Boulder Diversity in the Nightingale Region of Asteroid (101955) Bennu and Predictions for Physical Properties of the OSIRIS-REx Sample

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Abstract The sample of asteroid (101955) Bennu was collected from the Nightingale sample site by the Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer spacecraft and arrived on Earth on 24 September 2023. To better understand Bennu's parent body, we identified boulders over 2 m in diameter around the Nightingale region and analyzed normal albedo, morphology, and surface roughness. We found that boulders can be separated into two groups based on albedo, and four groups using morphology including angularity, texture, and the presence or absence of clasts, layers, and bright spots: Type A is rounded, rugged, and clastic, with the highest root-mean square deviation roughness; Type B is sub-angular with intermediate roughness and polygonal surface fractures; Type C is angular, has distinct fractures, and the lowest roughness; and Type D is sub-angular with intermediate roughness and bright spots. Unsupervised clustering algorithms showed that our Type A-D classification represents the diversity in the morphology and albedo data. Using documented contacts between boulder groups, we conclude that boulders on Bennu originated on a single, heterogeneous parent body that experienced vertical mixing via impacts prior to or during its disruption. The boulder morphologies on Bennu bear striking resemblance to those on asteroid Ryugu, potentially suggesting a shared origin. Finally, from analyses of sample collection images, we predict that the sample will be heterogeneous in morphology, brightness, and degree of aqueous alteration and dominated by darker Type A and B material. These predictions are supported by initial analyses of the Ryugu sample.

Plain Language Summary Asteroid Bennu is composed of fragments of an ancient, disrupted parent body. The Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer spacecraft investigated Bennu and collected a sample, which arrived on Earth on 24 September 2023. We investigated the brightness, appearance, and roughness of boulders near where the sample was collected to better understand the parent body and the diversity of Bennu's surface materials. We found that boulders can be broken into four groups: Type A are dark, rough, and have clasts; Type B are smoother and are similarly bright and rough to Type A; Type C boulders are brighter and very smooth; and Type D boulders have distinct bright spots and similar brightness as Type C. Certain boulders contain more than one morphology, suggesting they formed near each other on the parent body, and impacts onto the parent body mixed rocks from different depths and cemented them into the boulders we observe on Bennu. Bennu boulders resemble those on Ryugu, which may mean they are related. We predict that dark Type A and B particles will be most abundant in the returned sample.

1. Introduction

The Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) mission has enabled unprecedented analyses of the near-Earth asteroid (NEA) (101955) Bennu, and the sample collected from the Nightingale sample site in the high latitudes of the northern hemisphere (Lauretta et al., 2022) arrived on Earth on 24 September 2023. Initial observations of Bennu confirmed that it is a microgravity cumulative or “rubble pile” asteroid (e.g., Richardson et al., 2022) formed from the accreted fragments of a parent body asteroid that was catastrophically disrupted. Bennu's surface is dominated by boulders (meter-scale and larger rocks) with a surprising lack of fines (cm and smaller particles) (DellaGiustina et al., 2019; Walsh et al., 2019).
The rubble pile origin of Bennu implies that the components of the asteroid—its boulders—are fragments directly inherited from the parent body (or bodies) and as such, the properties of these boulders can be used as tracers of parent body characteristics.

Preliminary investigations of Bennu's boulders found that there are at least two boulder groups that vary in characteristics including reflectance, morphology, and color (DellaGiustina et al., 2020a) (Figure 1); thermal inertia, which is indicative of distinct physical properties including porosity, competence, tensile strength, and degree of fracturing (Rozitis et al., 2020); and spectral characteristics including the presence of carbonates in the form of bright spots or apparent veins (Kaplan et al., 2020) and carbon-bearing materials including organics (Simon et al., 2020). These properties appear to be linked, where low reflectance boulders are rounded with rough surface textures and low thermal inertia, while high reflectance boulders are angular and smooth with higher thermal inertia. These initial analyses proposed that the variation in boulders on Bennu implicates a heterogeneous parent body that may have been widely sampled by the impact that fragmented it to form Bennu.

We sought to investigate and characterize boulder diversity in further detail in the region near the Nightingale sample site. This region is of high scientific priority as it surrounds and includes Hokioi crater which hosts the Nightingale site. Hokioi crater was found to be the darkest and reddest region on Bennu, indicating it could have formed in the past few hundred thousand years and contains some of the freshest (least space weathered) material (DellaGiustina et al., 2020a; Deshapriya et al., 2021; Rizos et al., 2021). Investigations of the geologic setting of Nightingale (Barnouin et al., 2022) argued that Hokioi crater should contain a mixture of materials of varying brightness, composition, and exposure age, and this diversity may be reflected in the returned sample. Additionally, detailed investigations of the particle size-frequency distribution (SFD) in the Nightingale sample site (Burke et al., 2021) found a shallower slope than the global distribution that indicates particles fragmented due to time-dependent disaggregation or impacts.

We integrated analyses from several instruments onboard OSIRIS-REx, including the OSIRIS-REx Camera Suite (OCAMS, Rizk et al., 2018) PolyCam, and the OSIRIS-REx Laser Altimeter (OLA, Daly et al., 2017), for all boulders ≥2 m in the Nightingale region and measured boulder size, morphology, normal albedo, and surface roughness. Through this analysis, our goal was to gain a nuanced understanding of the physical properties of boulders on Bennu in order to characterize the parent body and make predictions for the returned sample. Based on the initial characterizations discussed above, we hypothesized that at least two populations of boulders are present on Bennu which contain distinguishing surface properties that indicate variations in source regions from a single heterogeneous parent body. Using the classification we developed in this analysis, we then analyzed OCAMS SamCam images taken throughout the OSIRIS-REx sample collection maneuver and present several predictions for the physical properties of the returned sample.

Figure 1. Heterogeneous boulders on Bennu. (a) Very large dark, rough boulder with evidence of layering, PolyCam image 20190405t212351s202. (b) Bright, smooth, angular boulder, PolyCam image 20190412t174942s616. (c) Plot of boulder reflectance showing at least two major populations of boulders separated by reflectance, modified from DellaGiustina et al. (2020a).
2. Methods and Data Sets

2.1. Mapping Region and Basemaps

Our analysis area was the region around the Nightingale sample site and corresponds to the area covered by data taken during the Recon phase of the mission (Figure 2a). Recon data have the highest spatial resolution (Table 1) taken over a large region by multiple instruments, and were collected with the purpose of characterizing the four candidate sample sites on Bennu. We identified and mapped the outline of each boulder ≥2 m in a region ~130 m in diameter (Figure 2b) using the Detailed Survey (DS) global mosaic as a basemap (Bennett et al., 2020) with a combination of ArcGIS and the Small Body Mapping Tool (SBMT) (Ernst et al., 2018). This mosaic has a ground

Figure 2. (a) Nightingale site (star) and coverage during the Recon mission phase. Detailed Survey (DS) basemap in equirectangular projection. (b) The Nightingale mapping region (yellow outline) showing all boulders 2 m and larger (cyan). DS basemap in sinusoidal projection.

