
Supplementary information

Exogenic basalt on asteroid (101955) Bennu

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Supplementary Information | Exogenic Basalt on Asteroid (101955) Bennu

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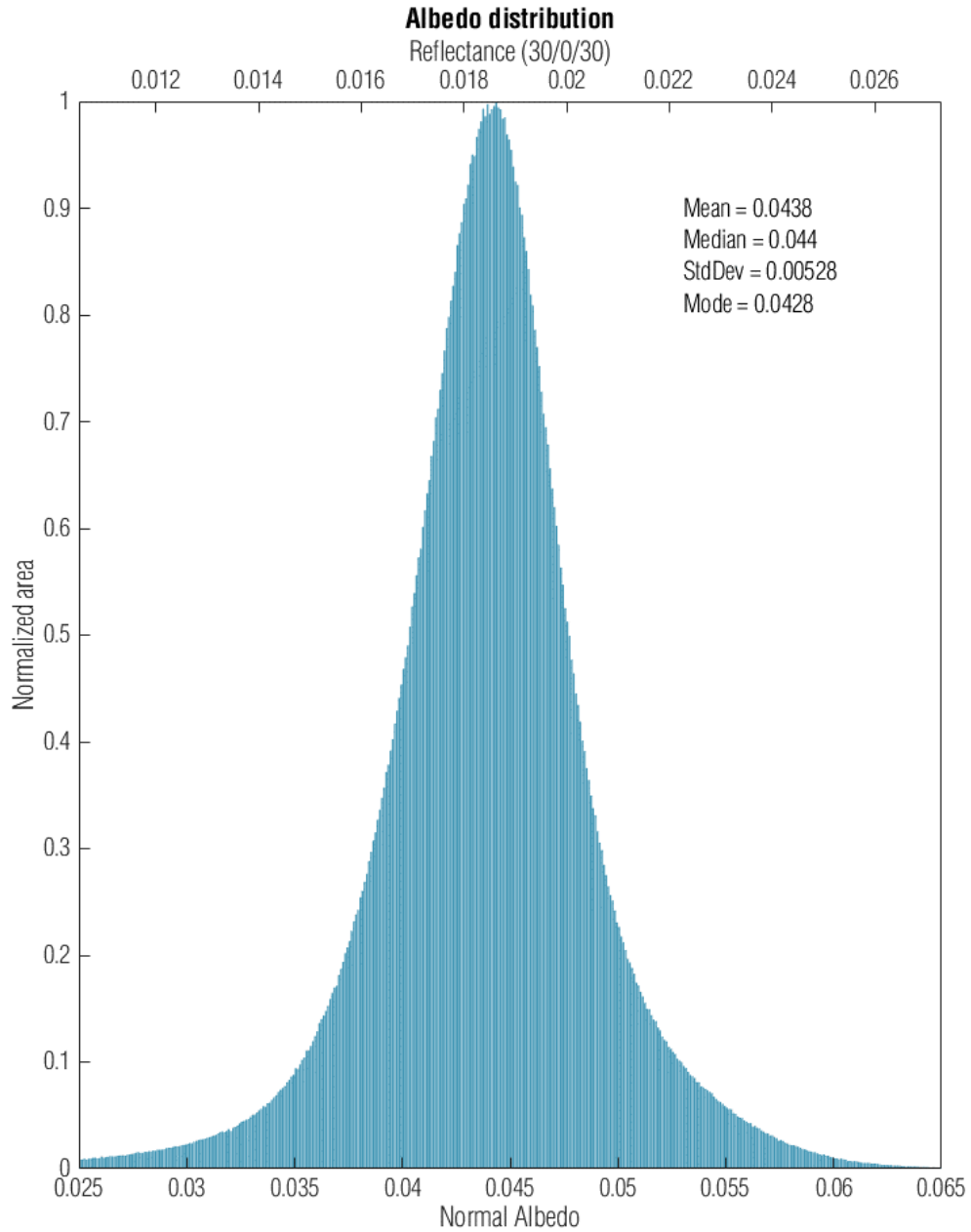
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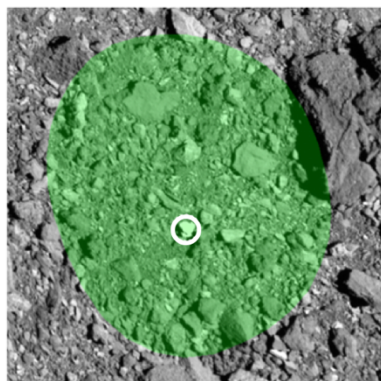
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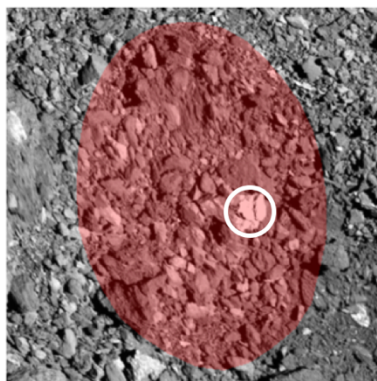
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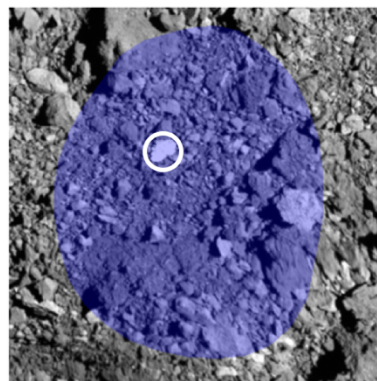
Supplementary Figure 1 | The global reflectance distribution of Bennu. The reflectance frequency distribution of Bennu in units of normal reflectance (albedo) (0, 0, 0) and standard reflectance (30, 0, 30) at approximately 32 cm/pixel from panchromatic MapCam data (see methods).



