Global Patterns of Recent Mass Movement on Asteroid (101955) Bennu

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Abstract The exploration of near-Earth asteroids has revealed dynamic surfaces characterized by mobile, unconsolidated material that responds to local geophysical gradients, resulting in distinct morphologies and boulder distributions. The OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer) mission confirmed that asteroid (101955) Bennu is a rubble pile with an unconsolidated surface dominated by boulders. In this work, we documented morphologies indicative of mass movement on Bennu and assessed the relationship to slope and other geologic features on the surface. We found globally distributed morphologic evidence of mass movement on Bennu up to ~70° latitude and on spatial scales ranging from individual boulders (meter scale) to a single debris flow ~100 m long and several meters thick. The apparent direction of mass movement is consistent with the local downslope direction and dominantly moves from the midlatitudes toward the equator. Mass movement appears to have altered the surface expression of large (≥30 m diameter) boulders, excavating them in the midlatitudes and burying them in the equatorial region. Up to a 10 ± 1 m depth of material may have been transported away from the midlatitudes, which would have deposited a layer ~5 ± 1 m thick in the equatorial region assuming a stagnated flow model. This mass movement could explain the observed paucity of small (<50 m diameter) craters and may have contributed material to Bennu’s equatorial ridge. Models of changes in slope suggest that the midlatitude mass movement occurred in the past several hundred thousand years in regions that became steeper by several degrees.

Plain Language Summary Mass movement is the flow of loose material such as rock fragments across the surface of a planetary body (for instance, a landslide). We searched images of the surface of asteroid (101955) Bennu for evidence of mass movement. We found that rocks of various sizes have moved downslope, and evidence of this movement is apparent at most locations on the asteroid. By measuring the distribution of, and surface elevation around, the largest boulders on the surface of Bennu, we also found that the downslope movement of material appears to have excavated large boulders from the subsurface in the midlatitudes and buried large boulders near the equator. Our observation that material on Bennu has moved in what is currently the local downslope direction is not necessarily expected, because the downslope direction can change based on how quickly the asteroid is rotating, which varies over time. Thus, we can infer that this movement happened in the geologically recent past—probably within the past several hundred thousand years. These results can help us understand how geologic features like craters are erased, how the equatorial ridge formed, and how Bennu (and potentially other asteroids) change shape over time.

1. Introduction

Mass movement affects virtually all rocky planetary surfaces through the transport of material, largely under the force of gravity, on various spatial and temporal scales (e.g., Selby, 1993). On small airless bodies, where surface processes driven by atmospheric interactions (e.g., eolian, fluvial, and glacial processes) are absent,
mass wasting can play a dominant role, along with impact cratering, in shaping the surface. Investigations of near-Earth asteroids (NEAs) such as (433) Eros and (25143) Itokawa have shown that mass movement fundamentally influences the observed surface (e.g., Miyamoto et al., 2007; Thomas et al., 2002). Patterns of mass movement and the distribution of boulders on such bodies can be used to study their evolution (e.g., Mazrouei et al., 2014).

In the absence of other dynamical forces, mass movement is initiated by gravitationally and rotationally driven downslope movement. Particularly for small unconsolidated “rubble pile” asteroids (Richardson et al., 2002), changes to the spin period driven by the thermal torqueing process referred to as the Yarkovsky-O’Keefe-Radzievskii-Paddack (YORP) effect can induce changes to the slope distribution (e.g., Bottke et al., 2006; Rubincam, 2000). Currently, Bennu is undergoing an increase in rotation rate due to the YORP effect (Hergenrother et al., 2019; Nolan et al., 2019). Identifying the relationship between mass movement direction and the current slope distribution can indicate approximately when mass movement occurred (e.g., Sugita et al., 2019).

NASA’s Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer (OSIRIS-REx) spacecraft is currently investigating NEA (101955) Bennu (Lauretta et al., 2017; Lauretta, DellaGiustina, et al., 2019). Bennu, a rubble pile, exhibits a diverse surface geology including craters ranging in size from <10 to over 150 m in diameter (Walsh et al., 2019), an equatorial ridge, at least four high-standing longitudinal ridges that in two cases extend nearly pole to pole (Barnouin et al., 2019), and millions of boulders (defined here as particles >20 cm) that range in morphology (Jawin et al., 2019) and size, with the largest exceeding 50 m (DellaGiustina et al., 2019).

Early OSIRIS-REx observations of Bennu’s surface identified evidence of mass movement, including a potential mass flow and variations in boulder concentrations across the surface (Walsh et al., 2019). Slope transitions have also been identified that are consistent with mass wasting in the Bennu geopotential field (Scheeres et al., 2019). In addition, the concentration of large (>20 m) boulders at nonequatorial latitudes has been cited as evidence that mass movement is altering the distribution of boulders on the surface (DellaGiustina et al., 2019). Similar variability in boulder distribution has been observed on asteroid (162173) Ryugu (Michikami et al., 2019).

In this work, we documented evidence of global patterns of mass movement on the surface of Bennu. We identified morphologies indicative of mass movement at the meter scale and larger and interpreted the direction of movement indicated by each morphology. We then analyzed the magnitude and direction of slopes at each location of mass movement. Finally, we estimated the volume of transported material using the distribution and variation in surface elevation of the largest boulders on Bennu. Unraveling how mass movement has affected the surface of Bennu can inform our understanding of the processes of crater erasure, equatorial ridge construction, and global reshaping of this and other asteroids through time.

### 1.1. Mass Movement on Small Asteroids

The mass movement that has been documented on NEAs to date can provide insight into their evolution. On (433) Eros, bright and dark streaks associated with crater walls, talus cones, ponded fine particulates, and a deficiency of small craters (≤1 km diameter; Veverka et al., 2001) were identified as examples of material transport. This transport indicates an active surface characterized by a global regolith layer at least tens of meters deep and overlying a substrate with some competence several hundred meters below the surface (Robinson et al., 2002).