<table>
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<th>Instrument</th>
<th>Pixel scale</th>
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<tr>
<td>Detailed survey</td>
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Table 1

Data Sets Used in the Work
sample distance of 5 cm, was ground-controlled to the 80 cm image-derived Bennu shape model with a mean accuracy of 30 cm and normalized to 30° phase angle. We used the Bennu v20 PTM OLA global shape model (Seabrook et al., 2022) with a facet size of ~1.5 m for mapping and geospatial analyses in SBMT, which was made with data taken during the Orbital B mission phase. This PTM shape model can handle complex boulder shapes, including overhangs that may be present on large boulders, and is therefore well suited to mapping complex boulder outlines.

Boulders 2 m and larger were critical for this analysis as they are among the most abundant on the surface of Bennu and include both high-reflectance and low-reflectance boulders—unlike the population of larger boulders (>15 m) that exclusively have low reflectance and rough surface textures (e.g., DellaGiustina et al., 2019). Boulders smaller than ~2 m are too small to adequately resolve surface properties such as morphology and surface roughness, and are excluded from our analysis.

2.2. Albedo and Morphology

We measured the mean normal albedo of each boulder using the Bennu normal albedo mosaic (Golish et al., 2021). As this mosaic only covers the surface up to ~50° latitude, about half the analysis region, some boulders do not have quantified albedos. Due to variations in viewing geometry during the different orbital phases, boulder outlines drawn on the DS mosaic do not exactly match boulder shapes as visible in the Approach phase albedo mosaic (Figure 3). As such, we drew separate outlines on the albedo mosaic from which we extracted albedo values.

We performed morphologic analyses using Recon PolyCam images, with an average pixel scale of ~0.3 cm and a phase angle of ~30° for Recon A and ~70° for Recon B. We identified PolyCam images in SBMT and using the Small Body Image Browser (https://sbib.psi.edu/data/PDS-Bennu/index.html) and selected multiple images for each boulder that covered a range of illumination directions to better assess morphology. To systematically assess and compare boulder morphology, we assessed a suite of characteristics based on initial morphologic investigations and assigned a letter code to each boulder (Table 2) for properties including angularity, texture, and the presence or absence of clasts, layers, and bright spots. “Bright spots” here refers to the types of features identified in Kaplan et al. (2020) (they referred to bright spots as “veins”) that were spectrally linked to the presence of carbonates and found to have normal albedos of at least 10%–19%, while the host boulders had normal albedos of 6%–7.6% (brighter than average Bennu). Bright spots were identified as discrete spots or larger irregular to linear exposures. We did not include the presence or absence of fractures as a morphologic category as they are observed on boulders of all scales on Bennu and have been linked to active processes such as thermal fatigue (e.g., Delbo et al., 2022; Molaro et al., 2020).

The translation of unstructured, qualitative data (such as boulder morphology) into conceptual categories is common practice in the humanities and social sciences and is referred to as coding, used to identify broad themes or concepts within a data set (Neuman, 2011). In coding, one generates a set of short text labels or phrases that

<table>
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<td>Morphologic Properties and Categories/Codes Assigned to Each Boulder</td>
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</tr>
<tr>
<td>Sub-angular/sub-rounded</td>
</tr>
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<td>Rounded</td>
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</table>

*If a boulder was heterogenous, we assigned multiple labels, for example, TR/TI. If a characteristic was ambiguous (e.g., due to shadowing or partial burial), we assigned a “U” label, for example, TU.*
represent the diversity of the data; these codes can then be used for rapid and often semi- or fully-automated computational analysis (e.g., Marathe & Toyama, 2018). There has been extensive study over decades devoted to the technique of coding, and this methodology has been applied to a vast range of topics including education, the arts, business, and healthcare, among many others (Saldaña, 2013). In this work we developed the morphologic codes in a deductive and inductive framework (Saldaña, 2013), meaning we generated the codes (Table 2) based on previous published investigations (DellaGiustina et al., 2020a; Rozitis et al., 2020) and initial investigations, and iterated on the codes as necessary to characterize the dominant morphologic diversity.

2.3. Surface Roughness

OLA returned over 3 billion measurements of the surface of Bennu at precisions of approximately 1 cm. We used these data to assess the topographic roughness of boulders in the Nightingale region. Bennu’s surface has been sufficiently sampled by OLA such that a visual comparison between the mapped boulder outlines, images, and the point cloud data allowed us to identify the correct boulders in the OLA data set. We extracted the topographic data of the boulders from high-resolution digital terrain models (Seabrook et al., 2022) available in SBMT. We extracted four profiles that transect a boulder’s long axis, perpendicular axis, and profiles offset by approximately 45°. Figure 4 shows an example of profiles drawn on a boulder in SBMT, and the topographic data extracted at sampling intervals between 1.7 and 3 cm.

We used the boulder profiles to measure standard roughness parameters such as root-mean square (RMS) height, deviation, and slope (Shepard et al., 2001). We used community-standard procedures to filter the data (detrending the long-wavelength slope) and sample the data to measure the roughness parameters at scales from the sampling length (a few cm) up to 20% of the profile length (Shepard et al., 2001).

For each profile of these boulders we calculated the following properties: (a) profile length, (b) sample interval, (c) detrended slope, (d) RMS height versus scale, (e) RMS deviation versus scale, (f) Hurst exponent, (g) break points and associated Hurst exponents (if they exist), (h) uncertainties in RMS height and deviation and propagated those to uncertainties in Hurst exponent and break point, and (i) compared roughness properties for different profiles of the same boulder to check for surface anisotropies.

Anisotropies can arise for surfaces generated or modified by directional processes. In the case of boulders on an asteroid surface, this may include in situ breakdown processes such as thermal fatigue (e.g., Molaro et al., 2020) and/or mass wasting (e.g., Jawin et al., 2020). Alternatively, these may reflect parent body processes such as fluid flow in the interior of large (>100 km) planetesimals generated by radiogenic decay of 26Al (e.g., Grimm
& Mcsween, 1989). Furthermore, natural breakpoints in the Hurst exponent usually denote a change in the major geologic process controlling roughness at that scale. This could distinguish processes inherited from Bennu's parent body versus later evolution on Bennu.

We followed the methodology outlined by Shepard et al. (2001) to calculate the surface roughness of boulders at spatial scales between 10 and 50 cm. The lower end of the range was set by the resolution limit of the data. The higher end of the range was set by the size of the boulders we analyzed, aiming for roughness approximately an order of magnitude smaller than the size of a typical boulder in our database.

### 2.4. Boulder Classification and Clustering Algorithm

We developed a classification system for boulders and assessed it using automated clustering routines. Our initial classification arose from only the morphologic data, which we refer to as our manual classification. We then implemented an automated unsupervised clustering algorithm on (a) albedo data, (b) morphology data, and (c) albedo and morphology combined, and compared these clustering results against our manual classification. The clustering technique we applied to the albedo data was k-means, one of the most commonly used unsupervised classification methods for a given number, k, of clusters. This approach has previously been used on Bennu for doing a pixel-by-pixel classification of MapCam data (Rizos et al., 2021). k-means is used for continuous numeric data (e.g., albedo) but variations on this technique have been developed, including k-modes which can cluster categorical data (non-numerical, which we used to analyze our morphologic data, Table 2), and k-prototypes which can cluster mixed numeric and categorical data (Huang, 1998) that we applied to both albedo and morphology data together.

