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1 **1. Extended Data**

2

3



Figure #	Figure title One sentence only	Filename This should be the name the file is saved as when it is uploaded to our system. Please include the file extension. i.e.: <i>Smith_ED_Fi_1.jpg</i>	Figure Legend If you are citing a reference for the first time in these legends, please include all new references in the Online Methods References section, and carry on the numbering from the main References section of the paper.
Extended Data Fig. 1	Comparing high- and low-resolution OVIRS spectra of Site #6	ExtendedData_abc-CS6.eps	a, The lower-resolution spectrum (magenta) of Site #6 shown in the main-text as compared to three higher-resolution pyroxene spectra obtained of Site #6 (teal) during a lower altitude (~1.5 km) regional flyby of Bennu by the OSIRIS-REx spacecraft. The lower-resolution spectrum (magenta) has been ratioed by Bennu’s global average spectrum to bring out the subtle pyroxene absorption features near 1 and 2 μm , whereas the high-resolution spectra do not require any ratioing to observe these absorption features. b, The band I and II centers (1 and 2 μm) calculated for the pyroxene absorption features plotted against each other, for the lower-resolution (ratioed, magenta) and higher-resolution (unratioed, teal) spectra of Site #6. The spectral ratioing does not affect the band centers obtained beyond the uncertainty assigned by the fitting procedure. c, HCP% versus the ratio of the LCP to the HCP band strengths for the lower-resolution (ratioed, magenta) and higher-resolution (unratioed, teal) spectra of Site #6, which again shows that the ratioing procedure does not affect the results obtained by applying the MGM to these spectra.

4 *Delete rows as needed to accommodate the number of figures (10 is the maximum allowed).*

5 **2. Supplementary Information:**

6 **A. Flat Files**

7

Item	Present?	Filename This should be the name the file is saved as when it is uploaded to our system, and should include the file extension. The extension must be .pdf	A brief, numerical description of file contents. i.e.: <i>Supplementary Figures 1-4, Supplementary Discussion, and Supplementary Tables 1-4.</i>
Supplementary Information	Yes	SupplementaryInformation_Pyroxene_on_Bennu_200714_FINAL.pdf	Supplementary Figures 1-9, Supplementary Tables 1-4
Reporting Summary	No		

8

9

Exogenic Basalt on Asteroid (101955) Bennu

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Summary Paragraph:

When rubble-pile asteroid 2008 TC₃ impacted Earth on October 7, 2008, the recovered rock fragments indicated that such asteroids can contain exogenic material [1,2]. However, spacecraft missions to date have only observed exogenous contamination on large, monolithic asteroids that are impervious to collisional disruption [3, 4]. Here we report the presence of meter-scale exogenic boulders on the surface of near-Earth asteroid (101955) Bennu—the 0.5-km, rubble-pile target of the OSIRIS-REx mission [5] which has been spectroscopically linked to the CM carbonaceous chondrite meteorites [6]. Hyperspectral data indicate that the exogenic boulders have the same distinctive pyroxene composition as the howardite–eucrite–diogenite (HED) meteorites that come from (4) Vesta, a 525-km-diameter asteroid that has undergone differentiation and extensive igneous processing [7, 8, 9]. Delivery scenarios include the infall of Vesta fragments directly onto Bennu or indirectly onto Bennu's parent body, where the latter's disruption created Bennu from a mixture of endogenous and exogenic debris. Our findings demonstrate that rubble-pile asteroids can preserve evidence of inter-asteroid mixing that took place at macroscopic scales well after planetesimal formation ended. Accordingly, the presence of HED-like material on the surface of Bennu provides previously unrecognized constraints on the collisional and dynamical evolution of the inner main belt.

57 We discovered six unusually bright boulders >1.5 m in diameter on the surface of Bennu (Fig. 1) in images
58 acquired by the OSIRIS-REx Camera Suite (OCAMS) [10]. These boulders are observed in the equatorial to
59 southern latitudes some are found in clusters, whereas others are more dispersed (Fig. 2a).

60
61 The bright boulders exhibit extremely different albedos than the bulk of the asteroid's surface, which has an
62 average albedo of 4.4% [11, 12]. The global albedo distribution based on data from the OCAMS MapCam
63 and PolyCam imagers is unimodal at centimeter scales [11]; however, these boulders are outliers at 13σ to
64 40σ above the mean (Fig. 2b; Supplementary Fig. 1). Furthermore, MapCam colour images show that the
65 0.70/0.85 μm band ratio of these boulders is distinct from that of the global average spectrum of Bennu (Fig.
66 2b). The band ratio suggests the presence of an absorption feature beyond 0.85 μm and is consistent with
67 the presence of mafic minerals, such as pyroxene or olivine. The substantial albedo and colour deviation of
68 this population of boulders, as well as their rarity, suggests a separate provenance from the rest of Bennu's
69 regolith.

70
71 Spectra collected by the OSIRIS-REx Visible and InfraRed Spectrometer [13] show that these six bright
72 boulders contain pyroxene, and not olivine, as indicated by a second absorption near 2 μm (Fig. 2c, Extended
73 Data Fig. 1a). Pyroxene is a major rock-forming mineral in planetary materials, and numerous studies have
74 quantitatively linked pyroxene compositions with spectral signatures in the visible and near infrared
75 [14,15,16,17]. Pyroxenes can crystallize in different systems (monoclinic clinopyroxenes and orthorhombic
76 orthopyroxenes) and with differing calcium cation chemistry. These factors influence the absorption bands I
77 and II—near 1 and 2 μm —and yield a systematic relationship between high- and low-calcium pyroxene
78 [14,15,18]. The bright boulders studied here have band I centers that range from ~0.90 to 0.95 μm and band
79 II centers from ~1.95 to 2 μm (Fig. 3a, Extended Data Fig. 1b).

80 Although band centers can be used to distinguish between pyroxene compositions, they are less diagnostic
81 for mineral mixtures that contain multiple pyroxenes. Thus, we also applied the Modified Gaussian Model
82 [16] to OVIRS spectra of the bright boulders (Fig. 2c, Extended Data Fig. 1a); this allowed us to resolve
83 overlapping absorption features near 1 and 2 μm that arise from different mafic silicates. A major application
84 of MGM is to separate absorptions of high-calcium pyroxene (HCP) from those of low-calcium pyroxene
85 (LCP) to estimate the abundance of HCP as a percentage of total pyroxene (HCP%). HCP% is an indicator of
86 igneous differentiation in asteroids because as chondritic material melts, the partial melt is enriched in HCP,
87 and the residue is strongly depleted in HCP [17].

88 We find HCP% values that range from 45 to 55%, indicating that the pyroxene identified on Bennu came
89 from a body large enough to support igneous processes (Fig. 3b, Extended Data Fig. 1c). These values are
90 not consistent with chondritic material, either from Bennu's parent body or from contamination by ordinary
91 chondrites [17,19]. This composition, combined with the overall carbonaceous chondrite-like nature of
92 Bennu, indicates that the observed pyroxene is exogenic. The alternative would require the formation of
93 HCP as an incipient melt on Bennu's parent body, which is not compatible with the hydrated, phyllosilicate-
94 rich composition of Bennu [6]. In terms of both estimated HCP% and band centers, the pyroxene-bearing
95 boulders on Bennu correspond to HED meteorites, and in particular eucrites (Fig. 3a-b, Extended Data Fig.
96 1c-b).

97
98 A difference is that HED meteorites are nearly 5x brighter than the exogenic boulders that we observe on
99 Bennu [20]. Laboratory studies, however, indicate that the reflectance of eucrite samples exponentially
100 decreases as they are mixed with CM meteorite powders [21]; a similar effect can be observed by linearly
101 combining spectra from carbonaceous chondrite and pyroxene from various meteorites in the visible
102 wavelengths (Methods; Supplementary Fig. 3). On Vesta, dark terrains have been attributed to the infall of
103 low-albedo carbonaceous material and have a reflectance that is 2-3x less than endogenous bright surface

104 units [3, 4]. It is therefore possible that the exogenic boulders have been optically mixed with low-albedo
105 endogenous material from Bennu, thereby decreasing their overall reflectance. Additionally, the pyroxene-
106 bearing boulder with the highest albedo also shows the deepest 1- μm band (Fig. 2b), suggesting that
107 boulder brightness may correspond to pyroxene exposure.