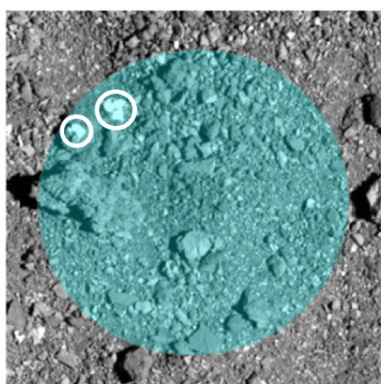
Site 1
-37.5°, 52.6°



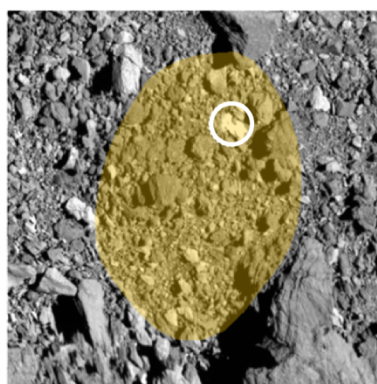
Site 2
-51.6°, 60.9°



Site 2
-47.2°, 68.1°



Site 4
-4.4°, 150.9°

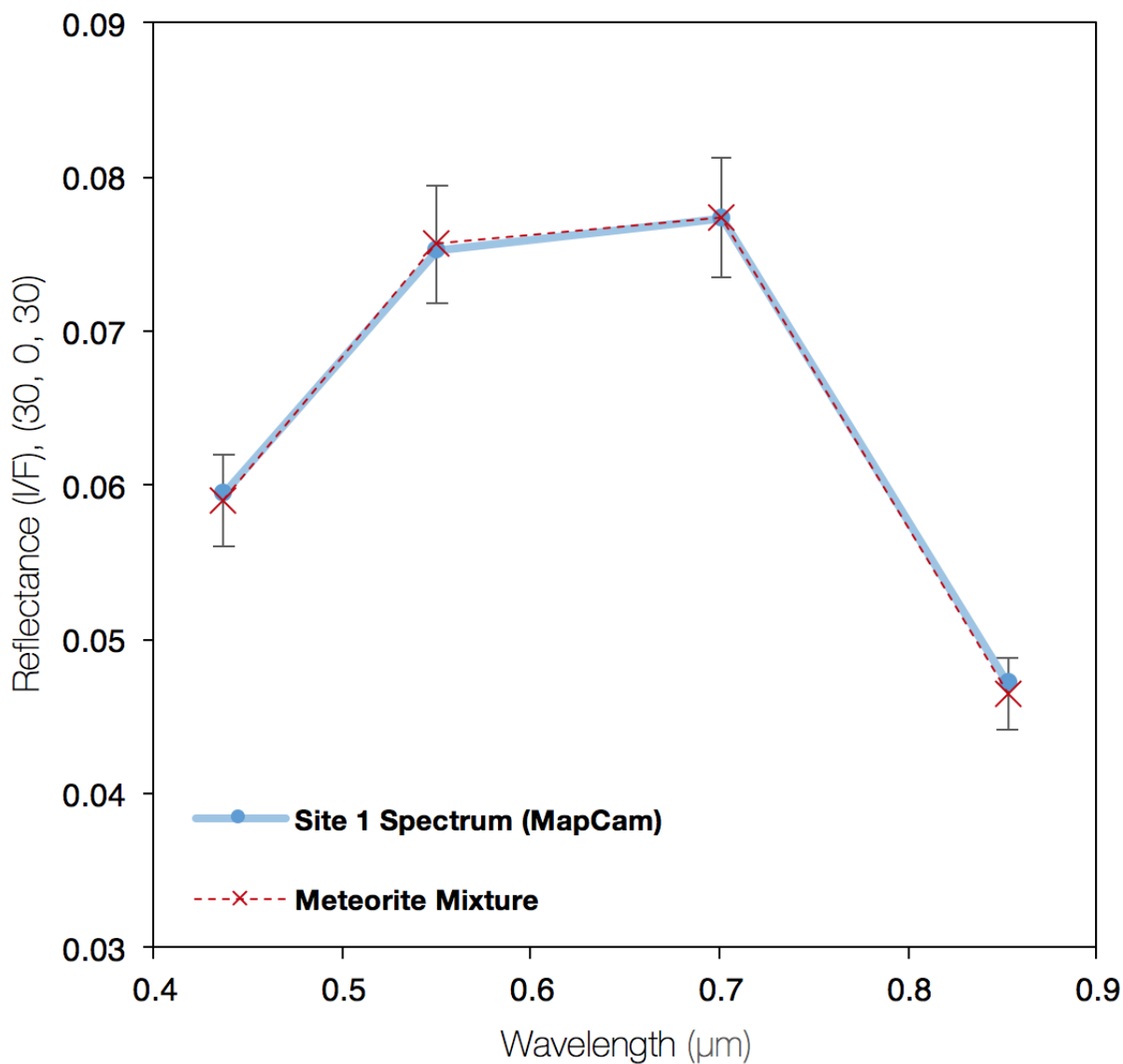


Site 4
-44.6°, 166.4°

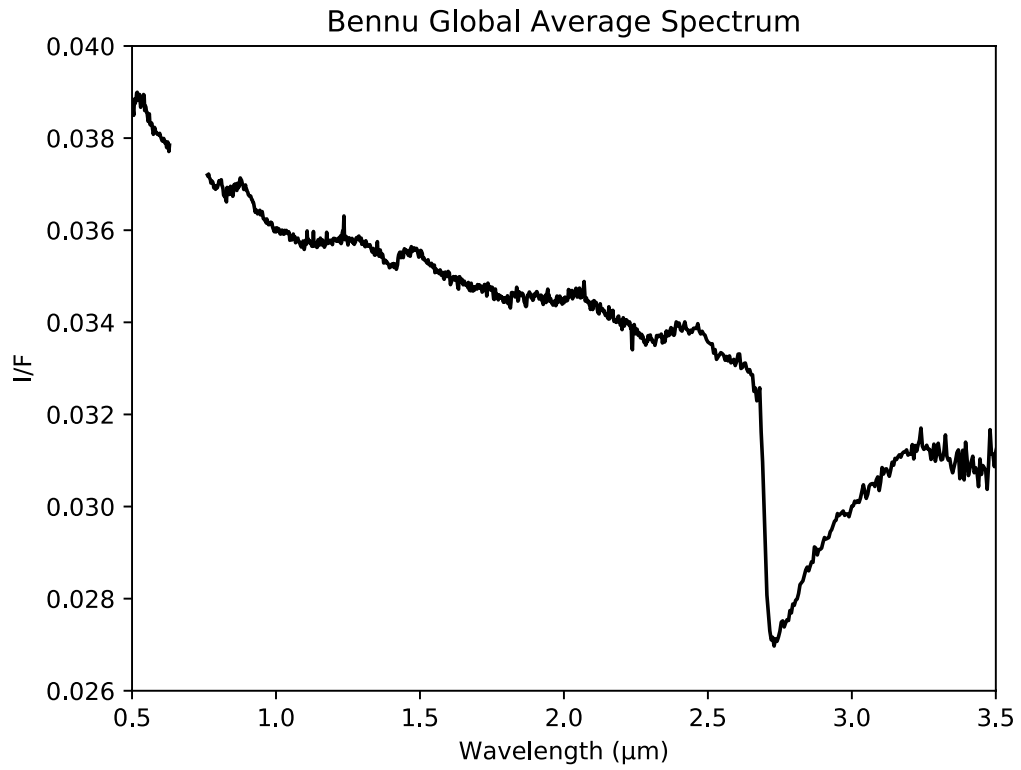


Site 6
11.7°, 190°

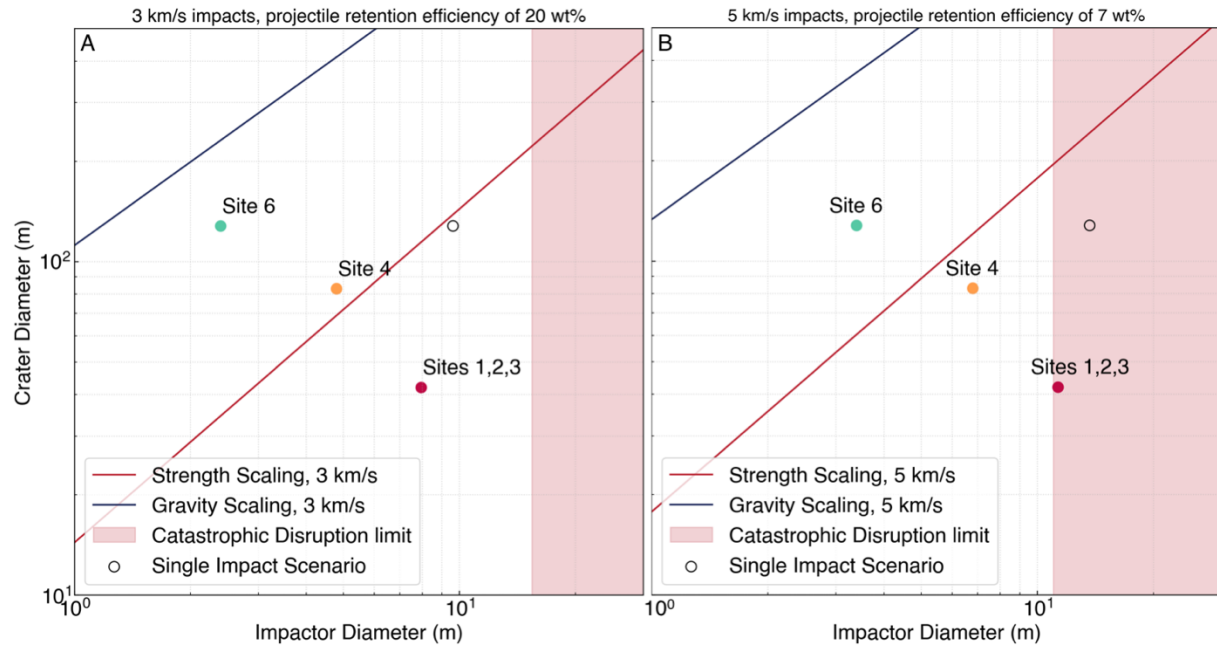
Supplementary Figure 2 | OVIRS footprints compared to the size of the pyroxene-bearing boulders. The coverage of