The k-means technique partitions n data points into a user-specified k clusters by randomly initializing k centroids and assigning each data point to its closest centroid. Then the within-cluster sum of squared errors (SSE) is calculated for each cluster in Euclidian space, which is a metric of clustering performance (minimizing the SSE is desired). The mean of each cluster is calculated to identify new centroids, and points are again assigned to their closest centroid. SSE is again calculated and if the new SSE is smaller, the new cluster centroid is kept. This is repeated until the centroid position does not change.

As categorical data cannot be clustered using k-means (since they are not quantified values, and it is not possible to calculate their mean or SSE in Euclidian space), the k-modes algorithm instead uses a matching dissimilarity measure that applies a frequency-based method to find the mode of each cluster (Huang, 1998). In this manner, rather than calculating the mean of a cluster, the mode is used to calculate cluster centroids. And rather than minimizing SSE as in k-means, the number of mismatches in attribute categories is minimized, and the fewer mismatches there are, the more similar two points are considered to be. We applied this k-modes technique to cluster the morphological data for each boulder. We also wanted to cluster both morphologic and albedo data simultaneously, which are of mixed data types (categorical and numeric). For this, we used the k-prototypes technique, which integrates k-means and k-modes simultaneously, with equal weight to each data type—although the weight of the categorical data can be altered by changing what is referred to as the gamma parameter (Huang, 1997).

In all three clustering algorithms, the number of clusters, k, is user-specified. The variance within each group should decrease as k increases, so care must be taken when choosing this value. Various techniques exist to identify the “best” number of clusters in numeric data, two of the most common being the elbow method and the Silhouette score. The elbow method computes the inertia or within-cluster SSE for all clusters in Euclidian space, and plots SSE across a range of k clusters. As k increases, the SSE should rapidly decrease and then flatten out to a relatively constant value, and the “elbow” in the curve, indicating the k value where this change in slope occurs, should indicate the best value of k. In comparison, the Silhouette score or coefficient measures how well each data point fits to its assigned cluster by measuring its distance to all other points in the same cluster, and the distance to points in other clusters according to the equation \((b - a)/\max(a, b)\), where \(a\) is the mean intra-cluster distance (distance between a point and the other points in that cluster), and \(b\) is the mean nearest-cluster distance (distance between a point in a given cluster and points in the nearest other cluster). Scores for each cluster are averaged to get a single value for a given k. The Silhouette scores range from −1 to 1, where higher scores indicate greater cohesion of clusters, and negative values indicate that points within a cluster are not similar to each other. The main difference between the elbow method and the Silhouette score is that the elbow method provides a rapid assessment of how internally coherent a cluster is, while the Silhouette score provides more insight into
the variation within clusters, such as skewness. The elbow method has a drawback that sometimes it is difficult to identify the correct point of the elbow.

As both the elbow method and the Silhouette score were developed for continuous numeric data, the calculation for categorical data (in k-modes and k-prototypes) is slightly different. For categorical data, rather than calculating SSE, a “cost” parameter is calculated, which is the sum of all dissimilarities in the clusters. For mixed-type data, cost is calculated by adding total dissimilarities (from the categorical data) and total within-cluster SSE (from the numeric data).

For completeness, we assumed a range of k values from one to six, calculated both the elbow method and the Silhouette score (Silhouette score requires a minimum of two clusters) and selected a value of k based on the two results (i.e., where k was indicated by the location of the “elbow,” and the maximum Silhouette score).

The k-means implementation we used was from the scikit-learn Python package (Pedregosa et al., 2011), the same implementation as used in Rizos et al. (2021). We implemented the k-modes and k-prototypes clustering algorithms using the open-source Python package KModes (de Vos, 2015), which use the Huang (1997, 1998) techniques described above and are modeled after the scikit-learn Python package. By using these clustering algorithms, we sought to test and validate our manual classification using both morphology and albedo data. We did not incorporate the surface roughness data into the clustering as we only calculated these data for a subset of boulders in the region and therefore had a much smaller data set on which to run the clustering algorithm.

3. Results

3.1. Nightingale Boulder Albedo and k-Means Clustering

We identified and analyzed 389 boulders in the Nightingale region (Figure 3b) which ranged in diameter from 2 to 24 m. We measured the mean albedo of 308 boulders covered by the normal albedo mosaic which ranged from 0.040 to 0.068, with an average (mean) of 0.050 ± 0.005 (median: 0.049). The distribution of albedo around Nightingale (Figure 5a) closely resembles that of the global boulder distribution (>5 m diameter) of normal reflectance at 0.55 μm (I/F) from MapCam (DellaGiustina et al., 2020a), namely a multimodal distribution with peaks at ∼0.046 and ∼0.055 (Figure 1c).

As a preliminary classification, and as an additional comparison against the results of DellaGiustina et al. (2020a), we ran k-means clustering on the albedo data. We calculated the elbow method and Silhouette score to determine the appropriate number of clusters to use, which was two (Figure 5b). The results of the clustering analysis are shown in Figure 5c, where the two cluster centroids are at albedo values of 0.046 and 0.055 (Table 3), with a transition value ∼0.050—agreeing with the normal reflectance values for the dark and bright boulders from DellaGiustina et al. (2020a). The largest boulders (>10 m diameter) are all dark, while boulders between 2 and ∼9.5 m range in albedo.

3.2. Boulder Morphology and Manual Classification

Our morphologic analysis builds on, but departs slightly from, the results of the albedo analysis. We assigned five adjectival descriptors to each boulder which together provide a generalized summary of boulder morphology.
and found that, as has been noted previously, dark and bright boulders have distinct morphologies (DellaGiustina et al., 2019, 2020a). However, we also identified additional morphologic variation within these two sub-groups: while many dark boulders follow the characterization of DellaGiustina et al. (2020a) and are rounded, rugged, and clastic (Figure 6a), other dark boulders (<0.050 albedo) are less rugged, more angular, and have few to no visible clasts (Figure 6b). Likewise, within the bright boulder population, many boulders follow the morphology described by DellaGiustina et al. (2020a) and are angular and smooth (Figure 6c), while other equally bright boulders are more rounded and have a slightly more rugged surface texture and contain distinct bright spots (Figure 6d). To distinguish these four characteristic morphologies, we refer to them in the order described above as Types A, B, C, and D.

Type A boulders can be characterized in the morphologic coding scheme as rounded (AR), rugged in texture (TR), containing clasts (CP), layers may or may not be visible (LP/LA), and do not contain bright spots (BA) (Figures 7a and 7b). Resolvable clasts in Type A boulders are on the scale of ~10–120 cm, with a median clast size of 16–18 cm (Pajola et al., 2020), although it is likely that smaller clasts are also present below the resolution limit of the PolyCam images used in that analysis. The largest boulder on Bennu, Roc Saxum, displays a Type A morphology. The average albedo of Type A boulders we investigated is 0.045 ± 0.002 (Table 3).