The NEA (25143) Itokawa is believed to be a rubble pile (Fujiwara et al., 2006), similar to Bennu. Itokawa’s surface is covered in unconsolidated gravels at about the millimeter scale and larger, which have become size segregated, leading to accumulations of fine particles in geopotential lows (Miyamoto et al., 2007). Vibrations induced by seismic shaking, tidal effects, and/or thermal processes drove granular processes including surface migration, convection, and size sorting and led to the formation of the smooth terrains Muses Sea and Sagamihara (Fujiwara et al., 2006; Miyamoto et al., 2007). The smooth terrains are devoid of any large boulders and may have formed by downhill regolith migration and mantling of preexisting rougher terrain in a layer ~2 m thick (Barnouin-Jha et al., 2008). In the rough terrains, gravels are imbricated (consistent overlapping of rock edges), collected on the uphill sides of slopes, and consistently aligned. Alignment occurred with boulder long axes oriented transverse to the direction of gravel migration.
which consistently matched the local slopes, implicating gravitationally induced motion (Miyamoto et al., 2007). Itokawa, like Eros, was found to have a deficiency of small craters (e.g., Michel et al., 2009), in both cases suggesting a crater erasure process.

Ryugu is similar to Bennu in its shape and physical characteristics and shows evidence of mass movement in the form of crater wall slumping, asymmetric regolith deposition on imbricated boulders, a paucity of small craters (<100 m) (Sugita et al., 2019), and a variable number density of boulders indicative of boulder burial (Michikami et al., 2019). The observed direction of mass movement from the top of the equatorial ridge toward the higher latitudes is consistent with the current geopotential of Ryugu (Sugita et al., 2019).

The depletion of small craters observed on several NEAs has been largely credited to resurfacing via mechanisms including seismic shaking (Miyamoto et al., 2007; Richardson et al., 2005; Tatsumi & Sugita, 2018; Yasui et al., 2015). Impacts on the surface of an asteroid are accompanied by a shock wave that in some cases can induce shaking and result in downslope motion of loose, unconsolidated material. This effect may be particularly enhanced for small bodies such as NEAs because seismic energy is not able to attenuate as rapidly as it would on a larger body (Murdoch et al., 2015; Richardson et al., 2005). However, seismic shaking may not be an efficient mechanism on all small bodies and could depend on composition or structure, particularly if the porosity is high enough to attenuate impact-induced shock waves over short distances; for example, no evidence was found for seismic shaking on Ryugu from the Small Carry-on Impactor (SCI) experiment performed by Hayabusa2 (Nishiyama et al., 2020). Therefore, other mechanisms to drive mass movement may dominate on asteroids like Bennu.

Slope changes due to a variable spin period are an alternate source of energy for mass movement. For example, a decrease in spin period (where the asteroid rotates more quickly, referred to as “spin-up”) as a result of the YORP effect will alter the effective slope on the surface on timescales of millions of years or less (e.g., Bottke et al., 2006; Rubincam, 2000). If the critical angle of repose is exceeded owing to spin-up, slopes are likely to fail, resulting in downslope motion and potentially altering the shape of the asteroid (e.g., Keller et al., 2010; Sanchez & Scheeres, 2020; Scheeres, 2015; Walsh, 2018). YORP spin-up is dependent on the detailed shape of a body; by changing that shape with each successive landslide or bulge, it may be a self-limiting process (Statler, 2009). Slope oversteepening due to YORP spin-up may play a role in mobilizing material on Bennu, particularly if the asteroid is not prone to seismic shaking, or if the rate at which YORP changes the spin period becomes much shorter than that required for impact-induced global seismicity.

2. Methods and Datasets

2.1. Identification of Mass Movement

We identified morphologic evidence of mass movement on Bennu by assessing images of the surface taken by the PolyCam instrument, which is part of the OSIRIS-REx Camera Suite (OCAMS) (Golish et al., 2020; Rizk et al., 2018). PolyCam is a narrow-angle adjustable-focus (field of view, 13.8–14.3 mrad) panchromatic (~500–800 nm) Ritchey-Chrétien camera designed to image the low-reflectance surface of Bennu.

We used two global mosaics at different pixel scales as the basis for our investigation. The first mosaic is composed of images taken during the Approach phase of the mission, with a pixel scale of 40 cm and larger, and solar phase angle of ~35° (DellaGiustina et al., 2019). This mosaic was used to search for large-scale features, such as mass flows and the distribution and partial burial of the largest boulders (described in section 3.1).

The second mosaic was created from images taken during the Detailed Survey phase of the mission (Bennett et al., 2020) and is better suited for identifying small-scale mass movement morphologies. The mosaic is globally controlled to the Bennu shape model with a mean spatial accuracy of ~30 cm and a pixel scale of ~5 cm, with solar phase angles of 30–50° in the midlatitudes (Bennett et al., 2020). This second mosaic was used for identifying smaller-scale features that made up the majority of our data set, including perched boulders, particle size grading, and imbricated boulders. The ground control of this mosaic means it is well registered to the shape model, making it well suited to linking images and surface slopes.

Both mosaics enabled visual assessments of Bennu’s surface at latitudes up to ~80°N and S with full confidence. Latitudes >70° have degraded image resolution in the Approach mosaic. The Detailed Survey mosaic has full polar coverage; however, latitudes >80° have long shadows that prevented complete morphologic
assessment at the highest latitudes. We therefore excluded latitudes >80° from our analysis of mass movement morphologies.

We searched Bennu's surface for morphologies associated with mass movement as observed on other small bodies, such as imbricated boulders, perched boulders, partly buried boulders, or evidence of particle sorting (i.e., accumulations of particles of similar sizes). The search for mass movement morphologies was conducted with the mosaics draped over a 3,000,000 facet shape model (v42) with ~80 cm facets, displayed in the Small Body Mapping Tool (SBMT) (Ernst et al., 2018). The shape model was generated using stereophotoclinometry (SPC) (Barnouin et al., 2019, 2020; Gaskell et al., 2008). Certain mass movement morphologies (e.g., imbrication) can be subtle or may be falsely identified as a result of illumination conditions; to minimize false identifications, each candidate location of mass movement in a global mosaic was checked against one or more unprojected PolyCam images taken under different illumination conditions (DellaGiustina et al., 2018). Features were only recorded if we observed unambiguous morphologic evidence under multiple illumination conditions.

Once a location of mass movement was identified and confirmed, the morphologic type was defined, and the direction of apparent motion was determined and recorded in SBMT with a line segment such that the orientation could be assessed. Orientation angles were defined such that 0° corresponds to movement to the north, 90° is movement to the east, 180° is movement toward the south, and 270° is movement to the west. The direction of apparent motion was determined by assessing the relative stratigraphy and directionality of each instance of mass movement. For example, if one face of a boulder was buried (e.g., Figure 1), we inferred that the stratigraphically younger material mantling the boulder was deposited on top of it, and the distribution of this material relative to the surrounding terrain allowed for an orientation to be determined. There is inherent uncertainty in these orientation measurements, as there is natural variation in the direction that individual particles would have traveled, and each orientation measurement therefore represents the general direction of movement rather than the exact motion of each particle.

