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The pristine interior of comet 67P revealed by the combined Aswan outburst and cliff collapse

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Introduction Paragraph

Outbursts occur commonly on comets [1], with different frequencies and scales [2,3]. Despite multiple observations suggesting various triggering processes [4,5], the driving mechanism is still poorly understood. Landslides have been invoked to explain some outbursts on comet 103P/Hartley 2 [6], although the process required a pre-existing dust layer on the verge of failure. The Rosetta mission observed several outbursts from its target comet 67P/Churyumov-Gerasimenko, which were attributed to dust generated by crumbling of materials from collapsing cliffs [7,8]. However, **none of the aforementioned works included definitive evidence** that landslides occur on comets. **Amongst the many features observed by Rosetta on the nucleus of the comet, one peculiar fracture 70 m long and 1 m wide was identified on images obtained in September 2014 at the edge of a cliff named Aswan [9].** On 10 July 2015 the Rosetta Navigation Camera captured a large plume of dust that could be traced back to an area encompassing the Aswan escarpment [7]. Five days later, the OSIRIS camera observed a **fresh**, sharp and bright edge on the Aswan cliff. Here we report the first unambiguous link between an outburst and a cliff collapse on a comet. We establish a new dust-plume formation mechanism that does not necessarily require the breakup of pressurised crust or the presence of super volatile material, as suggested by previous studies [7]. Moreover, the collapse revealed the fresh icy interior of the comet, which is characterised by an albedo > 0.4 , and provided the opportunity to study how the crumbling wall settled down forming a new talus.

Main text

The evolution of the collapse of the Aswan cliff [9], observed by the OSIRIS Narrow Angle Camera (NAC, [10]) and the Rosetta Navigation camera (NavCam) is shown in Fig. 1. We estimated a total outburst ejected mass of cometary material between $0.5\text{-}1.0 \times 10^6$ kg for the 10 July event. By applying stereo-photogrammetric methods (SPG, [11]) using multiple OSIRIS images (Supplementary Table 1), we determined the total volume of material that collapsed from the Aswan cliff. In Fig. 2, the dataset that depicts the aspect of the cliff before and after the collapse is presented. By using pre- and post-collapse 3D models (see Methods) we have been able to measure the dimensions of the collapsed overhang (Supplementary Figures 1-2), deriving a total volume of 2.20×10^4 m³, with a 1σ uncertainty of 0.34×10^4 m³.

On 19 July 2015, the interior of 67P's Aswan cliff was imaged with all NAC filters (Supplementary Table 1), facilitating the spectrophotometric study of five areas located on the wall (see Fig. 3 A, B and Methods). This analysis showed that the edge of the cliff (the green triangle in Fig. 3 B, C and D) was found to be highly saturated in the 600-900 nm range (the image acquired on 15 July 2015 (Fig. 1C) at 649.2 nm was saturated as well). As a result, the normal albedo of this area is only a lower limit, resulting in values > 0.40 at 650 nm, i.e. at least 6 times brighter than the overall surface of the nucleus itself [12]. High albedo regions on the 67P nucleus have been associated with the exposure of water ice observed in clustered bright spots in both hemispheres [13-15]. For these reasons, the spectrophotometric behaviour of the Aswan cliff indicates a clear exposure of pristine material enriched in water ice. On the contrary, the Aswan plateau shows a steeper and redder trend similar to other dark, dusty deposits of 67P [12]. The presence of fresh exposed water ice on the cliff face is indirectly confirmed by the temporal evolution of its normal albedo. On 26 December 2015 the bright cliff was imaged again with the NAC (Fig. 1D), and the resulting normal albedo at its edge was 0.16-0.18 (50% less than ~ 5 months before, i.e. most of the exposed water ice had already sublimated). On 6 August 2016, we re-computed the normal albedo on data with a higher spatial resolution (Supplementary Table 1), and determined that the cliff has returned to the dark value (< 0.12 at 650 nm) similar to the 67P terrains depleted in volatiles [12] (Fig. 3 G, Methods).

109 Despite that, there is still one bright block (ROI#1 Fig. 3 G,H,I) visible on the wall characterised by
110 a normal albedo ~ 0.18 : this is the biggest remnant of the originally exposed water ice.