Type B boulders, in contrast, can be slightly more angular than Type A, which we characterized as sub-angular/sub-rounded (AS), have a texture of intermediate roughness (TI), generally do not contain visible clasts (CA) or layers (LA) and do not contain bright spots (BA) (Figures 7c and 7d). The Type B morphology is distinct from Type A in its lack of visible clasts, slightly smoother surface texture, and distinct network of intersecting polygonal fractures. These fractures could have formed on Bennu or they could have been inherited from the parent body and therefore indicate geologic activity prior to disruption. Similar networks of polygonal fractures on comet 67P were linked to thermal insolation weathering or volatile desiccation (El-Maarry et al., 2015). However, a thorough investigation of fracture networks on Bennu and links to boulder properties is outside the scope of this work. This texture is readily apparent on larger boulders but can be difficult to identify on boulders smaller than a few meters in diameter, which can make identifying Type B boulders tricky. The first boulder

<table>
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<td>D</td>
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<td>0.054 ± 0.004</td>
<td>AS, TI, CA, LA, BP</td>
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</tr>
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</table>

*2-k-prototypes results with four clusters. For results with two clusters, see Table S2 in Supporting Information S1. RMS roughness at 10 cm baseline, units of cm, errors represent 1-sigma standard deviation of each class. Morphologic codes listed in Table 2. Variable properties observed in the boulder group. For example, certain Type A boulders visible layers, while others did not (LP and LA), while otherwise adhering to the Type A morphology. Similarly, Type C boulders may or may not have contained bright spots (BP and BA).
Figure 7. Morphology of the four boulder groups. (a, b) Type A with rugged texture and visible clasts. (c, d) Type B with smoother surface texture and polygonal fractures. (e, f) Type C with smooth angular appearance. (g, h) Type D with slightly rougher texture and bright spots. PolyCam images (a) 20191012t220348s866, (b) 20191026t215531s657, (c) 20190321t202426s075, (d) 20190329t185228s895, (e) 20191026t214514s803, (f) 20191026t220147s823, (g) 20191026t211251s139, and (h) 20191012t224413s035.
identified on Bennu, Benben saxum (Nolan et al., 2013) has Type B morphology. The average albedo of Type B boulders is 0.047 ± 0.002, which is within one standard deviation of the average Type A albedo (Table 3).

Type C boulders are usually easy to identify due to their angularity (AA), smooth texture (TS), and lack of clasts (CA) and layers (LA), and they may or may not contain bright spots (BP/BA) (Figures 7e and 7f). These boulders often show distinct fractures (through-going and/or surface-parallel), as well as pits such as would form from impacts (e.g., Ballouz et al., 2020). We note that while Type C boulders contain distinct fractures and pits, these features are not unique to this morphology—fractures and impact pits are present on all four boulder morphologies. However, given the smooth texture of Type C boulders, any fractures or pits are distinct and easily identifiable. The average albedo of Type C boulders is 0.055 ± 0.004, which is brighter than the average Type A and B boulders (Table 3).

Type D boulders, while equally as bright as Type C, are slightly more rounded—we classified them as sub-angular/sub-rounded (AS), slightly more rugged surface texture than the Type C which we classified as intermediate in roughness (TI), no visible clasts (CA) or layers (LA), and always contained bright spots (BP) (Figures 7g and 7h). The presence of bright spots and a slightly rugged surface texture are the most distinguishing surface characteristic of Type D boulders (smoother Type C’s can contain bright spots, but not always). Type D boulders can also lack the distinct fractures and pits of the Type C boulders, although this could be an observational bias due to their less smooth texture. The average albedo of Type D boulders is within one standard deviation of the Type C, 0.054 ± 0.004 (Table 3).

A small number of boulders (~20) in the Nightingale region contained multiple morphologies. The most common of these were contacts between Type A and B morphologies (~10 boulders), which we refer to as Type A/B (Figure 8a). In these boulders, Type B material is generally present as an apparent rind or coating on Type A material (Figure 8a), but in larger boulders on Bennu Type B material can be present as discrete layer(s) interbedded with Type A material (e.g., Figure 1a). We also observed several (~6) contacts between Type C and D (Figure 8b), which we label Type C/D. Other rare contacts include apparent Type A/D (2 boulders), and one B/D
We also found two ∼10 m diameter boulders in the Nightingale region that did not clearly fall into any of these categories, and as such we marked them as ungrouped, or “U” (Figures 8c and 8d). These ungrouped boulders have albedos consistent with a Type A or B dark boulder, 0.044 and 0.050, and had a morphology that had features characteristic of Types A, B, and D: they have a rugged surface texture with polygonal surface fractures, several visible clasts, as well as bright spots. These boulders do not resemble several small, exogenous boulders found on Bennu’s surface (DellaGiustina et al., 2020b).

Based on the manual classification, most boulders in the Nightingale region are Type A (Figure 9a) and include the largest three boulders, >10 m (Figure 9b). The smallest boulders (2 m), meanwhile, are a mixture of all four types and range in all measured albedos.

3.3. k-Modes and k-Prototypes Clustering Results

As validation for our manual classification, and to integrate morphologic and albedo data, we implemented the algorithms k-modes to cluster the morphology data, and k-prototypes for the morphology and albedo data together. When clustering the morphologic data, we ignored any boulder that had a mixed-type label (e.g., TR/ TI), mixed-type manual classification (e.g., A/B), or an uncertain observation (e.g., TU). Removing these data left 266 boulders in our catalog.

We first investigated the number of optimal clusters in the morphologic data with k-modes by using the elbow method and the Silhouette score. We found that often the values of k did not agree between the two methods and varied from 3 to 4 (Figure S1 in Supporting Information S1). In cases where the algorithm preferred four clusters, the four centroids very closely matched our manual classification (compare manual classification to k-modes centroids in Table 3). In other runs where the elbow and/or Silhouette score suggested three clusters, the three centroids were consistent: (a) one centroid approximated the Type A morphology (e.g., cluster centroid of AR, TR, CP, LA, BA), (b) the second resembled the Type C morphology (AA, TS, CA, LA, BA), and (c) the third effectively combined Types B and D (“AS” “TI” “CA” “LA” “BP”). We believe the occasional preference of k = 3 arose due to our choice of morphologic classification criteria, which inadvertently led to Type B and D boulders sharing four of the five criteria: both are generally sub-rounded/sub-angular (AS), have an intermediate surface texture (TI), and do not generally contain visible clasts or layers (CA, LA). The only distinct difference (in the coded morphology criteria at least) between Types B and D is the absence or presence of bright spots (respectively). Despite the similarities in the coded morphologic data, the two boulder types have discernible differences in surface texture, associations with other morphologic types, and albedo, which suggests they are distinct. This potential conflation of the two boulder groups by the automated clustering data illustrates that great care must be taken when developing quantitative methods for inherently qualitative observations.

Based on the above results investigating k and its relationship to the morphologic data, we chose to run k-modes with k = 4. When the number of clusters was set to four, the k-mode clustering results were in very good agreement with our manual classification (Table 3). To quantify the level of misclassification in the clustering results,
we ran $k$-modes 1,000 times with $k = 4$ and assessed whether each of the four clusters matched each of our four morphologic types, and then calculated the number of mismatches per cluster (Figure S2 in Supporting Information S1). All runs of the model successfully generated four clusters with centroids that matched one of our morphologic groups (Types A-D). Within each cluster, there was an average mismatch of 20% or less—in other words, all the clustering results generated one cluster each for Types A, B, C, and D, and within each cluster, there was at least 80% agreement with our manual classification. We also investigated which specific morphologic parameters affected the clustering results as they relate to our manual classification, which is summarized in Text S1 and Table S1 in Supporting Information S1.