each OVIRS footprint (coloured ellipse) for the spectra shown in Fig. 2b, overlaid on OCAMS image mosaics. For each site, the pyroxene-bearing boulder is highlighted by a circle (white solid line) and occupies <1% of the OVIRS field of view. The coordinates (latitude and longitude) of the sites are given below the images.



Supplementary Figure 3 | Meteorite spectral mixtures compared to the MapCam photometric spectrum of the Site 1 boulder. A simple linear mixing model of achondritic pyroxene and CI/CM chondrite spectra is able to reproduce the range of albedos that we see for the exogenic boulders on Bennu for each MapCam wavelength (0.47, 0.55, 0.70, and 0.85 μm), using Site 1 as an example (blue line). The red dashed line is the fit resulting from an extensive search of all possible combinations of RELAB meteorite spectra.

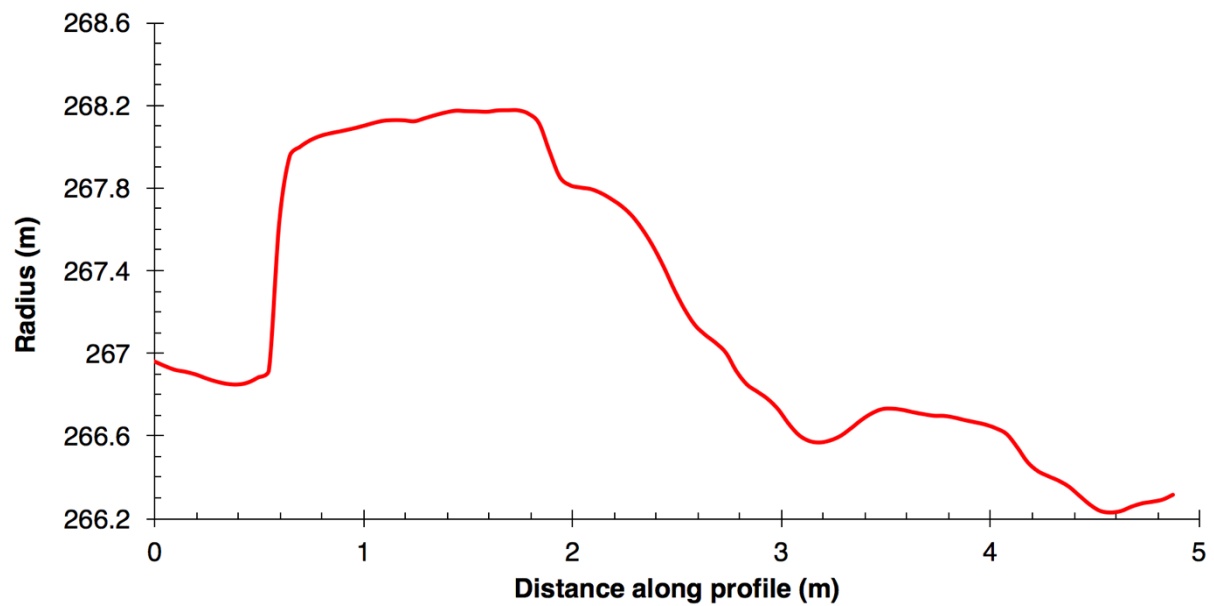
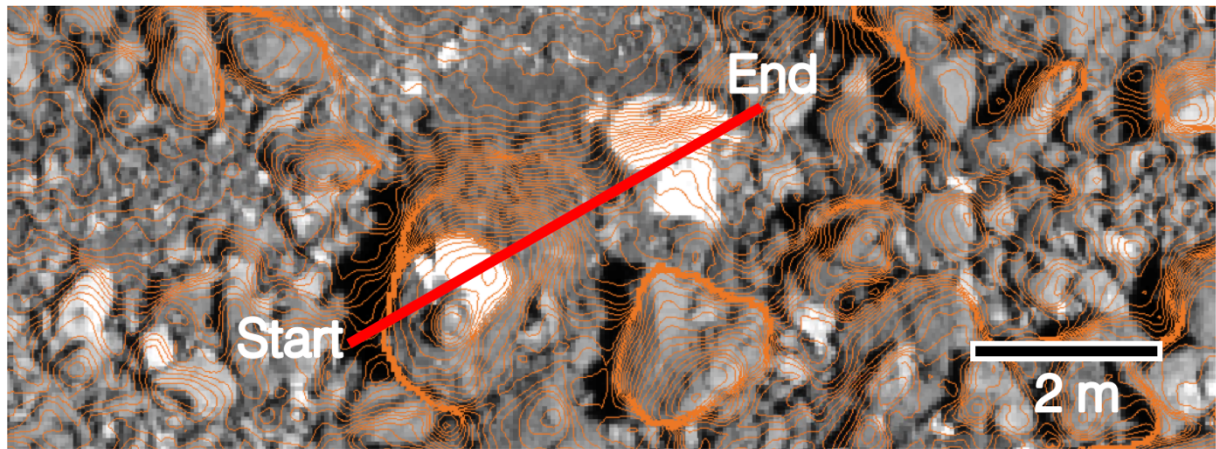