111 **Laboratory experiments [16] showed that diurnal thermal cycles lead to thermal stresses that**
112 **can breakdown consolidated material into smaller pieces to form the fine regolith that is**
113 **observed on asteroid surfaces, as well as contributing to rock breakdown on Earth [17,18].**
114 **Recent studies based on OSIRIS images have speculated that thermal stresses may influence**
115 **surface features on 67P as well [19], eventually predisposing cliffs collapses [20]. In addition,**
116 **[21] indicated that abrupt diurnal temperature changes in 67P's neck region occur due to**
117 **mutual shadowing effects between the two lobes, suggesting that the early activity of the**
118 **comet was correlated with temperature-related effects causing thermal cracking that**
119 **propagates into the interior and induces sublimation within the crack itself [22,23]. In order**
120 **to investigate whether thermal effects (or thermal cracking) could be the predisposing factors**
121 **that weakened the already fractured Aswan cliff structure, we have carried out an analysis of**
122 **the thermophysical conditions at the cliff before its breakdown (Fig. 4, Methods). We chose**
123 **two facets that represent the diverging conditions occurring on the cliff (Fig. 4A). The cliff wall**
124 **facet is located at the bottom of the sheet that created the landslide, i.e. where thermal cracking**
125 **might be more important. Contrarily, the plateau facet shows the thermal environment on top of the**
126 **cliff, at the location of the opening fracture. 67P's equinox was passed on 10 May 2015, and less**
127 **than 2 months later the sub-solar point had already moved to 30° south. The north-facing neck areas**
128 **of 67P drastically changed their illumination pattern, and instead of being illuminated twice per**
129 **day, their periods of direct illumination became much shorter. In contrast, the Aswan cliff face was**
130 **directly and perpendicularly illuminated for just ~ 1.5 h (Supplementary Video 1). This situation led**
131 **to high maximum heat flux values of up to 740 W/m^2 on 10 July 2015, against the 450 W/m^2 at**
132 **equinox. In contrast, the fractured plateau situated above the cliff did not receive direct sunlight**
133 **except for short periods (maximum 66 W/m^2) in July, versus the 270 W/m^2 of May 2015 (Fig. 4B).**
134 **Despite shorter illumination durations and a smaller heliocentric distance in July, our thermal**
135 **simulations show more extreme temperatures than those at equinox. Calculated surface**
136 **temperatures vary between 100 and 340K at the cliff wall and between 85 and 180K at the plateau**
137 **(Fig. 4C and D), whereas in May the simulated temperatures vary between 130-315K and 105-**
138 **260K respectively (the temperature range decreases when we consider deeper layers – at a depth of**
139 **0.01 m both simulations show a range of 50 K or less (Fig. 4C and D).). The reason for this**
140 **behaviour is the bilobate shape of 67P and the tilt of its rotation axis [24,25], which leads to nearly**
141 **perpendicular illumination conditions on the cliff at local sunrise in July. Supported by the low**
142 **thermal inertia of the surficial layers of 67P ($15\text{-}50 \text{ J m}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}$, [26,27]), a strong temperature**
143 **rise of the upper layers occurs. At the cliff, the surface temperature rises from 130 to 320K in ~ 20**
144 **minutes (Supplementary Figure 3A, B), with a maximum of 30K/min shortly after sunrise.**
145 **Subsurface layers (e.g. at 1 mm depth) still exhibit significant temperature rates-of-change up to 12**
146 **K/min. The low thermal conductivity induces high temperature gradients in the upper layers of the**
147 **cliff face, with a maximum of 155 K/mm and exceeding 40 K/mm for about an hour (Fig. 4E),**
148 **although these numbers depend on the detailed thermal properties of the surface layer. The plateau**
149 **shows significantly lower gradients, 95 K/mm for May and 55 K/mm in July (Fig. 4F).**
150 **Remarkably, deeper cometary layers still exhibit gradients in the order of 10 K/mm, being**
151 **maintained for about an hour. While the integrated diurnal insolation on the Aswan cliff did not**
152 **considerably increase in the months before the collapse, the cliff temperatures drastically changed.**
153 **In the same timescale, the fractured plateau received less sunlight and cooled down significantly in**
154 **the uppermost layers, but due to low thermal inertia of the material, temperature waves are not**
155 **expected to penetrate to depths of more than a metre.**

156 Despite such extreme factors, the collapse occurred during local midnight (denoted with the blue
157 bars in Fig. 4). At this time, the thermal gradients have significantly lowered and became negative
158 for all investigated depths. For this reason, it is not possible to suggest that such gradients have