108
109 HED meteorites, as well as most pyroxene-rich basaltic objects in the inner main belt, are sourced from the
110 vestoids [22, 23]—a family of asteroids that originated from, and have similar orbits to, Vesta [7, 8, 9, 22, 23].
111 This is likely the provenance of pyroxene-bearing boulders on Bennu, which have compositional
112 homogeneity and are a close spectral match to the HED meteorites (Fig. 3a-b, Extended Data Fig. 1c-b).
113 Furthermore, the population of inner main belt vestoids dynamically overlaps with the source regions of
114 Bennu (Supplementary Fig. 8), providing a pathway for these boulders to be implanted on it or its parent
115 body's surface [24, 25].

116
117 Dynamical models suggest that Bennu's parent body, which was >100 km, disrupted ~0.8 to 1.5 Ga ago from
118 an inner main belt asteroid family, resulting in the formation of Bennu [24, 25]. After its formation, Bennu
119 drifted across the inner main belt to a dynamical resonance that would take it to its current near-Earth orbit,
120 a few Ma to tens of Ma ago [24, 25, 26]. En route, Bennu may have been impacted by one or more small
121 vestoids, leaving behind the observed exogenic boulders. Alternatively, Bennu's parent body could have
122 been contaminated by vestoids, which litter the present day inner main belt [8]. The impactors would have
123 left behind meter-scale or larger material near or on the surface. When Bennu's parent body was
124 subsequently disrupted, Bennu would have been created from a scramble of parent body and exogenic
125 debris.

126
127 Laboratory collision experiments on porous surfaces show that up to 20% of a projectile's material can
128 survive unmelted at low impact speeds < 2.6 km s⁻¹ and vertical incidence [27, 28]. However, most impacts in
129 the main belt would have occurred at higher velocities; we find that only 10 to 44% of all vestoids could have
130 encountered Bennu at < 2.6 km s⁻¹ (Methods). Although small projectiles moving at these low velocities
131 could account for meter-sized exogenic boulders on Bennu, they cannot readily explain the multi-meter
132 ones. This is because the progenitors of boulders ~4 m would require impactors so large that they should
133 catastrophically disrupt Bennu, even at low impact velocities (Methods).

134
135 Another possibility is that Bennu accumulated from the remnants of a catastrophic collision between its
136 precursor and a vestoid. Vestoids, however, do not dominate the present-day main belt at small sizes [29],
137 and meteorites from Vesta only account for 6% of falls [30]. It is conceivable that circumstances existed
138 shortly after the formation epochs of the vestoids, near 1 and 2 Ga ago [31, 32], where Vesta fragments
139 dominated the main belt at small sizes for a brief period of time. Even so, the probabilities of creating and
140 preserving Bennu under this scenario remain small (Methods).

141
142 This leads us to favor the parent body scramble scenario. Although modeling this scenario presents several
143 complexities, the longer lifetime and larger surface area of the parent body relative to Bennu would have
144 resulted in a higher number of probable impacts (Methods). Furthermore, the parent body was large enough
145 to withstand high-velocity projectiles that would disrupt Bennu, increasing its overall number of probable
146 impacts relative to Bennu. The parent body scramble scenario is also consistent with the geological setting
147 of the exogenic boulders. Although half are proximal to putative impact craters, crater-scaling relationships
148 show it is unlikely that the exogenic boulders produced those craters (Methods; Supplementary Fig. 5 and
149 Tab. 2). Moreover, at Site 4, we observe bright pyroxene-bearing clasts embedded within the darker host
150 matrix of a larger partially buried boulder (diameter ~ 5 m) whose overall colour and albedo are similar to
151 Bennu's average surface (Fig. 1d, Supplementary Fig. 6). This suggests that the boulder is an impact breccia

152 (rather than two distinct rocks), and comparable textures observed at Sites 2 and 3 may be further examples
153 of breccias. If so, these would likely have originated on Bennu's parent body, because meter-scale
154 brecciation requires energies that would disrupt Bennu [33, 34].
155

156 It is not yet clear why we observe HED-like boulders and no other exogenic material on Bennu, but higher-
157 resolution data from regional OSIRIS-REx mission phases, and ultimately analysis of the returned sample,
158 may reveal contributions from other impactors. For now, the presence of HED lithologies offers insights into
159 other small asteroids; assuming that Bennu is representative, meter-scale exogenic material should exist on
160 many and may not have been detected owing to observational limitations. This is consistent with prior
161 studies which speculated that dark boulders found on the small (~0.3 km) S-type asteroid Itokawa are
162 exogenous in origin [35]. Additionally, our observations complement the finding of ordinary chondrite-like
163 boulders on (162173) Ryugu, the ~1-km rubble-pile target of the Hayabusa2 mission that is similar to Bennu
164 in terms of its albedo and composition [36, 37, 38]. Differing exogenic lithologies on Bennu and Ryugu
165 indicates they may have experienced different collisional histories.

166 The exogenic boulders on Bennu also provide context for recent discoveries of pyroxene clasts embedded in
167 CM meteorites [39, 40]; conversely, xenolithic fragments of CM meteorites have been observed in some
168 HEDs [41]. Our findings suggest that the OSIRIS-REx sample returned from Bennu may yield material that
169 originated from Vesta. Such a finding could merge our understanding of the collisional processes observed
170 on planetary surfaces with that of xenoliths observed in the meteorite collection.

171 **Figure Captions**

172
173 **Figure 1 | In OCAMS PolyCam images, six unusually bright boulders exhibit a variety of textures.** a, The
174 boulder at Site 1 appears to have a flat, planar, exposed face (See Supplementary Fig. 9). b-c, Sites 2 and 3
175 are more angular and hummocky boulders with textures that indicate potential layering or brecciation. d,
176 Whereas some bright boulders appear to be resting on the surface of the asteroid, Site 4 includes two bright
177 pyroxene-bearing clasts that appear embedded within a large partially buried boulder whose albedo is
178 similar to Benu's average. As with Sites 2 and 3, this may be indicative of brecciation. e-f, The boulders at
179 Sites 5 and 6 have variable albedos that change across their faces. The diffuse appearance may result from
180 variable illumination caused by the texture of the boulder faces or be due to a layer of fine low-albedo dust
181 coating the boulders. See Supplementary Table 1 for boulder dimensions.

182
183 **Figure 2 | Physical and spectrophotometric properties of Benu's bright pyroxene-bearing boulders.** a,
184 The bright pyroxene-bearing boulders (coloured circles) are observed in the equatorial to southern latitudes
185 on Benu and their distribution appears non-uniform, perhaps owing to resolution limitations at scales ≤ 1 m
186 in global OSIRIS-REx MapCam data. The diameter of each circle indicates the relative size of the boulder
187 (not to scale with the background basemap). Three boulders form a cluster near 60° longitude, but the
188 others are more distributed. b, The $0.70/0.85 \mu\text{m}$ band ratio for each boulder from MapCam (~ 25 cm/pixel)
189 versus its panchromatic normal reflectance from PolyCam data (~ 7 cm/pixel). Colors correspond to panel a
190 and error bars signify the radiometric uncertainty of reflectance values (Methods). Benu's global average
191 $0.70/0.85 \mu\text{m}$ band ratio and normal reflectance are shown for context (dashed lines) along with their 1σ
192 variation (blue shaded envelopes). c, The OVIRS spectrum for each site (colors correspond to panel a)
193 divided by the global average OVIRS spectrum of Benu. The OVIRS spot size is ~ 20 m for these spectra;
194 therefore, the boulders occupy $<1\%$ of the field of view (Supplementary Fig. 2). Dividing by the global
195 average spectrum of Benu highlights the subtle absorption features associated with the boulders. The band
196 depth at $0.92 \mu\text{m}$ (dashed line) is labeled for each spectrum just below the absorption feature to show the
197 relative strength of the band I center for every boulder.