Supplementary Figure 4 | Bennu global average OVIRS spectrum from the 12:30pm LST observations. The global average spectrum of Bennu used to perform spectral ratioing in order to isolate the spectrum of the pyroxene-bearing boulders.

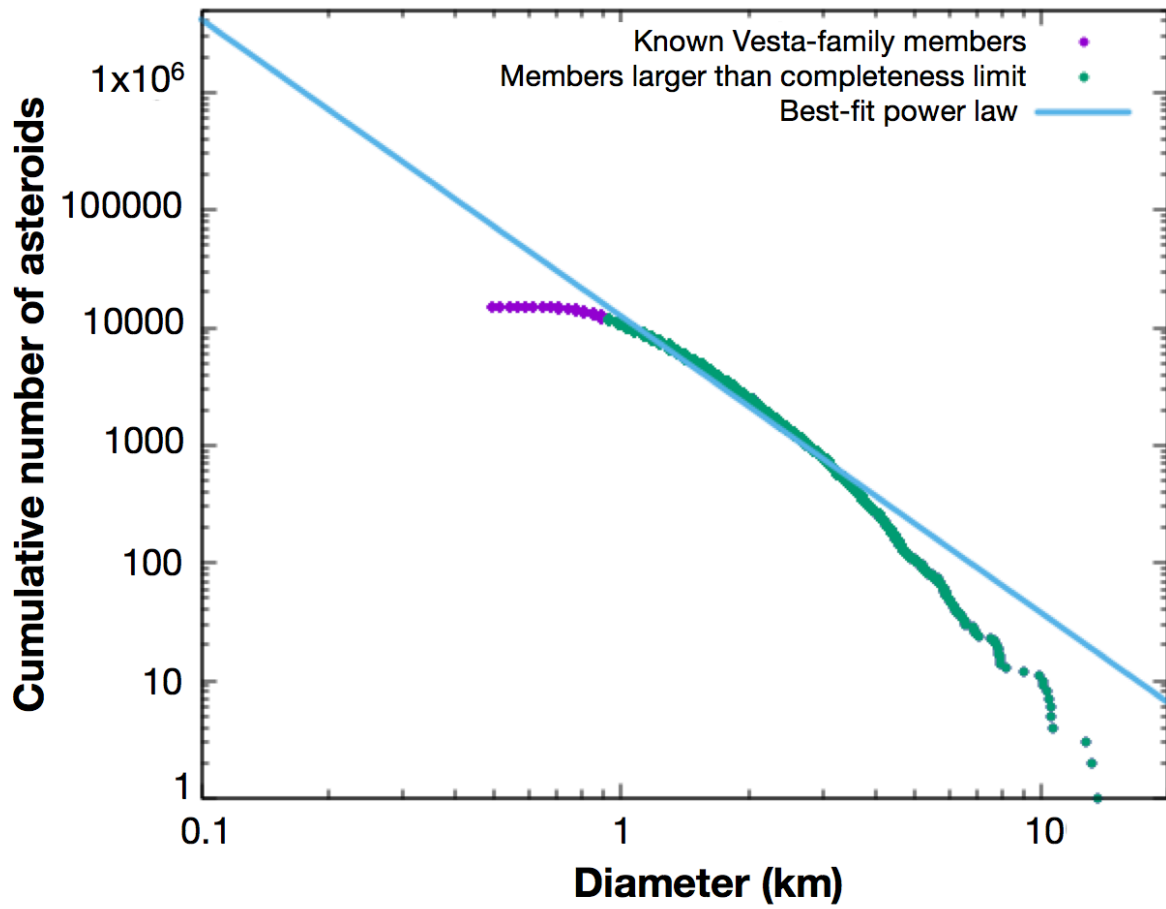


Supplementary Figure 5 | Direct delivery to Bennu of a pyroxene-bearing projectile is unlikely.

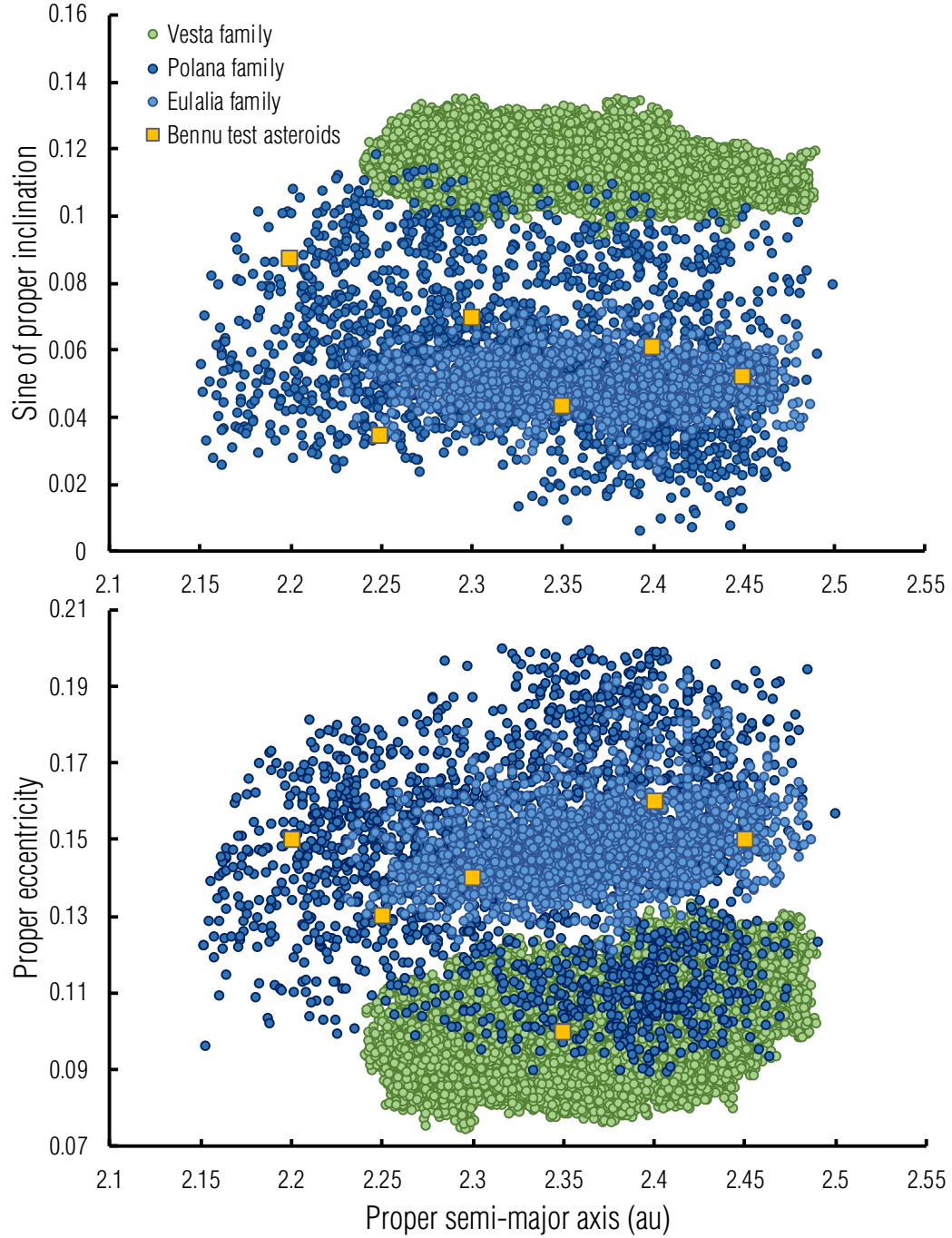
We measured the diameters of craters co-located with five of the six sites and compared them to calculated impactor diameters expected given the sizes of the associated pyroxene-bearing boulders (also see Supplementary Data Table 2) and assumed projectile retention efficiencies for two different impact speeds. Sites 1, 2, and 3 are clustered and co-located with the same 42-m-diameter crater. We compare these measured crater scalings to theoretical crater-scaling laws for dry soil [66]. A strict upper limit on impactor diameter is derived from catastrophic disruption laws [67]. **a**, Assuming an impact speed of 3 km s^{-1} , the observed inverse proportionality between crater and impactor diameters indicates an unlikely collisional origin by multiple impactors. However, a single-impactor scenario may be feasible. **b**, Assuming an impact speed of 5 km s^{-1} , neither multiple- nor single-impact delivery scenarios are feasible.