We then incorporated albedo into the morphologic clustering with the $k$-prototypes algorithm, and again investigated the appropriate number of clusters to use. As with the $k$-modes results (and, indeed, because $k$-prototypes essentially reproduces the $k$-means and $k$-modes clustering described above), the elbow method and Silhouette score did not converge on a single “best” number of $k$ clusters, but ranged from two to four. The results could be affected by changing the weighting parameter gamma between the numeric and categorical data—a $k$ value of 2 was indicated when gamma was less than 1 (i.e., the albedo data weighted more heavily), and $k$ could be higher when the categorical data were weighted more (gamma > 1).

For consistency with the $k$-modes analysis above, we ran $k$-prototypes with $k = 4$ and compared them against our manual classification. Cluster centroids matched our manual classification very closely in both morphology and albedo (compare manual characterization and cluster centroids in Table 3). The sorting of boulders into each cluster closely matched the manual classification (compare Figures 9b and 9c), such that each of the four clusters matched our Type A, B, C, and D. The average mismatch of individual boulders into each group (compared to our manual classification) was 16%, a similar magnitude to the $k$-modes results (Figure S2 in Supporting Information S1). As $k = 2$ was also suggested by the elbow method and Silhouette scores, we also ran $k$-prototypes with two clusters. The two cluster centroids have very similar albedos (0.046, 0.054) to the other clustering results, and the average albedo values of Types A and B (dark boulders) and Types C and D (bright boulders) from the manual classification (compare Table 3 and Table S2 in Supporting Information S1). One slight difference is that more variation in albedo is present in the two $k$-prototypes clusters than in the $k$-means clustering (compare Figure 5c to Figure S3a in Supporting Information S1). The two cluster centroid morphologies approximate Type A and Type D boulders (Table S2 in Supporting Information S1), although both clusters contain a mixture of three or four types from our manual classification (Figure S3b in Supporting Information S1).

Based on our unsupervised clustering analysis of $k$-means, $k$-modes, and $k$-prototypes, we found that the albedo and morphology of boulders systematically vary on Bennu. In terms of boulder classification, when considering albedo alone, two groups effectively characterize the diversity in the data in the form of bright boulders and dark boulders (Figure 5b), following the results of DellaGiustina et al. (2020a). However, when considering morphology—or morphology and albedo together—more than two groups better characterize the diversity in the population. This diversity is well represented by the four groups, Type A, B, C, and D, combined with the two albedo groups (average 0.046 and 0.055 for dark and bright). Slight albedo variations exist within the dark Type A and B boulders, and within the bright Type C and D boulders, but not enough to distinguish the four groups on albedo alone. However, morphology alone can potentially be used as a predictor of average albedo. The analysis of additional boulders in other locations on Bennu, incorporating additional data sets into this analysis, and investigations of the returned sample may all provide further insights into whether two or four groups (or another number) best represent the diversity in the boulder population.

### 3.4. Surface Roughness Analysis

We mapped profiles on 161 Nightingale boulders which have diameters ranging from 2 to 24 m. Figure 10 shows an example of the RMS deviation for a boulder in the Nightingale region as a function of baseline length. This analysis allowed us to extract the Hurst exponent, $H$, as well as identify any natural breakpoints in $H$ (denoted as $H_s$ and $H_i$ in Figure 10). This type of scaling behavior is observed in natural topography and reflects the self-affine properties of natural surfaces. A low Hurst exponent ($H < 1$) would indicate that a surface is rough at small scales but smooth at large scales. A large Hurst exponent ($H > 1$) would imply that a surface tends to maintain its roughness as the scale increases. At $H = 1$, the surface is self-similar and equally rough at any scale.
measured. For context, the Hurst exponent can be converted to the fractal dimension through a simple linear formulation (see Equation 7 in Shepard et al. (2001)): for one-dimensional roughness profiles, as we report on here, the fractal dimension would be $2 - H$.

We then examined the variation in roughness properties for different boulder types based on our manual classification. Violin plots of the 10-cm scale RMS deviation, $\nu(10\,\text{cm})$, for each of the boulder classes (Figure 11a) show that Type A boulders have the highest roughness (median values $\nu(10\,\text{cm}) = 7.5\,\text{cm}$) which is nearly twice that of the smoothest Type C boulders (median values $\nu(10\,\text{cm}) = 3.9\,\text{cm}$), consistent with the qualitative roughness analysis based on morphology (Table 3). Type B and D boulders have intermediate roughness (median values $\nu(10\,\text{cm}) = 5.2$ and $4.6\,\text{cm}$, respectively). Figure 11b shows the distribution of $H$ for the four boulder types, with median values of $H = 0.67$, $0.76$, $0.74$, and $0.69$ for Types A, B, C, and D, respectively. The similar values of $H$ for all four groups indicate that at the largest scales, boulders appear similarly rough—although we note that the spread in $H$ is smallest for Type D boulders.

4. Boulder Group Relationships and Links to the Parent Body

The analyses described above allow us to propose links between boulder groups and lithification zones on the parent body. Previous analyses argued that the dark and bright boulders formed on a single heterogeneous parent body where dark, brecciated, porous, low thermal inertia boulders formed near the surface, and bright, denser, higher thermal inertia boulders with carbonate-bearing veins formed in the interior (DellaGiustina et al., 2020a; Kaplan et al., 2020; Rozitis et al., 2020). DellaGiustina et al. (2020a) also proposed that the dark boulders, which are slightly redder and brighter in the near-UV region and which can contain a weak 0.7 $\mu$m absorption feature, have a higher abundance of organic molecules and have been less aqueously altered than the bright boulders; additionally, Rozitis et al. (2020) argued that bright boulders have a higher thermal inertia and lower porosity due to the deposition of carbonates filling in pore space and fractures during a period of aqueous alteration.

Our results are consistent with these previous investigations and support a single heterogeneous parent body. From the analysis of surface roughness, we found similarity in the value of $H$ which suggests that similar geologic processes control the roughness of boulders, regardless of type. At the largest scales, this is likely controlled...
by the collisional fragmentation that led to the gravitational reaccumulation of Bennu as a rubble-pile asteroid (Michel et al., 2020), and subsequent evolutionary changes due to micrometeorite impacts (Ballouz et al., 2020) and thermal fatigue (Molaro et al., 2020). The combined finding of a variation in roughness at small scales (similar to pixel scales of PolyCam images) with a similarity in $H$ (which reflects geologic process) suggests that boulder texture is a feature that was inherited from Bennu's parent body.

In light of this determination, the morphologic analysis of boulder texture can be used as a direct proxy for the lithification zone on the parent body, and similarly contacts found between boulder types point to proximity of these lithification zones. The abundant contacts we found between various boulder morphologies illustrate this—the most common contact being between Types A and B (Type A/B) (Figure 8a). We also found contacts between Type C and D boulders but with less clear stratigraphic relationships (owing in part to the few observations and small scale of the Type C/D boulders). Additionally, Type A boulders often contain clasts with diverse morphologies resembling the other three morphologic types (Figure 12). The few boulders we classified as mixed types (A/D, B/D) are additional evidence that there are contacts—albeit rare—between the four types. The physical contacts found between boulders of all four types indicate that the boulders on Bennu formed in relative proximity to each other. As Types A/B and C/D are the most abundant (compared to others such as A/D, B/D), the lithification regions for Types A and B must have been located in similar regions on the parent body, and similarly for Types C and D. The few observations of other mixed-types—A/D, B/D, and Type A's with diverse clasts—shows that there was a degree of interaction of all four types on the parent body.