198
199 **Figure 3 | Benu's bright pyroxene-bearing boulders are spectrally similar to the HED meteorites.** a, The
200 band centers for the 1- and $2\text{-}\mu\text{m}$ absorption features plotted against each other for spectra of bright
201 pyroxene-bearing boulders on Benu. Band centers for several HED meteorites [18] and synthetic pyroxene
202 samples are shown for context [15]. Error bars signify the standard deviation from the Monte Carlo fitting
203 procedure used to estimate the band centers (see Methods). Site 5 was excluded from this analysis as its
204 spectrum possessed a low signal-to-noise ratio. b, HCP% versus the ratio of the LCP to the HCP band
205 strengths for bright pyroxene-bearing boulders on Benu, as determined by applying the MGM to OVIRS
206 spectra. The ranges for meteorites, including eucrites, ordinary chondrites, and lodranites, are shown for
207 context [17]. Error bars signify the standard deviation from the Monte Carlo fitting by the MGM (see
208 Methods). Sites 4 and 5 were excluded from this analysis as their OVIRS spectra possessed low signal-to-
209 noise ratios that interfered with fitting by the MGM.

210 **Methods**

211

212 **Image data processing**

213 Bennu's average terrain exhibits a much lower albedo than the exogenic boulders described in this study.
214 Thus, in many MapCam and PolyCam images, these boulders are saturated. All reflectance information
215 reported here is obtained from unsaturated pixels (>98% radiometric linearity); saturated pixels (DN > 14,000
216 in uncalibrated Lo MapCam images, DN > 12500 in uncalibrated Lo PolyCam images; [42]) were discarded
217 from our analysis. OCAMS images are calibrated into units of reflectance (also known as radiance factor or
218 I/F) with a 5% absolute radiometric uncertainty according to procedures described by Golish et al., (2019)
219 [42]. Images were photometrically corrected to I/F values at 0° phase angle, 0° emission angle, and 0°
220 incidence angle ($0^\circ, 0^\circ, 0^\circ$) and ($30^\circ, 0^\circ, 30^\circ$) using the ROLO phase function and Lommel-Seeliger disk
221 function as described by Golish et al., 2020 [43].

222

223 MapCam colour images that first detected the pyroxene-bearing boulders were acquired on March 14, 2019,
224 from 17:37 to 22:19 UTC, and their presence was confirmed in colour images acquired on September 26,
225 2019 from 17:12 to 21:50. Both days of MapCam observations provided global coverage with an approximate
226 pixel scale of ~25 cm, phase angle of ~8.5° and local solar time (LST) of ~12:49PM. For each boulder, the data
227 were acquired in nearly identical colour sets taken at short, medium, and long exposure times; we selected
228 short-exposure sets for our analysis to avoid saturated pixels. Even for the lowest exposure times, however,
229 50% of the pixels were removed due to saturation at Site 1 for the data obtained March 14, 2019. Hence, we
230 used the low-exposure-time data from September 26, 2019, for determining band ratios, as those data did
231 not experience saturation. The global MapCam panchromatic normal reflectance map was used to
232 determine the global reflectance distribution of Bennu at a pixel scale of ~32 cm. It is constructed from
233 12:30PM LST images collected from 17:39 to 22:21 UTC at a phase angle of ~8°. To the measure colour and
234 reflectance information, MapCam images were registered to the tessellated global shape model of Bennu
235 (v28; 80-cm ground sample distance (GSD)) [44] using the Integrated Software for Imagers and
236 Spectrometers version 3 (ISIS3). Mosaics and colour cubes were produced using techniques described by
237 DellaGiustina et al., 2018 [45].

238

239 PolyCam panchromatic images used to determine boulder panchromatic normal reflectance include:
240 20190307T173147S243_pol_iofL2pan.fits (Site 1), 20190328T194159S619_pol_iofL2pan.fits (Site 2 and 3),
241 20190321T191242S629_pol_iofL2pan.fits (Site 4), 20190321T190056S516_pol_iofL2pan.fits (Site 5), and
242 20190321T184411S010_pol_iofL2pan.fits (Site 6). For Sites 2 to 6, the images used to calculate the normal
243 reflectance of exogenic boulders were chosen based on the highest available resolution (~5.25 cm/pixel) and
244 lowest available emission angle. For Site 1, we selected an image with a pixel scale of ~7 cm and the lowest
245 available exposure time and no saturated pixels, as this boulder is overexposed in higher resolution images.
246 At short exposure times, however, PolyCam data experience a high degree of charge smear and 'icicle'
247 artifacts [42]. The OCAMS PolyCam charge smear correction algorithm depends on the image data to
248 determine the amount of signal to remove and is less accurate for images with icicles, as these artifacts
249 overwrite the valid data that inform the correction algorithm. This yields a lower-fidelity charge smear
250 correction and results in an additional uncertainty of 5% in short-exposure-time data. To measure the
251 dimensions and panchromatic reflectance of the exogenic boulders, PolyCam images were registered to
252 high-resolution digital terrain models (5 to 6 cm GSD) produced from OSIRIS-REx Laser Altimeter (OLA)
253 data [46].

254

255 Using ISIS3, reflectance values in PolyCam and the four MapCam bands were obtained by manually tracing
256 polygons around each pyroxene-bearing boulder in the panchromatic and colour image cubes, and
257 extracting the average pixel value from within the polygons.

258
259 PolyCam images that characterize the overall size and morphology of pyroxene boulders were acquired on
260 several days under varying illumination conditions throughout the Orbital A and Detailed Survey mission
261 phases [5] and include: 20190321T201326S593_pol_iofL2pan.fits, 20190328T194159S619_pol_iofL2pan.fits,
262 20190321T190958S257_pol_iofL2pan.fits, 20190307T-203057S263_pol_iofL2pan.fits
263 20190307T203526S248_pol_iofL2pan.fits, and 20190227T041127S994_pol_iofL2pan.fits.
264

265 Spectral data processing

266
267 Global OVIRS data used in this study were obtained from a 5-km altitude flyby which resulted in a ~20 m
268 instrument spot size (not accounting for along-track smear; see Supplementary Fig. 2). Thus, in global
269 observations, the pyroxene boulders described here occupy <1% of the field of view of OVIRS spectra. For
270 completeness, we also examined data collected by the OSIRIS-REx Thermal Emission Spectrometer [OTES;
271 47] over the same areas, but no distinct signatures for pyroxene have been confidently detected in them.
272 This is likely because OTES data cover sufficiently large areas (~40 m instrument spot size, not accounting
273 for along-track smear) such that the pyroxene boulders are a minute fraction of the field of view.
274

275 Global OVIRS data were acquired at 12:30PM and 10:00AM LST during the Detailed Survey Equatorial
276 Station observations on May 9, 2019 and May 16, 2019, respectively. Spectra were obtained in north-to-
277 south spacecraft scans that mapped Bennu's surface as the asteroid rotated. Individual filter segments are
278 converted from calibrated radiance to I/F by resampling onto a continuous wavelength axis, subtracting a
279 modeled thermal emission, and dividing by range-corrected solar flux [48]. In these global data, the spectral
280 signatures associated with pyroxene have very shallow band depths of 1% or less, and the best method for
281 displaying them is to divide by a global average spectrum to remove any spectral artifacts or other globally
282 prevalent absorption signatures. The global average was calculated using ~2000 OVIRS spectra acquired at
283 the same LST and has a weak linear blue slope of less than -1% per 100 nm from 0.5-2.5 μm (Supplementary
284 Fig. 4). After dividing all spectra by the global average, regions with potential pyroxene signatures were
285 identified by a manual search and by an automated search for a broad absorption feature at 0.92 μm . Both
286 methods identified the same locations for the strongest signatures, corresponding to the brightest boulders
287 in OCAMS images.
288

