Exogenic basalt on asteroid (101955) Bennu

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When rubble-pile asteroid 2008 TC₃ impacted Earth on October 7, 2008, the recovered rock fragments indicated that such asteroids can contain exogenic material. However, spacecraft missions to date have only observed exogenous contamination on large, monolithic asteroids that are imperiously linked to the CM carbonaceous chondrite meteorites. Delivery scenarios for such asteroids can contain exogenic material. However, spacecraft missions to date have only observed exogenous contamination on large, monolithic asteroids that are imperiously linked to the CM carbonaceous chondrite meteorites. Delivery scenarios for such asteroids can contain exogenic material.

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. 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 endogenic 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.

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

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

Spectra collected by the OSIRIS-Rex Visible and Infrared Spectrometer (OVIRS) show that these six bright boulders contain pyroxene, and not olivine, as indicated by a second absorption near 2 μm (Fig. 2c and Extended Data Fig. 1a). Pyroxene is a major rock-forming mineral in planetary materials, and numerous studies have quantitatively linked pyroxene compositions with spectral signatures at visible and near infrared wavelengths. Pyroxenes can crystallize in different systems (monoclinic clinopyroxenes and orthorhombic orthopyroxenes) and with differing calcium content chemistry. These factors influence the absorption bands I and II—near 1 and 2 μm—and yield a systematic relationship between high- and low-calcium pyroxene. The bright boulders studied here have band I centres that range from ~0.90 to 0.95 μm and band II centres from ~1.95 to 2 μm (Fig. 3a and Extended Data Fig. 1b).

Although band centres can be used to distinguish between pyroxene compositions, they are less diagnostic for mineral mixtures that contain multiple pyroxenes. Thus, we also applied the modified Gaussian model (MGM) to OVIRS spectra of the bright boulders (Fig. 2c and Extended Data Fig. 1a); this allowed us to resolve overlapping absorption features near 1 and 2 μm that arise from different mafic silicates. A principal application of MGM is to separate absorptions of high-calcium pyroxene (HCP) from those of low-calcium pyroxene (LCP) to estimate the abundance of HCP as a percentage of total pyroxene (HCP%). HCP% is an indicator of igneous differentiation in asteroids because as chondritic material melts, the partial melt is enriched in HCP, and the residue is strongly depleted in HCP.
studies, however, indicate that the reflectance of eucrite samples position of Bennu 6. In terms of both estimated HCP% and band appearance may result from variable illumination caused by the texture of 2 and 3, this may be indicative of brecciation. The boulders at sites 5 e pyroxene-bearing clasts that appear embedded within a large partially be resting on the surface of the asteroid, site 4 includes two bright d to be resting on the surface of the asteroid, site 4 includes two bright pyroxene-bearing boulders on Bennu correspond to centres, the pyroxene-bearing boulders on Bennu correspond to matte of low-albedo endogenous material from Bennu, thereby decreas- ing their overall reflectance. Additionally, the pyroxene-bearing boulder with the highest albedo also shows the deepest 1 μm band (Fig. 2b), suggesting that boulder brightness may correspond to pyroxene exposure.

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

Dynamical models suggest that Bennu's parent body, which was >100 km, disrupted ~0.8 to 1.5 billion years (Ga) ago from an inner main belt asteroid family, resulting in the formation of Bennu. After its formation, Bennu drifted across the inner main belt to a dynamical resonance that would take it to its current near-Earth orbit, a few million years (Ma) to tens of Ma ago (refs. 19–21). En route, Bennu may have been impacted by one or more small vestoids, leaving behind the observed exogenic boulders. Alternatively, Bennu's parent body could have been contaminated by vestoids, which litter the present-day inner main belt. The impactors would have left behind metre-scale or larger material near or on the surface. When Bennu's parent body was subsequently disrupted, Bennu would have been created from a scramble of parent body and exogenic debris.

