Cite as: S. Watanabe *et al.*, *Science*
10.1126/science.aav8032 (2019).

Hayabusa2 arrives at the carbonaceous asteroid 162173 Ryugu—A spinning top-shaped rubble pile

S. Watanabe^{1,2*}, M. Hirabayashi³, N. Hirata⁴, N. Hirata⁵, R. Noguchi², Y. Shimaki², H. Ikeda⁶, E. Tatsumi⁷, M. Yoshikawa^{2,8}, S. Kikuchi², H. Yabuta⁹, T. Nakamura¹⁰, S. Tachibana^{7,2}, Y. Ishihara^{2,†}, T. Morota¹, K. Kitazato⁴, N. Sakatani², K. Matsumoto^{11,8}, K. Wada¹², H. Senshu¹², C. Honda⁴, T. Michikami¹³, H. Takeuchi^{2,8}, T. Kouyama¹⁴, R. Honda¹⁵, S. Kameda¹⁶, T. Fuse¹⁷, H. Miyamoto⁷, G. Komatsu^{18,12}, S. Sugita⁷, T. Okada^{2,7}, N. Namiki^{11,8}, M. Arakawa⁵, M. Ishiguro¹⁹, M. Abe^{2,8}, R. Gaskell²⁰, E. Palmer²⁰, O. S. Barnouin²¹, P. Michel²², A. S. French²³, J. W. McMahon²³, D. J. Scheeres²³, P. A. Abell²⁴, Y. Yamamoto^{2,8}, S. Tanaka^{2,8}, K. Shirai², M. Matsuoka², M. Yamada¹², Y. Yokota^{2,15}, H. Suzuki²⁵, K. Yoshioka⁷, Y. Cho⁷, S. Tanaka⁵, N. Nishikawa⁵, T. Sugiyama⁴, H. Kikuchi⁷, R. Hemmi⁷, T. Yamaguchi^{2,†}, N. Ogawa², G. Ono⁶, Y. Mimasu², K. Yoshikawa⁶, T. Takahashi², Y. Takei², A. Fujii², C. Hirose⁶, T. Iwata^{2,8}, M. Hayakawa², S. Hosoda², O. Mori², H. Sawada², T. Shimada², S. Soldini², H. Yano^{2,8}, R. Tsukizaki², M. Ozaki^{2,8}, Y. Iijima^{2,§}, K. Ogawa⁵, M. Fujimoto², T.-M. Ho²⁶, A. Moussi²⁷, R. Jaumann²⁸, J.-P. Bibring²⁹, C. Krause³⁰, F. Terui², T. Saiki², S. Nakazawa², Y. Tsuda^{2,8}

¹Nagoya University, Nagoya 464-8601, Japan. ²Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), Sagami-hara 252-5210, Japan. ³Auburn University, Auburn, AL 36849, USA. ⁴University of Aizu, Aizu-Wakamatsu 965-8580, Japan. ⁵Kobe University, Kobe 657-8501, Japan. ⁶Research and Development Directorate, JAXA, Sagami-hara 252-5210, Japan. ⁷University of Tokyo, Tokyo 113-0033, Japan. ⁸SOKENDAI (The Graduate University for Advanced Studies), Hayama 240-0193, Japan. ⁹Hiroshima University, Higashi-Hiroshima 739-8526, Japan. ¹⁰Tohoku University, Sendai 980-8578, Japan. ¹¹National Astronomical Observatory of Japan, Mitaka 181-8588, Japan. ¹²Chiba Institute of Technology, Narashino 275-0016, Japan. ¹³Kindai University, Higashi-Hiroshima 739-2116, Japan. ¹⁴National Institute of Advanced Industrial Science and Technology, Tokyo 135-0064, Japan. ¹⁵Kochi University, Kochi 780-8520, Japan. ¹⁶Rikkyo University, Tokyo 171-8501, Japan. ¹⁷National Institute of Information and Communications Technology, Kashima 314-8501, Japan. ¹⁸Università d'Annunzio, 65127 Pescara, Italy. ¹⁹Seoul National University, Seoul 08826, Korea. ²⁰Planetary Science Institute, Tucson, AZ 85710, USA. ²¹Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA. ²²Université Côte d'Azur, Observatoire de la Côte d'Azur, Centre national de la recherche scientifique (CNRS), Laboratoire Lagrange, 06304 Nice, France. ²³University of Colorado, Boulder, CO 80309, USA. ²⁴NASA Johnson Space Center, Houston, TX 77058, USA. ²⁵Meiji University, Kawasaki 214-8571, Japan. ²⁶DLR (German Aerospace Center), Institute of Space Systems, 28359 Bremen, Germany. ²⁷CNES (Centre National d'Etudes Spatiales), 31401 Toulouse, France. ²⁸DLR, Institute of Planetary Research, 12489 Berlin-Adlershof, Germany. ²⁹Institute d'Astrophysique Spatiale, 91405 Orsay, France. ³⁰DLR, Microgravity User Support Center, 51147 Cologne, Germany.

*Corresponding author. E-mail: seicoro@eps.nagoya-u.ac.jp

†Present address: National Institute for Environmental Studies, Tsukuba 305-8506, Japan.

‡Present address: Mitsubishi Electric Corporation, Kamakura 247-8520, Japan.

§Deceased.

The Hayabusa2 spacecraft arrived at the near-Earth carbonaceous asteroid 162173 Ryugu in 2018. We present Hayabusa2 observations of Ryugu's shape, mass, and geomorphology. Ryugu has an oblate 'spinning top' shape with a prominent circular equatorial ridge. Its bulk density, $1.19 \pm 0.02 \text{ g cm}^{-3}$, indicates a high porosity (>50%) interior. Large surface boulders suggest a rubble-pile structure. Surface slope analysis shows Ryugu's shape may have been produced if it once spun at twice the current rate. Coupled with the observed global material homogeneity, this suggests that Ryugu was reshaped by centrifugally induced deformation during a period of rapid rotation. From these remote-sensing investigations, we identify a suitable sample collection site on the equatorial ridge.