289 Ratioing these spectra by the global average removed artificial discontinuities that correspond to the OVIRS
290 filter segment boundaries at 0.65, 1.05 and 1.7 μm , and also eliminated the presence of ubiquitous narrow
291 absorption features at 1.4, 1.9 and 2.3 μm that are not associated with pyroxene. Additionally, we obtained
292 an opportunistic regional OVIRS observation of the Site #6 pyroxene at higher-resolution (~5 m spot size)
293 during a low-altitude (~1.4 km) flyby performed on October 26, 2019 at 20:07 UTC (Extended Data Fig. 1a).
294 During this observation, the Site #6 boulder more completely filled the OVIRS field of view; thus, the
295 pyroxene absorption features are clearly present, and there was no need to ratio these spectra with the
296 global average spectrum of Bennu. Comparing higher-resolution spectra of Site #6 (unratioed) to those
297 obtained at lower resolution (ratioed) indicates that the ratioing procedure used here does not influence the
298 results of our analyses beyond the assigned uncertainties (Extended Data Fig. 1).
299

300 In the global data, the OVIRS field-of-view was continuously scanned across the surface and regions with
301 sharply contrasting features can show "jumps" in the spectrum from 0.4 to 0.66 μm or 0.66 to 1.08 μm , as
302 different wavelength regions were acquired over a slightly different part of the surface. Thus, the manual
303 inspection was necessary to rule out false positive pyroxene detections and to identify other nearby spectra
304 that were missed in the automated search. Any "jumps" were corrected by adjusting that portion of the
305 spectrum to match the absolute brightness of the spectrum on either side of the jump. Co-located

306 detections were averaged together to produce a site-averaged spectrum, which was then smoothed using a
307 3-sigma Gaussian kernel. Finally, the continuum was removed using a linear fit between 0.7 and 2.5 μm .
308 Uncertainties in 0.92- μm band depth were estimated using a five-channel standard deviation in the
309 unsmoothed data.

310
311 To determine band centers, we fit Gaussian curves to the 1- and 2- μm pyroxene absorptions in the
312 continuum-removed ratioed spectra and found the Gaussian center wavelength. We used a Monte Carlo
313 approach, in which the initial Gaussian centers were varied by a random value less than or equal to $\pm 0.05 \mu\text{m}$
314 and the best fit was recorded for each of 10,000 model fits to determine the uncertainty on our estimated
315 band centers. A similar approach was used to resolve individual absorptions.

316
317 To resolve pyroxene absorptions due to HCP and LCP, we applied the MGM to OVIRS data from 0.4 to 2.6
318 μm and fit six to seven Gaussians to the region after analyzing initial runs [49]. Of these Gaussians, two were
319 fit to LCP absorptions (~ 0.92 and $1.90 \mu\text{m}$) and three to HCP absorptions (1.00 , 1.20 , and $2.30 \mu\text{m}$) [17]. In the
320 model, Gaussian curves are superimposed on a baseline continuum, which is linear in wavenumber space,
321 and the model is inverted to solve for Gaussian center, amplitude, and width, and the continuum
322 simultaneously. Model constraints control the magnitude of change possible for each of these parameters
323 and do not allow for unphysical solutions (e.g., inverted Gaussians). Supplementary Table 3 and 4 provide
324 the MGM fit and Gaussians used in this analysis.

325
326 We used a Monte Carlo approach to calculate uncertainty on model output parameters by systematically
327 varying the model starting conditions. Although the MGM has built-in methods for estimating uncertainty
328 on each model parameter from known physical properties, we have limited knowledge of a priori
329 uncertainty given that these are spacecraft detection of unknown materials with unknown origin. Therefore,
330 we ran the model 10,000 times and changed the initial Gaussian band center estimates for each of the seven
331 Gaussians by an independent, random number normally distributed between $\pm 0.50 \mu\text{m}$ (or approximately
332 10 OVIRS channels) for each model run. We recorded initial band positions and model results, using the full
333 set of 10,000 runs to estimate uncertainty values on each parameter; a model was considered successfully fit
334 if the full set of results converged and we found that in all cases, we were able to use the same set of starting
335 parameters and achieve model convergence.

336
337 Average Gaussian amplitudes from the MGM runs were used to calculate the "component band strength
338 ratio" [49], or the ratio of LCP to HCP band strengths. We use the ratio of band strengths in the 1- μm band,
339 rather than the 2- μm band, because of potential uncertainty in 2- μm band calibrations due to temperature
340 [18].

341 **Spectral mixing model**

342 We constructed a simple linear mixing model to assess whether the lower albedo of pyroxene-bearing
343 boulders on Bennu, relative to that of HED meteorites, can be explained by combining the spectra of CI/CM
344 chondrites and achondritic pyroxenes. Specifically, we used a "checkerboard" approach [50] that assumes
345 that the compositions are optically separated, so that multiple scattering occurring between the
346 constituents is negligible.

347
348 We considered an areal ratio in the order of A% for the basaltic material and B% for carbonaceous material.
349 The combination can be expressed with the formula $R_f = A \times R_{\text{PYX}} + B \times R_{\text{CC}}$, where R_f is the reflectance
350 spectrum, R_{PYX} is the median spectrum of meteoritic pyroxenes, and R_{CC} is the median spectrum of CI/CM
351 chondrites. We applied the model to linear combinations of achondritic and CM/CI meteorite spectra from
352 RELAB [51]. By searching all possible combinations, we found that the spectrophotometric match observed
353 for the MapCam pyroxene-bearing boulders is best fit by linear combinations of 5–20% of various meteoritic

354 pyroxenes with 95–80% carbonaceous chondrites (CMs and Cls). This is exemplified in Supplementary Fig. 3,
355 which shows that a small amount of basaltic material mixed with CM material can result in the observed
356 effect. The best fit obtained for the pyroxene-bearing boulder in Site 1 corresponds to a combination of the
357 spectrum ($A = 20\%$) of ALHA77005,193 pyroxene (Sample ID: DD-MDD-034, RELAB file: C1DD34) with the
358 spectrum ($B = 80\%$) of the Murchison meteorite (Sample ID: MS-CMP-002-E, RELAB file: CEMS02).
359

360 Collisional model

361 We examined whether Bennu or its parent body could have been plausibly contaminated by debris from the
362 vestoids. We also explored whether the pyroxene-bearing boulders could have come from the disruption of
363 Bennu's contaminated parent body. For the latter, we assume that Bennu is a first-generation rubble pile
364 based on work which shows that the fraction of bodies that escape the Polana and Eulalia asteroid families
365 are dominated by first-generation objects [52]. This is in contrast to the possible intermediate parent-body
366 stages for the asteroid Ryugu [37], inferred in part by its partial dehydration, which is not observed on Bennu
367 [6]. Our work takes advantage of established methods and codes (e.g., Bottke et al. 1994 [53]; Avdellidou et
368 al. 2018 [54]; Briani et al. 2011[55]; Gayon-Markt et al. 2012 [56]; Turrini et al., 2014 and 2016 [57, 58]).
369

370 For the population of projectiles, we considered the present-day Vesta family, which includes 15,238 known
371 asteroids with proper semi-major axis between 2.24 and 2.48 AU, 0.075–0.133 proper eccentricity, 5–8°
372 proper inclination, and absolute magnitude H between 12 and 18.3 [59]. Diameters (D) have been measured
373 for 1889 of these asteroids; when the diameter is not known, it is possible to estimate it using the average
374 geometric visible albedo $p_V = 0.34$ of the family and the H values of each asteroid with the equation $D(\text{km}) =$
375 $1329 (p_V)^{-1/2} 10^{(-H/5)}$. The cumulative size-frequency distribution for asteroids with $12 < H < 17$ (the upper limit
376 corresponds to the current completeness of the main belt) can be fit by a power law of the form $N_{\text{vestoids}} =$
377 $D^a 10^b$ with $a = -2.5$ and $b = 4.1$, allowing us to extrapolate the Vesta family population to sizes smaller than
378 what is currently observable (Supplementary Fig. 7). Because we expect that the Vesta family has lost
379 members by collisional grinding, the present-day vestoid population represents a lower limit. In particular,
380 the vestoids likely formed at two different epochs, near 2 and 1 Ga ago, linked to the formation of the
381 Veneneia and Rheasilvia basins on Vesta [31, 32]. As a result, the first generation of vestoids experienced a
382 decline at $D > 1$ km due to collisional grinding, before being combined with the second generation.
383