Taking the clastic, brecciated texture of Type A, coupled with prior evidence of high porosity (Rozitis et al., 2020) as evidence for their origin in the brecciated zone at or near the surface of the parent body (as argued in DellaGiustina et al. (2020a), we can therefore propose that Type B boulders formed in close proximity to the surface as well. The lack of clastic texture of the Type C and D boulders suggests they formed in the deeper interior, beneath the surficial zone of brecciation. However, as we found clasts of Type C and/or D material in Type A boulders, we can conclude that the region of Type C/D boulders was probed and transported to the lithification zone of Type A boulders at/near the surface. This most likely occurred through a large impact(s) on the parent body, which excavated deep into the interior, depositing bright ejecta on the surface, which later became lithified into a Type A polymict breccia. This interpretation argues that the parent body experienced extensive bombardment throughout its history, even before it was catastrophically disrupted in the impact that led to the formation of Bennu.

Identification of morphologically similar brecciated boulders on asteroid Ryugu containing exogenous, anhydrous clasts (Sugimoto et al., 2021a) indicates that the timing of impact brecciation on the Ryugu parent body occurred after the cessation of aqueous alteration (in order to preserve the mafic absorption in the clasts). DellaGiustina et al. (2020a, 2020b) identified evidence of exogenous basaltic material present as clasts in apparently brecciated

Figure 12. Type A boulder with diverse clasts, including meter-scale clast (or potentially eroding rind) of Type B, and multiple clasts with bright spots characteristic of Type C or D. Inset (b) extent is indicated by white box in panel (a). These diverse clasts implicate a single heterogeneous parent body that experienced impacts which excavated Type C/D material from the subsurface prior to lithification into Type A breccias. PolyCam image 20200122t002026s292.
(Type A) boulders, so this result from Ryugu would also apply to brecciation on the Bennu parent body. As the main phase of aqueous activity would have occurred within the first ~few Myr after accretion of the parent body when liquid water was still present (based on models of water duration and temperature on CM parent bodies, e.g., Cohen & Coker, 2000), any lithification of anhydrous exogenous materials is likely to have occurred at least several Myr after parent body accretion. Alternatively, the catastrophic disruption of the parent body itself could have resulted in the vertical mixing of material from different body depths, as shown in N-body simulations of the gravitational reaccumulation of rubble piles (Michel et al., 2020).

When developing the Type A-D classification, we considered the possibility that the morphologic distinctions between Types A and B, and between Types C and D, could be due to superficial differences relating to factors such as exposure age—for example, micrometeorite bombardment could change the apparent surface texture, or a freshly broken face may have a different appearance than the rest of a boulder. However, we dismissed this idea for Types A and B, as the exposures of these two morphologies on Type A/B boulders appear on discrete portions of boulders, with Type B material presenting as apparent rinds or coatings on Type A, or as discrete layers within Type A materials. These associations cannot be explained by a recently broken face, and indicate that two different materials lithified or were modified in proximity to each other. Confirming or rejecting this possibility for Types C and D, however, is not as straightforward, namely due to the limited number of identified Type C/D boulders (6) and their small size (≤4 m). The few Type C/D boulders appear to have Type C and D morphologies present on separate faces (e.g., Figure 8b), which would be consistent with a single boulder that was broken apart, exposing a rougher interior and smoother (original) exterior. Additionally, the similar albedo and presence of bright spots on both Type C and D boulders could support a shared origin for the Type C and D boulders. The automated clustering analysis supports two separate groups for Types C and D because they are morphologically distinct, which cannot help resolve the issue. Further analysis of additional boulders at similar spatial scales is necessary to fully determine whether Type C and D boulders were lithified separately or share a common origin.

Based on the relative abundance of the four morphologies on Bennu, we discard the possibility that any of these four groups could be sourced from the impactor that disrupted the parent body. The impactor size that could lead to catastrophic disruption of a 100-km parent body at Main Belt impact speeds was quantified by Michel et al. (2020) to be in the range of 7–10 km diameter (depending on the impact angle). It follows then that if impactor and parent body material were equally mixed in the resulting asteroid family members, we would expect to find that impactor material is represented at abundances of 0.3%–0.8%. In reality, the parent body would retain most of the target material, so we would expect that target material to be even less represented on Bennu (Sugita et al., 2023). Note that this does not discount the possibility of finding exogenous material in the Bennu sample. For example, DellaGiustina et al. (2020b) identified basaltic material on Bennu, which was likely sourced from impacts on Bennu's parent body, but which made up a very small fraction of Bennu's surface. In contrast, the major boulder lithologies we describe here are better represented on the surface of Bennu by orders of magnitude.

5. Comparisons to Boulders on Ryugu

Rubble pile NEA (162173) Ryugu, target of the JAXA Hayabusa 2 mission (Watanabe et al., 2019), shares many similarities with the boulder properties reported here for Bennu. For example, Sugita et al. (2019) identified four groups of boulders on Ryugu: Types 1, 2, 3, and 4, which vary in size, morphology, and color properties (compare their Figures 4–6). Most boulders fall into two categories: Type 1 boulders which appear dark, rugged, clastic, and layered, and Type 2 boulders that are bright, smooth, and layered. Type 3 boulders are bright and mottled with no visible layers, and the one Type 4 boulder on Ryugu, Otohime saxum (the largest boulder on Ryugu), is notably bright, smooth, and angular with distinct fractures. The major morphologies characteristic of boulders from orbit were also identified in the returned Hayabusa2 sample, including both rugged and smooth surface textures, and other properties including color, shape, and structure of returned pebbles that are consistent with Ryugu surface materials (Tachibana et al., 2022).

Morphologically, Type 1 boulders on Ryugu bear striking resemblance to Type A boulders on Bennu, while the Type 4 Otohime saxum resembles Bennu Type C boulders. The bright and smooth Type 2 boulders on Ryugu somewhat resemble Type C boulders, although we have not identified layering in Type C. The bright, mottled appearance of Type 3 boulders may resemble Type D boulders with their ubiquitous bright spots, although additional analysis would be needed to compare the brightness of Type 3 Ryugu boulders to the bright spots on Bennu. Other boulders on Ryugu were found to contain bright clasts or exposures, some of which were spectrally consistent
with S-type anhydrous material (probably of exogenic origin) (Tatsumi et al., 2021), and others are more consistent with C-type material resembling average Ryugu materials, but which may have experienced different levels of thermal metamorphism (Sugimoto et al., 2021a, 2021b; Tatsumi et al., 2021). These bright boulders are morphologically similar to Type D boulders on Bennu (compare Sugimoto et al., 2021a, Figure 5a to Figure 7g), and the incorporation of bright particles into dark boulders on Ryugu is consistent with our identification of bright clasts in Type A boulders on Bennu (compare Sugimoto et al., 2021a, Figures 6e–6g with Figure 12). The bright Type C-D boulders on Bennu are spectrally consistent with other Bennu materials and not with an exogenous origin (unlike the anomalously bright boulders that have been linked to HED meteorites, DellaGiustina et al., 2020b), so it is more likely that the Bennu Type D bright boulders (and Type C boulders with bright spots) resemble the Ryugu Type-C bright boulders, as opposed to the S-type. This may not be true for all Type A boulders with bright clasts, as DellaGiustina et al. (2020b) found localized evidence of brecciated boulders containing clasts of exogenous basaltic material—similar to what was found on Ryugu (Sugimoto et al., 2021a)—so brecciated boulders on Bennu could resemble dark Ryugu boulders containing both C-type and S-type clasts.