Carbonaceous (or C-complex) asteroids are leftover debris from planet formation in the solar nebula. Studying their formation, evolution, and volatile content provides information on formation processes around the snow line—the boundary between the inner and outer Solar System (SS). Carbonaceous asteroids may have delivered water and organic materials to the early Earth [e.g., (1)]. The Hayabusa2 mission goal is to rendezvous with a carbonaceous asteroid and probe these issues via a combination of remote-sensing observations from the spacecraft, in-situ surface measurements by deployed rovers and a lander, execution of an artificial impact experiment, and analyses of samples returned to Earth (2, 3). The

spacecraft was developed by the Japan Aerospace Exploration Agency (JAXA) as a successor to Hayabusa (4) and was launched by an H-IIA rocket on 3 December 2014. Its target is the near-Earth carbonaceous asteroid 162173 Ryugu (provisional designation 1999 JU₃). Hayabusa2 reached its target in June 2018; NASA's OSIRIS-REx spacecraft (5) reached another carbonaceous asteroid 101955 Bennu in December 2018.

After a 3.5-year cruise, a satellite search during approach to the asteroid detected no natural satellites >0.1 m within 100 km (6). Hayabusa2 arrived at the Home Position (HP), located at an altitude of ~20 km above Ryugu, on 27 June 2018 (6). The spacecraft did not enter into circum-asteroid

orbit but hovered at HP during the initial mapping phase. The remote-sensing instrument suite onboard Hayabusa2 includes the Optical Navigation Camera - Telescopic (ONC-T) with a wideband and seven narrowband filters (7, 8), a Thermal Infrared Imager (TIR) (9), a Near-Infrared Spectrometer (NIRS3) (10), and a laser Light Detection and Ranging (LIDAR) system (11). Coordinated observations among these instruments (fig. S1) (6) enabled an initial assessment of Ryugu's general physical characteristics. The spectral data obtained by ONC-T and NIRS3, indicated Ryugu is a Cb-type asteroid with a low geometric albedo of $4.5 \pm 0.2\%$ at $0.55 \mu\text{m}$ (8, 10).

ONC-T images reveal geomorphological features including the presence of numerous boulders on the surface (Fig. 1). From these images, we constructed global shape models with two different methods; stereophotoclinometry (SPC) (12) and the Structure-from-Motion (SfM) technique (13). These methods yielded shape models with polygon mesh resolutions of ~ 1 m. The two model topographies are in good agreement with each other (the standard deviation of height differences between them is ~ 1.5 m), except for around some boulders and in the polar regions (fig. S2) (6). Figure 2 shows the SfM-based shape model.

Ryugu's derived orbital and physical parameters are summarized in table S1 (6). The SPC-based shape model provided an estimate of the asteroid spin parameters: an axis with a right ascension $96.40^\circ \pm 0.03^\circ$ and declination $-66.40^\circ \pm 0.03^\circ$ in equinox J2000.0, and a period of 7.63262 ± 0.00002 hours. Our derived rotation period is consistent with ground-based observations, while our pole direction fits the second most probable solution compiled from ground- and space-based observations (6, 14). The obliquity—the angle between Ryugu's orbital and rotational poles—is $171.64^\circ \pm 0.03^\circ$, close to perfectly retrograde rotation (which would be at 180°). No wobble or change of the rotation rate have been detected (15).

Ryugu has an oblate body with an equatorial radius of 502 ± 2 m and polar to equatorial axis ratio of 0.872 ± 0.007 . The total volume obtained from the SPC-based shape model is 0.377 km^3 with an uncertainty of 1.3%. We conducted a gravity measurement (6) during a spacecraft ballistic descent down to 0.85 km from the asteroid surface and a subsequent ballistic ascent up to 5.4 km (6). The estimated mass is $4.50 \times 10^{11} \text{ kg}$ with an uncertainty of 1.3%, mainly due to uncertainties in the solar radiation pressure on the spacecraft. The bulk density is therefore $1.19 \pm 0.02 \text{ g cm}^{-3}$, less than the bulk densities (1.6 to 2.4 g cm^{-3}) measured for hydrated carbonaceous asteroids (Ch- and Cgh-type) (16). However, it falls within the 0.8 – 1.5 g cm^{-3} range measured for BCG-types [B-, C-, Cb-, and Cg-type; Ryugu is Cb-type (8)], which might be related to unheated icy asteroids (16).

NIRS3 observations indicate that OH-bearing minerals are ubiquitous on the surface of Ryugu (10). The presence of

water ice could explain the low bulk densities of main-belt carbonaceous asteroids, but is unlikely at Ryugu because the radiative equilibrium temperature ($\sim 250 \text{ K}$) is higher than the ice sublimation temperature ($\sim 230 \text{ K}$) even at its calculated central pressure of $\sim 8 \text{ Pa}$, and the estimated thermal diffusion time ($< 10^5 \text{ yr}$) is much shorter than the typical dynamical lifetime of near-Earth asteroids ($\sim 10^7 \text{ yr}$) (6).

The total porosity is derived (6) to be $> 50\%$ if the constituent grain density is similar to those of carbonaceous chondrites, of which the lowest known is the $2.42 \pm 0.06 \text{ g cm}^{-3}$ Orgueil CI meteorite (17). The estimated total porosity is slightly higher than the rubble-pile asteroid Itokawa ($44 \pm 4\%$) (6), suggesting that Ryugu is also a rubble pile, i.e., an aggregate of numerous rocky blocks bound primarily by self-gravity, with low cohesive strength and high bulk porosity. This is consistent with the hypothesis that all SS bodies with diameter of $\sim 1 \text{ km}$ are rubble piles (18). These asteroids might have originally formed from re-accumulation of fragments generated by catastrophic disruption events of $\sim 100\text{-km}$ sized parent bodies (19). Ryugu's high porosity could be ascribed to loss of volatile components during or after the formation of the rubble pile, if its parent body was an icy asteroid.

Further evidence for a rubble-pile structure is the abundance of large boulders on the surface. The largest, Otohime, is located near the south pole and $\sim 160 \text{ m}$ in its longest axis (Fig. 1). The spatial density of boulders on Ryugu with longest axes $> 20 \text{ m}$ is more than twice that on Itokawa (8). Gravitational capture of ejecta after impact cratering on this body cannot be responsible for these large boulders, because their sizes are larger than the ejecta expected from even the largest crater Urashima ($\sim 290 \text{ m}$ in diameter) (8, 20). These boulders are most likely fragments that accreted during the formation of Ryugu, after disruption of its parent body (19).

Little was known about Ryugu's shape prior to Hayabusa2's arrival, due to a lack of radar imaging data and limited constraints from light curve observations (14). Hayabusa2 images reveal that Ryugu is a spinning-top-shaped asteroid; there is an elevated ridge around the equator, from which near conical surfaces extend to the mid-latitudes, with an average surface tilt angle of $34 \pm 4^\circ$ relative to its spin axis (Fig. 2, fig. S3, and table S2) (6). Ryugu's shape is similar to that of Bennu (5, 21). Other spinning-top-shaped near-Earth asteroids have been observed via ground-based radar (table S3). However, Ryugu's shape was unexpected because its rotation rate is slower than most of the currently known spinning-top-shaped asteroids (22).

