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The spatial distribution of impact craters on Ryugu

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- 1 Title
- 2 The spatial distribution of impact craters on Ryugu
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- 44 **Proposed Running Head:** Craters on Ryugu
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| 50 | Ke | y Words |
| 51 | Ast | teroid |
| 52 | Im | pact processes |
| 53 | Ge | ological processes |
| 54 | Hi | ghlights |
| 55 | | We examined the spatial distribution of impact craters on Ryugu |
| 56 | | We completed a global impact crater catalogue of Ryugu (D>20 m) |
| 57 | | Crater density variations cannot be explained by the randomness of |
| 58 | | cratering |
| 59 | | More craters are seen at lower latitudes and less at higher latitudes |
| 60 | | There are fewer craters in the western bulge and more around the |
| 61 | | meridian |
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63 Abstract

64 Asteroid 162173 Ryugu has numerous craters. The initial measurement of impact craters on Ryugu, by Sugita et al. (2019), is based on 65Hayabusa2 ONC images obtained during the first month after the arrival of 66 Hayabusa2 in June 2018. Utilizing new images taken until February 2019, 67 68 we constructed a global impact crater catalogue of Ryugu, which includes all craters larger than 20 m in diameter on the surface of Ryugu. As a result, we 69 identified 77 craters on the surface of Ryugu. Ryugu shows variation in 70 crater density which cannot be explained by the randomness of cratering; 7172there are more craters at lower latitudes and fewer at higher latitudes, and 73fewer craters in the western bulge (160°E – 290°E) than in the region around 74the meridian (300°E – 30°E). This variation implies a complicated geologic history for Ryugu. It seems that the variation in crater density indicates that 75

76 the equatorial ridge located in the western hemisphere is relatively young,
77 while that located in the eastern hemisphere is a fossil structure formed
78 during the short rotational period in the distant past.

79 1. Introduction

80 Ryugu is a top-shaped asteroid with a mean radius of 448 m and a rotational obliquity of 8 degrees (Watanabe et al., 2019). Since JAXA's 81 Hayabusa2 spacecraft arrived at asteroid 162173, Ryugu, on June 27, 2018, 82 83 the onboard optical navigation cameras (ONC) have obtained numerous images of Ryugu and revealed many surface features, including abundant 84 impact craters (Sugita et al., 2019). This cratering suggests that a major 85 process in the formation of the surface of Ryugu has been via impacts from 86 other bodies. The low bulk density of Ryugu implies that the asteroid is 87 88 composed of fragments that probably resulted from catastrophic disruption (Watanabe et al., 2019). The initial report of impact craters on Ryugu (Sugita 89 90 et al. 2019) was produced via the utilization of ONC images from July to August 1, 2018, which identified approximately 30 impact craters from the 9192 limited coverage of Ryugu. The surface crater retention age was estimated to 93 be in the order of 10⁷ or 10⁸ years, based on the number density of craters of 94 100 - 200 m in diameter (D). In addition, Sugita et al. (2019) reported that the crater size-frequency distribution (CSFD) of Ryugu shows a lack of small 95 craters (D < 100 m), which indicates that the average resurfacing of the top 96 \sim 1-meter layer on Ryugu takes less than 10⁶ years. Ryugu has a west/east 97 dichotomy (Sugita et al. 2019); its western side, the so-called western bulge, 98(160°E – 290°E), has a high albedo, a low number density of large boulders, 99 is topographically high, and has a bluish color as compared to the eastern 100101 side. The equatorial ridge located in the eastern hemisphere is slightly offset 102towards the south.

The main purpose of this paper is (i) to present the basic information 103104 (the location and size of each craters), which is not listed in the initial report by Sugita et al. (2019), (ii) to accomplish a global catalogue of all the craters 105 $(D \ge 10 - 20 \text{ m})$, utilizing additional images acquired after the publication by 106 107Sugita et al. (2019) which have allowed the investigation of craters over the 108 entire surface of Ryugu, (iii) to investigate the statistical significance of the spatial distribution of the impact craters. Note that we do not discuss the 109crater size-frequency distribution or the depletion and retention time of 110 small craters, as these topics will be included in Morota et al. (in 111 112preparation).