159 eventually been the immediate triggering factor that led to the cliff collapse. Nevertheless, we
160 underline that pervasive fracturing is present over the entire Aswan wall (both in the pre- and post-
161 collapse case, Supplementary Figure 2). We therefore advance the idea that the diurnal thermal
162 gradients, as well as their seasonal and annual variations, may have driven cyclic and cumulative
163 opening of such fractures, in a process similar to that observed on Earth [17]. If thermal gradients
164 have widened and deepened the fractures into the subsurface volatile-rich strata (as suggested in
165 [22]), heat may have been transferred to deeper layers causing the loss of in-depth ice. Moreover,
166 the gas suddenly released by the subliming material could have been infiltrated within the fractures
167 [23] broadening them as well. For this reason, we suggest that the cumulative effect lead by the
168 thermal gradients could be a weakening factor of the cliff structure predisposing it to the subsequent
169 collapse (material anisotropy, voids and volatile sublimation can be others).

170 The Aswan cliff collapse is the first one witnessed on the surface of a cometary nucleus. To
171 complement the above results and to provide a complete picture of the effects of this event, we
172 focused on the newly-appeared deposit located at the cliff feet. Using three NAC images
173 (Supplementary Table 1), we identified all boulders ≥ 1.5 m in size located on the Aswan talus,
174 before and after the collapse (Fig. 5, Methods). The resulting pre-collapse cumulative number of
175 boulders ≥ 1.5 m is 11784/km², while after the breakdown, this number changed to 18438/km².
176 Such increase of density and surface roughness is evident in Fig. 5 and is not biased by a different
177 spatial scale of the images (Supplementary Table 1). On the contrary, this is due to the increase of
178 the boulder sizes in the 1.5-3.0 m range, as a result of the collapse itself. Indeed, the boulders' size-
179 frequency distribution (SFD, Methods and Supplementary Material) indicates that the crumbling
180 wall has produced predominantly smaller chunks. This is similarly observed on Earth, where the
181 intrinsic weakness of the cliff material by penetrative fracturing strongly affects the resulting size of
182 the debris, and typically results in a crumble of finer material, instead of only few large chunks
183 [29]. Moreover, by extrapolating the SFD to smaller sizes (0.50 m), we estimate that 99% of the
184 volume of the collapsed wall is distributed in the talus, in blocks ranging from 0.5 to 10 m in
185 diameter. This means that 1% of this volume has been lost to space during the collapse. By
186 assuming a density of 535 kg m⁻³ for the cometary material [11], this volume translates into
187 1.08×10^5 kg of material, consistent with our estimate of the mass present in the outburst plume.

188 **On 67P, multiple taluses are identified in association with cliffs [20] suggesting that cliff**
189 **collapses are important processes reshaping cometary surfaces. Eventually, thanks to the**
190 **Rosetta OSIRIS and NavCam images we have witnessed such a breakdown, providing a**
191 **definitive link between the collapse, the outburst event and the talus formation.**

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Author Contributions

294 M.P. conceived, led and designed the study, analysed the cliff setting before and after the collapse,
295 contributed to the spectrophotometric study, made the overall boulder size-frequency analysis and
296 wrote the main text and Methods; S.H. carried out the thermophysical analysis and wrote part of the
297 main text and Methods; J.B.V. performed the outburst analysis and wrote part of the main text; N.O.

298 carried out the 6 August 2016 post-collapse spectrophotometric analysis, wrote part of the main text
299 and Methods; F.S. and F. P. were responsible for the stereo-photoclinometric model and the 3D
300 reconstruction of the pre- and post-collapse cases, wrote part of the main text and Methods; S.M.
301 contributed to the thermophysical analysis and made the illumination conditions video of 10 July
302 2015; G.N. contributed to designing the study and data interpretation; S.F carried out the 19 July
303 2015 spectrophotometric analysis, wrote part of the main text and Methods; S.L. contributed to the
304 thermophysical analysis and wrote part of the main text; C.F. and P.H.H. contributed to the
305 spectrophotometric study; C.G. and C.T. contributed to the data interpretation and made the Aswan
306 observations possible; H.S., C.B., P.L., R.R., D.K. and H.R. are the lead scientists of the OSIRIS
307 project. The other authors are all co-investigators who built and ran this instrument and made the
308 observations possible, and associates and assistants who participated in the study.

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Main Figure Legends

315 Figure 1. **The Aswan cliff outburst.** **a**, OSIRIS NAC reference image taken on 4 July 2015. The
316 Aswan cliff location on the main body of 67P is indicated with the red spot in the upper miniature
317 (0). No bright features appear on the cliff yet. **b**, NavCam image taken on 10 July 2015. The white
318 arrow shows the outburst occurred in the Aswan area. The usual, observed jet activity occurring
319 over the illuminated side of the comet is also visible. **c**, OSIRIS NAC image obtained on 15 July
320 2015 showing the bright, pristine material on the cliff. **d**, OSIRIS NAC image taken on 12
321 December 2015, depicting the bright Aswan cliff.