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

Another possibility is that Bennu accumulated from the remnants of a catastrophic collision between its precursor and a vestoid. Vestoids, however, do not dominate the present-day main belt at small sizes, and meteorites from Vesta only account for 6% of falls. It is conceivable that circumstances existed shortly after the formation epochs of the vestoids, near 1 and 2 Ga (refs. 21–23), where Vesta fragments dominated the main belt at small sizes for a brief period of time. Even so, the probabilities of creating and preserving Bennu under this scenario remain small (Methods).

This leads us to favour the parent body scramble scenario. Although modelling this scenario presents several complexities, the longer lifetime and larger surface area of the parent body relative to Bennu would have resulted in a higher number of probable impacts (Methods). Furthermore, the parent body was large enough to withstand high-velocity projectiles that would disrupt Bennu, increasing its overall relative number of probable impacts. The parent body scramble scenario is also consistent with the geological setting of the exogenic boulders. Although half are proximal to putative impact craters, crater scaling relationships show it is unlikely powders; a similar effect can be observed by linearly combining spectra from carbonaceous chondrite and pyroxene from various meteorites in the visible wavelengths (Methods and Supplementary Fig. 3). On Vesta, dark terrains have been attributed to the infall of low-albedo carbonaceous material and have a reflectance that is 2–3 times less than endogenous bright surface units. It is therefore possible that the exogenic boulders have been optically mixed with low-albedo endogenous material from Bennu, thereby decreasing their overall reflectance.

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

A difference is that HED meteorites are nearly five times brighter than the exogenic boulders that we observe on Bennu. Laboratory studies, however, indicate that the reflectance of eucrite samples exponentially decreases as they are mixed with CM meteorite powders; a similar effect can be observed by linearly combining spectra from carbonaceous chondrite and pyroxene from various meteorites in the visible wavelengths (Methods and Supplementary Fig. 3). On Vesta, dark terrains have been attributed to the infall of low-albedo carbonaceous material and have a reflectance that is 2–3 times less than endogenous bright surface units. It is therefore possible that the exogenic boulders have been optically mixed with low-albedo endogenous material from Bennu, thereby decreasing their overall reflectance. Additionally, the pyroxene-bearing boulder with the highest albedo also shows the deepest 1 μm band (Fig. 2b), suggesting that boulder brightness may correspond to pyroxene exposure.

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that the exogenic boulders produced those craters (Methods, and Supplementary Fig. 5 and Supplementary Table 2). Moreover, at site 4, we observe bright pyroxene-bearing clasts embedded within the darker host matrix of a larger partially buried boulder (diameter ~5 m) whose overall colour and albedo are similar to Bennu’s average surface (Fig. 1d and Supplementary Fig. 6). This suggests that the boulder is an impact breccia (rather than two distinct rocks), and comparable textures observed at sites 2 and 3 may be further examples of breccias. If so, these are likely to have originated on Bennu’s parent body, because metre-scale brecciation requires energies that would disrupt Bennu33,34.

It is not yet clear why we observe HED-like boulders and no other exogenic material on Bennu, but higher-resolution data from regional OSIRIS-REx mission phases, and ultimately analysis of the returned sample, may reveal contributions from other impactors. For now, the presence of HED lithologies offers insights into other small asteroids; assuming that Bennu is representative, metre-scale exogenic material should exist on many and may not have been detected owing to observational limitations. This is consistent with previous studies that speculated that dark boulders found on the small (~0.3 km) S-type asteroid Itokawa are exogenous in origin35. Additionally, our observations complement the finding of ordinary

