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1 **Fine-regolith production on asteroids controlled by rock porosity**

2

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17

18 **Spacecraft missions observed regolith blankets consisting of unconsolidated sub-centimetre**
19 **particles on stony asteroids¹⁻³. Telescopic data suggested regolith blankets to be present**
20 **also on carbonaceous asteroids, including (101955) Bennu⁴ and (162173) Ryugu⁵. However,**
21 **despite observations of processes capable of comminuting boulders into unconsolidated**
22 **materials, such as meteoroid bombardment^{6,7} and thermal cracking⁸, Bennu and Ryugu**
23 **lack extensive areas covered in sub-centimetre particles^{9,7}. Here we report an inverse**

24 **correlation between the local abundance of sub-centimetre particles and the porosity of**
25 **rocks on Bennu. We interpret this finding to mean that accumulation of unconsolidated**
26 **sub-centimetre particles is frustrated where the rocks are highly porous, which appears to**
27 **be most of the surface¹⁰: these rocks are compressed rather than fragmented by meteoroid**
28 **impacts, consistent with laboratory experiments^{11,12}, and thermal cracking proceeds more**
29 **slowly than in denser rocks. We infer that regolith blankets are uncommon on**
30 **carbonaceous asteroids, which are the most numerous of all asteroid types¹³. By contrast,**
31 **these terrains should be common on stony asteroids, which have less porous rocks and are**
32 **the second-most populous group by composition¹³. The higher porosity of carbonaceous**
33 **asteroid materials may have aided in their compaction and cementation to form breccias,**
34 **which dominate the carbonaceous chondrite meteorites¹⁴.**

35

36 Between April and June 2019, the Origins, Spectral Interpretation, Resource Identification, and
37 Security-Regolith Explorer (OSIRIS-REx) Thermal Emission Spectrometer¹⁵ (OTES) measured
38 thermal infrared emission spectra from Bennu's surface at different local times of day. These
39 spectra are a function of surface temperatures, which vary throughout the day and night
40 differently depending on surface roughness and thermal inertia. Roughness (θ) is due to surface
41 irregularities that are not resolved in global topography but still affect temperatures due to
42 shadows and self-heating¹⁶. Thermal inertia (Γ) measures materials' resistance to temperature
43 change; it is determined by thermal conductivity κ , heat capacity c_p , and bulk density ρ
44 ($\Gamma=[\kappa c_p \rho]^{1/2}$), and allows distinguishing different geological units, such as fine regolith from
45 rocks.

46

47 Here fine regolith means unconsolidated particles of size smaller than the e-folding depth of the
48 diurnal thermal wave (l_s , a few centimetres on Bennu¹⁰), while rocks are defined as every
49 competent surface material of size $D_R > l_s$. The thermal inertia of fine regolith (Γ_P) is lower than
50 that of rocks of same composition (Γ_R) because radiative thermal conduction between particles is
51 less efficient than phononic heat transfer within an individual particle or rock¹⁶. Thus, fine
52 regolith is hotter than rocks during the day, and vice versa during the night. Both fine regolith
53 and rocks contribute to the infrared emission proportionally to their surface abundances α and
54 $(1-\alpha)$, respectively¹⁷.

55

56 To distinguish fine regolith from rocks on Bennu, we use a machine learning method¹⁷ that
57 explores all possible combinations of the spectral signals of fine regolith and rocks as a function
58 of their surface abundance, roughness and respective thermal inertia until the OTEs daytime and
59 night-time observations are simultaneously fitted (Methods). We use our method to derive Γ_P ,
60 Γ_R , and α in 122 quasi-randomly-distributed OTEs footprints (spots) of ~ 40 m in diameter
61 (Supplementary Table 1; Extended Data Figure 1). These spots include the two best-observed
62 areas on Bennu: the designated backup and primary sampling sites of OSIRIS-REx, respectively
63 called Osprey and Nightingale.

64

65 We find that α varies between a few and several tens of percent (Figure 1) and there is less fine
66 regolith at Osprey than at Nightingale, consistent with the surface abundance of unresolved
67 materials seen in PolyCam images (Extended Data Figure 2). The values of α are also consistent
68 with the surface abundance of unresolved materials in PolyCam images at coarser spatial
69 resolution (Methods; Extended Data Figure 3). The measured Γ_R encompasses a continuum of

70 values between $\sim 250 \text{ Jm}^{-2}\text{K}^{-1}\text{s}^{-0.5}$, close to that derived^{18,19} for Ryugu's boulders, and $>1,000$
71 $\text{Jm}^{-2}\text{K}^{-1}\text{s}^{-0.5}$, close to that of CM2 carbonaceous chondrites²⁰ of composition analogous to the
72 one spectroscopically inferred for Bennu²¹. For $\alpha \approx 0$, Γ_R is within the range of thermal inertia
73 values derived by a previous study¹⁰, which assumed that the surface in the OTES spot is
74 composed of a single geological unit.

75

76 We observe a direct correlation between Γ_R and α (Figure 1), with Spearman correlation
77 coefficient $R=0.56 \pm 0.06$ and a probability of non-correlation $p < 4 \times 10^{-3}$ (Methods; Extended Data
78 Figure 4). The correlation is robust ($R=0.54 \pm 0.07$; $p < 0.05$) when we reject spots where the
79 thermophysical model may confuse very low- Γ_R boulders as fine-regolith-covered areas
80 (Methods; Figure 1). The correlation is also robust against the choice of a model parameter that
81 represents the fine-regolith macroporosity (Methods; Extended Data Figure 5). Additionally, we
82 demonstrate that the correlation is not an artefact of thermophysical modelling (Methods;
83 Extended Data Figure 6). Finally, we do not see an inverse correlation between α and the size of
84 the largest boulders in the OTES spots (Methods; Extended Data Figure 7), thus ruling out that
85 the Γ_R - α correlation is due to boulders' sizes (large boulders may have lower Γ_R than smaller
86 ones¹⁰).

87

88 Because fine regolith is more abundant where rocks have higher Γ_R (Figure 1), and Γ_R is a
89 monotonically decreasing¹⁹ function of rock porosity (Methods), we deduce that the surface
90 abundance of fine regolith is lower where the nearby rocks are more porous (Figure 1).