384 First, we assessed the possibility of vestoid contamination of Bennu's parent body. Using the present-day
385 Vesta family, we calculated the intrinsic collision probability, P , and the impact velocity, V , between a
386 representative set of vestoids and Bennu's parent body given their semimajor axes (a), eccentricity (e), and
387 inclination (i) (e.g., see [53] for methodology). Dynamical models indicate that the source region of Bennu
388 could be the Polana (sometimes referred to as New Polana) or Eulalia asteroid families [24], with a 70% and
389 30% probability, respectively [24]. Accordingly, we considered each family's largest remnant as the putative
390 parent bodies: (142) Polana, with proper (a, e, i) of (2.4184 au, 0.1576, 3.316°), and (495) Eulalia, with proper
391 (a, e, i) of (2.4868 au, 0.1185, 2.516°). The sizes of the Eulalia and Polana parent bodies were estimated to be
392 at least 100 to 200 km in diameter, respectively [24]. We found that the average impact probability $\langle P \rangle$ of
393 vestoids impacting Polana and Eulalia is 8.9×10^{-18} and 8.6×10^{-18} impacts $\text{km}^{-2} \text{yr}^{-1}$, respectively, with
394 corresponding average impact velocities $\langle V \rangle$ of 3.5 and 4 km s^{-1} .

395 Next we considered direct contamination of Bennu's surface from meter-scale vestoid fragments. We
396 modeled Bennu test asteroids (assuming a 250 m radius) that were located within the Polana and the Eulalia
397 families at six different plausible locations in ($a, e, \sin i$) space (Supplementary Fig. 8). For the six test
398 asteroids, the value of $\langle P \rangle$ varies between 8.8×10^{-18} and 1.3×10^{-17} impacts $\text{km}^{-2} \text{yr}^{-1}$, and average impact
399 velocities $\langle V \rangle$ between 3.3 and 4.2 km s^{-1} . We modified our algorithm to account for orbital intersections
400 that correspond to lower impact velocities, $V < 2.6 \text{ km s}^{-1}$, for which we expect at least 20% of projectile
401 material to be retained as unmelted fragments on the porous granular target after impact [27, 28]. We note

402 here that observations of brecciated lithologies that included unmelted fragments were reported by Daly
403 and Schultz [60, 61] indicating that it is plausible for such fragments to be implanted at velocities up to 5 km
404 s^{-1} , though the proportion of unmelted material was not directly quantified by their studies. Due to the
405 different techniques to quantify the retention of preserved impactor material, we prefer to remain
406 conservative and use as cutoff $V < 2.6 \text{ km s}^{-1}$, noting that a higher cutoff velocity will improve the likelihood
407 of the scenarios under consideration here. Using the cutoff of $V < 2.6 \text{ km s}^{-1}$ also minimizes the possibility
408 that Bennu would have been catastrophically disrupted by the projectiles considered (see Crater Scaling
409 Model methods).

410 For the scenario where the impact velocity is $V < 2.6 \text{ km s}^{-1}$ we find that $\langle P \rangle$ of vestoids impacting Polana
411 and Eulalia is 1.4×10^{-18} and 2×10^{-18} impacts $\text{km}^{-2} \text{ yr}^{-1}$, respectively. On the Bennu test asteroids, $\langle P \rangle$ ranges
412 1.4×10^{-18} to 3.9×10^{-18} impacts $\text{km}^{-2} \text{ yr}^{-1}$. This demonstrates that average impact probabilities $\langle P \rangle$ of Vesta
413 family members impacting Polana, Eulalia, and Bennu (while it was in the main belt) are of the same order of
414 magnitude. From the ratio of probabilities calculated above with constrained and unconstrained impact
415 velocities, we conclude that between 16% (for Polana) and 23% (for Eulalia) of vestoids were available to
416 impact Bennu's parent body at $V < 2.6 \text{ km s}^{-1}$. Depending on whether its prior location was within either the
417 Polana and Eulalia families, as modeled by our six test asteroids, we find that anywhere from 10 to 44% of
418 vestoids were available to impact Bennu directly at $V < 2.6 \text{ km s}^{-1}$. This demonstrates that based on impact
419 probability alone, the likelihood of low-speed impacts between Bennu or its parent body and Vesta's
420 fragments are non-negligible. However, Eulalia and Polana would still capture more impactors by virtue of
421 their larger cross-sectional areas (exceeding Bennu's by a factor of 10^4 to 10^5).

422 We further assessed the likelihood of whether or not slow-moving impactors from the Vesta family could
423 have been added to Bennu. The number of impacts, N , that a target can undergo from a specific projectile
424 population can be approximated by [62]: $N = \langle P \rangle (A/\pi) \Delta T N_{\text{proj}}$, where A is the sum of the cross-section of
425 the target and of each impactor (i.e., π is included in $\langle P \rangle$, so we scale the A value by π), ΔT is the time
426 interval and N_{proj} is the number of potential impactors in a diameter range D (e.g. $N_{\text{proj}} = dN/dD \Delta D$). We
427 assumed that ΔT was 1 Ga, the approximate age of Bennu's source family [24], and that $(A/\pi) = 0.0625 \text{ km}^2$
428 (using a 250 m radius for Bennu). Poisson statistics control the number of impacts on a target; therefore, we
429 set $N = 3$ to have reasonable (95%) probability of at least one impact. By calculating $\langle P \rangle$ values for six Bennu
430 test asteroids, we determined that N_{proj} needs to be between 1.2×10^{10} and 3.4×10^{10} in order for Bennu to
431 have a 95% chance of experiencing at least one impact from a vestoid. We find that such values of N_{proj} in the
432 Vesta family size distribution correspond to meter-scale vestoids. Accordingly, it is plausible that some
433 meter-scale objects were added to Bennu.

434 While it is possible for meter-sized objects to strike Bennu at low velocities, we have not yet accounted for
435 how the projectiles will fragment upon impact. Our expectation is the surviving boulders will be smaller than
436 the observed boulders. It is possible that by adjusting parameters (e.g. considering impact speeds than < 4
437 km s^{-1}), we could deliver meter-scale boulders, for example 4 m in diameter, but that would not explain the
438 existence of the observed and intact 4 m boulder on Bennu.

439 An alternative scenario is that Bennu's parent body was contaminated by sufficient pyroxene impactors that
440 its disruption could plausibly produce the observed vestoid-like boulders on Bennu. Our goal here is to
441 conduct a plausibility study, such that certain details of the problem will be ignored for now. We believe
442 there are certain advantages in this hypothesis: (i) Bennu's parent body is large enough to withstand the
443 impacts of Vestoids that are many kilometers in size without difficulty, (ii) fragments produced by such an
444 impact can easily be both 1 to 4 m meters in size, and (iii) laboratory shot experiments into porous materials
445 indicate that craters on large carbonaceous chondrite bodies form in the compaction regime and produce
446 little ejecta; this suggests that considerable mass from the projectile would remain bound to the parent body

447 [63, 64].

448 For constraints, we first examined the meter-scale pyroxene-bearing boulders on Bennu. Their net volume is
449 at most $\sim 70 \text{ m}^3$ (Supplementary Table 1). We assumed that these boulders contaminated an exterior shell on
450 Bennu that is 3 to 5 m deep, yielding a volume of $2.3 \times 10^6 \text{ m}^3$ to $3.9 \times 10^6 \text{ m}^3$. If we assume that Bennu's
451 interior is as contaminated by exogenic boulders as its surface, the ratio of the two values, 3×10^{-5} to 1.8×10^{-5} ,
452 tells us the fraction of vestoid material that had to be included into the parent body material that
453 ultimately made Bennu. We call this target contamination value C_{target} .