Fig. 2 | Physical and spectrophotometric properties of Bennu’s bright pyroxene-bearing boulders. a, The bright pyroxene-bearing boulders (coloured circles) are observed in the equatorial to southern latitudes on Bennu and their distribution appears non-uniform, perhaps owing to resolution limitations at scales ≤1 m in the global OSIRIS-REx MapCam data. The diameter of each circle indicates the relative size of the boulder (not to scale with the background basemap). Three boulders form a cluster near 60° longitude, but the others are more distributed. b, The 0.70/0.85 µm band ratio for each boulder from MapCam (25 cm pixel⁻¹) versus its panchromatic normal reflectance from PolyCam (7 cm pixel⁻¹) data. Colours correspond to a and error bars signify the radiometric uncertainty of reflectance values (Methods). Bennu’s global average 0.70/0.85 µm band ratio and normal reflectance are shown for context (dashed lines) along with their 1σ variation (blue shaded envelopes). c, The OVIRS spectrum for each site (colours correspond to a) divided by the global average OVIRS spectrum of Bennu. The OVIRS spot size is approximately 20 m for these spectra; therefore, the boulders occupy <1% of the field of view (Supplementary Fig. 2). Dividing by the global average spectrum of Bennu highlights the subtle absorption features associated with the boulders. The band depth at 0.92 µm (dashed line) is labelled for each spectrum just below the absorption feature to show the relative strength of the band I centre for every boulder. The spectra are offset vertically for clarity. n/a, not available.
chondrite-like boulders on (162173) Ryugu, the ~1-km rubble-pile target of the Hayabusa2 mission that is similar to Bennu in terms of its albedo and composition. Differing eogenetic lithologies on Bennu and Ryugu indicates that they may have experienced different collisional histories.

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

Methods

Image data processing. Bennu’s average terrain exhibits a much lower albedo than the exogenic boulders described in this study. Thus, in many MapCam and PolyCam images, these boulders are saturated. All reflectance information reported here was derived from unsaturated pixels (>98% radiometric linearity); saturated pixels (data number (DN) > 14,000 in uncalibrated 1.0 MapCam images, DN > 12,500 in uncalibrated 1.0 PolyCam images) were discarded from our analysis. OCAMS images were calibrated into units of reflectance (also known as radiance factor or \( I/F \)) with a 5% absolute radiometric uncertainty according to procedures described in ref. 42. Images were binned in false colours representing the ratio of the LCP to the HCP band strengths for the pyroxene-bearing boulders on Bennu as determined by applying the MGM to their OVIRS spectra. The ranges for meteorites, including eucrites, ordinary chondrites and the HED meteorites.

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

Global OSIRIS data were acquired at 12:30 and 19:00 LST during the Detailed Survey Equatorial Station observations on 9 May 2019 and 16 May 2019, respectively. Spectra were obtained in north-to-south spacecraft scans that mapped
Bennu’s surface as the asteroid rotated. Individual filter segments are converted from calibrated radiation to J/F by resampling onto a continuous wavelength axis, subtracting a modelled thermal emission and dividing by range-corrected solar flux. Derived wavelengths are the spectral positions that, because of very shallow band depths of 1% or less, and the best method for displaying them is to divide by a global average spectrum to remove any spectral artefacts or other globally prevalent absorption signatures. The global average was calculated using ~2,000 OVIRS spectra acquired at the same lst and has a weak linear blue slope of less than ~1%/100 nm from 0.5–2.5 μm (Supplementary Fig. 4). After dividing, all spectra by the global average, regions with potential pyroxene signatures were identified by a manual search and by an automated search for a broad absorption feature at 0.92 μm. Both methods identified the same locations for the strongest signatures, corresponding to the brightest boulders in the OCAMS images.

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

In the global data, the OVIRS field of view was continuously scanned across the surface, and regions with sharply contrasting features can show ‘jumps’ in the spectrum from 0.4 to 0.66 μm or 0.66 to 1.08 μm, as different wavelength regions were acquired over a slightly different part of the surface. Thus, the manual inspection was necessary to rule out false positives to identify other nearby spectra that were missed in the automated search. Any jumps were corrected by adjusting that portion of the spectrum to match the absolute brightness of the spectrum on either side of the jump. Co-located detections were averaged together to produce a site-averaged spectrum, which was then smoothed using a 5 Gaussian kernel. Finally, the continuum was removed using a linear fit between 0.7 and 2.5 μm. Uncertainties in the 0.92 μm band depth were estimated using a five-channel standard deviation in the unsmoothed data.