91

92 We argue that the correlation of Figure 1 can be explained by the dependence of regolith-
93 forming processes, i.e., collisional and thermal fragmentation of rocks, on rock porosity.

94

95 Collisional fragmentation is driven by meteoroid impacts, craters from which were observed⁶ on
96 $D_R \gg 1_s$ rocks. Craters on rough-textured rocks were measured, by means of the OSIRIS-REx
97 Laser Altimeter, to have a higher depth-to-diameter ratio than those on smoother rocks⁶. Because
98 crater depth-to-diameter ratio typically increases with increasing target porosity^{11,22}, we deduce
99 that Bennu hosts rocks of different porosities, consistent with Figure 1 and ref. 10, but
100 independently of OTEs data. Impact experiments show that: (i) a lower-porosity rock requires a
101 lower energy per unit mass to be broken than a higher-porosity rock, because in the latter impact
102 energy is spent on pore-space collapse¹¹ and compaction¹² during initial crater formation; (ii)
103 crater ejecta's mass, which could partially contribute to fine regolith, decreases with increasing
104 target porosity¹¹; and (iii) craters formed on low-porosity ($\Phi \approx 25\%$) rock simulants of Bennu's
105 composition have spalls²³, which increase fragment production. Conversely, spalling was rarely
106 observed around craters on Bennu's rocks⁶. We deduce that collisional fragmentation increases
107 with decreasing rock porosity and is frustrated on Bennu's rocks, which typically have $\Phi > 25\%$
108 (Figure 2).

109

110 Asteroids' rocks can develop fatigue fractures to release mechanical stresses generated by diurnal
111 temperature cycling²⁴. It is postulated that these fractures grow until breaking the host rocks,
112 thereby producing regolith²⁴. Exfoliation fractures with sizes between a few centimetres and few
113 metres were observed⁸ on Bennu, consistent with the aforementioned process. To investigate
114 regolith formation by thermal fatigue, we model (Methods) the time to break two rocks on Bennu

115 that have porosity $\Phi=20\%$ and $\Phi=40\%$. We find that the break-up time is shorter for the rock
116 with $\Phi=20\%$ than for that with $\Phi=40\%$ (Extended Data Figure 8), suggesting that fine regolith is
117 more likely to be produced from the former. This is consistent with the correlation of Figure 1.

118

119 We infer that low-porosity rocks produce more fine regolith than high-porosity rocks by means
120 of both meteoroid impacts and thermal cracking (Figure 3). This explains the lack of extensive
121 fine-regolith-covered areas on Bennu⁹, where most rocks are highly porous (ref. 10; Figure 2).

122

123 We argue that the frustration of fine-regolith build-up in the presence of high-porosity rocks
124 could be a general phenomenon on asteroids.

125

126 Analysis of thermal images acquired by JAXA's Hayabusa2 mission^{18,25} indicated that Ryugu's
127 surface globally has $\Gamma \approx 225 \pm 45 \text{ Jm}^{-2}\text{K}^{-1}\text{s}^{-0.5}$, some $D_R > 50 \text{ m}$ boulders have $\Gamma_R \approx 115\text{--}160$
128 $\text{Jm}^{-2}\text{K}^{-1}\text{s}^{-0.5}$, and a few small boulders have $\Gamma_R \approx 600\text{--}1,000 \text{ Jm}^{-2}\text{K}^{-1}\text{s}^{-0.5}$, suggesting that most
129 rocks on Ryugu have porosities similar to Bennu's ($\Phi \approx 40\text{--}50\%$, Figure 2; Methods). For $\Phi \approx 40\text{--}$
130 50% , the correlation of Figure 1 indicates that Ryugu, like Bennu, should have less fine regolith
131 on the surface than asteroids with lower-porosity rocks.

132

133 Conversely, disk-integrated infrared measurements of the stony asteroid (25143) Itokawa
134 revealed¹⁷ that its rocks have $\Gamma_R \approx 900 \text{ Jm}^{-2}\text{K}^{-1}\text{s}^{-0.5}$, corresponding to $\Phi = 20 \pm 4\%$ (Methods), which
135 is lower than most rocks on Bennu and Ryugu (Figure 2). Hence, the correlation of Figure 1
136 implies that Itokawa's most common rocks produce more fine regolith than Bennu's and Ryugu's.
137 Spacecraft images show that Itokawa's geopotential lows are smooth terrains covered in

138 centimetre-sized regolith², whereas Bennu's and Ryugu's are not^{9,7}. Itokawa's smooth terrains
139 may have formed via global particle-size sorting induced by surface mass motion². Signatures of
140 mass motion were also observed on Bennu²⁶ and Ryugu⁷, but smooth fine-regolith-covered
141 terrains are lacking^{9,7}, suggesting that Bennu's and Ryugu's surface abundances of fine regolith
142 may be globally lower than Itokawa's. This is consistent with our analysis.

143

144 On small asteroids, fine regolith could be emplaced far from the source rock via electrostatic
145 lofting²⁷, ejection during thermal exfoliation⁸, and/or meteoroid impacts²². However, the
146 robustness of the Γ_R - α correlation rules out an isotropically fine-regolith redistribution from each
147 local source on Bennu. Further, (i) electrostatic lofting is inefficient at mobilizing centimetre-
148 sized particles²⁷; (ii) exfoliation is only one aspect of thermal cracking, the other being rock
149 breakup by through-going fracturing without fragment ejection; (iii) the current understanding²²
150 is that little mass should be retained by small asteroids from crater ejecta produced by impacts on
151 low-porosity rocks. However, rocks broken in tightly-clustered pieces were observed on Bennu
152 (Extended Data Figure 9; refs. 8, 9, and 28), suggesting that regolith is produced by in-situ
153 fragmentation of large rocks exposed on the surface, similar to what has been observed on the
154 Moon²⁹. Finally, Itokawa may lose more crater ejecta to space than Bennu and Ryugu because
155 average ejection velocities decrease with increasing target porosity²². Despite this, smooth
156 terrains were only observed on Itokawa^{2,7,9}, suggesting that its fine-regolith losses are
157 compensated by a higher production than Bennu's and Ryugu's.