113

1142. DATA and Method

2.1. Crater counting 115

116This study utilized 340 ONC images for crater counting (Table 1): (i) 11796 images obtained in July 20 2018 with a ground resolution of 0.72 m/pixel 118 providing global coverage excluding the polar regions > 70 degrees, (ii) 85 images obtained on August 1 2018 with a resolution of 0.69-0.55 m/pixel, 119 providing regional coverage of low latitudes < 40 degrees, (iii) 11 images 120obtained on October 4 2018 with a resolution of 0.32 m/pixel, providing 121122coverage of the north pole, (iv) 18 images on October 30 2018 with a resolution of 0.62 m/pixel providing coverage of the north and south poles (v) 12326 images obtained on February 28 2019 with a resolution of 0.67 m/pixel 124providing coverage of the north and south poles, (vi) 52 images obtained on 125126August 23 2018 with a resolution of 2.6 m/pixel providing coverage of the

south pole, (vii) 52 images obtained on January 24 2019 with a resolution of 1272.1 m/pixel providing coverage of the north pole. Because the Hayabusa 2 128spacecraft is generally remaining in the same position above the sub-Earth 129130 point of the asteroid's surface and the rotational obliquity of Ryugu is small, 131the emission angles of the images (i)-(v) are large for polar regions. The 132low-emission images of Ryugu's polar regions, (vi) and (vii), were obtained at a position distant from the equatorial plane. All of the impact craters were 133identified from these ONC images. These ONC images will be freely 134available at the end of 2020. Craters with diameters larger than 10-20 m 135136 could be clearly identified as these images had a resolution of at least 10 pixels (though they had a resolution of less than 10 pixels in the case of the 137138image subset (iv)). We note that the choice of the minimum pixel number for reliable crater identification requires care; it varies substantially depending 139140on imaging conditions, such as solar incidence angle. Also, stereo pair images 141greatly improve the robustness of crater identification. Because the 142Hayabusa2 ONC image dataset used in this study covers almost entire surface of Ryugu with multiple imaging and large solar incidence angles, 10 143pixel is sufficient for identifying craters on Ryugu. The images enabled us to 144identify all impact craters exceeding 10 - 20 meters diameter over the entire 145146surface of Ryugu. Therefore, to ensure that crater counting was not affected by image resolution, D = 20 m was set as the minimum diameter threshold. 147

We identified all circular or quasi-circular depressions as craters for this study. This included cases where the circular depression lacked a raised rim. However, we did not regard circular features without topographic

depressions as craters. Features such as topographic depression or rims were 151judged from (i) the shape model of Ryugu (Watanabe et al. 2019), (ii) visual 152observation using stereo pairs and (iii) visual observation based on shading 153of images at low sun. Based on these criteria, we classified all the candidate 154craters into types: I-IV (as summarized in Table 2). We judged those 155classified as types I-III to be distinct crater (Nos. 1-77 in Figure 1), and 156classification IV to be less-distinct crater. For this study, we assumed that 157type IV phenomena are not craters (Nos. 78-86 in Figure 1), and therefore 158these were not included in crater density and statistical analysis. 159160 Nonetheless, many craters were more or less degraded and infilled with regolith or boulders and often lacked distinct shape, and this interpretation 161was therefore often ambiguous. 162

163 To measure the size, latitude, and longitude of each crater we utilized 164 the Small Body Mapping Tool (Kahn et al., 2011), a global image mosaic map 165of Ryugu, and a shape model of Ryugu. The global image mosaic map was 166 built from the ONC images, and the shape model was derived from Watanabe et al. (2019). The Small Body Mapping Tool was used to measure 167the diameters and locations of the craters for the study. This software 168enabled measurement of the centers and diameters of craters based on three 169 points selected along the crater rim from a global mosaic map rendered onto 170171the shape model.