The aspect ratio of Ryugu's equatorial cross-section is 0.96 and the circularity—the ratio of the circumference of an equal area circle to the perimeter—is 0.93 (table S3) (6). This suggests rotation-induced deformation of Ryugu, due to a short spin period (19, 23, 24). However, the current spin rate is too slow to induce the deformation, because the magnitude ratio

of the centrifugal force to gravity at the equatorial radius is only ~ 0.2 . Thus, Ryugu must have spun faster in the past and later slowed down to its current rate. This deformation hypothesis would also explain surface tilt angles that are symmetric and independent of longitude in the low latitudes (6, 8). Exceptions are several crater-affected portions, which must have formed after the equatorial ridge.

To constrain the past spin rate that formed the spinning-top shape, we analyzed the distribution of surface slopes—the angle between the normal vector to the surface and that to the surface of equipotential gravitational field—at different spin rates (21). Assuming a uniform density distribution, we used the derived bulk density and shape to calculate the surface slope distributions (Fig. 3A) and maps (Fig. 3B). At the current rotation period, the majority of the surface has slopes $< 35^\circ$ with an average of 11.8° , but Ryugu exhibits latitudinal variation; the mid-latitudes have lower slopes while both sides of the equatorial ridge have higher slopes. This results from the surface geopotential that has local maxima in the equatorial and polar regions and becomes lowest at the mid-latitudes (fig. S4). At a rotation period P_a of 4.0 hours, the local minimum moves to the equator, while the slopes still have latitudinal variation (fig. S5). At $P_a = 3.5$ hours, which is almost equal to the critical spin limit at which the centrifugal force exceeds gravity at some surface points near the equator, the surface slope distribution is centered at $31^{+14}_{-11}^\circ$ (Fig. 3A). This distribution is consistent with a typical friction angle of granular materials ($\sim 35^\circ$) [e.g., (25)], suggesting topographic relaxation that homogenized the slope distribution (8). During this process, the variation in surface slopes minimizes at low- and mid-latitudes (Fig. 3, A and B, and fig. S5) as a result of a deformation process that produced the equatorial ridge (18, 21).

Geological features of the equatorial ridge (8) are: (i) large unperturbed craters overlying the ridge, suggesting the ridge formed before the craters, (ii) overlapped boulders indicating surface mass wasting from the equator to the mid-latitudes, (iii) no evidence of grain-size segregation, unlike Itokawa (4), suggesting a lower degree of global surface activity. No structural linear features have been confirmed around the equatorial region, due to limited lighting conditions in available high resolution images.

To determine the material properties of the equatorial ridge, we analyzed observation data acquired for the purpose of evaluating candidate sample collection sites: four (L sites) on the equatorial ridge and three (M sites) at higher latitudes (15° to 30°) (fig. S6 and table S4) (6). Each candidate region has a size of 14° by 14° (about 110 by 110 m^2), which were targeted for detailed investigation. The variation between these regions in the visible and NIR reflectance data is less than 15%, suggesting efficient mixing processes in the surface layer (8, 10). Within this limited spectral variation, a

difference was found in ONC-T data on the spectral slope γ between the b- and x-bands (0.48 to $0.86 \mu m$) (6, 8). High-resolution maps of γ at candidate sampling sites reveal that bluish (lower γ) and reddish (higher γ) materials are mixed in different degrees (Fig. 4A). The slope γ was found to correlate with the v-band reflectance factor r_v (6, 8). The sites along the equatorial ridge (L-sites), especially L08, have brighter bluish spectra, whereas those in higher latitudes (M-sites), especially M01, exhibit darker reddish spectra (Fig. 4B). The trend of r_v with γ may be ascribed to the effect of space exposure on fresh bright-blue materials leading to reddening and darkening (8). Thus, mass wasting after spin down of Ryugu probably exposed fresh subsurface materials on the equatorial ridge.

Our current observations are insufficient to identify when and how the spinning-top shape formed. Possible timings are either an early re-accumulation stage after catastrophic disruption of Ryugu's parent body (19) and/or a later stage due to quasi-static rotational acceleration (23, 24). Early stage formation may explain the presence of large craters on the equatorial ridge. However, the conditions for producing a spinning-top shape are unclear, because Ryugu would need to gain a high enough angular momentum during re-accumulation to produce its axisymmetric shape and circular ridge, but avoid a non-axisymmetric rotational instability that makes the shape elongated (26).

In the later stage the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect, a radiation recoil torque affecting the rotation state of a small asteroid, is responsible for the quasi-static acceleration of asteroids [e.g., (18)]. When a spheroidal asteroid spins rapidly, strong centrifugal forces may induce deformation processes either on the surface (23, 27) or in the interior (28, 29), depending on the internal structure (29, 30). The large porosity of Ryugu, the dominance of large grains (> 1 cm) across its surface (8), and the lack of observed flat floors in its largest craters (8) suggest that the internal cohesive strength of the asteroid may be uniform and low.

Given the bulk density, shape, and uniform structure, we calculated the failure mode of Ryugu by using a plastic finite element model (FEM) technique (6, 22). This FEM method models continuum media to describe irreversible deformation of the regolith in asteroids. If Ryugu rotates at $P_a < 3.75$ hours, tension plays a dominant role in deformation in the interior (fig. S7). At $P_a = 3.5$ hours, the first structural failure occurs in the central region (Fig. 3C) if the cohesive strength (31) is uniformly ~ 4 Pa, which is similar to the predicted cohesive strength of small bodies (24, 28). While the van der Waals force may contribute to cohesion (24), density inhomogeneity or particle interlocking may also produce equivalent mechanical strength. The failed region spreads over the interior, driving outward, radial deformation parallel to the equatorial plane and inward, vertical deformation

around the spin axis (Fig. 3C). This model may support a lower degree of global surface activity on Ryugu (8). However, we do not rule out contributions from surface landslides to spinning-top-shape formation (29), which can be driven by local heterogeneities (15) or a gradual increase in strength of the asteroid with depth. These scenarios predict differing freshness of the subsurface material beneath the equatorial ridge due to the time available for space weathering.