158

159 The wide range of rock porosities measured on Bennu and Ryugu likely originated on their
160 parent bodies²⁵. We postulate that high-porosity rocks subjected to impacts can be compacted

161 without target disruption³⁰. Crushing in high-porosity materials can enhance shear strain and
162 cause associated frictional heating³¹; this may have assisted lithification of the chondrite
163 precursors into the lower-porosity carbonaceous breccias that dominate the CM and CI meteorite
164 collection¹⁴ and were also observed on Bennu²⁸ and Ryugu⁷.

165

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233

234 **Fig. 1. The thermal inertia of Bennu's rocks is positively correlated with the local surface**
235 **abundance of fine regolith.** The data points are grey-shaded in terms of Φ estimated from Γ_R
236 (Methods). The red points correspond to 13 areas where α could be overestimated because of the
237 presence¹⁰ of boulders whose Γ_R could be lower than the threshold value between fine regolith
238 and rocks (Methods). The plotted solutions have $\chi^2_r < 3$ as goodness-of-fit (Methods), which is
239 satisfactory for these types of observations. The error bars correspond to 1 standard deviation
240 (Supplementary Table 1; Methods) computed on ~670 samples on average.

241

242 **Fig. 2. The porosity of most of Bennu's and Ryugu's rocks is much higher than Itokawa's.**
243 The porosity values of Bennu's rocks are weighted according to rock abundance ($1-\alpha$) and are
244 binned using the Freedman-Diaconis rule. The magenta- and green-shaded areas indicate the
245 estimated surface-averaged ranges of rock porosity on asteroids Ryugu^{18,19} and Itokawa¹⁷,
246 respectively. About 70% of the rocks on Bennu are as porous as Ryugu's, while only ~5% of
247 Bennu's rocks have porosity similar to Itokawa's.

248

249 **Fig. 3. Fine-regolith production is frustrated in the presence of high-porosity rocks.** On
250 asteroids, rocks with higher porosity are compacted by meteoroid impacts rather than

251 excavated¹². Thermal stresses in a more porous rock are weaker in magnitude than in a denser
252 rock⁸, implying that the former could be less prone to producing fine regolith than the latter.

253

254 **Methods**

255 **Two-component thermophysical modelling**

256 The global mosaic of images³² acquired by the PolyCam imager of the OSIRIS-REx Camera
257 Suite (OCAMS³³) with resolution 5 cm pixel⁻¹ shows that Bennu's surface is composed of a
258 mixture of rocks and, to a lesser extent, unresolved materials^{28,34}. The latter may include fine
259 regolith with particle size $D_P < l_s = [\kappa / (c_p \rho) P / \pi]^{1/2}$, where P is the asteroid's rotation period. These
260 observations motivate us to determine the surface abundance of fine regolith (α) with respect to
261 the surface abundance ($1-\alpha$) of rocks with size $D_R > l_s$.

262

263 To this end, we select 122 quasi-randomly-distributed regions (OTES spots; Extended Data
264 Figure 1) and use a machine learning two-component thermophysical model¹⁷ to simultaneously
265 fit infrared radiance spectra emitted from the asteroid at the local times 3:20 a.m. and 3:00 p.m.
266 to derive the surface properties (θ , Γ_P , Γ_R , α). The 3:20 a.m. station is the coldest and farthest in
267 time from sunrise, when the brightness temperature of smaller rocks may approach that of colder
268 fine regolith; the 3:00 p.m. station is diametrically opposed to the 3:20 a.m. station, close to the
269 time of peak surface temperature, and not at the crossing point between diurnal temperature
270 curves for different Γ values, where the thermophysical solution could be degenerate (Figure 2 in
271 ref. 10). Furthermore, the spots on the surface for the 3:00 p.m. and 3:20 a.m. stations are well
272 aligned, which minimises mismodelling. Modelling 122 areas instead of the full surface makes
273 the machine-learning analysis computationally feasible while still investigating a representative

274 sample of Bennu's surface. Among the 122 spots, 100 are randomly selected and 22 were
275 manually added to be centred as much as possible on distinct, interesting and representative
276 geological features such as (i) the designated sampling sites; (ii) large boulders filling the OTES
277 spot; (iii) regions with high boulder abundance; and (iv) areas with low boulder abundance.

278

279 For each area and time of day, we use the OTES' acquisition mid-observation time and boresight
280 to calculate the longitude and latitude of the OTES spot's centre and diameter projected on
281 Bennu's surface. The surface is modelled using the 6-m-resolution SPC/OLA v34 shape model
282 composed of triangular facets and derived from a combination of stereophotoclinometry and
283 laser ranging³⁵; its pole orientation^{9,10} is J2000 ecliptic longitude 69.92° and latitude -83.45°. The
284 observation geometry for each spot and time of the day (i.e., ephemerides of the OSIRIS-REx
285 spacecraft and the asteroid) is computed using the spiceypy Python-wrapper for the SPICE
286 Toolkit. The kernel files are directly sourced from the SPICE kernels produced by the mission.
287 For each observation geometry, we build the local set of facets of Bennu's topographic model by
288 drawing concentric circles (with radius ranging between 0 and that of the OTES spot and centred
289 at the spot's centre) and by drawing radial vectors with origin in the spot's centre and length
290 between 0 and the spot's radius. Since we limited our survey to latitudes between $\pm 60^\circ$, each
291 OTES spot is well-approximated by a circle with a diameter of 40 m that corresponds to the
292 instrument footprint. All the unique facets that lie at the intersection between a circle and a radial
293 vector belong to the local set.

294

295 For each OTES spot and for each observation time, we set up thermophysical simulations using a
296 well-defined model¹⁶ that uses the aforementioned observation geometry, asteroid illumination,

297 asteroid spin state, and local sets of facets of Bennu's shape model as input. We create lookup
298 tables of simulations where Γ varies between 25 and 2,500 $\text{Jm}^{-2}\text{K}^{-1}\text{s}^{-0.5}$ (the upper limit
299 corresponding to low-porosity meteorites²⁰) with step 25 and θ is modelled using hemispherical
300 craters with surface crater density (f_c) ranging between 0 and 0.99 with step 0.14 (as such,
301 $\theta=49f_c^{1/2}$ represents roughness RMS slope¹⁰). We assume a fixed value of Bolometric Bond's
302 albedo equal to 0.02 and infrared emissivity $\epsilon=0.95$ (as previously done¹⁰). The shape model's
303 rotation and daily temperature cycle are simulated for 15 Julian days until the temperature cycle
304 converges to a stable cycle. After this, we output the simulated radiance at the epoch of the
305 OTES observation between 6 and 50 μm , where the OTES noise equivalent spectral radiance
306 (NESR, which represents the 1σ variation in calibrated radiance) is the lowest¹⁵.