It has been proposed that Ryugu and Bennu may have a shared origin, potentially originating from the same parent body (e.g., Michel et al., 2020). The notable similarities in boulder morphologies on the two asteroids could further be evidence of a shared origin, although a definite answer may not be revealed until the Bennu samples are analyzed and compared to those from Ryugu. If the two asteroids shared a parent body, the observed differences in their boulder morphologies may be due to the two rubble piles originating from different regions of the parent body (e.g., Michel et al., 2020) or to different evolutionary pathways post-parent body breakup. One caveat affecting morphologic comparisons is differences in illumination conditions from the cameras on Hayabusa2 (Optical Navigation Camera Telescope, ONC-T, Kameda et al., 2017) and OSIRIS-REx (OCAMS, Rizk et al., 2018). Differences in the phase angle can significantly affect morphologic identification of, for example, the presence of layering or surface texture. One noted difference between the two asteroids is that on Ryugu, Otohime saxum is the largest boulder (160 m diameter) but the only example of a Type 4 morphology. This is most similar to Bennu Type C boulders, which are absent from the population of boulders larger than ~15 m, but common at smaller sizes (e.g., Figure 9a). Additionally, there does not seem to be a direct link between Bennu Type B boulders and any of the four groups on Ryugu. The Ryugu Types 2–3 do not have an obvious link to Bennu boulders—although one of our ungrouped boulders (Figure 8b) is brighter than Type A’s, is smooth, lacks clasts, and appears to have layers—all similar to Ryugu Type 2.

6. Analysis of the Nightingale Sample Site and Predictions for the Returned Sample

The OSIRIS-REx sample collection maneuver was conducted on 20 October 2020, and estimates indicate that approximately 317 g of material was collected by the Touch-And-Go Sample Analysis Mechanism (TAGSAM)—far exceeding the minimum mission requirement of 60 g—as well as tens of particles trapped on the steel Velcro contact pads on the exterior of TAGSAM (Lauretta et al., 2022). However, after sample collection but before TAGSAM was stowed in the Sample Return Canister, particles were observed to leak out of TAGSAM, resulting in a loss of ~67 g of material and a predicted returned sample mass of 250 g (Lauretta et al., 2022).

How can our results and boulder classification help to anticipate the physical properties of the several hundred grams of collected sample? Within the Nightingale region, we found that the most abundant boulder was Type A (Figure 9a), so we could expect that the sample would be dominated by dark, clastic, porous, low-thermal inertia material. However, our investigation only analyzed boulders as small as 2 m, which is an order of magnitude larger than the upper limit of the expected sample particle size. To postulate on the distribution of sizes more relevant to the returned sample (cm and smaller), we analyzed the SFD of boulders in the region. Due to the relatively small number of boulders in each of the four types (<100 boulders), a derived power-law slope would not be robust for each of our four morphologic groups; thus, we grouped Types A and B together and Types C and D together (Figure 13). The bright boulders (Type C and D) have a steeper power-law slope (~3.3) compared to the dark boulders (~2.6), suggesting that at particle sizes less than ~1.5 m, bright particles would outnumber dark. This observation is consistent with previous analyses of the global SFD of the dark (~2.5) and bright (~4.4) boulders (DellaGiustina et al., 2019). Therefore, at the sub-cm scale of the returned sample, the SFDs predict that bright Type C and D particles should be the most abundant. We note that the SFD slopes reported above are steeper than the cumulative SFD slopes found by Burke et al. (2021) in the Nightingale sample site (~1.9 to ~2.3), although our calculated slope for the relatively more abundant dark particles is similar to the slope
found by Burke et al. (2021). This relationship follows the observations of DellaGiustina et al. (2019), where the global SFD slope (~2.9) is more similar to the dark boulder SFD slope than the bright boulder slope.

To further explore the characteristics of the returned sample, we applied our classification to OCAMS SamCam images with an unrestricted view of the contact area (the full region covered by the TAGSAM head) before the TAGSAM head descended far enough to block part of the site from view. Using these images, we mapped the visible extent of all particles with resolvable morphology. Due to the pixel scale relative to the small particle size and extensive shadowing in the image, it was not possible to distinguish between all four morphologic classes. Rather, we grouped Types A and B together, and Types C and D together (Figures 14a and 14b). Type A and B particles, in line with our large-scale classification, were dark, rounded, and rougher with resolvable clasts. Type C and D particles were brighter, smoother, and angular. We mapped 72 particles using a combination of single images and multi-image gifs, of which 46 were type A, B and 26 were Type C, D. The darker Type A and B particles cover approximately twice the visible area as the brighter particles (although ~63% of the sample site was covered by shadowing and therefore not mappable).

We then thresholded the image pixel I/F values into three bins (shadows, dark pixels, bright pixels) such that their distribution matched our mapped boundaries (Figures 14c and 14d). Shadowed pixels covered most of the image, with reflectance values of IOF < 0.006. Dark Type A, B particles have a mean I/F of 0.010 ± 0.002, while the brighter Type C, D particles have a mean I/F of 0.019 ± 0.008—the difference in average reflectance is therefore of a similar scale (~0.01) to our larger analysis using PolyCam normal albedo data, as well as global-scale analyses of MapCam normal reflectance (DellaGiustina et al., 2020a). Note that the dark Type A and B particles have a heterogeneous reflectance with apparently brighter clasts in a darker matrix—consistent with the analysis of the larger boulders (e.g., Figure 12).

As the dark Type A, B particles cover approximately twice the visible surface area as the brighter Type C, D particles, we predict that the sample will likewise be dominated by darker particles (in contrast to the slopes from the SFD above)—however, this prediction requires that the surface distribution of particles mirrors that of the subsurface. To investigate this possibility, we analyzed two sets of images taken in the period following sample collection but preceding the stowing of the TAG head in the SRC. The first set of SamCam images was taken as the spacecraft fired its thrusters and backed away from the surface, lofting extensive subsurface material and resolving several particles that were likely liberated from the subsurface. These images show several morphologies including apparently rounded particles and those with heterogeneous surface brightness, potentially indicating a clastic texture (Figures 15a and 15b), as well as distinctly smooth particles (Figure 15c). Similar morphologic heterogeneity of rugged and smooth lofted particles was found on Ryugu after sample collection by the Hayabusa2 spacecraft (Tachibana et al., 2022), further emphasizing morphologic similarities on the two asteroids.

The second set of images we analyzed were taken immediately prior to stowage in the SRC, as particles were observed to leak out of the TAG head (Lauretta et al., 2022) (Figure 15d). Images of these particles display similarly diverse morphologies, including knobby (Figure 15e) and angular flakey particles (Figure 15f). Taken together, we can conclude that particles on the surface and subsurface show morphologic diversity similar to that found at the boulder scale—despite evidence for a difference in the average particle size at the surface and in the near-surface (Bierhaus et al., 2023). Additionally, we found evidence for morphologic diversity within the particles that were actually collected by the spacecraft (albeit lost to space), which suggests that similar diversity will be present in the remaining sample.