A fairly accurate surface area is required to obtain the number density of the craters. In the case of an irregular-shaped asteroid, the definition of the surface area is complicated. When defining it from a shape model, the surface area increases infinitely as the resolution of the shape model increases. To simplify, the surface area was not determined as the total area of the surface polygons composing the shape model, but was instead calculated as the surface of a sphere with a radius of 448 m. The total surface area of Ryugu was thus calculated to be 2.5 km². We note that the shape model of Ryugu (SHAPE_SFM_200k_v20180804.obj), which describes Ryugu as 196608 plates, has the surface area of 2.77 km².

182 2.2. The statistical analysis of the spatial distribution

A statistical test was then performed to evaluate the significance of 183184variations in the crater density. The nearest-neighbor analysis was thus used to discover whether the variation can be explained merely by randomness, 185186 following the methodology of Squyres et al. (1997). The distance between each point (i.e. the center of a crater) and its nearest neighboring point (i.e. 187 188 the center of the nearest neighbor crater) was determined and averaged, and 189the mean distance observed was compared with the mean distance expected 190 under random distribution. If the observed value was significantly smaller (greater) than the expected value, the distribution was considered to be 191significantly clustered (ordered) and not random. This method has been 192applied to evaluate the distribution of craters on various solar system objects. 193 194Phillips et al. (1992) found that, although Venus has a variation in crater density, the variation cannot be distinguished from a completely random 195196 distribution; therefore, the variation can be explained by the randomness of the crater production on that planet. Squyres et al. (1997) found that the 197 crater distributions on Callisto and Rhea are not random but are 198

significantly ordered. The spatial distribution of observed craters in heavily cratered terrain transition from random to ordered because craters that form in sparse areas obliterate the relatively few existing craters, filling in the spaces, whereas craters that form in areas of existing crater clustering obliterate the existing craters and reduce the clustering (Lissauer et al. 1988; Squyres et al. 1997). Moreover, partial resurfacing such as lava flow or the mass-movement of rock tends to create clustered crater distribution.

Following Squyres et al. (1997), the Z value was determined to assess the degree by which the value of the observed mean distance (d_{obs}) deviates from randomness:

209
$$Z \equiv \frac{d_{obs} - d_{exp}}{\sigma} , (1)$$

where d_{exp} is the expected mean distance when the distribution is completely 210211random and σ is the standard deviation of d_{exp} . A positive Z value indicates that the distribution of points is ordered, a negative Z value indicates that it 212is more clustered, and a value of Z close to 0 indicates that the distribution 213cannot be distinguished from random. A value for Z was obtained for the 214distribution of all craters that exceeded a given diameter. The Z-statistic was 215not calculated in cases where the number of craters was lower than n = 2. 216The observed distance between two points was determined on the basis of 217218the great-circle distance between the two points on the unit sphere, although the shape of Ryugu is not spherical. Values for d_{exp} and σ were calculated 219220numerically using the Monte Carlo simulation, following Hirata (2017). This 221study assumed that (1) *n* points were produced on the unit sphere, (2) these points were randomly generated because the impactors were assumed to 222

have come from all directions, (3) the mean distance to the nearest neighbor (d_i in i^{th} trial) was measured using the average of the lengths defined by the great-circle distance between two points, (4) based on these three assumptions, 10000 trials were performed, and (5) the average and deviation of d_i (i = 1,2,3,...10000) were obtained as d_{exp} and σ , respectively.

228

229 3. Results

230On the surface of Ryugu, 77 craters were identified (Fig. 1); the diameters and locations of these craters are listed in Table 3. Figure 2 shows 231232the global distribution of craters that are bordered with rims as lines on the global mosaic map projected in a simple cylindrical projection. We again 233234confirmed a lack of small craters (20 m < D < 100 m) relative to the number of large craters, as has also been found on other small asteroids such as 235Itokawa, Eros, and Bennu (Thomas and Robinson, 2005; Michel et al. 2009; 236237Walsh et al. 2019). The largest crater on Ryugu is Urashima, at 290 m in 238diameter, which is equivalent to 32% of the diameter of Ryugu. The second and third largest craters are Cendrillon (224 m) and Kolobok (221 m), 239respectively. Only these three craters exceed 200 meters in diameter. The 240average crater density over Ryugu is 4.4 craters/km² for $D \ge 100$ m and 25.0 241242craters/km² for $D \ge 20$ m.