307

308 Next, for each OTES spot and for each observation time, we use the aforementioned look-up
309 table of thermophysical simulations to train a neural network that generalizes the prediction of
310 the radiance as a function of Γ and θ . The step of training the neural networks and using them in
311 the fitting routine makes the exploration of the large, multi-dimensional parameter space of
312 solutions computationally possible. This approach is particularly potent for the case of Bennu as
313 both day-side and night-side data are available with a wide spectral wavelength range^{15,17}. The
314 70% of model radiances is used for training via stochastic gradient descent and a neural network
315 architecture with 1 hidden layer of 10 neurons, which is the optimal scheme¹⁷. Another 15% of
316 the dataset is used to protect the networks against overfitting the training data. We use the last
317 15% of the dataset to assess the networks' performance on unseen data in terms of mean squared
318 error between the predicted and target radiances. The networks generalise well the prediction of
319 the model radiances at testing: the average errors are equal to 0.2% and 0.9% of the radiance

320 peak value for $\Gamma=350 \text{ Jm}^{-2}\text{K}^{-1}\text{s}^{-0.5}$ and $\theta=43^\circ$ (which are the average surface thermophysical
 321 properties of Bennu¹⁰) for the 3:20 a.m. and 3:00 p.m. observations, respectively; the correlation
 322 coefficient between predicted and target radiances is >0.99 .

323

324 Next, we use the networks to simulate the radiance L_{regolith} emitted by fine regolith of thermal
 325 inertia Γ_P and that emitted by rocks of thermal inertia Γ_R (L_{rock}), and linearly combine them to
 326 model the radiance L_{model} emitted by a mixture of fine regolith and rocks:

$$327 \quad L_{\text{model}}[f_s, \theta, \Gamma_P, \Gamma_R, \alpha] = f_s \times (\alpha L_{\text{regolith}}[\Gamma_P, \theta] + (1-\alpha) L_{\text{rock}}[\Gamma_R, \theta]), \quad (1)$$

328 where f_s is an optional scaling factor which is adjusted during the model fit to account for small
 329 modelling errors caused by (unknown) inaccuracies in the topographic model and/or potential
 330 deficiencies of the surface roughness¹⁰. Γ_P can assume values between $25 \text{ Jm}^{-2}\text{K}^{-1}\text{s}^{-0.5}$ and Γ_c ,
 331 and Γ_R between Γ_c and $2,500 \text{ Jm}^{-2}\text{K}^{-1}\text{s}^{-0.5}$, where Γ_c is the thermal inertia “cut-off” value of
 332 regolith whose particles have $D_p=1_s$. It is computed as follows. For each area, we postulate that
 333 fine regolith is produced by the comminution of local rocks by meteoroid impacts³⁶ and thermal
 334 cracking²⁴. This implies that fine regolith particles inherit the thermal conductivity κ , grain
 335 density ρ_s , and porosity Φ of the rock. κ is obtained using the fit of meteorite values³⁷

$$336 \quad \kappa(\Phi) = \frac{\Gamma_R^2}{c_p \rho_s (1-\Phi)} = \frac{0.11(1-\Phi)}{\Phi} \quad (2)$$

337 where $\rho_s=2920 \text{ kg m}^{-3}$ for CM meteorites³⁸ and c_p is the heat capacity for the meteorite CM2
 338 Cold Bokkeveld²⁰ at the OTES spot's mean diurnal temperature¹⁰. Although alternative
 339 relationships of thermal conductivity versus rock porosity are available¹⁹, Eq. 2 is the model that
 340 also fits well more recent results for super-weak CM-like materials²³. Since Γ_R is a fitted
 341 parameter, the procedure for determining Γ_c is necessarily iterative; we initialise the iteration
 342 assuming Γ_R equal to the single-component thermal inertia derived by previous studies¹⁰. We use

343 a standard³⁹ regolith model to calculate particulate regolith bulk thermal conductivity (κ_p) as a
344 function of particle diameter D_p . These values are compared to respective values of $l_s=l_s(\kappa_p)$ to
345 find the value of κ_p where $D_p=l_s$. This value of κ_p is combined with c_p and $\rho=\rho_s \times (1-\Phi) \times (1-\phi)$ to
346 calculate Γ_c (ϕ is the regolith macroporosity, that is, the volume of voids between particles). We
347 use published¹⁰ model parameters and assume: $\zeta=0.68+7.6 \times 10^{-5} D_p^{-1}$ as the ratio of the effective
348 distance of radiative heat transfer in the voids between particles to the void geometric
349 size^{39,40}, $\xi=0.12$ as the degree of reduction of the thermal conductance at the contacts between
350 particles owing to the microscopic surface roughness³⁹, infrared emissivity¹⁰ $\varepsilon=0.95$, and regolith
351 macroporosity $\phi=40\%$. The latter is an often-used value and represents a loose random packing
352 of spherical particles⁴¹. We take into account thermal gradients within individual regolith
353 particles using the non-isothermal correction factor⁴¹ as in previous work¹⁰.