To determine band centres, we fit Gaussian curves to the 1 and 2 μm pyroxene absorption bands in the continuum-removed ratioed spectra and found the Gaussian centre wavelength. We used a Monte Carlo approach to calculate uncertainty on model output parameters by systematically varying the model starting conditions. Although the MGM has built-in methods for estimating uncertainty on each model parameter from known physical properties, we do not have knowledge of the a priori uncertainty given that these are spacecraft detection of unknown materials with unknown origin. Therefore, we ran the model 10,000 times and changed the initial Gaussian band centre estimates for each of the seven Gaussians by an independent, random amount (uniformly distributed between ±0.2 μm in the 0.6–2.6 μm range; Supplementary Table 1) for each model run. We recorded initial band positions and model results, using the full set of 10,000 runs to estimate uncertainty values on each parameter; a model was considered successfully fit if the full set of results converged, and we found that in all cases we were able to use the same set of starting parameters and achieve model convergence.

Average Gaussian amplitudes from the MGM runs were used to calculate the ‘component band strength ratio’ (m), or the ratio of LCP to HCP band strengths. We used the ratio of band strengths in the 1 μm band, rather than the 2 μm band, because of potential uncertainty in the 2 μm band calibrations due to temperature.

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

We considered an areal ratio in the order of 4% for the basaltic material and 8% for carbonaceous material. The combination can be expressed with the formula

$$R_i = A \times R_{ci} + B \times R_{ba},$$

where $R_i$ is the reflectance spectrum, $R_{ci}$ is the median spectrum of CI/CM chondrites, $R_{ba}$ is the pyroxene-bearing boulder spectrum from 0.4 to 2.6 μm, and $A$ and $B$ are the proportions of CI/CM chondrites and basaltic material, respectively.

By searching all possible combinations, we found that the spectrophotometric match observed for the MapCam pyroxene-bearing boulders is best fit by linear combinations of 5–20% of various meteoritic pyroxenes with 95–80% carbonaceous chondrites (CMs and CIIs). This is exemplified in Supplementary Fig. 5, which shows that a small amount of basaltic material mixed with CM material can result in the observed effect. The best fit obtained for the pyroxene-bearing boulder in site 1 corresponds to a combination of the spectrum (A = 20%) of ALHA77005,193 pyroxene (sample ID: DD-MMD-034, RELAB file: CEM-MS-CMP-002-E, RELAB file: CEMS092).

Collisional model. We examined whether Bennu or its parent body could have been plausibly contaminated by debris from the vestoids. We also explored whether the pyroxene-bearing boulders could have come from the disruption of Bennu’s contaminated parent body. For the latter, we assume that Bennu is a first-generation rubble pile based on work that shows that the fraction of bodies that escape the Polana and Eulalia asteroid families are dominated by first-generation objects. This is in contrast to the possible intermediate parent body hypothesis for the Vestas family (Extended Data Fig. 1). We used a Monte Carlo approach to calculate uncertainty on model output parameters by systematically varying the model starting conditions. Although the MGM has built-in methods for estimating uncertainty on each model parameter from known physical properties, we do not have knowledge of the a priori uncertainty given that these are spacecraft detection of unknown materials with unknown origin. Therefore, we ran the model 10,000 times and changed the initial Gaussian band centre estimates for each of the seven Gaussians by an independent, random amount (uniformly distributed between ±0.2 μm in the 0.6–2.6 μm range; Supplementary Table 1) for each model run. We recorded initial band positions and model results, using the full set of 10,000 runs to estimate uncertainty values on each parameter; a model was considered successfully fit if the full set of results converged, and we found that in all cases we were able to use the same set of starting parameters and achieve model convergence.