454 Using the diameters above, the estimated volumes of Eulalia and Polana are $5.2 \times 10^{14} \text{ m}^3$ to $4.2 \times 10^{15} \text{ m}^3$. As
455 an upper limit, we assumed that any basaltic material that struck the surface of these bodies remained [63,
456 64]. If Bennu came from a disruption event that completely mixed the contaminated surface of the parent
457 body with its interior, the net volume of vestoids able to reproduce C_{target} corresponds to spherical impactors
458 with diameters of 2.6 to 3.1 km and 5.3 to 6.2 km for the 100- and 200-km parent bodies, respectively. The
459 question is whether this is plausible given what we know about the existing population of the Vesta family.

460 Using the equation $N = \langle P \rangle (A/\pi) \Delta T N_{\text{proj}}$, we can determine whether any of these projectile sizes could have
461 plausibly hit Bennu's parent body prior to its disruption. Using the data from the present-day Vesta family
462 (as shown in Supplementary Fig. 7), we find that $N_{\text{proj}} = 446$ and 30 for objects that range in diameter from
463 2.6 to 3.1 km and 5.3 to 6.2 km, respectively. The cross-section of the parent body is in the range of $A/\pi =$
464 2500 km^2 (for a 100-km diameter) to 10000 km^2 (for a 200-km diameter). As derived above, $\langle P \rangle$ is 8.9×10^{-18}
465 $\text{km}^{-2} \text{ yr}^{-1}$ to $8.6 \times 10^{-18} \text{ km}^{-2} \text{ yr}^{-1}$ for Polana and Eulalia, respectively. If $N = 3$, we find that time ΔT needed
466 to get the C_{target} level of contamination for the 100-km Eulalia parent body is 31 Ga, while for the 200-km
467 Polana parent body, it is 112 Ga. These values are much longer than the age of the Solar System, so we can
468 reject this scenario as described.

469 A more plausible scenario may be that the exterior shell of Bennu's parent body was contaminated by
470 multiple vestoids, and these were among the debris that reaccumulated to form Bennu following
471 catastrophic disruption. Such a scenario would require us to consider many additional aspects of the
472 collisional evolution of the vestoids (e.g., [65]). For example, the Vesta family size frequency distribution
473 shown in Supplementary Fig. 7 represents a simple estimate of the initial family size distribution, but
474 collisional evolution over the age of the family (as linked to the formation of the Rheasilvia and Veneneia
475 craters on Vesta) would require additional changes to reproduce the present-day family (e.g., additional $D >$
476 1-km bodies). This could lead to enhanced contamination, which in turn could compensate for the
477 possibility that the fraction of projectile material retained on the parent body is less than 1 (e.g., [57]; [63]).
478 Another factor is that Bennu's parent body could have sustained impacts from vestoids linked to the
479 formation Veneneia basin, ~ 2 Ga ago [31, 32] and prior to Bennu's formation ~ 1 Ga [24, 25, 26]. This would
480 increase the likelihood that the contamination occurred on the parent body rather than on Bennu.

481 Modelling these scenarios is complicated for several reasons: (1) There are no observational constraints on
482 the sub-kilometer population of vestoids. Thus, at a minimum, the extrapolated size-frequency distribution
483 cannot exceed the estimated ejected volumes of the basins on Vesta. (2) Collisions with main belt bodies
484 disrupt the Vesta family over time, and larger disruption events partially replenish the population of small
485 vestoids. The observed vestoid population loses bodies, so it represents a lower limit, while the estimated
486 extrapolated population does not account for collisional grinding, so it represents an upper limit. (3) It is
487 necessary to consider the formation ages of the Rheasilvia and Veneneia basins, whose creation produced
488 different components of the Vesta family, and the disruption age of Bennu's parent body, which was struck
489 by vestoids. In particular, because Rheasilvia basin overprints Veneneia, the surfaces of Veneneia were likely
490 modified by the later event. Accordingly, although Veneneia's estimated crater retention age is ~ 2 Ga, the

491 real age of Veneneia, as well as the oldest portion of the Vesta family, may be much older. Knowledge of the
492 precise age of Veneneia could help test our hypothesis.

493 Overall, however, computations performed here illustrate that it is plausible that vestoids could have been
494 added to either Bennu or its parent body. However, Bennu can likely only withstand impacts of lower speed,
495 whereas the parent body could capture more impactors due to its larger cross-sectional area and ability to
496 withstand higher-velocity collisions. Thus, it is more likely that contamination occurred on the parent body
497 than on Bennu.

498 **Crater Scaling Model**

499 We identified craters spatially associated with five of the six exogenic boulder sites. Sites 1, 2, and 3 are
500 clustered in and around a 42 m-diameter crater, Site 4 is close to the center of an 83 m-diameter crater, and
501 Site 6 is located in the southern wall of a 128-m-diameter crater. Although crater co-location may suggest a
502 common origin, indicating direct delivery to Bennu, crater scaling and catastrophic disruption laws suggest
503 otherwise.
504

505 There are two scenarios that may explain exogenic boulders in the context of direct contamination of Bennu:
506 1) three individual impacts that created the associated craters and left behind proximal pyroxene-bearing
507 boulders, or 2) a single impact event that produced a single crater, resulting in proximal and distal pyroxene-
508 bearing boulders. For both scenarios, we considered hypervelocity impacts at speeds of 3 km s^{-1} and 5 km s^{-1}
509 with corresponding projectile retention efficiencies of 20% [28] and 7% [66].

510 For the first scenario, the projectile retention efficiencies were used to derive the original diameter of the
511 pyroxene-bearing projectile corresponding to each of the three craters (labeled filled circles in
512 Supplementary Fig. 5). We combined the volumes of the pyroxene-bearing boulders in Sites 1, 2, and 3 to
513 calculate the size of a single projectile that created the co-located 42-m-diameter crater. We compared the
514 relationship between the projectile and crater sizes to strength- and gravity-dominated crater scaling laws
515 [66]. For both the 3 km s^{-1} and 5 km s^{-1} cases, the measured crater diameter is inversely proportional to the
516 calculated projectile size (Supplementary Table 2). This is contrary to crater scaling expectations, suggesting
517 that a multiple-impact scenario directly on Bennu is an unlikely explanation for the origin of the exogenic
518 boulders.

519 For the second scenario, the volumes of all six boulders were combined. The diameter of a single pyroxene-
520 bearing progenitor was then calculated for each impact speed case using the corresponding projectile
521 retention efficiency (unlabeled open circle in Supplementary Fig. 5). We used the largest co-located crater
522 (128-m diameter) to compare with crater scaling laws. We obtained an upper limit for a projectile size by
523 using the catastrophic disruption threshold for impacts onto a porous target [63, 64] with Bennu's size and
524 bulk density [44] (shaded region in Supplementary Fig. 5).

525 We find that an impact at 5 km s^{-1} by a single progenitor would exceed the catastrophic disruption threshold
526 (Supplementary Fig. 5b). An impact by that same progenitor at 3 km s^{-1} is below the threshold
527 (Supplementary Fig. 5a), and lies along the strength-dominated crater scaling relation (Supplementary Fig.
528 5a). This crater-scaling relation indicates a crater retention surface age of 0.1-1.0 Ga for the surface of Bennu
529 [33], which is compatible with the direct contamination collisional model outlined in the previous section.
530 However, we note the presence of a crater on the surface of Bennu with a diameter in excess of 200 m that,
531 if similarly scaled, would suggest an associated impactor with a specific impact energy that would exceed
532 the catastrophic disruption threshold.

533 Based on measurements of the craters on Bennu [33] and crater scaling laws, we find that direct
534 contamination on to Bennu by pyroxene projectiles is difficult. Of the scenarios explored here, the only

535 feasible pathway for direct contamination on Bennu would be an impact by a single 10.5-m-diameter
536 pyroxene projectile at a speed of 3 km s⁻¹. However, this would suggest a strength-dominated crater scaling
537 relationship (as shown by the open circle in Supplementary Fig. 5a, which lies on the solid red line). Use of a
538 strength-dominated scaling relationship implies that Bennu should have already been catastrophically
539 disrupted by the impactor that formed its largest craters (as the corresponding impactor diameter for such a
540 crater lies right on the catastrophic disruption threshold). Thus, it seems unlikely that a strength-dominated
541 scaling law is completely appropriate for Bennu, and therefore a direct contamination scenario less
542 plausible.