In-situ surface data that enable the assessment of possible material contrasts between the equatorial ridge and mid-latitudes was obtained by a lander. The Mobile Asteroid Surface Scout (MASCOT) (32, 33) landed in a mid-latitude region on Ryugu on 3 October 2018. Based on these assessments, we selected a potential landing site (L08) (fig. S6) on the equatorial ridge to perform material sampling, with the goal of constraining the evolution of this spinning-top-shaped asteroid.

REFERENCES AND NOTES

1. C. M. O. Alexander, R. Bowden, M. L. Fogel, K. T. Howard, C. D. K. Herd, L. R. Nittler; C. M. O'D. Alexander et al, The provenances of asteroids, and their contributions to the volatile inventories of the terrestrial planets. *Science* **337**, 721–723 (2012). [doi:10.1126/science.1223474](https://doi.org/10.1126/science.1223474) [Medline](#)
2. S. Tachibana, M. Abe, M. Arakawa, M. Fujimoto, Y. Iijima, M. Ishiguro, K. Kitazato, N. Kobayashi, N. Namiki, T. Okada, R. Okazaki, H. Sawada, S. Sugita, Y. Takano, S. Tanaka, S. Watanabe, M. Yoshikawa, H. Kuninaka, Hayabusa2: Scientific importance of samples returned from C-type near-Earth asteroid (162173) 1999 JU3. *Geochem. J.* **48**, 571–587 (2014). [doi:10.2343/geochemj.2.0350](https://doi.org/10.2343/geochemj.2.0350)
3. S. Watanabe, Y. Tsuda, M. Yoshikawa, S. Tanaka, T. Saiki, S. Nakazawa, Hayabusa2 mission overview. *Space Sci. Rev.* **208**, 3–16 (2017). [doi:10.1007/s11214-017-0377-1](https://doi.org/10.1007/s11214-017-0377-1)
4. A. Fujiwara, J. Kawaguchi, D. K. Yeomans, M. Abe, T. Mukai, T. Okada, J. Saito, H. Yano, M. Yoshikawa, D. J. Scheeres, O. Barnouin-Jha, A. F. Cheng, H. Demura, R. W. Gaskell, N. Hirata, H. Ikeda, T. Kominato, H. Miyamoto, A. M. Nakamura, R. Nakamura, S. Sasaki, K. Uesugi, The rubble-pile asteroid Itokawa as observed by Hayabusa. *Science* **312**, 1330–1334 (2006). [doi:10.1126/science.1125841](https://doi.org/10.1126/science.1125841) [Medline](#)
5. D. S. Lauretta, S. S. Balram-Knutson, E. Beshore, W. V. Boynton, C. Drouet d'Aubigny, D. N. DellaGiustina, H. L. Enos, D. R. Golish, C. W. Hergenrother, E. S. Howell, C. A. Bennett, E. T. Morton, M. C. Nolan, B. Rizk, H. L. Roper, A. E. Bartels, B. J. Bos, J. P. Dworkin, D. E. Highsmith, D. A. Lorenz, L. F. Lim, R. Mink, M. C. Moreau, J. A. Nuth, D. C. Reuter, A. A. Simon, E. B. Bierhaus, B. H. Bryan, R. Ballouy, O. S. Barnouin, R. P. Binzel, W. F. Bottke, V. E. Hamilton, K. J. Walsh, S. R. Chesley, P. R. Christensen, B. E. Clark, H. C. Connolly, M. K. Crombie, M. G. Daly, J. P. Emery, T. J. McCoy, J. W. McMahon, D. J. Scheeres, S. Messenger, K. Nakamura-Messenger, K. Righter, S. A. Sandford, OSIRIS-REx: Sample return from asteroid (101955) Bennu. *Space Sci. Rev.* **212**, 925–984 (2017). [doi:10.1007/s11214-017-0405-1](https://doi.org/10.1007/s11214-017-0405-1)
6. Materials and Methods are available as supplementary materials.
7. S. Kameda, H. Suzuki, T. Takamatsu, Y. Cho, T. Yasuda, M. Yamada, H. Sawada, R. Honda, T. Morota, C. Honda, M. Sato, Y. Okumura, K. Shibasaki, S. Ikezawa, S. Sugita, Preflight calibration test results for optical navigation camera telescope (ONC-T) onboard the Hayabusa2 spacecraft. *Space Sci. Rev.* **208**, 17–31 (2017). [doi:10.1007/s11214-015-0227-y](https://doi.org/10.1007/s11214-015-0227-y)
8. S. Sugita et al., The geomorphology, color, and thermal properties of Ryugu: Implications for parent-body processes. *Science* (2019). [doi:10.1126/science.aaw0422](https://doi.org/10.1126/science.aaw0422)
9. T. Okada, T. Fukuhara, S. Tanaka, M. Taguchi, T. Imamura, T. Arai, H. Senshu, Y. Ogawa, H. Demura, K. Kitazato, R. Nakamura, T. Kouyama, T. Sekiguchi, S. Hasegawa, T. Matsunaga, T. Wada, J. Takita, N. Sakatani, Y. Horikawa, K. Endo, J. Helbert, T. G. Müller, A. Hagermann, Thermal infrared imaging experiments of C-type asteroid 162173 Ryugu on Hayabusa2. *Space Sci. Rev.* **208**, 255–286 (2017). [doi:10.1007/s11214-016-0286-8](https://doi.org/10.1007/s11214-016-0286-8)
10. K. Kitazato et al., The surface composition of asteroid 162173 Ryugu from Hayabusa2 near-infrared spectroscopy. *Science* (2019). [doi:10.1126/science.aav7432](https://doi.org/10.1126/science.aav7432)
11. T. Mizuno, T. Kase, T. Shiina, M. Mita, N. Namiki, H. Senshu, R. Yamada, H. Noda, H. Kunimori, N. Hirata, F. Terui, Y. Mimasu, Development of the Laser Altimeter (LIDAR) for Hayabusa2. *Space Sci. Rev.* **208**, 33–47 (2017). [doi:10.1007/s11214-015-0231-2](https://doi.org/10.1007/s11214-015-0231-2)