This mapping effort provided a global data set on the preferred orientations of rock particles across the surface. To understand the nature and distribution of mass movement on Bennu, we needed to assess the local slope and downslope direction at each location of mass movement and compare these to the interpreted direction of movement. In some locations, the direction of motion could not be determined (e.g., poorly organized accumulations of boulders at topographic lows). In such instances, we noted the location but did not include it in our quantitative analysis.

2.2. Local Slopes

Derivation of local slopes across the shape model required the determination of the global geopotential gradient. Assuming uniform density, we defined the geopotential by computing the acceleration due to gravity at each shape model facet, which includes a spin term (following Barnouin-Jha et al., 2008). Surface slope is calculated by taking the dot product of the surface normal vector and the geopotential gradient, which is a function of the spin period and mass distribution. Slopes were measured on the same v42 SPC-derived shape model used for the initial mass movement documentation, but at a lower resolution (200,000 facets, ~3 m each). We used this lower-resolution shape model to derive slopes because the higher-resolution, ~80-cm-facet shape model was sensitive to localized topography driven by individual boulder faces, rather than the more relevant slope of the immediate neighborhood. The facet closest to each location of mass movement was identified, and the magnitude of the slope at that facet was recorded.

Our results confirm that on Bennu, the current geopotential is highest at the poles and lowest at the equator, so the surface slopes are generally oriented toward the equator (consistent with the global slope maps provided in Scheeres et al., 2019). Globally weighted mean slopes are ~17° (Barnouin et al., 2019), although a sharp transition in slope is present at ~20°N and S latitude (Scheeres et al., 2019). Owing to this sharp transition, the average slope within the equatorial region between 20°N and S is ~12°, and the average slope at higher latitudes is ~18° (Scheeres et al., 2019).

In this work, we consider the low-slope region between ±20° latitude to be the "equatorial region" (average slope ~12°), which is also the region that contains the equatorial ridge. Although the equatorial ridge is a topographically high feature, the region overall has relatively flat slopes. This distinction is due to the fact
that the ridge is a geomorphologic feature, whereas the slopes are dependent on the global geopotential, a function of the spin period and global mass distribution.

Outside the equatorial region, we considered the steeper-sloped regions from 20°–70°N and S latitude to be the “midlatitude regions” (average slope ~19°) and 70°–90°N and S to be the “polar regions” (average slope ~17°). With the slope field well understood, we were able to quantify the total mass movement over Bennu’s recent geologic history.

Figure 1. Examples of morphologies indicative of mass movement. Locations on Bennu are indicated in Figure 2a. (a, b) Boulder burial. Arrows indicate interpreted direction of movement. (a) Image center: 24.6°S, 22°E; ID, ocams20190328t201203s821. (b) Image center: 19°S, 258°E; ID, ocams20190411t210615s112. (c) Perched boulders, here called “rocks on rocks.” Image center: 3°N, 268°E; Detailed Survey mosaic (Bennett et al., 2020). Arrow indicates interpreted direction of movement. (d) Size grading of boulders. Image center: 22°N, 290°E; ocams20190329t184752s565. (e) The only identified large debris flow. Dashed arrows indicate the edge of the flow; solid arrow indicates direction of movement. Image center: 12°S, 260°E; ocams20181201t052541s304. (f) Well-sorted but poorly organized accumulation of boulders. Image center: 11°N, 18°E; ID, ocams20190329t174348s444 (Rizk et al., 2019).
2.3. Boulder Excavation and Burial: Mass Movement Quantification

We constrained the amount of material transported away from the midlatitudes by comparing the surface elevation (the height above or below a reference geopotential) upslope and downslope of the largest boulders on Bennu. We mapped the distribution of these boulders by systematically identifying all boulders ≥30 m (a total of 17 boulders) and recording their locations in SBMT. Although the extreme polar regions (>80°) were excluded from the documentation of mass movement morphologies due to the presence of large shadows in the image data, we included these regions for our inventory of large boulders, as features ≥30 m were apparent even in the presence of long shadows. We identified one large boulder in the extreme polar latitudes, near the south pole (~84°S, discussed in section 3.4.2). We also validated this high-latitude boulder using a shape model derived from laser altimeter data, which is not affected by polar shadows.

To perform the surface elevation analysis, we extracted topographic profiles over each boulder using local 15-cm digital terrain models (DTMs) from the v42 SPC-derived shape model. These local DTMs were used to obtain the most accurate surface elevation and slope around each boulder; they have an associated error of ~20 cm (1 sigma). We generated a line with the same slope and elevation as the surface upslope of each large boulder in each topographic profile and projected it to pass over the downslope surface. Our assumption was that the initial surface profile surrounding each large boulder followed a constant slope equal to that of the current surface upslope of the boulder. We infer that mass movement has led to the observed difference in elevation. Therefore, the current offset between the upslope and downslope elevation describes the depth of material removed near each boulder. We measured this difference in elevation between the projected original surface and the current downslope surface and assumed that the difference equated to the depth of material removed by mass movement. The surface roughness present on Bennu contributes to uncertainty to our estimates—the uneven surface both upslope and downslope of each large boulder can lead to slight differences in the elevation of the projected surface, as well the elevation difference between the projected and current downslope surface. We estimate that surface roughness leads to an uncertainty in our measurements of ± ~1 m (1-sigma). The distances over which these measurements were calculated are small enough (less than several tens of m) that we neglected the curvature of the surface of Bennu.

To quantify how much material has been transported across Bennu by mass movement, we converted our depth estimate into an estimated volume by multiplying the measured depth by a projected surface area (assuming that a constant depth of material was removed from a given area on the asteroid). Surface area calculations assumed a mean radius of 245 m.

Several caveats are inherent in this analysis. First, it provides an upper limit to the amount of surface deflation that occurred in the midlatitudes, as it assumes a constant depth of material was removed uniformly from the surface via mass movement and assumes no material was lost from the surface (e.g., via percolation into the interior or loss to space, such as in the particle ejection events described by Lauretta, Hergenrother, et al., 2019). Second, it assumes that the large boulders have not moved across the surface and the current distribution of large boulders reflects the original distribution in the surface and/or subsurface. Finally, it only considers the excavation of midlatitude boulder downslope faces, and not the burial of upslope boulder faces, which would act to increase the elevation of the upslope sides of the boulders. In reality, upslope burial and downslope excavation occur in tandem, and both processes have affected the visible extent of each boulder. Despite these caveats, our quantification serves as an initial estimation of the extent of mass movement in the resurfacing history of Bennu (e.g., Scheeres, 2015).