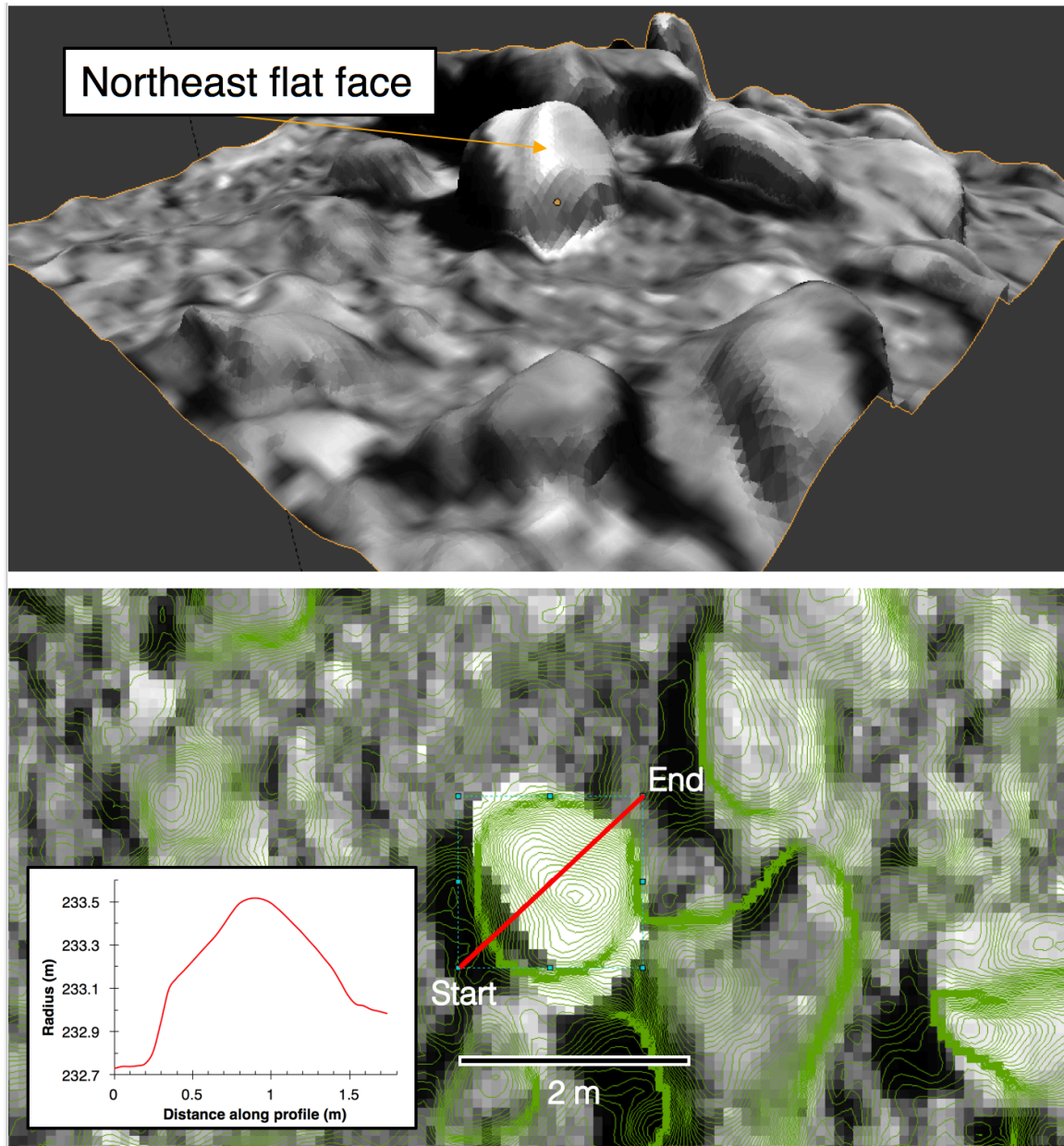
Supplementary Figure 6 | Site 4 image and terrain model. An OLA digital terrain model at 6-cm average facet size and 1-cm vertical resolution overlaid on a PolyCam image (top; 5.25 cm/pixel) for the pyroxene-bearing boulder at Site 4. The bright pyroxene-bearing clasts appear to be embedded in a boulder and are flush with its terrain to within 1 cm, rather than being perched upon it, suggesting a single geomorphic unit. Bottom, profile of the red line in the top panel.