354

355 For a given Γ_c and assuming θ from published¹⁰ results, we explore all possible combinations of
356 the free parameters $x=(f_s^{3:00 \text{ p.m.}}, f_s^{3:20 \text{ a.m.}}, \Gamma_p, \Gamma_R, \alpha)$ to identify the best-fit radiance that
357 minimises the error function:

$$358 \chi_r^2 = \frac{1}{\text{obs-df}} \left(\sum_{\lambda=6}^{50 \mu\text{m}} \frac{[L_{\text{model}}^{3:00 \text{ p.m.}}(x, \lambda) - L_{\text{OTES}}^{3:00 \text{ p.m.}}(\lambda)]^2}{\sigma^2} + \sum_{\lambda=6}^{50 \mu\text{m}} \frac{[L_{\text{model}}^{3:20 \text{ a.m.}}(x, \lambda) - L_{\text{OTES}}^{3:20 \text{ a.m.}}(\lambda)]^2}{\sigma^2} \right) \quad (3)$$

359 where L_{OTES} is the observed radiance re-sampled with step $1 \mu\text{m}$, σ is the error measurement
360 equal to 3 times the OTES' pre-flight¹⁵ 772 Hz NESR, obs is the number of observations and
361 $\text{df}=5$ is the number of parameters to fit. The uncertainties of the free parameters are computed as
362 the standard deviation of the set of solutions whose $\chi_r^2 < \min(\chi_r^2) + [2/(\text{obs}-\text{df})]^{1/2}$, as typically
363 done in thermophysical modelling⁴². Upon completion of the fitting, the best-fit Γ_R is used to
364 update the value of Γ_c , which is in turn used to re-compute the best-fit $(f_s^{3:00 \text{ p.m.}}, f_s^{3:20 \text{ a.m.}}, \Gamma_p, \Gamma_R,$
365 $\alpha)$. This loop is repeated until $|\Gamma_R^i - \Gamma_R^{i-1}| < \sigma_R^{i-1}$, where (i) indicates the present iteration and σ_R^{i-1}

366 is the standard deviation of Γ_R obtained at the iteration (i-1)-th. Convergence is typically reached
367 in four iterations. Once the analysis is completed, we add a cautionary 10% relative error to the
368 uncertainties because previous studies¹⁰ found that the thermophysical solution obtained by
369 fitting the 3:00 p.m. and 3:20 a.m. data is within 10% of the value obtained by including
370 additional OTES data acquired at other times of the day.

371
372 Finally, we reject 25 spots where the best-fit solutions have $\chi_r^2 > 10$ and/or for which no
373 convergence is found for $\Gamma_R \leq 2490 \text{ Jm}^{-2}\text{K}^{-1}\text{s}^{-0.5}$. We carry the analysis and tests reported below
374 on the remaining 97 spots (Supplementary Table 1).

375

376 **Tests of the robustness of the results**

377 We test whether the measured α -values are consistent with the surface abundance of unresolved
378 materials seen in PolyCam³³ images. We do this test for the spots 609505286:610098718 and
379 609504794:610100730 centred at Osprey and at Nightingale, for which Burke et al. (ref. 43)
380 performed rock mapping down to $D_p = 2 \text{ cm} \lesssim l_s$ (results are in Extended Data Figure 2). We note
381 that the OTES spots have areas at least 38 and 20 times larger than those within which rocks
382 were visually mapped at Osprey and Nightingale, respectively.

383

384 We also test that the value of α is always smaller or equal than the surface area of unresolved
385 materials that we can visually see, at coarser spatial resolution than at Osprey and Nightingale,
386 within the entire OTES spot. We choose the spots 609493058:610103962 and
387 609487186:610098206 where we perform rock mapping as similarly done in ref. 43 on PolyCam
388 images at a spatial resolution of 5 cm pixel^{-1} (thus, $> l_s$). The area of each rock is computed as

389 that of a circle with diameter equal to the rock's longest dimension. One minus the sum of rocks'
390 areas divided by the area of the OTES spot is provided as % of unresolved material in Extended
391 Data Figure 3, along with the value of α . We also check that the size distributions of the mapped
392 rocks are consistent with that globally mapped on Bennu³⁴, meaning that the two sites are
393 representative of average Bennu.

394

395 We use the two-sided Spearman test to reject the null hypothesis that a random distribution of
396 Γ_R - and α -values could produce the observed correlation of Figure 1 (Extended Data Figure 4).
397 To take into account uncertainties in the values of Γ_R and α , we perform the Spearman test
398 10,000 times, where at each trial we vary Γ_R and α within their uncertainties. We draw the
399 samples from Gaussian distributions with mean and standard deviation equal to the nominal
400 value and uncertainties of Γ_R and α .

401

402 We repeat the Spearman test after we reject 13 areas where large dark boulders fill the OTES
403 spot (red data points in Figure 1). Bennu's dark boulders tend to have low Γ_R values^{10,34}, although
404 the lower limit of Γ_R is unknown because only one boulder was spatially resolved by the OTES
405 instrument¹⁰. If the boulders' $\Gamma_R < \Gamma_c$, their surface abundance would erroneously contribute to the
406 surface abundance of fine regolith α instead of being counted as rocks, with the caveat that fine
407 regolith could be present on top of the boulders¹⁰.

408

409 We investigate whether the Γ_R - α correlation is sensitive to the assumed value of regolith
410 macroporosity ϕ (Extended Data Figure 5). We repeat the thermophysical modelling of all OTES
411 spots for a low-end value of $\phi=15\%$, which is an estimate for the whole asteroid based on a

412 boulder size-frequency distribution analysis⁴⁴, and a high-end value of $\phi=60\%$, which is a
413 compromise reduction from much higher values used in previous studies (e.g. $\phi=80\%$, ref. 45,
414 which we consider unlikely for a polydisperse size-frequency-distribution). We perform a 3σ test
415 on the solutions to identify those areas where $(\Gamma_P, \Gamma_R, \alpha)$ for $\phi=15\%$ and $\phi=60\%$ are statistically
416 distinct from those for $\phi=40\%$. This test is done considering only those spots where a converged
417 solution is found for both macroporosities: 93 spots ($\phi=40\%$ versus $\phi=15\%$) and 90 spots
418 ($\phi=40\%$ versus $\phi=60\%$). We repeat the Spearman test to assess the robustness of the correlation
419 against removing the areas with statistically distinct solutions from the dataset.

420

421 We investigate whether the Γ_R - α correlation may be an artefact due to the assumption of linear
422 mixing between the radiances emitted by fine regolith and rocks (Eq. 1). We simulate synthetic
423 radiances emitted from a single triangular facet with zero roughness and thermal inertia values
424 following the step function $\Gamma(\alpha)$: $\Gamma \leq \Gamma_c = 100 \text{ Jm}^{-2}\text{K}^{-1}\text{s}^{-0.5}$ for $\alpha=100\%$ and $100 < \Gamma < 2,500$
425 $\text{Jm}^{-2}\text{K}^{-1}\text{s}^{-0.5}$ for $\alpha=0\%$. We simulate the observation of these model radiances by OTES and fit
426 them using our thermophysical model to see whether we retrieve the modelled step function or a
427 correlation similar to that of Figure 1 is instead obtained (Extended Data Figure 6).