12. R. W. Gaskell, O. S. Barnouin-Jha, D. J. Scheeres, A. S. Konopliv, T. Mukai, S. Abe, J. Saito, M. Ishiguro, T. Kubota, T. Hashimoto, J. Kawaguchi, M. Yoshikawa, K. Shirakawa, T. Kominato, N. Hirata, H. Demura, Characterizing and navigating small bodies with imaging data. *Meteorit. Planet. Sci.* **43**, 1049–1061 (2008). [doi:10.1111/j.1945-5100.2008.tb00692.x](https://doi.org/10.1111/j.1945-5100.2008.tb00692.x)
13. R. Szeliski, *Computer Vision: Algorithms and Applications* (Science & Business Media, Springer, New York, 2010).
14. T. G. Müller, J. Durech, M. Ishiguro, M. Mueller, T. Kröhler, H. Yang, M.-J. Kim, L. O'Rourke, F. Usui, C. Kiss, B. Altieri, B. Carry, Y.-J. Choi, M. Delbo, J. P. Emery, J. Greiner, S. Hasegawa, J. L. Hora, F. Knust, D. Kuroda, D. Osip, A. Rau, A. Rivkin, P. Schady, J. Thomas-Osip, D. Trilling, S. Urakawa, E. Vilenius, P. Weissman, P. Zeidler, Hayabusa-2 mission target asteroid 162173 Ryugu (1999 JU3): Searching for the object's spin-axis orientation. *Astron. Astrophys.* **599**, A103 (2017). [doi:10.1051/0004-6361/201629134](https://doi.org/10.1051/0004-6361/201629134)
15. A small deviation (0.7° to 0.8°) of the principal axis of inertia from the spin axis was obtained, considering the shape models and assuming uniform density distribution (6).
16. P. Vernazza, M. Marsset, P. Beck, R. P. Binzel, M. Birlan, R. Brunetto, F. E. Demeo, Z. Djouadi, C. Dumas, S. Merouane, O. Mousis, B. Zanda, Interplanetary dust particles as samples of icy asteroids. *Astrophys. J.* **806**, 204 (2015). [doi:10.1088/0004-637X/806/2/204](https://doi.org/10.1088/0004-637X/806/2/204)
17. R. J. Macke, G. J. Consolmagno, D. T. Britt, Density, porosity, and magnetic susceptibility of carbonaceous chondrites. *Meteorit. Planet. Sci.* **46**, 1842–1862 (2011). [doi:10.1111/j.1945-5100.2011.01298.x](https://doi.org/10.1111/j.1945-5100.2011.01298.x)
18. K. J. Walsh, Rubble pile asteroids. *Annu. Rev. Astron. Astrophys.* **56**, 593–624 (2018). [doi:10.1146/annurev-astro-081817-052013](https://doi.org/10.1146/annurev-astro-081817-052013)
19. P. Michel, W. Benz, P. Tanga, D. C. Richardson, Collisions and gravitational reaccumulation: Forming asteroid families and satellites. *Science* **294**, 1696–1700 (2001). [doi:10.1126/science.1065189](https://doi.org/10.1126/science.1065189) [Medline](#)
20. T. Michikami, A. M. Nakamura, N. Hirata, R. W. Gaskell, R. Nakamura, T. Honda, C. Honda, K. Hiraoka, J. Saito, H. Demura, M. Ishiguro, H. Miyamoto, Size-frequency statistics of boulders on global surface of asteroid 25143 Itokawa. *Earth Planets Space* **60**, 13–20 (2008). [doi:10.1186/BF03352757](https://doi.org/10.1186/BF03352757)
21. D. J. Scheeres, S. G. Hesar, S. Tardivel, M. Hirabayashi, D. Farnocchia, J. W. McMahon, S. R. Chesley, O. Barnouin, R. P. Binzel, W. F. Bottke, M. G. Daly, J. P. Emery, C. W. Hergenrother, D. S. Lauretta, J. R. Marshall, P. Michel, M. C. Nolan, K. J. Walsh, The geophysical environment of Bennu. *Icarus* **276**, 116–140 (2016). [doi:10.1016/j.icarus.2016.04.013](https://doi.org/10.1016/j.icarus.2016.04.013)
22. M. Hirabayashi, D. J. Scheeres, Rotationally induced failure of irregularly shaped asteroids. *Icarus* **317**, 354–364 (2019). [doi:10.1016/j.icarus.2018.08.003](https://doi.org/10.1016/j.icarus.2018.08.003)
23. K. J. Walsh, D. C. Richardson, P. Michel, Rotational breakup as the origin of small binary asteroids. *Nature* **454**, 188–191 (2008). [doi:10.1038/nature07078](https://doi.org/10.1038/nature07078) [Medline](#)
24. P. Sánchez, D. J. Scheeres, Disruption patterns of rotating self-gravitating aggregates: A survey on angle of friction and tensile strength. *Icarus* **271**, 453–471 (2016). [doi:10.1016/j.icarus.2016.01.016](https://doi.org/10.1016/j.icarus.2016.01.016)
25. T. W. Lambe, R. V. Whitman, *Soil Mechanics* (Series in Soil Engineering, Wiley, Hoboken, NJ, 1969).
26. S. Chandrasekhar, *Ellipsoidal Figures of Equilibrium* (Yale University Press, New Haven, CT, 1969).
27. D. J. Scheeres, Landslides and Mass shedding on spinning spheroidal asteroids. *Icarus* **247**, 1–17 (2015). [doi:10.1016/j.icarus.2014.09.017](https://doi.org/10.1016/j.icarus.2014.09.017)
28. M. Hirabayashi, D. J. Scheeres, Stress and failure analysis of rapidly rotating asteroid (29075) 1950 DA. *Astrophys. J.* **798**, L8 (2014). [doi:10.1088/2041-8205/798/1/L8](https://doi.org/10.1088/2041-8205/798/1/L8)
29. M. Hirabayashi, D. P. Sánchez, D. J. Scheeres, Internal structure of asteroids having surface shedding due to rotational instability. *Astrophys. J.* **808**, 63 (2015). [doi:10.1088/0004-637X/808/1/63](https://doi.org/10.1088/0004-637X/808/1/63)