2.4. Spin Period and Slope Changes

Surface slopes, the geopotential, and the latitudes where the rotational Roche lobe (the region where material is energetically coupled to the surface of a body, as defined in Scheeres et al., 2019) intersects the surface are related to the spin rate of the asteroid. The transition in slopes at 20°N and S latitude coincides with the intersection of the rotational Roche lobe with the surface, with the equatorial region lying inside the lobe (Scheeres et al., 2019) at the current spin rate.

Bennu’s spin is accelerating owing to the YORP effect at an observed rate of ~3.6 × 10⁻⁶ degrees day⁻² (Hergenrother et al., 2019; Nolan et al., 2019). It is possible that past instances of mass loss via particle ejection (Lauretta, Hergenrother, et al., 2019) could have complicated the rotational evolution of Bennu; however, the currently observed ejections do not show evidence of the preferred directionality that would be
necessary to do this (Scheeres et al., 2020). We investigated the expected change to the slope distribution on Bennu resulting from different spin periods (e.g., Scheeres et al., 2016). Changing the spin term can reveal the slope distribution at different periods in Bennu's past (assuming no change in the mass distribution). We measured the change in slope at each shape model facet for a period of prior spin-up from a 5-hr spin period to the current 4.3 hr, as well as hypothetical future spin-up from 4.3 to 4 hr. We then compared these modeled slope changes to the observed locations of mass movement to determine how a change in slope could have affected the distribution of mass movement in Bennu's recent past.

3. Results

3.1. Morphologies Indicative of Mass Movement

We identified morphologic evidence of mass movement on Bennu in a range of expressions. The two most common morphologies indicating mass movement were (i) boulder faces buried by a mixture of particle sizes, ranging from unresolved material up to boulders several meters in diameter (Figures 1a and 1b) and (ii) boulders resting on other boulders, which we refer to as “rocks on rocks” (Figure 1c). The major distinction between the two is the presence of “fine-grained” material in the first case, meaning a component of partly resolved or unresolved particles in PolyCam images at 5 cm/pixel, which have buried one face of a boulder. In comparison, “rocks on rocks” indicates at least one distinct, well-resolved boulder(s) resting on another. Additional morphologies indicative of mass movement include apparent particle organization —such as size grading (Figure 1d), long-axis alignment, and imbrication—and a large-scale debris flow previously identified by Walsh et al. (2019) (Figure 1e).

In many locations, accumulations of boulders are present that appear to be well sorted: Only large, meter-scale boulders are visible, without any unresolved component (Figure 1f). Accumulations of boulders were previously interpreted by Walsh et al. (2019) and Barnouin et al. (2019) to indicate mass movement on Bennu. We found that these accumulations, though apparently well sorted, display minimal organization, making it challenging to infer a direction of movement. This disorganized appearance is distinct from the majority of mass movement morphologies identified elsewhere and discussed below. For this reason, we did not include poorly organized boulder accumulations in the following quantitative analysis of mass movement direction and comparison to local slope, although the well-sorted nature of these boulder accumulations implicates mass movement as a sorting process.

3.2. Distribution and Direction of Mass Movement

The global distribution of mass movement on Bennu is illustrated in Figure 2. We identified 87 distinct instances of mass movement, encompassing the morphologies described above (mass movement locations and associated data provided in Jawin et al., 2020a). The most frequent classification (53%) of mass movement was rocks on rocks (Table 1). Boulder burial was the second most common (37%), and particle organization the third most common (9%). The debris flow is the only example of its kind (~1% of all features).

Mass movement was identified at all latitudes analyzed (80°N to 80°S). The same number of mass movement features was identified in the southern hemisphere midlatitudes as in the equatorial region (34 features in each case; Table 2), but fewer were found in the northern hemisphere midlatitudes (18 features). In the southern hemisphere midlatitudes, buried boulders were the most common evidence of mass movement. One example of mass movement was identified in the southern polar region (between 70°S and our mapping boundary of 80°S), categorized as boulder burial. In the northern hemisphere midlatitudes and equatorial region, rocks on rocks were the most common (Table 2). The single identified mass flow is located in the equatorial region (~10°S, 270°E).

The direction of apparent movement was interpreted at each location based on stratigraphy and geometry (Figure 2). The apparent direction of mass movement is generally N-S (Figure 3) but varies with location; movement in the midlatitudes is almost entirely directed toward the equator, whereas movement in the equatorial region (20°S to 20°N) is less ordered but still dominantly N-S.

3.3. Mass Movement and Slopes

On Bennu, the location and orientation of mass movement closely match the current slope distribution (Figure 4). Slopes are steeper in the midlatitudes than in the equatorial region. In general, mass movement...
acts to decrease surface slopes by transporting material from steep, unstable surfaces to equipotential lows. So, on a global scale, morphologies of mass movement can be expected to be spatially correlated with low-sloped regions. However, on Bennu we found a correlation between locations of mass movement and relatively steep slopes in the midlatitudes. Slopes at the locations of mass movement in the midlatitude region can exceed 25° (mean: 21°) (Figures 4a and 4b), compared to the average midlatitude slope of ~18°. The equatorial region is flatter in general, and slopes at mass movement locations (mean: 14°) are approximately equal to the equatorial average slope (12°).

The apparent directions of mass movement agree well with the current downslope directions in their locations (Figures 4c and 4d); the difference between the downslope and movement directions was

| Table 1 |
|---|
| **Mass Movement Morphologic Types** |
| Type | Number | Percent of total |
| B | 32 | 37% |
| R | 46 | 53% |
| O | 8 | 9% |
| F | 1 | 1% |
| **Total** | **87** | **100%** |

*Note: Morphologic types include buried boulders (B), rocks on rocks (R), particle organization (O), and mass flows (F).*

**Figure 2.** Global mass movement map. Arrows indicate locations of morphologic evidence of mass movement, pointing in the direction of apparent motion. (a) Color-coded arrows indicate the type of morphology, overlain on the global approach base map (DellaGiustina et al., 2019). Locations of features shown in Figure 1 are indicated in white lettering. (b) Arrows from (a) with the base map and color-coding removed for clearer viewing of directions.
less than 90° everywhere, with the majority of locations showing <50° difference and around one third of mass movement locations showing a difference <10°. This difference shows a slight variation with latitude, with larger differences found at lower latitudes, where the slopes are shallower on average (average difference ~24°; Figure 4d).