428

429 Finally, it has been suggested^{10,34,46} that dark boulders (normal reflectance 0.034–0.049) are more
430 abundant, can reach higher diameters, and have lower thermal inertia than the bright boulders
431 (normal reflectance 0.049–0.074). These boulder properties could mimic the Γ_R - α correlation of
432 Figure 1 if α was also negatively correlated with the area of the largest boulder in the OTES spot.
433 Using the boulder database of ref. 46 we plot the α -value as a function of the size of the largest

434 boulder and perform the Spearman test to investigate whether these quantities are correlated
435 (results are in Extended Data Figure 7).

436

437 **Interpretation of the results**

438 For each OTES spot, we compute the rock porosity Φ from the best-fit Γ_R by means of Eq. 2,
439 assuming ρ_s and c_p as for the computation of Γ_c . The range of Φ -values for Ryugu in Figure 2
440 corresponds to that estimated¹⁹ using Eq. 2 for the boulder observed by the MASCOT infrared
441 radiometer, whose type is typical²⁵ on Ryugu. We use Eq. 2 also to compute Φ of the rocks on
442 Itokawa from the published¹⁷ value of $\Gamma_R=894\pm 122 \text{ Jm}^{-2}\text{K}^{-1}\text{s}^{-0.5}$ assuming the composition of LL
443 chondrites, which is that of the samples returned from Itokawa⁴⁷: $\rho_s=3220 \text{ kg m}^{-3}$ and $c_p=682$
444 $\text{Jkg}^{-1}\text{K}^{-1}$. We compute the uncertainty of Itokawa's Φ as $\sigma(\Phi)=\partial\Phi/\partial\Gamma_R\times\sigma(\Gamma_R)$, where $\sigma(\Gamma_R)$ is the
445 uncertainty of Itokawa's Γ_R from ref. 17.

446

447 Next, we use this information to estimate the time to break a rock of diameter D_R by thermal
448 fatigue (t_B). We use known models^{24,48} to simulate a bed of polydispersed spherical rocks, whose
449 surface is exposed to cyclic temperature variations driven by sunlight; on each rock, an initially
450 sub-mm-sized fracture placed on the surface propagates downward in the rock (i.e., towards the
451 centre of the asteroid), until its size, a , becomes equal to D_R , which is the condition for rock
452 break-up. The time to fracture, t_B , can be calculated from the fracture growth rate da/dN , which
453 is typically approximated²⁴ using Paris' law: $da/dN=C[\Delta K_I(a)]^n$, where N is the number of
454 temperature cycles, C and n have values determined from experiments or analogy with asteroid
455 simulant materials²⁴, and ΔK_I is the maximum variation of the stress intensity factor (K_I) for
456 fracture opening mode. The latter is related to the stress τ experienced by the material during a

457 temperature cycle. $\Delta K_I \propto \tau \propto \Delta T$, which is the maximum diurnal temperature excursion²⁴.
 458 Moreover, from Eq. 23 of ref. 48 we can write that $t_B/P = \Lambda' (D_R/l_s)^{1/m}$, where P is the asteroid
 459 rotation period; $m=1/(1-n)$ for $D_R/l_s \leq 1$ and $m=1/(n-1)$ for $D_R/l_s > 1$. Hence:

$$460 \quad \frac{t_B}{P} = N = \Lambda'' \left(\frac{D_R}{l_s} \right)^{\frac{1}{m}} (\Delta T)^{-n} \quad (4)$$

461 Given N cycles required to break a rock with a certain D_R/l_s , material properties, geometry and
 462 ΔT , we derive the value of Λ'' and use Eq. 4 to predict t_B for rocks of different sizes at different
 463 ΔT . First, we calculate l_s to be 6.4 and 8.6 cm for the carbonaceous and the ordinary chondrite of
 464 ref. 24 for which, at $D_R=l_s$, their Figure 1 gives $t=3.5 \times 10^3$ and 6.3×10^3 years, respectively,
 465 corresponding to $N=1.4 \times 10^6$ and $N=14 \times 10^6$ cycles, given their $P=6$ hours. We take ΔT from their
 466 Extended Data Figure 2. Next, we use Eq. 4 to derive t_B as a function of D_R for values of l_s , P
 467 and ΔT that are more appropriate for Bennu, Ryugu and Itokawa than those of ref. 24. From the
 468 latter reference we take the carbonaceous chondrite properties, but we use $\Gamma_R=500 \text{ Jm}^{-2}\text{K}^{-1}\text{s}^{-0.5}$,
 469 which is more appropriate for the high- Φ , low- Γ_R rocks that dominate Bennu's and Ryugu's
 470 surfaces (Figure 2 and ref. 18, 19, 25, respectively). For the ordinary chondrite, we use $\Gamma_R=900$
 471 $\text{Jm}^{-2}\text{K}^{-1}\text{s}^{-0.5}$, as the latter value was derived from astronomical observations¹⁷ of Itokawa, and we
 472 assume that these parameters could also represent low- Φ , high- Γ_R rocks which may be present
 473 on Bennu's and Ryugu's surface, but in lower abundance than the high- Φ , low- Γ_R rocks. The
 474 rotation periods are $P=4.296$, 7.63, and 12.1 hours for Bennu⁴⁹, Ryugu⁵⁰, and Itokawa⁵¹,
 475 respectively. However, since these rotation periods could have been different⁴⁹ in the past, due to
 476 the Yarkovsky–O'Keefe–Radzievskii–Paddack (YORP) effect, we consider generic low- Γ_R ,
 477 high- Φ and high- Γ_R , low- Φ cases with $P=4.296$ and 12.1 hours for a total of four cases. For each
 478 of them we calculate their l_s -values and run a thermophysical model to determine, at 1.2 au of

479 heliocentric distance, the values of ΔT . Finally, using Eq. 4 we produce the Extended Data
480 Figure 8.