543
544 **Data availability:** The OCAMS (MapCam and PolyCam), OLA, and OVIRS data that support the findings and
545 plots within this paper are available from the Planetary Data System (PDS) at
546 <https://sbn.psi.edu/pds/resource/orex/ocams.html>, <https://sbn.psi.edu/pds/resource/orex/ola.html>, and
547 <https://sbn.psi.edu/pds/resource/orex/ovirs.html>, respectively. Data are delivered to the PDS according to
548 the schedule in the OSIRIS-REx Data Management Plan, available in the OSIRIS-REx mission bundle at
549 <https://sbnarchive.psi.edu/pds4/orex/orex.mission/document/>. Data shown in Supplementary Figs. 7 and 8
550 were obtained from the Minor Planet Physical Properties Catalogue (MP3C, <https://mp3c.oca.eu/>) of the
551 Observatoire de la Côte d’Azur.

552
553 **Code availability:** The collisional analysis reported here uses a custom code that is based established
554 methods described in Bottke et al. 1994 [53]; Avdellidou et al. 2018 [54]; Briani et al. 2011[55]; Gayon-Markt
555 et al. 2012 [56]; Turrini et al., 2014 and 2016 [57, 58]). The ISIS3 code used to generate the image processing
556 data products is a customized version of code available from the US Geological Survey–Astrogeology
557 Science Center: <https://isis.astrogeology.usgs.gov/>. The MGM code used to analyze OVIRS spectral data is
558 available from RELAB at Brown University: <http://www.planetary.brown.edu/mgm/>

559 **Letter References:**

- 561 1. Jenniskens, P. A. et al. The impact and recovery of asteroid 2008 TC₃. *Nature* **458**, 485 (2009).
- 562 2. Bischoff, A., Horstmann, M., Pack, A., Laubenstein, M. & Haberer, S. Asteroid 2008 TC₃—Almahata
563 Sitta: A spectacular breccia containing many different ureilitic and chondritic lithologies. *Meteoritics &*
564 *Planetary Science* **45**, 1638-1656 (2010).
- 565 3. McCord, T. B. et al. Dark material on Vesta from the infall of carbonaceous volatile-rich material. *Nature*
566 **491**, 83-86 (2012).
- 567 4. Reddy, V. et al. Delivery of dark material to Vesta via carbonaceous chondritic impacts. *Icarus* **221**, 554-
568 559 (2012).
- 569 5. Lauretta, D. S. et al. OSIRIS-REx: sample return from asteroid (101955) Bennu. *Space Science Reviews*
570 **212**, 925-984 (2017).
- 571 6. Hamilton, V. E. et al. Evidence for widespread hydrated minerals on asteroid (101955) Bennu. *Nature*
572 *Astronomy* **3**, 332-340 (2019).
- 573 7. Consolmagno, G. J. and Drake, M. J. Composition and evolution of the eucrite parent body: Evidence
574 from rare earth elements. *Geochim. Cosmochim. Acta* **41**, 1271-1282 (1977).
- 575 8. Binzel, R. P., and Xu, S. Chips off of Asteroid 4 Vesta: Evidence for the Parent Body of Basaltic
576 Achondrite Meteorites. *Science* **260**, 186-191 (1993).
- 577 9. Russell, C. T. et al. Dawn at Vesta: Testing the protoplanetary paradigm. *Science* **336**, 684-686 (2012).
- 578 10. Rizk, B. et al. OCAMS: the OSIRIS-REx camera suite. *Space Science Reviews* **214**, 26 (2018).
- 579 11. Lauretta, D. S. et al. The unexpected surface of asteroid (101955) Bennu. *Nature* **568**, 55-60 (2019).

- 580 12. DellaGiustina, D. N., et al. Properties of rubble-pile asteroid (101955) Bennu from OSIRIS-REx imaging
581 and thermal analysis. *Nature Astronomy* **3**, 341-351 (2019).
- 582 13. Reuter, D. C. et al. The OSIRIS-REx Visible and InfraRed Spectrometer (OVIRS): Spectral maps of the
583 asteroid Bennu. *Space Science Reviews* **214**, 55 (2018).
- 584 14. Cloutis, E. A. & Gaffey, M. J. Pyroxene spectroscopy revisited: Spectral-compositional correlations and
585 relationship to geothermometry. *Journal of Geophysical Research: Planets* **96**, 22809-22826 (1991).
- 586 15. Klima, R. L., Pieters, C. M. & Dyar, M. D. Characterization of the 1.2 μm M1 pyroxene band: Extracting
587 cooling history from near-IR spectra of pyroxenes and pyroxene-dominated rocks. *Meteoritics &*
588 *Planetary Science* **43**, 1591-1604 (2008).
- 589 16. Sunshine, J. M., Pieters, C. M. & Pratt, S. F. Deconvolution of mineral absorption bands: An improved
590 approach. *Journal of Geophysical Research: Solid Earth* **95**, 6955-6966 (1990).
- 591 17. Sunshine, J. M. et al. High-calcium pyroxene as an indicator of igneous differentiation in asteroids and
592 meteorites. *Meteoritics & Planetary Science* **39**, 1343-1357 (2004).
- 593 18. Burbine, T. H., et al. "Can Formulas Derived From Pyroxenes and/or HEDs Be Used to Determine the
594 Mineralogies of V-Type Asteroids?" *Journal of Geophysical Research: Planets* **123**, 1791-1803 (2018).
- 595 19. Brearley, A.J. & Jones, R. H., in *Planetary Materials*, Vol. 36 (Papike, J.J., ed.), pp. 3.001-3.398
596 (Mineralogical Society of America, 1998).
- 597 20. Cloutis, E. A. et al. Spectral reflectance properties of HED meteorites + CM2 carbonaceous chondrites:
598 Comparison to HED grain size and compositional variations and implications for the nature of low-
599 albedo features on Asteroid 4 Vesta. *Icarus* **223**, 850-877 (2013).
- 600 21. Le Corre, L. et al. How to characterize terrains on 4 Vesta using Dawn Framing Camera color bands?
601 *Icarus* **216**, 376-386 (2011).
- 602 22. Moskovitz, N. A. et al. A spectroscopic comparison of HED meteorites and V-type asteroids in the inner
603 Main Belt. *Icarus* **208**, 773-788 (2010).
- 604 23. Hardersen P. S. et al. Basalt or not? Near-infrared spectra, surface mineralogical estimates, and
605 meteorite analogs for 33 Vp-type asteroids. *The Astronomical Journal* **156**, 11 (2018).
- 606 24. Bottke, W. F. et al. In search of the source of asteroid (101955) Bennu: Applications of the stochastic
607 YORP model. *Icarus* **247**, 191-217 (2015).
- 608 25. Campins, H. et al. The origin of asteroid 162173 (1999 JU3). *The Astronomical Journal* **146**, 26 (2013).
- 609 26. Walsh, K. J., Delbó, M., Bottke, W. F., Vokrouhlický, D. & Lauretta, D. S. Introducing the Eulalia and new
610 Polana asteroid families: Re-assessing primitive asteroid families in the inner Main Belt. *Icarus* **225**, 283-
611 297 (2013).
- 612 27. Avdellidou, C., Price, M. C., Delbo, M., Ioannidis, P. & Cole, M. J. Survival of the impactor during
613 hypervelocity collisions–I. An analogue for low porosity targets. *Monthly Notices of the Royal*
614 *Astronomical Society* **456**, 2957-2965 (2016).
- 615 28. Avdellidou, C., Price, M. C., Delbo, M. & Cole, M. J. Survival of the impactor during hypervelocity
616 collisions–II. An analogue for high-porosity targets. *Monthly Notices of the Royal Astronomical Society*
617 **464**, 734-738 (2017).
- 618 29. Bottke Jr, W. F., et al. Linking the collisional history of the main asteroid belt to its dynamical excitation
619 and depletion. *Icarus* **179**, 63-94 (2005).
- 620 30. Burbine, T. H. et al. in *Asteroids III*, (W.F. Bottke et al., eds.) pp. 653-668 (Univ. of Arizona Press, 2002).