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respectively. On the Bennu test asteroids, \(<P>\) ranges from 1.4 × 10^{-18} to 3.9 × 10^{-18} impacts km⁻² yr⁻¹. This demonstrates that average impact probabilities \(<P>\) of Vesta family members impacting Polana, Eulalia and Bennu (while it was in the main body) are of the order of magnitude of calculated values. Calculations based on constrained and unconstrained impact velocities, we conclude that between 16% (for Polana) and 23% (for Eulalia) of vestoids were available to impact Bennu's parent body at \(V < 2.6 \text{ km s}^{-1}\). Depending on whether its previous location was within either the Polana or Eulalia families, as modelled by our six test asteroids, we find that anywhere from 10 to 44% of vestoids were available to impact Bennu directly at \(V > 2.6 \text{ km s}^{-1}\). This demonstrates that based on impact probability alone, the likelihood of low-speed impacts between Bennu or its parent body and Vestas' fragments are non-negligible. However, Eulalia and Polana would still capture more impactors by virtue of their larger cross-sectional areas (exceeding Bennu's by a factor of 10 to 100).

We assumed a likelihood of whether or not slow-moving impactors from the Vestas family could have been added to Bennu. The number of impacts, \(N\), that a target can undergo from a specific projectile population can be approximated by:

\[
N = \frac{\langle P \rangle (A/\pi) \Delta T N_{\text{proj}}}{\Delta A},
\]

where \(A\) is the cross-sectional area of the target and \(\Delta A\) is the interval of time over which the target was observed. We set \(N = 3\) to have reasonable (95%) probability of at least one impact. By calculating \(<P>_\text{Vesta}\) for six Vesta family members, we determined that the probability of an impact on Bennu is 20% (ref. \(30\)).

We assumed that \(\Delta T\) was 1 G, the approximate age of Bennu's source family\(^2\), and that \(A/N\) was 0.0625 km². Poisson statistics control the number of impacts on a target; therefore, we set \(N = 3\) to have reasonable (95%) probability of at least one impact. By calculating \(<P>_\text{Vesta}\) for six Vesta family members, we determined that the probability of an impact on Bennu is 20% (ref. \(30\)).

While it is possible for metre-sized objects to strike Bennu at low velocities, we have no evidence for how the projectiles will fragment upon impact. Our expectation is the surviving boulders will be smaller than the observed boulders. It is possible that by adjusting parameters (for example, considering impact speeds \(<4 \text{ km s}^{-1}\)), we could deliver metre-scale boulders, perhaps up to 4 m in diameter, but that would not explain the existence of the observed and intact 4 m boulder on Bennu.

An alternative scenario is that Bennu's parent body was contaminated by sufficient pyroxene impactors that its disruption could plausibly produce the observed vestoid-like boulders on Bennu. Our goal here is to conduct a plausibility study, such that certain details of the problem will be ignored for now. We believe there are certain advantages in this hypothesis: (1) Bennu's parent body is large enough to withstand the impacts of vestoids that are many kilometres in size without difficulty, (2) fragments produced by such an impact can easily be 1 to 4 m in size, and (3) laboratory shot experiments into porous materials indicate that craters on large carbonaceous chondrite bodies form in the compaction regime and produce little ejecta; this suggests that considerable mass from the projectile would remain bound to the parent body\(^4\).

For constraints, we first examined the metre-scale pyroxene-bearing boulders on Bennu. Their net volume is at most ~70 m³ (Supplementary Table 1). We assumed that these boulders contaminated an exterior shell on Bennu that is 3 to 5 m deep, yielding a volume of 2.3 × 10^{10} m³ to 3.9 × 10^{10} m³ if we assume that Bennu's interior is contaminated by pyroxene boulders as its surface, the ratio of the two values, 3.5 × 10^{10} to 1.8 × 10^{10}, tells us the fraction of vestoid material that had to be included into the parent body material that ultimately made Bennu. We call this target contamination value \(C_{\text{target}}\).