322 Figure 2. **The Aswan cliff pre- and post-collapse.** NAC images taken at different spatial scales
323 (0.1-0.5 m/pixel) showing the Aswan cliff and fracture setting before (**a,b,d** and **e**) and after (**c-f**)
324 the collapse. The white circle shows the same boulder in all images. The white arrows show the
325 fracture before the collapse and the new sharp edge after the collapse. The white box in **c** marks the
326 location shown in Supplementary Figure 1.

327 Figure 3. **The spectrophotometric analysis after the cliff-collapse.** 19 July 2015 case includes **a-d**
328 panels, **while** panels **e-i** are related to the 6 August 2016 case. **a**, RGB image obtained using the
329 NAC images centred at 882 nm (R), 649 nm (G) and 480 nm (B). **b**, Zoom into the Aswan cliff and
330 selection of the five regions of interest located along the cliff. **c**, Normal albedo computed for each
331 area in each filter. The edge of the cliff represented by the green triangle is highly saturated, so the
332 albedo is underestimated. **d**, Relative reflectance computed on the five regions of interest. **e** context
333 NAC image. **f**, spectral slopes computed on the Aswan cliff. **g**, colour composite of the cliff using
334 the images taken at 882.1 nm, 649.1 nm and 480.7 nm in the RGB channels respectively. Selected
335 regions of interest (ROIs) are enumerated and overlaid. **h**, ROIs normal albedo. **i**, ROIs relative
336 reflectance normalized at 480.7 nm.

337

338 Figure 4. **The thermophysical analysis on the Aswan cliff and plateau.** Thermophysical model
339 results for 10-05-2015 and 10-07-2015 for 1.5 comet rotation of 12.4 hours [28]. In all panels the
340 blue bar denotes the observed NavCam outburst cliff collapse time, while the red line indicates the
341 rotation period. **a**, 3D view showing the location of the Aswan cliff wall and the plateau facets
342 where we derived the following plots. The temperatures are computed at 2.5 h of the simulation

343 time (see Methods). **b**, Illumination conditions (heat flux by solar irradiation) on cliff wall and
344 plateau on 10 July and 10 May 2015, respectively. These two dates are the same also for plots **c-e**. **c**,
345 Temperatures for the cliff wall at three depths (surface, 5 and 10 mm). **d**, Temperatures for the
346 plateau at three depths (surface, 5 mm and 10 mm). **e**, Average temperature gradients for the cliff
347 wall at three depths (0-1mm, 0-5mm and 5-10mm). **f**, Average temperature gradients for the plateau
348 at three depths (0-1mm, 0-5mm and 5-10mm).

349 Figure 5. **The talus boulder analysis during pre- and post-collapse**. First column: the three
350 original NAC images used for the boulder identification. The white arrows show the illumination
351 direction. Second column: the spatial distribution of the boulders grouped in size (m) present on
352 three similar zoomed areas. The talus roughness and boulder density increase is observable in the
353 post-breakdown images and is quantified in the Supplementary Material.

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Methods

356 DTM Methodology and Anaglyph generation:

357 To compute the total volume that collapsed from the Aswan cliff, we applied stereo-
358 photogrammetric methods (SPG [11]) using the highest resolution images available from the
359 OSIRIS NAC camera. The specific location of the Aswan cliff on the comet's nucleus (close to the
360 edge of the neck region between the two lobes and near 67P's north pole), as well as the
361 illumination conditions during the Rosetta mission (typically high phase angles up to 90°) limit the
362 number of OSIRIS NAC images suitable for stereo reconstruction. The most appropriate post-
363 collapse stereo images in terms of geometric properties (high image resolution, sufficient stereo
364 angles for reliable three-dimensional shape reconstruction), and in terms of proper illumination
365 conditions (minimised cast shadowed areas) were taken during the SHAP8 OSIRIS NAC sequence
366 on 8-9 June 2016. A set of three images (NAC_2016-06-08T14.34.26, NAC_2016-06-09T02.30.44,
367 NAC_2016-06-09T14.43.35) provides views of the cliff with spatial scale of 0.5 m/pixel, combined
368 with acceptable stereo and illumination conditions (10°-21° stereo angles, almost no cast shadows
369 in the area of interest). We used this set within a SPG adjustment that relates the images to the sub-
370 pixel accuracy level.