30. Y. Zhang, D. C. Richardson, O. S. Barnouin, P. Michel, S. R. Schwartz, R.-L. Ballouz, Rotational failure of rubble-pile bodies: Influences of shear and cohesive strengths. *Astrophys. J.* **857**, 15 (2018). [doi:10.3847/1538-4357/aab5b2](https://doi.org/10.3847/1538-4357/aab5b2)
31. The cohesive strength σ_c of Ryugu-formed aggregates is given by $\sigma_c = \sigma_t \tan \theta$, where σ_t and θ are the tensile strength and the angle of friction of the aggregates, respectively.
32. R. Jaumann, N. Schmitz, A. Koncz, H. Michaelis, S. E. Schroeder, S. Mottola, F. Trauthan, H. Hoffmann, T. Roatsch, D. Jobs, J. Kachlicki, B. Pforte, R. Terzer, M. Tschentscher, S. Weisse, U. Mueller, L. Perez-Prieto, B. Broll, A. Kruselburger, T.-M. Ho, J. Biele, S. Ulamec, C. Krause, M. Grott, J.-P. Bibring, S. Watanabe, S. Sugita, T. Okada, M. Yoshikawa, H. Yabuta, The camera of the MASCOT asteroid lander on board Hayabusa 2. *Space Sci. Rev.* **208**, 375–400 (2017). [doi:10.1007/s11214-016-0263-2](https://doi.org/10.1007/s11214-016-0263-2)
33. J.-P. Bibring, V. Hamm, V. Langevin, C. Pilorget, A. Arondel, M. Bouzit, M. Chaigneau, B. Crane, A. Darié, C. Evesque, J. Hansotte, V. Gardien, L. Gonnod, J.-C. Leclech, L. Meslier, T. Redon, C. Tamiatto, S. Tosti, N. Thoores, The MicrOmega investigation onboard Hayabusa2. *Space Sci. Rev.* **208**, 401–412 (2017). [doi:10.1007/s11214-017-0335-y](https://doi.org/10.1007/s11214-017-0335-y)
34. F. Mignard, Radiation pressure and dust particle dynamics. *Icarus* **49**, 347–366 (1982). [doi:10.1016/0019-1035\(82\)90041-0](https://doi.org/10.1016/0019-1035(82)90041-0)
35. D. P. Hamilton, J. A. Burns, Orbital stability zones about asteroids: II. The destabilizing effects of eccentric orbits and of solar radiation. *Icarus* **96**, 43–64 (1992). [doi:10.1016/0019-1035\(92\)90005-R](https://doi.org/10.1016/0019-1035(92)90005-R)
36. A. S. McEwen, Photometric functions for photoclinometry and other applications. *Icarus* **92**, 298–311 (1991). [doi:10.1016/0019-1035\(91\)90053-V](https://doi.org/10.1016/0019-1035(91)90053-V)
37. K. Wada, M. Grott, P. Michel, K. J. Walsh, A. M. Barucci, J. Biele, J. Blum, C. M. Ernst, J. T. Grundmann, B. Gundlach, A. Hagermann, M. Hamm, M. Jutzi, M.-J. Kim, E. Kürt, L. Le Corre, G. Libourel, R. Lichtenheldt, A. Maturilli, S. R. Messenger, T. Michikami, H. Miyamoto, S. Mottola, T. Müller, A. M. Nakamura, L. R. Nittler, K. Ogawa, T. Okada, E. Palomba, N. Sakatani, S. E. Schröder, H. Senshu, D. Takir, M. E. Zolensky, Asteroid Ryugu before the Hayabusa2 encounter. *Prog. Earth Planet. Sci.* **5**, 82 (2018). [doi:10.1186/s40645-018-0237-y](https://doi.org/10.1186/s40645-018-0237-y)
38. J. D. Giorgini, “NASA JPL Horizons On-Line Ephemeris System”, (2015; <http://ssd.jpl.nasa.gov/?horizons>).
39. W. M. Folkner, J. G. Williams, D. H. Boggs, R. S. Park, P. Kuchynka, “The planetary and lunar ephemerides DE430 and DE431” (Interplanetary Network Progress Rep. 42–196, Jet Propulsion Lab., 2014).
40. B. G. Marsden, Z. Sekanina, D. K. Yeomans, Comets and nongravitational forces. *V. Astron. J.* **78**, 211–225 (1973). [doi:10.1086/111402](https://doi.org/10.1086/111402)
41. Y. Tsuda, M. Yoshikawa, M. Abe, H. Minamino, S. Nakazawa, System design of the Hayabusa2—Asteroid sample return mission to 1999 JU3. *Acta Astronaut.* **91**, 356–362 (2013). [doi:10.1016/j.actaastro.2013.06.028](https://doi.org/10.1016/j.actaastro.2013.06.028)
42. T. Kominato, M. Matsuoka, M. Uo, T. Hashimoto, J. Kawaguchi, Optical hybrid navigation and station keeping around Itokawa. AIAA/AAS Astrodynamics Specialist Conference and Exhibit, Keystone, CO, 23 August 2006 (AIAA, 2006).
43. F. Terui et al., “GN&C of Hayabusa2 in cruising phase and asteroid proximity phase” in *Guidance, Navigation, and Control 2016*, D. A. Chart. Ed. (Advances in the Astronautical Sciences Series **157**, Univelt, San Diego, 2016), pp. 667–678 (AAS 16-106).
44. H. Morita, K. Shirakawa, T. Kubota, T. Hashimoto, J. Kawaguchi, Hayabusa’s real-time landmark tracking navigation for descents and touching-downs. AIAA/AAS Astrodynamics Specialist Conference and Exhibit, Keystone, CO, 23 August 2006 (AIAA, 2006).
45. N. Sakatani, K. Ogawa, M. Arakawa, S. Tanaka, Thermal conductivity of lunar regolith simulant JSC-1A under vacuum. *Icarus* **309**, 13–24 (2018). [doi:10.1016/j.icarus.2018.02.027](https://doi.org/10.1016/j.icarus.2018.02.027)
46. G. J. Consolmagno, M. W. Schaefer, B. E. Schaefer, D. T. Britt, R. J. Macke, M. C. Nolan, E. S. Howell, The measurement of meteorite heat capacity at low temperatures using liquid nitrogen vaporization. *Planet. Space Sci.* **87**, 146–156 (2013). [doi:10.1016/j.pss.2013.07.009](https://doi.org/10.1016/j.pss.2013.07.009)