Table 2

| Type | South polar region | South midlatitude region | Equatorial region | North midlatitude region | South polar region | South midlatitude region | Equatorial region | North midlatitude region |
|------|--------------------|--------------------------|-------------------|-------------------------|--------------------|--------------------------|-------------------|-------------------------|
| B    | 1                  | 19                       | 8                 | 4                       | 100%               | 56%                      | 24%               | 22%                     |
| R    | 0                  | 14                       | 21                | 11                      | 0%                 | 41%                      | 62%               | 61%                     |
| O    | 0                  | 1                        | 4                 | 3                       | 0%                 | 3%                       | 12%               | 17%                     |
| F    | 0                  | 0                        | 1                 | 0                       | 0%                 | 0%                       | 3%                | 0%                      |
| Total| 1                  | 34                       | 34                | 18                      | 100%               | 100%                     | 100%              | 100%                    |

Note: Morphologic type abbreviations are the same as Table 1: buried boulders (B), rocks on rocks (R), particle organization (O), and mass flows (F). Latitude regions are the same as described in the text. The equatorial region is between ±20° latitude, the midlatitude regions are from 20 to 70° latitude in both hemispheres, and the polar regions are >70° latitude. No morphologic evidence of mass movement was found in the north polar region.

Figure 3. Rose diagrams showing the direction of mass movement on Bennu. Angles were defined such that 0° indicates movement to the north, 90° indicates movement to the east, and so forth. (a) Orientation of all instances of observed mass movement. The dominant orientation is N-S. (b) Mass movement in the northern hemisphere is almost exclusively southward. (c) Mass movement in the equatorial region (within ±20° latitude) has a wider distribution of orientations. (d) Mass movement in the southern hemisphere is almost exclusively northward.
3.4. Mass Movement and Other Geologic Features

3.4.1. Topographic Depressions: Longitudinal Ridges and Craters

Barnouin et al. (2019) identified several high-standing longitudinal ridges apparent in the spherical harmonic degree 4 sectoral term of the shape model. At least four of these ridges are present in the northern hemisphere, two of which continue into the southern hemisphere. Although the maximum relief of these ridges is only ~25 m, they exceed 700 m in length (Barnouin et al., 2019). Boulders appear to be concentrated adjacent to or between these ridges and in other topographic depressions (see Figure 2A of Walsh et al., 2019), which Barnouin et al. (2019) credited to mass wasting. Our results support that initial identification. We found that these boulder-rich areas are well sorted but are often poorly ordered, without a visibly obvious direction of movement (e.g., Figure 1f).

Walsh et al. (2019) identified candidate impact craters on Bennu (12 distinct and ~40 less distinct) ranging from ~10 to ~150 m in diameter; additional candidate craters exist at smaller sizes (Bierhaus et al., 2019). We found evidence of mass movement inside several of the identified candidate craters (hereafter craters;...
e.g., Figure 2a), particularly in the equatorial region, where they are more abundant (Walsh et al., 2019); for example, one ~70 m-diameter equatorial crater at ~0°N, 150°E shows three instances of material slumping toward the crater floor. We also observed accumulations of boulders in some crater interiors and at the bases of slopes, as previously noted by Barnouin et al. (2019) (see their Figure 4).

In addition to boulders within craters, the debris flow initially identified by Walsh et al. (2019) appears to have originated from a large N-S scarp at ~140°W and traveled east ~100 m, overtopping the western ridge of a 160 m-diameter crater and terminating in the interior of the crater in a distinct toe. There appears to be a mixture of particle sizes in this feature, including large boulders on the scale of tens of meters, as well as meter-scale and smaller particles. Topographic profiles taken over portions of this deposit suggest a depth of ~6 m of material could have been displaced and transported into the crater interior (Walsh et al., 2019).

3.4.2. Largest Boulders

Mass movement features are often visible around the largest boulders on Bennu, and the surface expression of large boulders may have been affected by mass movement, as has been proposed for Ryugu (Michikami et al., 2019). As such, we assessed the distribution and state of burial of Bennu’s largest boulders (≥30 m in diameter). There are 17 of these boulders (Figure 5a), all but three of which are located in the midlatitude region. Two are present in the equatorial region, and one is located near the south pole. Of the 14 midlatitude boulders ≥30 m, there is an asymmetric distribution between the north and south hemispheres: 12 are in the southern hemisphere (86%), while only two are in the northern hemisphere.

Scaling for surface area and normalizing to the maximum boulder abundance, the relative abundance of these largest boulders (Figure 5b) changes with latitude: Equatorial regions have a low relative abundance, which increases with latitude up to the polar regions. The total number of the largest boulders is low (n = 17), and boulders from both hemispheres have been combined to create this distribution. The highest relative abundance is at the south pole, owing to the presence of one large boulder in this region where the surface area is the smallest (~84°S).

Most of these largest boulders (88%) are partly buried in the subsurface (e.g., Figures 1a and 1b). The only two that are not visibly partly buried are in the midlatitudes (~5°E, 30°S and ~130°E, 50°S) and appear to be perched on the surface, rising several tens of meters above their surroundings (Figure 5c and noted in Walsh et al., 2019).

For the largest boulders in the midlatitudes and the southern polar region, only upslope boulder faces are buried, with consistently higher surface elevations relative to their downslope faces (Figures 6a and 6b). To quantify the difference in upslope and downslope surface elevation, we measured the difference in elevation between the predicted original downslope surface (extrapolated linearly from the current upslope elevation) and the current downslope surface (as described in section 2.3 and illustrated in Figure 6b). The surfaces on the downslope sides of the largest boulders show an average difference in elevation of ~10 m in the midlatitudes and near the pole (Figure 6c).

The two boulders ≥30 m in the flatter equatorial region appear to be mostly buried and have minimal surface relief from the surrounding terrain (e.g., Figure 5d). The slope across these boulders is lower, with an average difference in upslope and downslope elevation of ~1 m (Figure 6c).