371
372 During the pre-collapse period, both illumination and viewing geometry were less favourable to
373 stereo reconstruction. There is not a single set of images that display the cliff adequately for a
374 reliable SPG reconstruction in high-resolution. Good illumination for the area of interest is
375 available only for the images acquired during the early months of the Rosetta mission where the
376 sub-solar latitude and incidence angles are high. Unfortunately, these images are characterised by a
377 relatively low spatial scale (2-5 m/pixel). Nonetheless, later on in the mission, a few images provide
378 much better spatial scale (up to ~1 m/pixel). Therefore, the overall SPG adjustment towards the
379 global SHAP4S shape model [11] using all stereo-suitable OSIRIS NAC images provides the most
380 complete and most accurate description of the Aswan cliff before its collapse, Supplementary
381 Figure 1. The relevant subset of this global model and a model that we derived from SHAP8 images
382 were finally used for the computation of the volume of the Aswan cliff that collapsed.

383
384 We first tied/aligned both 3D models together using surface features in the immediate vicinity of
385 the collapse area as a reference and then computed the difference between both cliff volumes as
386 $33.7 \times 10^3 \text{ m}^3$, Supplementary Figure 1. It is obvious (from visual inspection of the pre-collapse
387 images) that, as a result of particular deficits of the pre-collapse stereo dataset, the pre-collapse
388 shape of the cliff is generally too flat and does not describe the cliff wall concavities well enough.
389 We have taken this systematic effect into account and estimated the portion of unconsidered pre-

390 collapse concavity to 30-50%. Considering this effect, we get a final estimation of the overhanging
391 volume of the collapsed Aswan cliff of $2.20 \times 10^4 \text{ m}^3$, with a 1-sigma uncertainty of $0.34 \times 10^4 \text{ m}^3$.
392 In addition, four different anaglyphs of the Aswan area have been prepared in order to provide clear
393 views that depict the cliff setting before and after the collapse, Supplementary Figure 2. In
394 particular, by means of Supplementary Figure 2a and b, the overhanging nature (12 m at the block's
395 top, 0 m at its feet) of the detaching block is evident.

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398 **Colour Analysis Methodology:**

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400 The normal albedo presented in Fig. 3c has been evaluated from images (Supplementary Table 1)
401 that have been photometrically corrected using a Hapke model [30] and the parameters determined
402 by [12, Table 4] from resolved photometry in the orange filter centred at 649.2 nm (filter called
403 F22). We have assumed that the phase function at 649.2 nm also applies at the other wavelengths.
404 Moreover the SHAP4S model was used to calculate the photometric angles at the time of the
405 observation [11] to correct the images for different illumination conditions. The flux from the five
406 regions of interest (ROI) in Fig. 3b,c,d in each of the 11 filters has been integrated over 2x2 pixel
407 boxes, i.e. a surface of $\sim 36 \text{ m}^2$.

408

409 The OSIRIS NAC images used in Fig. 3f,g,h,i (Supplementary Table 1) are sequentially recorded at
410 882.1 nm (F41), 649.2 nm (F22), 480.7 nm (F24). Therefore, they have to be co-aligned in order to
411 eliminate colour artefacts created by misalignment of the images. The images are then
412 photometrically corrected using the Lommel-Seeliger disk function [31] to eliminate the effects due
413 to different illumination conditions. USGS ISIS3 [32] software is used for both corrections. The
414 photometric angles are calculated from the 3D shape model described in [11], reduced to one
415 million facets to limit the necessary computational time. The SPICE kernels are used with the
416 'SPICE toolkit for C' for the alignment of the shape at the observing time of the reference image
417 (the one taken at 649.2nm). A detailed description of image registration and photometric correction
418 of subsequent OSIRIS NAC images are described in [33], Appendix A.

419

420 The spectral slopes presented in Fig. 3f are calculated by using equation:

421

$$422 \text{ Spectral slopes (\%/100nm)} = [(F41-F24) \times 10000] / [F24 \times (882.1-480.7)]$$

423

424 This methodology is used to detect variegation within the region shown in Fig. 3e. The in-
425 homogeneity of the exposed cliff and its vicinity is investigated in smaller regions (six different
426 regions of interest (ROIs), four located on the wall (ROIs 1,2,3,4), and two on the overlying terrace;
427 ROIs 5,6 of Fig. 3g), where some variegation was detected (see Main Text) via spectral slopes and
428 RGB colours. The mean spectra within the selected regions are calculated (Fig. 3h). However,
429 direct comparison between spectra is achieved by using spectra normalized at 480.7nm (Fig. 3i).