Using the diameters above, the estimated volumes of Eulalia and Polana are 5.2 × 10^{10} m³ to 4.2 × 10^{10} m³. As an upper limit, we assumed that any basaltic material that struck the surface of these bodies remained\(^5\). If Bennu came from a disruption event that completely mixed the contaminated surface of the parent body with its interior, the net volume of vestoids able to reproduce \(C_{\text{target}}\) corresponds to spherical impactors with diameters of 2.6 to 3.1 km and 5.3 to 6.2 km for the 100-km and 200-km parent bodies, respectively. The question is whether this is plausible given what we know about the existing population of the Vestas family.

Using the equation \(\langle P \rangle = A(N/\pi) \Delta T N_{\text{proj}}\), we can determine whether any of these projectile sizes could have plausibly hit Bennu's parent body before its disruption. Using the data from the present-day Vestas family (as shown in Supplementary Fig. 7), we find that \(N_{\text{proj}}\) is ~446 and 30 for objects that range in diameter from 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 \(A/\pi = 2.5\times10^{10}\) m² (for a 100-km diameter) to 10,000 m² (for a 200-km diameter). As derived above, \(\langle P \rangle\) is 8.9 × 10^{-18} km⁻² yr⁻¹ and 8.6 × 10^{-19} km⁻² yr⁻¹ for Polana and Eulalia, respectively. If \(N = 3\), we find that the time \(\Delta T\) needed to get the \(C_{\text{target}}\) level of contamination for the 100-km Eulalia parent body is 31 Ga, while for the 200-km Polana parent body, it is 112 Ga. These values are much longer than the age of the Solar System, so we can reject this scenario as described.

A more plausible scenario may be that the exterior shell of Bennu's parent body was contaminated by multiple vestoids, and these were among the debris that reaccumulated to form Bennu following catastrophic disruption. Such a scenario would require us to consider many additional aspects of the collisional evolution of the vestoids\(^6\). For example, the Vestas family size–frequency distribution shown in Supplementary Fig. 7 represents a simple estimate of the initial family size distribution, but collisional disruption (as linked to the formation of the Rhesiavilla and Veneneia craterers on Vestas) would require additional changes to reproduce the present-day family (for example, additional \(D > 1 \text{ km bodies}\)). This could lead to enhanced contamination, which in turn could compensate for the possibility that the fraction of projectile material retained on the parent body is less than 1%. Another factor to consider is that Bennu's parent body could have sustained impacts from vestoids linked to the formation of the Veneneia basin, ~2 Ga (refs. \(31\),\(^\*)\) and before Bennu's formation ~1 Ga (refs. \(10\),\(^\*)\). This would increase the likelihood that the contamination occurred on the parent body rather than on Bennu.

Modelling these scenarios is complicated for several reasons. First, there are no observational constraints on the sub-kilometre population of vestoids. Thus, we face a significant discrepancy in understanding the size–frequency distribution of Vestas family members impacting Bennu. The number of impacts, \(\langle P \rangle\), is constrained by the nebular model outlined in the previous section. However, we note the presence of a crater scaling relation indicates a crater retention surface age of 0.1–1.0 Ga for the parent body. In particular, because Rhesiavilla basin overprints Veneneia, the surfaces of Veneneia were likely modified by the latter event. An older crater ring would suggest an associated impactor with a specific impact energy that would correspond to metre-scale vestoids. Accordingly, it is plausible that contamination occurred on the parent body rather than on Bennu.

Crase scaling model. We identified craters spatially associated with five of the six exogenic boulder sites. Sites 1, 2 and 3 are clustered in and around a 42-m-diameter crater, site 4 is close to the centre of an 83-m-diameter crater and site 5 is located in the southern wall of a 128-m-diameter crater. Although crater co-location may suggest a common origin, indicating direct delivery to Bennu, crater scaling and catastrophic disruption laws suggest otherwise. There are two scenarios that may explain exogenic boulders: (1) direct contamination of Bennu: (1) three individual impacts that created the associated craters and left behind proximal pyroxene-bearing boulders, or (2) a single impact event that produced a single crater, resulting in proximal and distal pyroxene-bearing boulders. For both scenarios, we considered hypervelocity impacts at speeds of 3 km s⁻¹ to 5 km s⁻¹ with corresponding projectile retention efficiencies of 20%\(^1\) and 7%\(^2\).