481

482 **Data Availability**

483 Raw through calibrated OTES⁵² and OCAMS⁵³ data are available via the Planetary Data System
484 at <https://sbn.psi.edu/pds/resource/orex/>. The SPC/OLA v34 shape model is available via the
485 Small Body Mapping Tool at <http://sbmt.jhuapl.edu/>. The IDs of the OTES observations used in
486 this study and the best-fit solutions for the thermophysical model are in Supplementary Table 1.
487 The boulder size, location and reflectance used to test the robustness of the results are in refs. 34
488 and 46.

489

490 **Code Availability**

491 The thermophysical analysis reported here uses a custom code based on the Thermophysical
492 Model of ref. 16, available at
493 www.oca.eu/images/LAGRANGE/pages_perso/delbo/thermops.tar.gz. The code to compute the
494 geometry of the OTES acquisitions and boresight is available in Zenodo with the identifier
495 10.5281/zenodo.4781752 (ref. 54). The code to compute the values of Γ_c for the thermophysical
496 analysis is available in Zenodo with the identifier 10.5281/zenodo.4763783 (ref. 55). The rock
497 mapping of Extended Data Figure 3 was performed using the SAOImageDS9 software available
498 at cfa.harvard.edu/saoimageds9. Other codes that support the findings of this study are available
499 in Zenodo with the identifier 10.5281/zenodo.4771035 (ref. 56).

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558

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572

573 **Author Contribution**

574 S.C. led the project, the interpretation of the results and manuscript development, and performed
575 the thermophysical simulations and data analysis. M.D. provided the thermophysical software,
576 performed the thermal cracking calculations and contributed to the interpretation of the results
577 and to the development of the manuscript. G.P. developed the pipeline to retrieve OTES detailed
578 survey data and performed rock mapping in PolyCam images. C.A. curated the discussion on
579 meteoroid bombardment and contributed to the writing of the manuscript. A.J.R. contributed
580 with the code to convert thermal inertia values in fine regolith particle size and developed the
581 iterative approach to determine the cut-off value of thermal inertia together with S.C. J.D.P.D.
582 contributed by extracting the observation geometry of the spacecraft and Bennu from mission
583 kernels. R.-L.B. contributed by proposing important tests of the robustness of the results. E.A,
584 W.F.B. and J.R.B. contributed to the interpretation of the data and the writing of the manuscript.
585 D.N.D., K.N.B., C.A.B. and K.J.W. contributed by providing support in the interpretation of
586 spacecraft imagery. J.P.E. and B.R. contributed to the data interpretation during the OSIRIS-REx
587 Thermal Analysis Working Group meetings, and to design of the observations and data
588 acquisition. M.A.B. and E.C. contributed to the interpretation of the results. D.S.L. made this
589 study possible as the PI of the OSIRIS-REx mission and contributed to the discussion of the
590 results.

591

592 **Author information**

593 Supplementary Information is available for this paper. Reprints and permissions information is
594 available at www.nature.com/reprints. The authors declare no competing interests.
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597

598 **Extended Data Fig. 1. The thermal inertia of Bennu's rocks and the surface abundance of**

599 **fine regolith were measured in 122 quasi-randomly-distributed regions.** a, OTES spots on

600 Bennu plotted on the global basemap of Bennu³² as function of longitude and latitude (red: 3:00

601 p.m. station, or EQ1; blue: 3:20 a.m. station, or EQ2). b, comparison between modelled and

602 observed radiance for one of the 122 areas (ID: 609491396:610102222). c, comparison between

603 the emissivity of Bennu and the residuals of the analysis for the spots 609491396:610102222;

604 the residual curves closely resemble Bennu's emissivity, which is not modelled by our

605 thermophysical model. The error bars correspond to 3 times the Noise Equivalent Spectral

606 Radiance of the OTES instrument¹⁵.

607

608 **Extended Data Fig. 2. There is less fine regolith at the OSIRIS-REx's backup sampling site**

609 **Osprey than at the primary sampling site Nightingale.** Blue and yellow pixels represent areas

610 where no particles bigger than 2 cm, ~ 1 s, were mapped by ref. 43. The value $D_p \approx 1_s$ is the upper

611 limit for the sizes of fine regolith detected by our thermophysical model. There are less blue and

612 yellow pixels at Osprey (image resolution: 0.3 cm pixel⁻¹, panels a, b) than at Nightingale (image

613 resolution: 0.4 cm pixel⁻¹, panels c, d), implying that Osprey has less unresolved material than

614 Nightingale. Consistently and independently, our thermophysical model indicates

615 $\alpha_{\text{Osprey}} < \alpha_{\text{Nightingale}}$ (Supplementary Table 1, spots 609505286:610098718 and
616 609504794:610100730, respectively).

617

618 **Extended Data Fig. 3. The fine regolith abundance derived from OTES data is lower than**
619 **the areas of unresolved material measured in Bennu's images.** Our visual mapping and size
620 measurement of rocks within two OTES spots: a, OTES spots 609493058:610103962; b, OTES
621 spots 609487186:610098206. In both areas, the values of α from our thermophysical solution are
622 smaller than the area of unresolved materials seen in the images. Given the coarse PolyCam³²
623 resolution, it is possible that there are unmapped particles larger than l_s (but smaller than the
624 image resolution) that our thermophysical model detects as rocks and thus do not contribute to
625 the value of α .

626

627 **Extended Data Fig. 4. The correlation between Γ_R and α is statistically significant.** a,
628 Spearman correlation coefficient. b, Spearman p-value; a Spearman $p < 0.05$ indicates that the
629 correlation between Γ_R and α is statistically significant. The figure corresponds to the results for
630 a value of regolith macroporosity of $\phi = 40\%$.

631

632 **Extended Data Fig. 5. The correlation between Γ_R and α is robust against the choice of the**
633 **fine-regolith macroporosity.** The results for macroporosity $\phi = 15\%$ and $\phi = 60\%$ have Spearman
634 correlation coefficients 0.56 ± 0.06 and 0.58 ± 0.06 , probability of non-correlation $p < 0.05$, and are
635 within 3 standard deviations of the best-fit values for regolith macroporosity of $\phi = 40\%$ in 99%
636 and 92% of the cases, respectively. The correlations are robust against removing the areas whose
637 solutions are statistically distinct from the dataset with macroporosity $\phi = 40\%$ (Spearman

638 correlation index: 0.55 ± 0.07 and $p < 0.05$ in 100% of 10,000 trials). The error bars correspond to
639 1 standard deviation (Supplementary Table 1; Methods) computed on ~ 450 and ~ 880 samples on
640 average. The results for a regolith macroporosity of $\phi = 40\%$ are described in the main text
641 (Figure 1).