Supplementary Figure 7 | The size-frequency distribution of vestoids. Vesta-family asteroids with known diameters from the MP3C database (mp3c.oca.eu) are shown. For asteroids with unknown diameters, we estimate a value using the average geometric visible albedo p_V of the family and their H values as $D(\text{km}) = 1329 (p_V)^{-1/2} \times 10^{-H/5}$. The fit is $N = D^a 10^b$ with $a = -2.5$ and $b = 4.1$.



Supplementary Figure 8 | The Vestoids, Polana and Eulalia asteroid families together with the six Bennu test asteroids simulated in this study, as described in the collisional modeling section of the methods.



Supplementary Figure 9 | Site 1 image and terrain model. An OLA digital terrain model at 9.6-cm average facet size and 1-cm vertical resolution overlaid on a PolyCam image (top; 5.25 cm/pixel) for the pyroxene-bearing boulder at Site 1. The bright pyroxene-bearing boulder has a distinct planar face, as illustrated by the profile of the face shown in the bottom panel.

Site #	Latitude (°)	Longitude (°)	Long axis (m)	Short axis (m)	Height (m)	Rectang. volume (m ³)	Spherical volume (m ³)
1	-37.5	52.6	1.53	0.818	0.67	0.8	1.9
2	-51.6	60.9	3.93	2.11	1.35	11.2	31.8
3	-47.2	68.1	2.62	0.842	0.65	1.4	9.4
4a	-4.4	150.9	1.6	0.703	0.37	0.4	2.1
4b			0.927	0.498	0.292	0.1	0.4
5	-44.6	166.4	3.221	2.25	0.494	3.6	17.5
6	11.7	190	1.453	0.636	0.771	0.7	1.6
Net Volume (m³)						18	65

Supplementary Table 1 | Dimensions of the exogenic boulders and clasts. Boulder and clast dimensions as measured from PolyCam images overlaid on OLA terrain data. Latitude is north (+Z) positive and longitude is specified in a 0-360° system. The uncertainty associated with the long and short axes is limited by the PolyCam pixel scale of 5.25 cm, and the uncertainty on the height is estimated at 1 cm based on the vertical precision of the OLA digital terrain models.

Site #	Crater Diameter (m)	Projectile Diameter for 7% retention (m)	Projectile Diameter for 20% retention (m)
1, 2, 3	42	11.3	7.9
4	83	6.8	4.8
6	128	3.4	2.4

Supplementary Table 2 | Dimensions of craters that are co-located with the sites of exogenic boulders and clasts. Sites 1, 2, and 3 are co-located in the same crater. Site 5 sits on a region not associated with an identifiable crater. The size of the impactor associated with the exogenic boulders and clasts for different impactor material retention efficiencies (7% and 20%) are given. The sizes of the crater and impactor diameters are inversely proportional. This defies expectations from cratering mechanics, making it unlikely that these exogenic boulders are the result of direct contamination on Bennu itself.

Site	LCP - 1 μm^*	HCP - 1 μm^*	LCP - 2 μm^*	HCP - 2 μm^*	Ratio - 1 μm	Error	Ratio - 2 μm	Error
Site1	-0.0077	-0.0042	-0.0078	-0.0036	1.8363	0.0476	2.1554	0.0417
Site2	-0.0055	-0.0033	-0.0047	-0.0046	1.6469	0.4032	1.0129	0.058
Site3	-0.0058	-0.0029	-0.0033	-0.0013	2.015	0.149	2.4941	0.6605
Site4	na	na	na	na	na	na	na	na
Site5	na	na	na	na	na	na	na	na
Site6	-0.0052	-0.0028	-0.0081	-0.0057	1.8616	0.0833	1.4218	0.029
Site6-Recon1	-0.1498	-0.0834	-0.1346	-0.0638	1.7972	0.0001	2.1087	0.0001
Site6-Recon2	-0.1435	-0.0738	-0.1373	-0.0642	1.9427	0.0001	2.1385	0.0001
Site6-Recon3	-0.1515	-0.0821	-0.1581	-0.0594	1.8447	0.0001	2.6613	0.0001
*Gaussian amplitude								

Supplementary Table 3 | MGM fit results for the 4 site spectra that were fit. Site6-Recon1 to -3 are the three higher-resolution spectra of Site #6 shown in Extended Data Figure 1.

	Position (nm)	Width	Amplitude
G1	414	239	-0.004
G2	589	282	-0.003
G3	879	199	-0.005
G4	952	182	-0.003
G5	1159	287	-0.003
G6	1818	784	-0.008
G7	2236	783	-0.006

Supplementary Table 4 | Gaussian position, width, and amplitudes used in the MGM model. These are the initial parameters that were used in the modeling of the Bennu pyroxenes.