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437 **Thermophysical Analysis Methodology:**

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439 The goal of the thermophysical analysis is to work out the driving temperature conditions of the
 440 cliff between the time of its collapse, and the months before. We set up a thermophysical model that
 441 takes into account solar irradiation, shadowing, radiative heat exchange between cometary surfaces,
 442 and conductive heat transfer perpendicular to the uppermost layers of the cometary nucleus. For
 443 simplicity reasons, sublimation and phase-change effects are neglected, and we treat the cometary
 444 layers to have uniform thermophysical properties. We follow a widely used (e.g. [34-36]) 1D heat
 445 diffusion approach to determine temperatures and fluxes in the subsurface layers of the Aswan cliff:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(\lambda(T) \frac{\partial T}{\partial x} \right)$$

446 where ρ , c and $\lambda(T)$ describe material density, specific heat and thermal conductivity. The thermal
 447 conductivity of the cometary bulk material is assumed to be driven by radiative exchange and
 448 therefore temperature-dependant. We adopt an approach described in [37] (and references therein)
 449 that is based on the size of the agglomerates which constitute the cometary material. Hence, the
 450 obtained conductivity for agglomerates of 1mm size varies between 0.0005 W/mK and 0.02 W/mK
 451 in the temperature range between 100 and 370 K. The synthetic thermal inertia $\Gamma = \sqrt{\rho c \lambda}$ of the
 452 cometary material ranges between 15 and $90 J m^{-2} s^{-1/2} K^{-1}$, which corresponds to the low inertia
 453 estimations, gained by measurements of 67Ps superficial layers by remote sensing, e.g. [38,39].
 454 Such a low conductivity, which results in penetration depths of the thermal heat wave of a few
 455 centimeters negates the requirement for a 3D modelling approach.

456 The boundary condition at the surface node is described by

$$(1 - A) \frac{S}{AU^2} f_{illum} \cos \theta + F_{scatter} + \sum_j REF_{i,j} T_j^4 - \varepsilon \sigma T_i^4 - \lambda(T) \left(\frac{dT}{dx} \right)_{x=0} = \rho c \Delta x \frac{dT}{dt}$$

457 The first term describes the absorbed solar heat flux, with $A=0.03$ being the bolometric Bond
 458 albedo of the surface, S the solar constant, AU the heliocentric distance of 67P (in astronomical
 459 units), and $f_{illum}(0;1)$ a marker if the surface is shadowed. The parameter θ describes the angle
 460 between the surface normal and the solar vector. The second term $F_{scatter}$ denotes scattered light
 461 from other facets; as we assume lambertian scattering, it is a function of the nucleus geometry. Both
 462 terms are calculated using a Monte Carlo ray-tracing method.

463 **Cliff wall and plateau facet temperatures are given by T_i , facets that create the radiative**
 464 **environment for every facet i are denoted by $j \neq i$, their temperature is T_j .** Infrared radiative
 465 exchange is accounted for in the third term: REF is the radiative exchange factor between surfaces
 466 in contact; for facets whose area is small compared to its distance r_{ij}^2 it can be approximated by

$$REF_{i,j} = dA_j \varepsilon^2 \sigma \frac{\cos \delta_i \cos \delta_j}{\pi r_{ij}^2}$$

467 Here, δ specifies the angle between the facet normal to the connection vector between both surfaces
 468 i and j ; the emissivity ε is assumed to be 0.97, and the Stefan-Boltzmann-Constant is denoted by σ .
 469 $REF_{i,j}$ values are calculated **using** a Monte Carlo ray-tracing method, this method includes
 470 scattering at other facets.

471 The fourth term describes the **thermal infrared emission to other surface element and to space.**
 472 **We neglect thermal emission and backscattering of the dust coma.**

473 The fifth term is the conductive heat flux, dependent on conductivity $\lambda(T)$ and temperature gradient
474 $\frac{dT}{dx}$ between the surface node and the neighboring node underneath, as described in Equation 1.

475 The term on the right side of the equation describes the nodal energy storage and consists of density
476 ρ (being 530 kg/m³, within the range of values determined by [40]), the nodal height Δx , and the
477 material heat capacity c (assumed 800 J/kgK). We deviate from the widely accepted approach of
478 formulating a surface boundary that is in instantaneous radiative equilibrium with the environment.
479 As our model assumes a highly porous cometary material composed of agglomerates of grains,
480 solar irradiation penetrates to small depths until being fully absorbed. Any instant equilibrium leads
481 to unphysical, extremely high gradients at the onset of solar illumination. As this analysis focuses
482 on the estimation of thermal gradients in the subsurface layers, the usage of a boundary node with
483 non-zero thermal capacity circumvents this problem without neglecting the basics of heat transfer.

