxa.jp/pub/hayabusa2/paper/Sakatani_2021. The other data that support the plots within this paper are available from the corresponding author upon reasonable request.

## Additional References

30. Takita, J., Senshu, H. & Tanaka, S. Feasibility and accuracy of thermophysical estimation of asteroid 162173 Ryugu (1999 JU3) from the Hayabusa2 thermal infrared imager. *Space Sci. Rev.* **208**, 287–315 (2017).
31. Ishiguro, M. *et al.* Optical properties of (162173) 1999 JU3: In preparation for the JAXA Hayabusa 2 sample return mission. *Astrophys. J.* **792**, 74 (2014).
32. Vasavada, A. R. *et al.* Lunar equatorial surface temperatures and regolith properties from the Diviner Lunar Radiometer Experiment. *J. Geophys. Res. E Planets* **117**, E00H18 (2012).
33. Miura, A., Sakatani, N., Yokota, Y. & Honda, R. A study on methods of generating asteroid shape models. *J. Sp. Sci. Informatics Japan* **9**, 33–44 (2020).
34. Matsumoto, K. *et al.* Improving Hayabusa2 trajectory by combining LIDAR data and a shape model. *Icarus* **338**, 113574 (2020).
35. Senshu, H. *et al.* Numerical simulation on the thermal moment from Ryugu-like rough surface asteroid. In *51st Lunar and Planet. Sci. Conf.* abstr, 1990 (2020).
36. Hamm, M. *et al.* Thermal conductivity and porosity of Ryugu's boulders from in-situ measurements of MARA - the MASCOT Radiometer. In *50th Lunar and Planet. Sci. Conf.* abstr, 1373 (2019).
37. Avdellidou, C. *et al.* Very weak carbonaceous asteroid simulants I: Mechanical properties and response to hypervelocity impacts. *Icarus* **341**, 113648 (2020).
38. Grott, M. *et al.* Macroporosity and grain density of rubble pile asteroid (162173) Ryugu. *J. Geophys. Res. Planets* **125**, e2020JE006519 (2020).
39. Flynn, G. J., Consolmagno, G. J., Brown, P. & Macke, R. J. Physical properties of the stone meteorites: Implications for the properties of their parent bodies. *Chemie der Erde* **78**, 269–298 (2018).
40. Wada, K. *et al.* Asteroid Ryugu before the Hayabusa2 encounter. *Prog. Earth Planet. Sci.* **5**, 82 (2018).
41. Krause, M., Blum, J., Skorov, Y. V. & Trieloff, M. Thermal conductivity measurements of porous dust aggregates: I. Technique, model and first results. *Icarus* **214**, 286–296 (2011).
42. Krause, M. *et al.* Modeling the early thermal evolution of meteorite parent bodies based on new thermal conductivity measurements of highly porous aggregates. In *42nd Lunar and Planet. Sci. Conf.* abstr, 2696 (2011).

43. Blum, J. & Schräpler, R. Structure and mechanical properties of high-porosity macroscopic agglomerates formed by random ballistic deposition. *Phys. Rev. Lett.* **93**, 115503 (2004).

44. Tatsumi, E. *et al.* Updated inflight calibration of Hayabusa2's optical navigation camera (ONC) for scientific observations during the cruise phase. *Icarus* **325**, 153–195 (2019).

45. Tatsumi, E. *et al.* Global photometric properties of (162173) Ryugu. *Astron. Astrophys.* **639**, A83 (2020).

46. Iwata, T. *et al.* NIRS3: The Near Infrared Spectrometer on Hayabusa2. *Space Sci. Rev.* **208**, 317–337 (2017).

47. Riu, L. *et al.* Spectral characterization of the craters of Ryugu as observed by the NIRS3 instrument on-board Hayabusa2. *Icarus* **357**, 114253 (2021).

48. Matsumoto, M. *et al.* Discovery of fossil asteroidal ice in primitive meteorite Acfer 094. *Sci. Adv.* **5**, eaax5078 (2019).

49. Bischoff, A., Scott, E. R. D., Metzler, K. & Goodrich, C. A. Nature and origins of meteoritic breccias. in *Meteorites and the Early Solar System II* 679–712 (2006).

50. Consolmagno, G. J., Britt, D. T. & Macke, R. J. The significance of meteorite density and porosity. *Chemie der Erde* **68**, 1–29 (2008).

51. Macke, R. J., Consolmagno, G. J. & Britt, D. T. Density, porosity, and magnetic susceptibility of carbonaceous chondrites. *Meteorit. Planet. Sci.* **46**, 1842–1862 (2011).

52. Kiefer, W. S., MacKe, R. J., Britt, D. T., Irving, A. J. & Consolmagno, G. J. The density and porosity of lunar rocks. *Geophys. Res. Lett.* **39**, 1–5 (2012).

53. Neumann, W. & Kruse, A. Differentiation of Enceladus and retention of a porous core. *Astrophys. J.* **882**, 47 (2019).

54. Neumann, W., Jaumann, R., Castillo-Rogez, J., Raymond, C. A. & Russell, C. T. Ceres' partial differentiation: undifferentiated crust mixing with a water-rich mantle. *Astron. Astrophys.* **633**, A117 (2020).

55. Amiguet, E. *et al.* Creep of phyllosilicates at the onset of plate tectonics. *Earth Planet. Sci. Lett.* **345–348**, 142–150 (2012).

56. Schwenn, M. B. & Goetze, C. Creep of olivine during hot-pressing. *Tectonophysics* **48**, 41–60 (1978).

57. Cloutis, E. A., Hiroi, T., Gaffey, M. J., Alexander, C. M. O. D. & Mann, P. Spectral reflectance properties of carbonaceous chondrites: 1. CI chondrites. *Icarus* **212**, 180–209 (2011).

58. Cloutis, E. A., Hudon, P., Hiroi, T., Gaffey, M. J. & Mann, P. Spectral reflectance properties of carbonaceous chondrites: 2. CM chondrites. *Icarus* **216**, 309–346 (2011).

59. Mei, S., Bai, W., Hiraga, T. & Kohlstedt, D. L. Influence of melt on the creep behavior of olivine-basalt aggregates under hydrous conditions. *Earth Planet. Sci. Lett.* **201**, 491–507 (2002).

60. Klahr, H. & Schreiber, A. Turbulence sets the length scale for planetesimal formation: Local 2D simulations of streaming instability and planetesimal formation. *Astrophys. J.* **901**, 54 (2020).

61. Klahr, H. & Schreiber, A. Testing the Jeans, Toomre and Bonnor-Ebert concepts for planetesimal formation: 3D streaming instability simulations of diffusion regulated formation of planetesimals. Preprint at https://arxiv.org/abs/2011.07849 (2020).

62. Opeil, C. P., Consolmagno, G. J., Safarik, D. J. & Britt, D. T. Stony meteorite thermal properties and their relationship with meteorite chemical and physical states. *Meteorit. Planet. Sci.* **47**, 319–329 (2012).

63. Hamm, M., Pelivan, I., Grott, M. & de Wiljes, J. Thermophysical modelling and parameter estimation of small solar system bodies via data assimilation. *Mon. Not. R. Astron. Soc.* **496**, 2776–2785 (2020).