4. Discussion

4.1. Boulder Excavation and Burial Indicates Midlatitude Surface Deflation

The observed variation in the distribution of the largest boulders on Bennu (Figure 5b) suggests that resurfacing played a role. Specifically, the abundance of the largest boulders in the midlatitudes (where slopes are steepest), relative to their two partially buried counterparts near the equator (where slopes are low), implicates mass movement driven by YORP spin-up as the dominant process that excavated the largest boulders from the subsurface. The discrepancy in the abundance of the largest boulders between the northern and southern hemisphere midlatitudes (Figures 5a and 5b) could either be due to different rates of mass movement or a difference in the initial concentration of large boulders in the different hemispheres. The two analyzed northern hemisphere boulders were found to have similar upslope/downslope surface elevation differences to the southern hemisphere boulders at similar latitudes (boulder data available in Jawin et al., 2020b), suggesting that similar amounts of material may have been removed from both midlatitude
regions. If mass movement rates were similar in both hemispheres, then there may have been more boulders at or near the surface in the southern hemisphere than the northern, which became exposed due to mass movement. Initially heterogeneous distributions of large boulders have been observed in numerical studies of gravitationally reaccumulated bodies (e.g., Bagatin et al., 2020), supporting this hypothesis.

The transport of smaller midlatitude particles downslope toward the equator would lead to surface deflation and exposure of the largest boulders in the midlatitudes and near the pole, whose upslope faces are buried and downslope faces are exposed, as we observe. Mobilized particles would be deposited at lower latitudes.

Figure 5. Bennu’s largest boulders. (a) Distribution of Bennu’s largest boulders (diameter ≥30 m), overlain on the global approach base map (DellaGiustina et al., 2019). Letters indicate the locations of boulders shown in parts (c) and (d). (b) Abundance of the largest boulders, scaled for surface area and then normalized. Fewer of these boulders are in the equatorial region than in the midlatitudes. One large boulder is present near the south pole. (c) Perched midlatitude boulder. Image center: 42°S, 129°E; ID, ocams20181202t075657s697. (d) Partly buried equatorial boulder. Image center: 5°N, 67°E; ID, ocams20190411t214923s915.
where slopes decrease, which would partially or completely bury the largest boulders, as observed. In this model of midlatitude surface erosion and equatorial accumulation, the observed difference between the upslope and downslope elevation at the largest boulders can be viewed as a proxy for the depth of material removed from these regions. Differences in surface elevation between the upslope and downslope faces of the largest boulders (Figure 6c) average ~10 m in the midlatitudes and polar region, ~1 m near the equator. Inherent surface roughness introduces measurement uncertainties of ±1 m.

To quantify an upper limit of the total amount of material transported across Bennu by mass movement, we assumed that this 10-m difference represents the average depth of material transported away from the entire midlatitude and polar region. We can then estimate how much material could have been deposited at the equator by calculating a total volume of transported material: If we assume an average depth of 10 m was transported from the entire region containing exposed large boulders (~20° to 85° latitude in one hemisphere), this would equate to a volume of material ~2.5 × 10^6 m^3 (multiplying 10 m by the projected surface area at constant radius of the region from 20° to 85° latitude, 2.5 × 10^5 m^2) per hemisphere. This material would eventually be deposited in the equatorial region, the global geopotential minimum. As the equatorial region also lies entirely within the rotational Roche lobe, it is possible for material to become trapped within this region and randomly redistribute itself across the surface (Scheeres et al., 2019), potentially resulting in a relatively uniform layer. If the transport of material was perfectly efficient, the entire volume (~2.5 × 10^6 m^3) would have been deposited in the equatorial region. If this volume were evenly distributed across the equatorial region of the hemisphere (0–20° latitude, a surface area of ~1.3 × 10^7 m^2), it would have formed a layer ~19 m thick. This suggests that a spherical 30-m boulder that was initially half buried at the equator of Bennu could have been effectively buried by the deposition of 19 m of material. However, this model is an
upper estimate; the largest boulders in the midlatitude region appear to be partly buried on their upslope faces (e.g., Figures 1a and 1b), suggesting that at least some material became trapped in the midlatitudes when it accumulated on the upslope sides of boulders. Thus, this efficient transport model is most likely an overestimate.

Alternatively, we can assume a more conservative model, where the transport of material was not efficient, and material only traveled a short distance before becoming trapped, potentially due to larger stationary boulders preventing further downslope motion. For example, if we break the surface of the asteroid into 10° latitude bins, material from the 60–70° latitude bin would have been transported to the 50–60° latitude bin, where it stalled. Likewise, material in the 50–60° latitude bin would have migrated only to the 40–50° latitude bin. In this stagnated transport model, only material from the 20–30° latitude bin would have been deposited in the equatorial region. Assuming the same depth of material was transported as in the efficient transport model (10 m), but only from the region between 20° and 30° latitude (a surface area of ~6.0 × 10^4 m²), a volume of ~6.0 × 10^5 m³ that was evenly distributed across the equatorial region would be ~5 m thick. This model is supported by the observation of buried upslope boulder faces. Our estimated thicknesses of equatorial deposition, ~5 to 19 m, have implications for crater erasure and equatorial ridge formation and are discussed in the following sections.

4.2. Crater Erasure

Walsh et al. (2019) found that there is a depletion of craters ~10 to 50 m in diameter on Bennu compared to the expected production rate (see their Figure 3d), with an apparent concentration of craters in the equatorial region. Impact craters on Bennu exhibit a wide range of depth-to-diameter ratios: 0.04 to 0.16 with respect to elevation, with a median of 0.09 (Daly et al., 2020). Therefore, to erase evidence of craters 10 to 50 m in diameter, any resurfacing process would need to transport ~1 to 5 m of material.

Mass movement may account for the observed scarcity (erasure) of craters in this size range on Bennu. In the midlatitudes (and also from the southern polar region), a ~10-m thickness of material may have been transported away. Although this is an upper limit, the removal of only half of this material would erase craters <50 m in diameter in the midlatitudes.

As noted by Walsh et al. (2019), several craters >50 m in diameter are present at the equator. If our upper estimate of ~19-m thickness of efficiently transported material was deposited at the equator, all of the equatorial craters currently observed (up to the largest, ~150 m) would have been erased. This interpretation is further evidence that the model of efficient transport is an overestimate. In comparison, the estimated depth of equatorial deposition from the stagnated flow model, ~5 m, could explain erasure of small (<50 m) craters but would not have erased the larger ones currently visible on the surface. We therefore favor the model of less efficient (stagnated) material transport, leading to the contribution of ~5 m of material to the equatorial region.