47. B. Gladman, P. Michel, Ch. Froeschlé, The near-Earth object population. *Icarus* **146**, 176–189 (2000). [doi:10.1006/icar.2000.6391](https://doi.org/10.1006/icar.2000.6391)
48. A. Tsuchiyama, M. Uesugi, T. Matsushima, T. Michikami, T. Kadono, T. Nakamura, K. Uesugi, T. Nakano, S. A. Sandford, R. Noguchi, T. Matsumoto, J. Matsuno, T. Nagano, Y. Imai, A. Takeuchi, Y. Suzuki, T. Ogami, J. Katagiri, M. Ebihara, T. Ireland, F. Kitajima, K. Nagao, H. Naraoka, T. Noguchi, R. Okazaki, H. Yurimoto, M. E. Zolensky, T. Mukai, M. Abe, T. Yada, A. Fujimura, M. Yoshikawa, J. Kawaguchi, Three-dimensional structure of Hayabusa samples: Origin and evolution of Itokawa regolith. *Science* **333**, 1125–1128 (2011). [doi:10.1126/science.1207807](https://doi.org/10.1126/science.1207807) [Medline](https://pubmed.ncbi.nlm.nih.gov/21611111/)
49. R. A. Werner, D. J. Scheeres, Exterior gravitation of a polyhedron derived and compared with harmonic and mascon gravitation representations of asteroid 4769 Castalia. *Celestial Mech. Dyn. Astron.* **65**, 313–344 (1996).
50. E. G. Kahn et al., A tool for the visualization of small body data. *Proc. Lunar Planet. Sci. Conf.* **43**, abstr. 1618 (2011).
51. C. A. Schneider, W. S. Rasband, K. W. Eliceiri, NIH Image to ImageJ: 25 years of image analysis. *Nat. Methods* **9**, 671–675 (2012). [doi:10.1038/nmeth.2089](https://doi.org/10.1038/nmeth.2089) [Medline](https://pubmed.ncbi.nlm.nih.gov/22755611/)
52. M. W. Busch, J. Giorgini, S. Ostro, L. Benner, R. Jurgens, R. Rose, M. Hicks, P. Pravec, P. Kusnirak, M. Ireland, Physical modeling of near-Earth Asteroid (29075) 1950 DA. *Icarus* **190**, 608–621 (2007). [doi:10.1016/j.icarus.2007.03.032](https://doi.org/10.1016/j.icarus.2007.03.032)
53. M. W. Busch, L. A. M. Benner, S. J. Ostro, J. D. Giorgini, R. F. Jurgens, R. Rose, D. J. Scheeres, C. Magri, J.-L. Margot, M. C. Nolan, A. A. Hine, Physical properties of near-Earth Asteroid (33342) 1998 WT24. *Icarus* **195**, 614–621 (2008). [doi:10.1016/j.icarus.2008.01.020](https://doi.org/10.1016/j.icarus.2008.01.020)
54. S. J. Ostro, J.-L. Margot, L. A. M. Benner, J. D. Giorgini, D. J. Scheeres, E. G. Fahnestock, S. B. Broschart, J. Bellerose, M. C. Nolan, C. Magri, P. Pravec, P. Scheirich, R. Rose, R. F. Jurgens, E. M. De Jong, S. Suzuki, Radar imaging of binary near-Earth asteroid (66391) 1999 KW4. *Science* **314**, 1276–1280 (2006). [doi:10.1126/science.1133622](https://doi.org/10.1126/science.1133622) [Medline](https://pubmed.ncbi.nlm.nih.gov/16511111/)
55. M. W. Busch, S. J. Ostro, L. A. M. Benner, M. Brozovic, J. D. Giorgini, J. S. Jao, D. J. Scheeres, C. Magri, M. C. Nolan, E. S. Howell, P. A. Taylor, J.-L. Margot, W. Briskin, Radar observations and the shape of near-Earth Asteroid 2008 EV5. *Icarus* **212**, 649–660 (2011). [doi:10.1016/j.icarus.2011.01.013](https://doi.org/10.1016/j.icarus.2011.01.013)
56. M. C. Nolan, C. Magri, E. S. Howell, L. A. M. Benner, J. D. Giorgini, C. W. Hergenrother, R. S. Hudson, D. S. Lauretta, J.-L. Margot, S. J. Ostro, D. J. Scheeres, Shape model and surface properties of the OSIRIS-REx target Asteroid (101955) Bennu from radar and lightcurve observations. *Icarus* **226**, 629–640 (2013). [doi:10.1016/j.icarus.2013.05.028](https://doi.org/10.1016/j.icarus.2013.05.028)
57. E. Tatsumi, T. Kouyama, H. Suzuki, M. Yamada, N. Sakatani, S. Kameda, Y. Yokota, R. Honda, T. Morota, K. Moroi, N. Tanabe, H. Kamiyoshihara, M. Ishida, K. Yoshioka, H. Sato, C. Honda, M. Hayakawa, K. Kitazato, H. Sawada, S. Sugita, Updated inflight calibration of Hayabusa2’s Optical Navigation Camera (ONC) for scientific observations during the cruise phase. *Icarus* **325**, 153–195 (2019). [doi:10.1016/j.icarus.2019.01.015](https://doi.org/10.1016/j.icarus.2019.01.015)
58. B. Hapke, Bidirectional reflectance spectroscopy: 4. The extinction coefficient and the opposition effect. *Icarus* **67**, 264–280 (1986). [doi:10.1016/0019-1035\(86\)90108-9](https://doi.org/10.1016/0019-1035(86)90108-9)
59. M. Ishiguro, D. Kuroda, S. Hasegawa, M.-J. Kim, Y.-J. Choi, N. Moskovitz, S. Abe, K.-S. Pan, J. Takahashi, Y. Takagi, A. Arai, N. Tokimasa, H. H. Hsieh, J. E. Thomas-Osip, D. J. Osip, M. Abe, M. Yoshikawa, S. Urakawa, H. Hanayama, T. Sekiguchi, K. Wada, T. Sumi, P. J. Tristram, K. Furusawa, F. Abe, A. Fukui, T. Nagayama, D. S. Warjurkar, A. Rau, J. Greiner, P. Schady, F. Knust, F. Usui, T. G. Müller, Optical properties of (162173) 1999 JU3: In preparation for the JAXA Hayabusa 2 sample return mission. *Astrophys. J.* **792**, 74–82 (2014). [doi:10.1088/0004-637X/792/1/74](https://doi.org/10.1088/0004-637X/792/1/74)
60. H. Si, TetGen, a delaunay-based quality tetrahedral mesh generator. *ACM Trans. Math. Softw.* **41**, 11 (2015). [doi:10.1145/2629697](https://doi.org/10.1145/2629697)