The distribution of craters on Ryugu is variable, with differences in crater density depending on longitude and latitude (Fig 3a, b). The Z value (Fig. 3c) suggests that the craters on Ryugu are spatially distributed in clusters, in a statistically significant manner. Therefore, the spatial

distribution of craters on Ryugu cannot be explained by the randomness of 247cratering itself. There are more craters at lower latitudes and fewer craters 248at higher latitudes (Fig. 3b). Polar regions of greater than 40 degrees latitude 249have only a few craters. There are more craters around the meridian 250 $(300^{\circ}\text{E}-30^{\circ}\text{E})$, and fewer at the western bulge $(160^{\circ}\text{E} - 290^{\circ}\text{E})$. Because of 251this we termed the region between 300°E-30°E and 40°S-40°N the cratered 252terrain. The crater density in this region is 57.3 craters/km² (D \geq 20 m), twice 253the global average. However, as shown in Fig 3a, the crater density of the 254western bulge is roughly half the global average. Although less-cratered 255256terrain is often found both surrounding and on the inside of large craters such as Shoemaker crater on Eros (Robinson et al. 2002), we could not 257identify any landform that could be associated with a putative large crater at 258either the polar regions or the western bulge of Ryugu. 259

260Ryugu has 11 craters (D \geq 100 m), of which 5 cut the crest of the 261equatorial ridge, Ryujin Dorsum. Note that we concluded that it is unlikely 262that some of the impact craters found on this ridge did not originate from impacts (i.e., the ridge is a landform made by another mechanism such as 263mass-movement). This is because the large craters cutting across the ridge 264(No. 1, 3, 4, 6, 8 in Fig. 1) are all clear and circular bowl-shaped depressions 265266and appear to be distinct impact craters, as discussed by Sugita et al. (2019). We therefore performed a statistical test to evaluate the statistical 267significance of the concentration of craters on the equatorial ridge, Ryujin 268Dorsum. Using the Monte Carlo method, we estimated the number of craters 269270expected across the equator under random distribution. In detail: (1) the 11

craters exceeding diameters of 100 m, are placed at random points on a 271sphere with a radius of 448 m using spherical uniform random numbers, (2) 272the number of craters across the equator is counted, and (3) the average 273value of the number and its dispersion are obtained from 1000 trials. Results 274275indicate that the expected number of large craters across the equator under random distribution is 2.1 with a dispersion of 1.3. We therefore concluded 276that the number of observed craters found on the equator (5 craters) was 277greater than that expected randomly. 278

279

280 4. Discussion

Possible explanations for the longitudinal variation in crater density 281282are: (i) resurfacing from processes such as seismic shaking is inert in the cratered terrain and is more active in the western bulge, (ii) differences in 283284the physical terrain inhibit the formation of an impact crater (e.g., Güttler et 285al. (2012) proposed an armoring effect owing to the presence of boulders), 286and (iii) the cratered terrain around the meridian (300°E -30°E) is geologically old, while the formation of the western bulge was relatively 287recent. Seismic shaking or armoring effects, as in (i) and (ii), should 288theoretically be more effective for smaller craters; however, even large 289290craters on Ryugu show longitudinal variation which indicates that (i) and (ii) 291are unlikely. We propose that (iii) is the most likely scenario. This is because 292the western bulge is a geologically distinct terrain, as mentioned in Section 1. The western bulge is proposed to have been caused by the deformation of 293294Ryugu, via a process that occurred on only the western side of the asteroid

during a short rotational period of Ryugu in the past, while the eastern 295hemisphere was left structurally intact (Hirabayashi et al. 2019). On the 296other hand, Scheeres (2015) proposed that regolith landslides occur on the 297surface of rapidly spinning asteroids, so the occurrence of such a landslide 298299from the polar regions toward the western hemisphere could be taken into 300 consideration as an alternative explanation for the formation of the western bulge. In addition, such a landslide could be responsible for the latitude 301302 variation in crater density (i.e. relatively less-cratered polar regions). In both cases, the crater density of the western bulge represents the timing of the 303 304 short rotational period of Ryugu, while the cratered terrain around the meridian was already an old surface when the western bulge formed. 305 306 Probably, the equatorial ridge located in the eastern hemisphere is a fossil structure formed during the short rotational period in the distant past. The 307 308 ridge that is slightly offset towards the south may indicate a polar shift of 309 Ryugu in the past.