In addition to the small-scale downslope migration of surface material driven by YORP spin-up (the majority of the mass movement we observed), larger, more energetic landslides could also have acted to erase craters on Bennu. The debris flow into an equatorial crater (Figure 1e) was found to be ~6 m thick by Walsh et al. (2019), which is similar to the entire depth we estimated for small-scale mass movement in our stagnated flow model. If large-scale debris flows were a common process in Bennu’s recent history, a small number could account for the observed crater depletion. However, we only found morphologic evidence of one such feature, suggesting that large-scale mass flow events may not have been frequent or globally distributed in the geologically recent history of Bennu when our inferred global mass movement is likely to have occurred. Alternatively, the flow margins may have been entirely removed or mantled such that they are no longer identifiable.

4.3. Formation of the Equatorial Ridge

Ridge formation and evolution from processes such as mass movement can, in theory, serve as a probe of internal structure and strength of a rubble pile. Hirabayashi et al. (2015) found that when a rubble pile is stressed by spin-up (presumably due to the YORP effect), it will suffer internal failure if its strength or cohesion is equal throughout the body. This effect can manifest as an internal flow of material pushing up in the equatorial regions (see Hirabayashi et al., 2019; Watanabe et al., 2019). If there is some internal strength, a gradient of strength, or a core, then the failure is more likely to occur on the surface in the midlatitudes,
resulting in mass movement or landslides toward the equator (see also Walsh et al., 2008). Both of these avenues for ridge formation rely on continued spin-up of the body (through the YORP effect) to gradually move mass and grow the ridge. Our findings support the latter model via the evidence of mass movement predominantly from the midlatitudes toward the equator (although our results do not necessarily disprove the former model of internal failure). These observations support the idea that there is some degree or gradient of strength in Bennu’s interior, as proposed by Barnouin et al. (2019) in their analysis of Bennu’s shape. The large-scale landslides predicted by Hirabayashi et al. (2015) may not be the dominant process for ridge formation, as we did not identify any evidence of large, distinct landslides of material toward the equator; however, this process could have been more important earlier in Bennu’s history, and its signatures may have since been eroded or overprinted by more recent activity.

Other possibilities for ridge formation may avoid complications of requiring continued YORP spin-up in the face of regular shape changes. If a rubble pile resists shape change during spin-up and instead experiences a singular failure (“fission”), a significant mass could be sent into orbit, which itself may break apart, raining back to the surface preferentially near the equator (Jacobson & Scheeres, 2011). This may produce recognizable geology given the potential for large blocks to hit and settle at speeds of centimeters per second. Two of the largest boulders (≥30 m) were identified near the equator (Figure 5b), which could potentially support this model, although large boulders are seen elsewhere on the surface, so we do not consider the fission model the most likely model of ridge formation based on our results.

It is also possible that the ridge is an artifact of the reaccumulation process following the catastrophic breakup of a parent asteroid in the main asteroid belt, which preferentially leads to a spheroidal or top-like shape (Michel et al., 2020). The ridge on Bennu appears to be a geologically old feature (Walsh et al., 2019) based on the number of large (~50- to 100-m diameter) craters superposing it, which supports the reaccumulation model of ridge formation. In addition, our estimate for the amount of material delivered to the equatorial region (~5 m) is insufficient to have constructed the entire ridge, supporting this model of ancient ridge formation. If the ridge did form in the earliest part of Bennu’s history, the observed mass movement would have contributed several meters of material to the equatorial region after its initial formation.

The deposition of ~5 m of material at the equator via mass movement would have mantled geologic features such as scarps, large blocks, or large ancient landslide features that would enable us to determine which ridge formation model most likely occurred. However, determining an approximate age for the observed mass movement can help constrain the timing and relative importance of recent delivery of material to the equatorial ridge, which may be of use in distinguishing between ridge formation theories.

4.4. When Did Mass Movement Occur?

The current slope distribution is set by the spin period, which is accelerating by ~3.6 × 10⁻⁶ degrees day⁻² (Hergenrother et al., 2019). Changes to the spin period over the past several hundred thousand years could have led to drastic changes in slope magnitude and direction, in some locations inverting completely (Figure 7). Because all of the mass movement morphologies that we documented are consistent with the current downslope direction, we infer that these visible instances of mass movement occurred recently (during the present spin-period regime). We do not find any obvious evidence of ancient mass movement preserved from a time of very different slope distribution.

Predictions of past spin-up into the current spin period regime (from 5 to 4.3 hr) indicate where slopes would have changed the most (Figure 8a) and show that the observed instances of midlatitude mass movement occurred in regions with moderate slope increases (average slope change of +5°). Slope changes at locations of mass movement in the midlatitudes were on average larger than the latitudinal average (Figure 9), while mass movement in the equatorial region occurred in locations both steeper and flatter than the latitudinal average.

Not all mass movement in the midlatitudes occurred in locally oversteepened regions. Approximately 30% of midlatitude mass movement occurred at locations that had similar or lower slope delta values than the latitudinal average (Figure 9). The magnitude of the initial slope may also determine where mass movement can occur. Figure 8b shows the slope delta map over the same period (spin-up from 5 to 4.3 hr from Figure 8a) but only for facets that started (i.e., at a spin rate of 5 hr) with slopes ≥25°. This plot demonstrates a correlation of mass movement with locations that were initially steep, most of which became steeper in the spin-up
to a 4.3-hr period. In these initially steep regions, only a small increase in slope may have been necessary to initiate particle motion. In addition, local geologic setting may play a role in determining 160/435 where mass movement is visible. For example, mass movement appears to be associated with the large boulders on Bennu—without these boulders, the same patterns of mass movement may not have been preserved.

These data suggest that mass movement has occurred in steep midlatitude locations that became steeper on relatively recent timescales: using the observed YORP spin-up rate of $3.6 \times 10^{-6}$ degrees day$^{-2}$, and assuming that YORP is constant rather than stochastic with no significant change to the mass distribution, this period of spin-up could have occurred within the past ~200,000 years. Mass movement is also expected to have occurred prior to this time, but the comparatively recent activity we identified in this work may have overprinted and/or erased evidence of it.

The timing of mass movement in the equatorial regions is less straightforward; ~25% of mass movement in the equatorial region (Figure 9) occurred in locations that have become flatter over the past ~200,000 years. This may suggest that mass movement in the equatorial region occurred earlier, at a different spin period, and has been preserved due to the relatively flat slopes in the region. Alternatively, the surface acceleration on Bennu reaches its minimum in the equatorial region (a value of 26 μm s$^{-2}$; Scheeres et al., 2019), and as such, very little energy is required to mobilize material in this region; it may therefore be possible currently to mobilize material within the equatorial region across very flat surfaces.