484 At a depth of 5 cm, diurnal temperature variations are less than one degree. Hence, we are safe to
485 assume an adiabatic boundary condition at a depth of 0.35 m.

$$\left(\frac{dT}{dx}\right)_{x=0.35m} = 0$$

486 The SHAP4S digital terrain model of 67P is scaled down to roughly 100k triangular facets. Each of
487 these facets represents a single surface node of the geometrical model. This resolution allows for a
488 compromise between high accuracy of the modelled terrain and its implications on shadowing and
489 self-heating, while significantly reducing the computational time required for the analysis. A typical
490 facet has side lengths of about 10 meters, so 3D heat transfer within the cometary layers can be
491 neglected [41]. We apply two thermal environments: for the 10 May 2015, we use a tilt of the
492 comet rotation axis of 0.2 degrees and a heliocentric distance of 1.76 AU; the 10 July 2015 applies
493 30.3 degrees and 1.31 AU [28]. We tested other dates in order to verify the tendency of the
494 presented results. We calculate the solar irradiation pattern for every 5 degrees of an entire comet
495 rotation, which results in one position every 10 minutes and a total of 72 calculated patterns.
496 Between these positions, we interpolate linearly to obtain the time-dependent solar irradiation
497 function for every facet. The temperature distribution in the surface layers of the cliff area is
498 modelled with 20 nodal layers, each between 1mm and 70 mm in depth.

499 In contrast, the nodes that form the radiative environment (all nodes that are not part of the cliff
500 itself) are modelled in a more simple way. These nodal temperatures are calculated by the following
501 approach that neglects subsurface conduction:

$$(1 - A) \frac{S}{AU^2} f_{illum} \cos \theta + F_{scatter} + \sum_j REF_{i,j} T_j^4 - \varepsilon \sigma T_i^4 = \rho c \Delta x \frac{dT}{dt}$$

502 We calculate temperatures for a time step of one minute with a Crank Nicholson numerical scheme
503 (e.g. [42]). After 40 rotational periods, the results converged to temperature deviations of less than
504 0.1 K. Supplementary Figure 3 is an example that shows the surface temperatures for 67P for two
505 moments, separated by twenty minutes and showing the sharp temperature increase over short
506 period of time at the Aswan cliff wall.

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511 **Boulder Analysis Methodology:**

512 The identification of the boulders located on the Aswan talus, both pre- and post-collapse, was
513 performed with the ArcGis software. We made use of three NAC images (Supplementary Table 1)
514 that were obtained at distances ranging between 25.4 and 29.5 km from the cometary surface and a
515 corresponding scale of 0.48-0.55 m/px. By considering the minimum three-pixels sampling rule,
516 that minimizes the likelihood of misidentifications of what we are detecting [43], we set the lowest
517 measurable boulder size at 1.5 m. The constant presence of shadows next to the boulders (the
518 observations were performed with phase angles varying from 47° to 77°), allowed us to identify
519 even smaller boulders (2 pixels diameter, ~1 m). However, as indicated in [20], we did not include
520 these smaller populations in the cumulative size-frequency distribution (SFD) because they do not
521 represent a complete dataset for such small sizes, as demonstrated by the clear roll-over below 1.5
522 m. Like [44-46], we considered a “boulder” (we underline that this terminology is not meant to
523 imply any structural similarity to the boulders normally seen on Earth, but when we identified a
524 feature with the mentioned characteristics, we inferred that it was a boulder) to be a positive relief
525 detectable in various images obtained with different observation geometries, with a constant
526 elongated shadow (if the phase angle is greater than 0°). Furthermore, the boulder needs to appear
527 detached from the ground on which it stands.

528 After these features were visually identified in the images, we measured their positions on the
529 surface of the comet and assumed their shapes to be circumcircles. Then, we derived their diameters
530 and the corresponding areas (see Supplementary Figure 4). Consequently, in order to obtain the
531 cumulative boulder size-frequency distribution (SFD) per km², we divided the cumulative numbers
532 by the corresponding total terrace area, 0.056 km², computed from the 3D shape model of 67P [11].
533 In the log-log plot, we then fitted a regression line to the binned data to obtain the power-law index
534 of each size distribution, while the error bars for each value indicate the root of the cumulative
535 number of counting boulders following [47]. We finally underline that the regression line does not
536 take into account those points that are cumulatively repeated, i.e. above 6.5 m. Indeed this is an
537 indication of a poor statistics, and if considered by the fit, it could lead to biased power-law indices.