642

643 **Extended Data Fig. 6. The correlation between Γ_R and α is not an artefact of**
644 **thermophysical modelling.** We fit model radiances emitted by a single triangular facet with
645 zero roughness; if the thermal inertia $\Gamma \leq \Gamma_c = 100 \text{ Jm}^{-2}\text{K}^{-1}\text{s}^{-0.5}$, then $\alpha = 100\%$, and if $\Gamma_c < \Gamma < 2,500$
646 $\text{Jm}^{-2}\text{K}^{-1}\text{s}^{-0.5}$, then $\alpha = 0\%$. We retrieve the expected step function of α as a function of Γ ,
647 indicating that the correlation in Figure 1 is unlikely to be an artefact of the model. The error
648 bars correspond to 1 standard deviation computed on $\sim 1.76 \times 10^4$ samples on average (Methods).

649

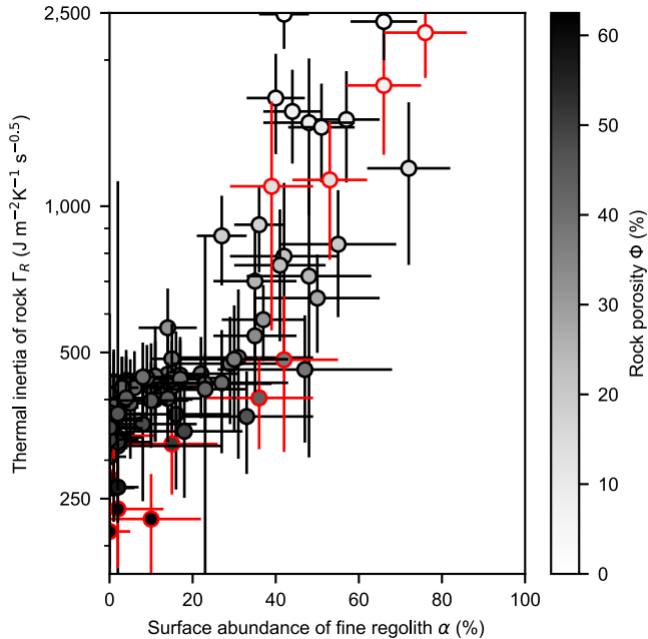
650 **Extended Data Fig. 7. The correlation between Γ_R and α is not a geometric effect due to**
651 **boulders' sizes.** a, PolyCam image of the surface corresponding to spots 609486110:610097198
652 where α is low probably because the spots are filled by a large, dark boulder. b, PolyCam image
653 of the surface corresponding to spots 609495164:610106090 where α does not correlate with the
654 size of the largest boulder; this is representative of most of the surveyed areas. c, plot of α as
655 function of the percentage of the OTEs spot covered by the largest boulder on the surface. The
656 Spearman test reveals that these two quantities have a probability of non-correlation above the
657 critical threshold of 0.05 in 99.99% of 10,000 trials. This indicates that the Γ_R - α correlation of
658 Figure 1 is not the result of geometric effects. The error bars in panel c correspond to 1 standard
659 deviation (Supplementary Table 1; Methods) computed on ~ 670 samples on average.

660

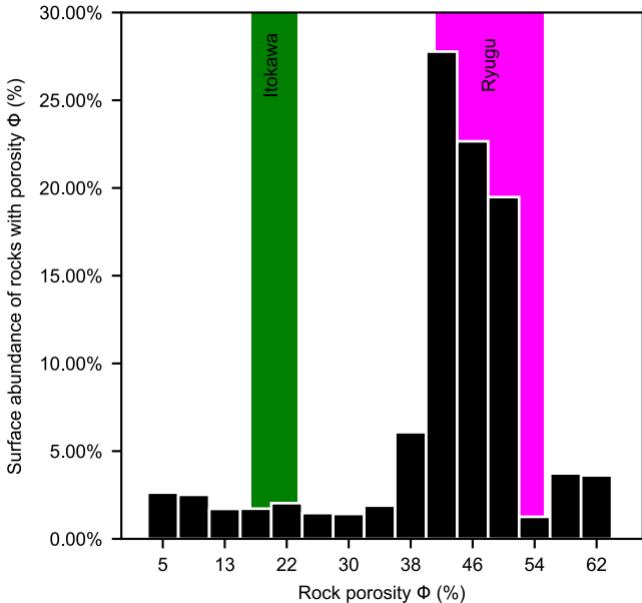
661 **Extended Data Fig. 8. The time required to thermally break rocks is shorter for low-**
662 **porosity rocks than for high-porosity rocks.** We consider the asteroid to be in near-Earth space
663 and explore a range of rotation periods corresponding to the shaded areas. The latter is to take
664 into account changes in the current rotation periods (4.296 h and 12.1 h for Bennu and Itokawa,
665 respectively) that these asteroids may have experienced in the past⁴⁹ due to the Yarkovsky–
666 O'Keefe–Radzievskii–Paddack (YORP) effect. We estimate that in their main belt source region,
667 at about 2.3 au from the Sun, the time to break is ~60 times longer.

668

669 **Extended Data Fig. 9. Examples of in-situ boulder fragmentation on Bennu.** a, a 5.4 m-
670 diameter boulder located at 22° N 157° E. b, a 5.6 m-diameter boulder located at 42° N 170° E.
671 c, a 5.3 m-diameter boulder located at 57° N 304° E. d, a 5 m-diameter boulder located at 39° S
672 203° E. The images are from the global mosaic³² acquired by the PolyCam³³ imager of OCAMS.

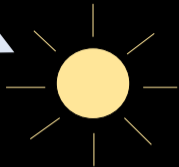


■ Benu's rocks



Diurnal illuminations cycles

drive thermal cracking



This rock is excavated and broken in situ by meteoroid impacts

This rock is compacted by meteoroid impacts

High-thermal-inertia, low-porosity rocks

Low-thermal-inertia, high-porosity rocks

Thermal cracking

Thermal cracking