We can also predict where mass movement may occur in the next ~100,000 years by decreasing the spin period from the current 4.3 to 4.0 hr (Figure 8c). The predicted future slope distribution shows steepening across the latitudinal bands from ~10°N to 20°N and S, with potential flattening at the equator. The locations of large increases in slope (e.g., 20°S, 40°E; 20°N, 110°E; 20°S, 180°E; 20°N, 300°E) may represent regions that will experience enhanced surface mass movement in the future. These predictions indicate that continued mass movement over the next several hundred thousand years will continue to contribute material to the equatorial ridge, regardless of the original ridge formation mechanism. The steepening in the ~10–20°N and S latitude regions in particular suggests that mass movement could lead the ridge to become more localized around the equator, similar to the more distinct ridge seen on Ryugu.

4.5. Mass Movement on Bennu and Other Asteroids

Mass movement on Bennu in many ways resembles that on other NEAs visited by spacecraft. We identified regions of variable boulder concentration, which were also documented on Itokawa, Eros, and Ryugu (e.g., Dombard et al., 2010; Michikami et al., 2008, 2019). Boulders on Bennu are sometimes organized, akin to the many imbricated boulders on Itokawa (Miyamoto et al., 2007). Mass movement may have led to the erasure of small craters on Bennu, as suggested for several other NEAs (e.g., Michel et al., 2009; Sugita et al., 2019;
Figure 8. Change in slope at different spin periods. (a) Slope changes that occurred in the recent past, during spin-up from 5 to 4.3 hr. Slope increase is indicated by positive delta values, and slope decrease is indicated by negative values. Black arrows are the locations of mass movement from Figure 2. (b) Slope delta map from (a) but with facets starting (at a 5-hr spin period) with slopes <25° masked out. Mass movement (black arrows) appears to be concentrated in locations that initially had steep slopes, most of which have become steeper. (c) Slope changes that could occur in a future spin-up from 4.3 to 4 hr.
The largest boulders on Bennu appear to have experienced excavation and partial burial, as has also been observed on Ryugu (Michikami et al., 2019; Sugita et al., 2019)—although the general direction of movement is reversed, with migration toward the equator on Bennu and migration away from the equator on Ryugu, off of the ridge and toward the low to middle latitudes (Sugita et al., 2019). The opposing direction of movement can be credited to different spin periods leading to distinct locations of the geopotential minima on the two asteroids—the equator on Bennu and the low to midlatitudes on Ryugu (Watanabe et al., 2019). Both Bennu and Ryugu have a single large boulder very close to their south poles (although Otohime Saxum on Ryugu is 160 m in diameter, larger than the ~40-m boulder on Bennu by a factor of 4, and larger by a factor of 64 in volume) (Watanabe et al., 2019).

Evidence of mass movement on Bennu also differs in some ways from that seen on other NEAs. On Bennu, boulders appear to accumulate in topographic lows rather than fine-grained material as on Itokawa and Eros (e.g., Dombard et al., 2010; Miyamoto et al., 2007). The concentration of boulders in local topographic lows may suggest that boulders are the mobile component of the surface and slowly migrate downslope given sufficient time. Conversely, boulders could have “accumulated” as a result of the preferential removal of smaller particles, leaving behind a lag of larger objects. The general paucity of resolvable fine-grained material on the surface of Bennu (e.g., Lauretta, DellaGiustina, et al., 2019) suggests that there could be a widespread process that acts to remove small particles from the asteroid; candidate processes include ejection off the surface (facilitated by the very low escape velocity; e.g., Lauretta, Hergenrother, et al., 2019; Scheeres et al., 2019), electrostatic levitation (e.g., Hartzell & Scheeres, 2013), or sequestration into the subsurface (percolation via the “Brazil-nut effect”; e.g., Rosato et al., 1987; Maurel et al., 2017). Preliminary evidence of a layer of finer-grained material in the near-surface has been identified in the interiors of small impact craters (Bierhaus et al., 2019), suggesting sequestration may be the process, rather than migration of boulders downslope.

If fine particles are the mobile component on the surface and become segregated into the near-subsurface through time, then the oldest surfaces on Bennu (and potentially other small rubble-pile asteroids) may be characterized by rough terrains dominated by boulders. Young surfaces, in contrast, may be those that contain a resolvable component of fine-grained material (potentially excavated through impacts) that have not yet been removed or sequestered. This is in direct contrast to larger planetary bodies such as the Moon, where boulders break down over time into smooth, boulder-free regolith layers (e.g., Basilevsky et al., 2015; Ghent et al., 2014).

5. Conclusions

Global analyses of mass movement morphologies on Bennu identified geologically recent transport of material of a range of sizes locally downslope, and more broadly from the midlatitudes and polar region toward the equator. Mass movement appears to have occurred on midlatitude slopes that steepened recently (past several hundred thousand years), which may have led to the excavation of the largest boulders in this region and burial in the equatorial region. Up to ~10-m thickness of material may have been transported from the midlatitudes, corresponding, conservatively, to a ~5-m layer deposited in the equatorial region, with an uncertainty of ±1 m. The net effect of this mass redistribution would have been to partly or completely bury boulders, erase small (<50-m diameter) craters, and contribute material to the equatorial ridge, all of which are consistent with observations of Bennu's surface geology. Further evidence of mass movement is likely to be identified in higher-resolution image data and laser altimetry measurements (Daly et al., 2017) acquired by the OSIRIS-REx mission. Mass movement is expected to continue operating on Bennu via the continued spin-up of the asteroid and resultant steepening of its surface slopes.

Figure 9. The change in slope at each location of mass movement relative to the latitudinally averaged slope delta (in 5° bins).
Data Availability Statement

Radiometrically calibrated PolyCam images are available via the OCAMS bundle in the Planetary Data System (https://sbn.psi.edu/pds/resource/orex/ocams.html) (Rizk et al., 2019). The base maps that we used to identify evidence of mass movement are shown in DellaGiustina et al. (2019) and Bennett et al. (2020). The mass movement that we identified in this work, including location, type, slope, orientation, slope, and slope delta, are given in Jawin et al. (2020a). The locations of large boulders and the elevation differences between their upslope and downslope sides are available in Jawin et al. (2020b).

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