310

311 5. Conclusion

We have identified 77 craters on the surface of Ryugu. The spatial distribution of the craters on Ryugu is not random, with variations in crater density that can be linked to latitude and longitude; more craters are seen at lower latitudes than at higher latitudes, and there are more craters in the region around the meridian than in the western bulge. The longitudinal variation in crater density could be a possible result of the formation of the western bulge, which is thought to have formed later than the rest of the asteroid due to its lower proportion of craters. The equatorial ridge located in
the eastern hemisphere would be a fossil structure formed during the short
rotational period in the distant past.

322

323 Acknowledgements

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Figure 1. Candidate craters that were identified. Numbers correspond tothose in Table 3.



Figure 2. The distribution of craters on Ryugu. Red lines roughly outline the rim of craters. On the left is a simple cylindrical projection mosaic map derived from the July 20, 2018 images. On the right is the azimuthal equidistant projection maps centered in the north (top) and south poles (bottom) derived from January 24, 2019 and August 23, 2018. Numbers correspond to Figure 1 and Table 3.

342



Figure 3. (a) The longitudinal variation in crater density ($D \ge 20$ m). (b) The latitudinal variation in crater density ($D \ge 20$ m). (c) The Z value for spatial distribution on Ryugu.

| 348 | Table : | 1. Images | utilized | in | this | work. |
|-----|---------|--------------|-----------------------|----|-------|-------|
| 010 | 100010 | L. LILLONGON | or of the trail of or | | 01110 | |

| | Date | Num. | Resolution | Note |
|-------|--------------|------|----------------|------------------------------|
| (i) | Jul. 20 2018 | 96 | 0.72 m/px | Low latitude < 70 degree |
| (ii) | Aug.1 2018 | 85 | 0.69-0.55 m/px | Low latitude < 40 degree |
| (iii) | Oct. 4 2018 | 11 | 0.32 m/px | North pole |
| (iv) | Oct. 30 2018 | 18 | 0.62 m/px | North and South poles |
| (v) | Feb. 28 2019 | 26 | 0.67 m/px | North and South poles |
| (vi) | Aug. 23 2018 | 52 | 2.6 m/px | South pole at small emission |

Table 2. Classification in this study.

| Classification | Characteristic | Our Judge |
|----------------|---------------------------------|------------|
| I | Circular depression with rim | Crater |
| II | Circular depression without rim | Crater |
| III | Quasi-circular depression | Crater |
| IV | Quasi-circular features | Not crater |

Table 3. Impact craters on Ryugu

| #* 1 | Lat. | Lon. (°E) | D (m) | CL^{*2} | | |
|-------------|----------------------|-----------|-------|-----------|--|--|
| | Classification I-III | | | | | |
| 1 | -7.19 | 92.99 | 290 | Ι | | |
| 2 | 28.34 | 353.68 | 224 | II | | |
| 3 | -0.70 | 330.28 | 221 | II | | |
| 4 | -14.83 | 51.20 | 183 | Ι | | |
| 5 | -50.56 | 9.84 | 173 | III | | |
| 6 | 0.42 | 157.84 | 154 | II | | |
| 7 | 30.37 | 145.99 | 145 | II | | |
| 8 | 3.24 | 229.95 | 142 | Ι | | |
| 9 | -17.19 | 14.29 | 133 | II | | |
| 10 | -31.50 | 47.26 | 131 | Ι | | |
| 11 | 17.02 | 332.23 | 100 | Ι | | |
| 12 | -1.88 | 289.49 | 90.2 | II | | |
| 13 | -63.73 | 24.45 | 85.0 | III | | |
| 14 | 16.90 | 6.44 | 79.0 | III | | |
| 15 | -4.54 | 95.52 | 78.9 | III | | |
| 16 | 6.01 | 308.75 | 77.1 | Ι | | |
| 17 | 23.70 | 205.33 | 76.2 | II | | |
| 18 | 20.86 | 322.68 | 73.9 | II | | |
| 19 | 57.73 | 342.98 | 73.3 | II | | |