For the first scenario, the projectile retention efficiencies were used to derive the original diameter of the pyroxene-bearing projectile corresponding to each of the three craters (labelled circles in Supplementary Fig. 5). We combined the sizes of the boulders in site 4 estimation (labelled open circle in Supplementary Fig. 5). We used the largest co-located crater (128-m diameter) to compare with crater scaling laws. We obtained an upper limit for a projectile size by using the catastrophic disruption threshold for impacts on a porous target\(^3\)\(^\*\) with Bennu's size and bulk density\(^4\) (shaded region in Supplementary Fig. 5).

We find that an impact at 5 km s⁻¹ by a single progenitor would exceed the catastrophic disruption threshold (Supplementary Fig. 5b). An impact by that same progenitor at 3 km s⁻¹ is below the threshold (Supplementary Fig. 5a), and lies along the strength-dominated crater scaling relation (Supplementary Fig. 5a). This crater scaling relation indicates a crater retention surface age of 0.1–1.0 Ga for the surface of Bennu\(^2\), which is compatible with the direct contamination collisional model outlined in the previous section. However, we note the presence of a crater on the surface of Bennu with a diameter in excess of 200 m that, if similarly scaled, would suggest an associated impactor with a specific impact energy that would exceed the catastrophic disruption threshold.

Based on measurements of the craters on Bennu\(^2\) and crater scaling laws, we find that direct contamination on to Bennu by pyroxene projectiles is difficult. Of
the scenarios explored here, the only feasible pathway for direct contamination on Bennu would be an impact by a single 10.5-m-diameter pyroxene projectile at a speed of 3 km/s. However, this would suggest a strength-dominated crater scaling relationship (as shown by the open circle in Supplementary Fig. 5a, which lies on the solid red line). Use of a strength-dominated scaling relationship implies that Bennu should have already been catastrophically disrupted by the impactor that formed its largest craters (as the corresponding impactor diameter for such a crater lies right on the catastrophic disruption threshold). Thus, it seems unlikely that a strength-dominated scaling law is completely appropriate for Bennu, and therefore a direct contamination scenario less plausible.

**Data availability**

The OCAMS (MapCam and PolyCam), OLA and OVIRS data that support the findings and plots within this paper are available from the Planetary Data System (PDS) at https://sbn.psi.edu/pds/resource/orex/ocams.html, https://sbn.psi.edu/pds/resource/orex/ovirs.html, respectively. Data are delivered to the PDS according to the schedule in the OSIRIS-REx Data Management Plan, available in the OSIRIS-REx mission bundle html, respectively. Data are delivered to the PDS according to the schedule in the OSIRIS-REx mission bundle html, respectively. Data are delivered to the PDS according to the schedule in the OSIRIS-REx mission bundle html, respectively. Data are delivered to the PDS according to the schedule in the OSIRIS-REx mission bundle html, respectively.

The OCAMS (MapCam and PolyCam), OLA and OVIRS data that support the findings and plots within this paper are available from the Planetary Data System (PDS) at https://sbnarchive.psi.edu/pds4/orex/orex.mission/document/. Data shown in Supplementary Figs. 7 and 8 were obtained from the Minor Planet Physical Properties Catalogue (MPFSC, https://mpfsc.oca.eu/) of the Observatoire de la Côte d’Azur.

**Code availability**

The collisional analysis reported here uses a custom code that is based on established methods described in refs. 21,22. The ISIS code used to generate the image processing data products is a customized version of code available from the US Geological Survey–Astrogeology Science Center: https://isis.astrogeology.usgs.gov/. The MGM code used to analyse OVIRS spectral data is available from RELAB at Brown University: http://www.planetary.brown.edu/mgm/.

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Extended Data Fig. 1 | Comparing high- and low-resolution OVIRS spectra of site 6.  

**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 (~1.4 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.