As a final analysis anticipating the diversity of the returned sample, we assessed where particles may have become trapped on the underside of the TAG head, on the 24 contact pads, 21 torq-set screws, or three pegs (Figure 16a). To do this, we mapped where in the contact region each of the contact pads, screws, and pegs would have touched. Our analysis anticipated that both dark Type A, B and bright Type C, D particles were contacted by the TAG head, and may have become trapped (Figure 16c). These particles, should they remain trapped on the contact pads, screws, and pegs throughout the journey to Earth, will provide an unequivocal sample from the surface of Bennu.
and will be critical for understanding processes such as space weathering. A summary of which type of particle may be present on specific contact pads, screws, and pegs is included in Table 4.

7. Conclusions

Bennu’s boulders are a veritable treasure trove of information about the properties, diversity, and evolution of its parent body prior to disruption. Our understanding of both the parent body and of Bennu will only expand once the returned sample is analyzed. From our analysis, we provided a framework through which the diverse boulders on Bennu can be rapidly sorted and analyzed based on orbital-scale remote sensing data, as well as links to sizes down to the scale of the returned sample. We propose that morphologic and physical diversity will be present in the sample that will enable links to meter-scale boulders on Bennu, and which will reveal the heterogeneity of the parent body.

Figure 14. Analysis of the contact site sampled by Touch-And-Go Sample Analysis Mechanism. (a) SamCam image of the contact area, SamCam image 20201020t214917s231. (b) The same image showing mapped outlines of all particles with resolvable morphology. (c) Thresholded portion of the SamCam image where three pixel values (dark, bright, shadow) match the mapped particle outlines in panel (b). Dark particles are ~0.01 darker than bright particles, consistent with investigations of albedo at boulder-scales. (d) Particle outlines on the thresholded image. Dark Type A, B particles cover ~twice the surface area as bright Type C, D particles, suggesting the sample will be dominated by dark, rugged particles.

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As a caveat, additional analyses may reveal more variation within the boulder groups than is apparent from this study. For example, Rozitis et al. (2022) described two boulders along the edge of Hokioi Crater that look similar but have quite distinct thermal inertia values. This difference could be attributed to different inherent properties, or could rather be due to varying degrees of surficial weathering, ejecta or fine-grained particle coating, or other superficial effects. If the difference is due to the former, this is evidence that there may be further variability within our defined boulder groups that is not captured by morphology, albedo, and roughness alone. Further analysis with additional data sets including thermal and spectral data is required, and ongoing.

We acknowledge that some of the characteristics described in this work, which are readily apparent at the meter scale, will be altered or not distinct at the sub-cm scale of the sample; therefore, the classification presented here may need to be updated in the context of the sample. For instance, it may not be possible to identify clasts that

Figure 15. (a–c) SamCam images taken after thrusters fired to back the spacecraft away from surface, excavating, and lofting subsurface particles. Particles appear rugged and potentially (a, b) clastic and (c) smooth. (d–f) SamCam Images showing sampled material leaking out of the TAG head. Images show heterogeneous particle morphologies including knobly (e) and angular and flakey (f). SamCam images (a) 20201020t214951s319, (b) 20201020t214956s189, (c) 20201020t214952s536, (d) 20201022t174421s506, (e) 20201022t174417s432, and (f) 20201022t174413s362.
have eroded out of a clastic Type A boulder or to distinguish them from a Type C particle not previously incorporated into a Type A boulder. However, initial analyses of the Ryugu sample from the Hayabusa2 mission show encouraging results, with observable differences in particle morphology that reflect the macroscale observations of boulders from orbit (and which bear striking resemblance to the morphologies on Bennu documented in this work)—with some rugged and irregularly-shaped particles (likely relating to Ryugu Type 1 boulders) and others that are smooth and have one or more broad, flat surfaces (likely linking to Ryugu Type 2 boulders) (Nakamura et al., 2022; Tachibana et al., 2022). Tachibana et al. (2022) also found that pebble-sized particles were present in the sample, the largest ~10 mm which is the maximum ingestible size by the sampler, demonstrating that

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**Figure 16.** Predictions for types of materials that may be present on contact pads, torq-set screws, and pegs on the Touch-And-Go Sample Analysis Mechanism (TAGSAM) head. (a) Numbering of contact pads, screws, and pegs on the underside of the TAGSAM head. (b) Mapped particle outlines inside the contact area from Figure 14b. (c) Overlay of TAGSAM on the mapped particles, with red outlines indicating potential contact on dark Type A, B particles and blue outlines indicating bright Type C, D particles (mixed color indicating both may be present. (d) Color-coded outlines with SamCam image removed. Both types of particles should have been contacted and may be included in the returned sample.
particles could remain intact through sample collection and atmospheric re-entry. These results are promising that similar variations in the Bennu sample will also be evident.

Data Availability Statement

All data used in this work are available via the Small Bodies Node and the USGS Annex of the Planetary Data System, including radiometrically calibrated OCAMS images (Rizk et al., 2021), TAGCAMS images (Bos et al., 2021), OLA data (Daly et al., 2022), and the Detailed Survey (Bennett et al., 2020) and normal albedo mosaics (Golish et al., 2021). The Small Body Mapping Tool can be downloaded at https://sbmt.jhuapl.edu/#download. The data collected in this work, including boulder location, morphology, and albedo, are available in an accompanying SI Figsshare file (Jawin et al., 2023).

Acknowledgments

We thank Soji Sugita and Ramy El-Maarry for thorough and insightful reviews of the manuscript. We thank Maurizio Pajola for discussions regarding size-frequency distribution calculations, and Daunon Golish for discussions about Recon image photometry. We thank Lisette Meledend and Tallulah Cassidy for their assistance assessing the morphology of Bennu's largest boulders. We thank Alexandre I.R. White for assistance developing the coding analysis and the application of qualitative social science methods to this work. We are grateful to the entire OSIRIS-REx Team for making the encounter with Bennu possible. This work was supported by NASA NFDAP Grant 80NSSC21K0827. BR acknowledges funding support from the UK Science and Technology Facilities Council (STFC).

Table 4

Summary of Predictions for the Physical Properties of the Returned Sample

<table>
<thead>
<tr>
<th>Property</th>
<th>Type A</th>
<th>Type B</th>
<th>Type C</th>
<th>Type D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical properties</td>
<td>Rounded, rugged, elastic, impact breccias</td>
<td>Rounded to sub-rounded</td>
<td>Angular, smooth, may contain carbonates</td>
<td>Sub-angular, contains carbonates</td>
</tr>
<tr>
<td>Normal albedo</td>
<td>0.045 ± 0.002</td>
<td>0.047 ± 0.002</td>
<td>0.055 ± 0.004</td>
<td>0.054 ± 0.004</td>
</tr>
<tr>
<td>Contact pads</td>
<td>2, 3, 5, 8, 9, 10, 17, 18, 19, 23, 24</td>
<td>1, 3, 6, 7, 14, 15, 18, 21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Torq-set screws and pegs</td>
<td>1, 8, 15, 16, 21, P1</td>
<td>2, 6, 13, 14, 18, 19, P2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abundance</td>
<td>More abundant (up to twice as much)</td>
<td>Less abundant</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

References

Ernst, C. M., Barnoun, O. S., Daly, R. T., & Small Body Mapping Tool Team. (2018). The small body mapping tool (SBMT) for accessing, visualizing, and analyzing spacecraft data in three dimensions. 49th Lunar and Planetary Science Conference, Abstract #1043.