ACKNOWLEDGMENTS

The Hayabusa2 spacecraft was developed and built under the leadership of JAXA, with contributions from the German Aerospace Center (DLR) and the Centre National d’Études Spatiales (CNES), and in collaboration with Nagoya University, University of Tokyo, National Astronomical Observatory of Japan, University of Aizu, Kobe University, and other universities, institutes, and companies in Japan. We thank NASA, DSN, and JPL for their support for the execution of the Hayabusa2 mission and Hayabusa2 Joint Science Team members for fruitful science discussions. We also thank the many engineers who have contributed to the success of the Hayabusa2 mission, especially Tetsuya Masuda, Seiji Yasuda, Kouta Matsushima, and Takeshi Ohshima at NEC Corporation. S.W. thanks to

Carolyn M. Ernst for her support of the development of the SPC-based shape model. T.N. thanks to Kana Amano, Hikari Mita, and Shiho Kobayashi for their support of the LSS process. M.Hi. acknowledges the use of ANSYS Mechanical APDL (18.1), which is licensed by Samuel Ginn College of Engineering at Auburn University. **Funding:** This study was supported by KAKENHI from the Japan Society for the Promotion of Science (JSPS) (Grant Nos. JP17H06459, JP17K05639, JP16H04059, JP17KK0097, JP26287108, JP16H04044, JP16H04044), the JSPS Core-to-Core program "International Network of Planetary Sciences", and National Institutes of Natural Sciences (AB302006). O.S.B. acknowledges funding support from NASA New Frontier Program (NNM10AA11C). P.M. acknowledges funding support from the French space agency CNES. **Author contributions:** Conceptualization: S.W., M.Hi., N.H. (Aizu), Y.Ii; Spacecraft operation and data acquisition: M.Yo, S.Ki., H.T., T.O., M.Ab., Y.Ya. S.Tan. (JAXA), K.S., M.Ya, T.Y., N.O., G.O., Y.M., K.Yoshik., T.T., Y.Ta., A.F., C.Hi., T.I., M.Ha., S.H., O.M., H.Sa., T.Sh., S.So., H.Yan., R.T., M.O., K.O., F.T., T.Sa., S.N., Y.Ts.; Analysis (shape models): S.W., M.Hi., N.H. (Aizu), N.H. (Kobe), R.N., Y.S., Y.Is., K.M., H.T., S.Su., R.G., E.P., O.S.B., Y.Ya. S.Tan (Kobe), N.Ni., T.Su., T.Y.; Analysis (gravity): H.I., M.Yo., A.S.F., J.M.W., D.J.S., Y.M., K.Yosik., S.So., Y.Ts.; Analysis (ephemeris): H.T.; Analysis (LSS): S.W. E.T., S.Ki., H.Yab., T.N., S.Tac., Y.Is., T.Mo., K.K., N.S., K.M., K.W., H.Se., C.Ho., T.Mi., T.K., R.Ho., S.Ka., T.F., H.M., G.K., I.M. P.M., P.A.A., S.Tan. (JAXA), M.M., Y.Yo., H.Su., K.Yoshio., Y.C., H.K., R.He.; Project administration: S.W., M.Yo., S.Tac., K.K., S.Su., T.O., N.Na., M.Ar., M.Ab., S.T. (JAXA), M.F., T.-M. H., A.M., R.J., J.-P. B., C.K., F.T., T.Sa., S.N., Y.Ts.; Writing: S.W., M.Hi., N.H. (Aizu), R.N., Y.S., H.I., E.T., S.Ki., T.N., S.Tac., K.W., H.T., T.K., G.K., O.S.B., P.M., D.J.S., P.A.A., S.So. All authors discussed the results and commented on the manuscript. **Competing interests:** Y.Ya. is also affiliated with Tokyo Metropolitan University. **Data and materials availability:** All images, the shape model, and original software presented in this paper are available at the JAXA Data Archives and Transmission System (DARTS) at http://www.darts.isas.jaxa.jp/pub/hayabusa2/paper/Watanabe_2019/. Additional data from the mission will be delivered to the DARTS archive at <https://www.darts.isas.jaxa.jp/planet/project/hayabusa2/>, and higher-level data products will be available in the Small Bodies Node of the Planetary Data System <https://pds-smallbodies.astro.umd.edu/> one year after departure from the asteroid. Distribution of the SPC software is legally restricted by the US International Traffic in Arms Regulation. US citizens (only) may request an SPC research license, with appropriate restrictions, at <http://spc.psi.edu>. For our FEM analysis, the input files to ANSYS Mechanical APDL are available at <http://hdl.handle.net/11200/49368>.

SUPPLEMENTARY MATERIALS

www.sciencemag.org/cgi/content/full/science.aav8032/DC1

Materials and Methods

Figs. S1 to S7

Tables S1 to S4

References (34–60)

29 October 2018; accepted 7 March 2019

Published online 19 March 2019

10.1126/science.aav8032

Fig. 1. Visible light images of Ryugu. Taken with ONC-T from 20 km altitude on 10 July 2018. White arrows represent the spin axis. The prime meridian is defined in (8). (A) Hemisphere centered at (5°S, 11°E) (image number hyb2_onc_20180710_121100_tvf). (B) Hemisphere centered at (5°S, 189°E) (hyb2_onc_20180710_082316_tvf).

Fig. 2. Shape model of Ryugu. (A to F) The model was generate using the SfM method with 3,145,728 facets (SFM20180804), based on 214 ONC-T images taken from 5.1- and 6.5-km altitudes. The body-fixed Cartesian coordinates (x , y , z) have their origin at the center of the figure, z along the spin axis, x pointing to the prime meridian, and are indicated in each panel. Viewed from (A) $+x$ -, (B) $+y$ -, (C) $-x$ -, (D) $-y$ -, (E) $+z$, (F) $-z$ -direction.

Fig. 3. Slope distribution and failure mode analysis. (A, B, and C) Reduced versions of SfM-based [(A) and (B), 49,152 facets] and SPC-based [(C), 3072 facets] shape models were used. The density is assumed to be constant at 1.2 g cm^{-3} . (A) Area-weighted slope distribution at spin periods of 7.63, 4.0, and 3.5 hours. (B) Slope maps projected onto the shape model at different spin periods. (C) Failed region (yellow) and deformation vectors on the meridional cross-section viewed from a longitude of 30°E at a spin period of 3.5 hours. The minimum cohesive strength to keep the original shape is ~ 4 Pa.

Fig. 4. Visible spectral properties of candidate sampling sites. In accordance with a safety index (fig. S6) (6), we chose seven candidate sampling sites, L05, L07, L08, L12, M01, M03, and M04, where L and M indicate low-latitude and mid-latitude (15° to 30°) regions, respectively. (A) ONC-T v-band images of two representative candidate sites, L08 (top, hyb2_onc_20180801_141045_tvf) and M01 (bottom, hyb2_onc_20180801_172245_tvf), from altitude of ~ 5 km, overlain with color maps of the b-x (0.48 to $0.86 \mu\text{m}$) spectral slope. (B) Spectral slope and reflectance factor (6) in the v-band for the 7 candidate landing sites. Symbols (L: +, M: x) and lines indicate the median values and $1-\sigma$ variations inside those sites, respectively (6).