- 621 31. Schenk, P. et al. The geologically recent giant impact basins at Vesta's south pole. *Science* **336**, 694-697
622 (2012).
- 623 32. Spoto, F., Milani, A. and Knežević, Z., Asteroid family ages. *Icarus* **257**, 257-289 (2015).
- 624 33. Bischoff, A., Edward, R. D. S., Metzler, K. & Goodrich, C. A. in *Meteorites and the Early Solar System II*
625 (Lauretta, D. S. & McSween H. Y. Jr, eds.), pp. 679-712 (Univ. Arizona Press, 2006).
- 626 34. Walsh, K. J., et al. Craters, boulders and regolith of (101955) Bennu indicative of an old and dynamic
627 surface. *Nature Geoscience* **12**, 242-246 (2019).
- 628 35. Hirata, N., and M. Ishiguro. Properties and possible origin of black boulders on the asteroid Itokawa.
629 Lunar and Planetary Science Conference **42**, abstract no. 1821 (2011).
- 630 36. De León, J., et al. Expected spectral characteristics of (101955) Bennu and (162173) Ryugu, targets of the
631 OSIRIS-REx and Hayabusa2 missions. *Icarus* **313**, 25-37 (2018).
- 632 37. Sugita, S., et al. The geomorphology, color, and thermal properties of Ryugu: Implications for parent-
633 body processes. *Science* **364**, 6437 (2019).
- 634 38. Tatsumi, E., et al., Bright boulders suggest a collision between an S-type asteroid and Ryugu's parent
635 body. *Nature Astronomy*, **This Issue**
- 636 39. Ebert, S., et al. Accretion of differentiated achondritic and aqueously altered chondritic materials in the
637 early solar system—Significance of an igneous fragment in the CM chondrite NWA 12651. *Meteoritics &*
638 *Planetary Science* **55**, 2985-2995 (2019).
- 639 40. Kerraouch, I., et al., A light, chondritic xenolith in the Murchison (CM) chondrite. *Geochemistry* **79**,
640 125518 (2019).
- 641 41. Zolensky, M. E., et al. Mineralogy of carbonaceous chondrite clasts in HED achondrites and the Moon.
642 *Meteoritics & Planetary Science* **31**, 518-537 (1996).
- 643
- 644 **Methods References:**
- 645 42. Golish, D. R., et al. Ground and In-Flight Calibration of the OSIRIS-REx Camera Suite. *Space Science*
646 *Reviews* **216**, 12 (2020).
- 647 43. Golish, D. R., et al. Disk-resolved photometric modeling and properties of asteroid (101955) Bennu.
648 *Icarus*, In Press doi: <https://doi.org/10.1016/j.icarus.2020.113724> (2020).
- 649 44. Barnouin, O. S., et al. Shape of (101955) Bennu indicative of a rubble pile with internal stiffness. *Nature*
650 *Geoscience* **12**, 247-252 (2019).
- 651 45. DellaGiustina, D. N., et al. Overcoming the Challenges Associated with Image-Based Mapping of Small
652 Bodies in Preparation for the OSIRIS-REx Mission to (101955) Bennu. *Earth & Space Science* **5**, 929-949
653 (2018).
- 654 46. Daly, M. G., et al. The OSIRIS-REx laser altimeter (OLA) investigation and instrument. *Space Science*
655 *Reviews* **212**, 899-924 (2017).
- 656 47. Christensen, P.R. et al. The OSIRIS-REx thermal emission spectrometer (OTES) instrument. *Space*
657 *Science Reviews* **214**, 87 (2018).
- 658 48. Simon, A.A. et al. OSIRIS-REx visible and near-infrared observations of the Moon. *Geophys. Res. Letters*
659 **46**, 6322-6326 (2019).
- 660 49. Sunshine, Jessica M., and Carlé M. Pieters. Estimating modal abundances from the spectra of natural
661 and laboratory pyroxene mixtures using the modified Gaussian model. *Journal of Geophysical Research:*
662 *Planets* **98**, 9075-9087 (1993).

- 663 50. Reddy, V., et al. Mineralogy and surface composition of asteroids, in Asteroids IV (P. Michel et al., eds.),
664 pp. 43-63 (Univ. of Arizona Press, 2015).
- 665 51. Pieters, C. M., & T. Hiroi. RELAB (Reflectance Experiment Laboratory): A NASA multiuser spectroscopy
666 facility. Lunar and Planetary Science Conference 35, abstract no.1720 (2004).
- 667 52. Walsh, K. J., et al. Likelihood for rubble-pile near-earth asteroids to be 1st or Nth generation: focus on
668 Bennu and Ryugu. Lunar and Planetary Science Conference 51, abstract no. 2253 (2020).
- 669 53. Bottke, W. F., Nolan, M. C., Greenberg, R., & Kolvoord, R. A. Velocity distributions among colliding
670 asteroids. *Icarus* **107**, 255-268 (1994).
- 671 54. Avdellidou, C., Delbo, M. & Fienga, A. Exogenous origin of hydration on asteroid (16) Psyche: the role of
672 hydrated asteroid families. *Monthly Notices of the Royal Astronomical Society* **475**, 3419-3428 (2018).
- 673 55. Briani, G., Morbidelli, A., Gounelle, M. & Nesvorný, D. Evidence for an asteroid-comet continuum from
674 simulations of carbonaceous microxenolith dynamical evolution. *Meteoritics & Planetary Science* **46**,
675 1863-1877 (2011).
- 676 56. Gayon-Markt, J., et al. On the origin of the Almahata Sitta meteorite and 2008 TC₃ asteroid. *Monthly*
677 *Notices of the Royal Astronomical Society* **424**, 508-518 (2012).
- 678 57. Turrini, D., et al. The contamination of the surface of Vesta by impacts and the delivery of the dark
679 material. *Icarus* **240**, 86-102 (2014).
- 680 58. Turrini, D., et al. Olivine on Vesta as exogenous contaminants brought by impacts: Constraints from
681 modeling Vesta's collisional history and from impact simulations. *Icarus* **280**, 328-339 (2016).
- 682 59. Nesvorný, D., Miroslav, B., & Valerio C. Identification and dynamical properties of asteroid families. In
683 Asteroids IV (P. Michel et al., eds.) pp. 297-321 (Univ. of Arizona Press, 2015).
- 684 60. Daly, R. T., and Schultz, P. H. Delivering a projectile component to the vestan regolith. *Icarus* **264**, 9-19
685 (2016).
- 686 61. Daly, R. T., and Schultz, P. H. The delivery of water by impacts from planetary accretion to present.
687 *Science Advances* **4.4**, eaar2632 (2018).
- 688 62. O'Brien, D. P., and Sykes, M. V. The Origin and Evolution of the Asteroid Belt—Implications for Vesta
689 and Ceres. *Space Science Reviews* **163**, 41 (2011).
- 690 63. Housen, K. R., Sweet, W. J., Holsapple, K. A. Impacts into porous asteroids. *Icarus* **300**, 72-96 (2018).
- 691 64. Avdellidou, C., et al. Very weak carbonaceous asteroid simulants I: Mechanical properties and response
692 to hypervelocity impacts. *Icarus* **341**, 113648 (2020).
- 693 65. Bottke, W. F. et al. Interpreting the Cratering Histories of Bennu, Ryugu, and Other Spacecraft-explored
694 Asteroids. *The Astronomical Journal*, In Press doi: 10.3847/1538-3881/ab88d3
- 695 66. Holsapple, K. Theory and equations for craters from impacts and explosions. St. Louis, MO: Washington
696 University (2003).
- 697 67. Jutzi, M., Michel, P., Benz, W., Richardson, D.C. Fragment properties at the catastrophic disruption
698 threshold: The effect of the parent body's internal structure. *Icarus* **207**, 54-65 (2010).

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