538 The power-law index of the boulder size-frequency distribution (SFD) carries information about the
539 boulder formation and evolution processes occurring both on comets, asteroids and on planetary
540 bodies [20,48,49,50]. The resulting power-law index we obtained for the Aswan pre-collapse case is
541 $-3.27 \pm 0.21 / -0.22$ (Supplementary Figure 5), indicative of a mixture of two boulder populations: the
542 talus population is located at the base of the cliff where thermal fracturing and consequent
543 sublimation occurs [20] and is characterised by a higher density of smaller (< 4 m) boulders; while
544 the distal detrital deposit [22] is located further out from the cliff and shows larger blocks with sizes
545 > 5 m and likely originated from an initial ceiling collapse forming the whole plateau [20,22]. The
546 resulting pre-collapse cumulative number of boulders per km² ≥ 1.5 m is 11784. After the collapse,
547 a new talus appeared below the wall resulting in a steeper power-law index of $-3.61 \pm 0.20 / -0.31$ and
548 a cumulative number of boulders per km² ≥ 1.5 m of 18438. When comparing the two SFDs
549 (Supplementary Figure 5 and Supplementary Table 2) the main post-collapse difference is in the
550 number increase of the bin sizes between 1.5 and 3.0 m that causes the steepening of the power-law
551 index. The clear blanketing effect of the boulders ≤ 3 m is observable in Supplementary Figure 6.
552 We point out that the $-3.61 \pm 0.20 / -0.31$ power-law index is consistent with the predicted range of -
553 3.5 to -4.5, suggested by [20] to be related to gravitational events triggered by sublimation and/or
554 thermal fracturing and supports the interpretation of a fresh gravitational accumulation for this
555 deposit. In addition, the boulder distribution that we derive in the Aswan talus highlights the fact
556 that the collapsing block has produced predominantly smaller chunks, as detailed in the Main Text.

557 In order to quantify the sensitivity of the presented results to the detected boulders, we performed a
558 numerical experiment in which we randomly changed the diameter of such boulders, within

559 selected ranges. Such analysis was performed both for the pre- and post-collapse cases
560 (Supplementary Figure 5). In particular, each previously detected diameter was first independently
561 perturbed by randomly adding an error sampled through a Monte Carlo procedure from uniform
562 distributions in the ranges from ± 0.005 to ± 1.0 m, secondly the SDF and the power-law index was
563 recomputed in the same range of diameters previously adopted, i.e. from 1.5 to 6.5 m. We note that
564 an error of ± 1.0 m means an over- or underestimation of 2 pixels, which is highly unlikely given
565 that all the considered boulders were detected above the three pixel sampling rule [44]. On the
566 contrary, an over or underestimation smaller than half pixel, i.e. ± 0.25 , is more plausible given that
567 we are considering only those boulders with dimensions above the three pixel sampling threshold.
568 For each selected perturbation we performed 10^5 simulations. The results are presented in
569 Supplementary Figure 7. As expected, in the case of minimal size changes, the obtained median
570 values coincide with the power-law indices previously computed, i.e. -3.21 and -3.61 for the pre-
571 and post-collapse case, respectively. On the contrary, when increasing the diameter perturbations
572 the analysis shows a decrease of the median values of the power-law index in the pre-collapse
573 study, up to 1.6% for the ± 1.0 m case, (i.e. from -3.21 to -3.27), while it shows an increase in the
574 post-collapse scenario, up to 2.95% in the same ± 1.0 m range (i.e. from -3.61 to -3.72). In addition,
575 both the pre- and post-collapse cases show a comparable increased variability in the power-law
576 indices with an increasing range of the selected perturbations. Nonetheless, even when bigger
577 perturbations are taken into account (1-2 pixels), the analysis suggest well distinct power-law
578 indices, corroborating our hypothesis of a lower power-law index for the pre-collapse case with
579 respect to the post-collapse one.

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Data Availability Statement

582 All data presented in this paper will be delivered to ESA's Planetary Science Archive
583 (<http://www.rssd.esa.int/index.php?project5PSA&page5rosetta>) and NASA's Planetary Data
584 System (<https://pds.nasa.gov/>) in accordance with the schedule established by the Rosetta project.
585 The authors declare no competing financial interests. Readers are welcome to comment on the
586 online version of the paper.

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