| 20 | -11.64 | 287.71 | 69.0 | III |
|----|--------|--------|------|-----|
| 21 | -8.44 | 119.53 | 69.0 | Ι |
| 22 | 8.28 | 111.52 | 65.8 | III |
| 23 | 18.59 | 149.73 | 65.8 | II |
| 24 | 19.65 | 136.94 | 62.1 | II |
| 25 | -12.18 | 179.11 | 61.0 | II |
| 26 | 28.48 | 213.16 | 58.2 | II |
| 27 | -16.28 | 199.13 | 53.6 | II |
| 28 | 36.81 | 121.83 | 52.2 | III |
| 29 | -36.18 | 176.65 | 51.3 | III |
| 30 | -0.07 | 329.24 | 51.3 | II |
| 31 | -17.20 | 307.19 | 48.8 | II |
| 32 | 33.09 | 81.45 | 48.4 | III |
| 33 | -26.28 | 17.83 | 46.6 | II |
| 34 | -1.87 | 279.89 | 44.2 | II |
| 35 | 33.50 | 217.25 | 44.1 | III |
| 36 | 24.37 | 335.50 | 43.1 | III |
| 37 | -3.08 | 47.02 | 42.7 | Ι |
| 38 | 18.62 | 20.92 | 42.5 | III |
| 39 | -69.03 | 170.39 | 41.7 | III |
| 40 | -19.49 | 150.94 | 41.4 | III |
| 41 | 11.91 | 334.53 | 39.9 | Ι |
| 42 | 17.52 | 323.27 | 39.7 | II |
| 43 | -15.38 | 328.28 | 37.2 | II |
| 44 | -14.87 | 115.35 | 36.5 | II |
| 45 | 55.75 | 357.50 | 36.0 | II |
| 46 | 7.79 | 173.00 | 34.6 | Ι |
| 47 | -34.51 | 263.82 | 34.4 | Ι |
| 48 | -10.68 | 176.31 | 32.0 | II |
| 49 | -28.57 | 9.83 | 30.6 | III |
| 50 | -7.92 | 26.75 | 29.3 | III |
| 51 | -6.30 | 319.67 | 28.1 | III |
| 52 | -5.81 | 9.76 | 27.6 | III |
| 53 | 52.36 | 57.31 | 27.5 | II |
| 54 | 37.10 | 73.44 | 26.5 | III |
| 55 | 79.00 | 209.00 | 26.0 | II |

| 56 | 21.44 | 13.71 | 25.3 | III |
|----|--------|--------------|------|-----|
| 57 | -0.89 | 4.52 | 24.4 | III |
| 58 | 4.61 | 301.74 | 23.6 | Ι |
| 59 | -24.00 | 346.55 | 21.7 | III |
| 60 | -19.26 | 102.14 | 21.5 | III |
| 61 | -2.08 | 263.10 | 21.0 | II |
| 62 | 37.02 | 78.22 | 20.9 | III |
| 63 | 31.21 | 208.26 | 20.2 | III |
| 64 | 8.40 | 225.72 | 17.2 | Ι |
| 65 | 25.81 | 196.97 | 16.2 | II |
| 66 | -69.00 | 211.00 | 16.0 | II |
| 67 | -31.59 | 174.66 | 14.5 | II |
| 68 | -6.96 | 195.40 | 14.4 | III |
| 69 | 9.65 | 149.10 | 14.0 | Ι |
| 70 | -8.37 | 201.10 | 14.0 | II |
| 71 | -12.89 | 221.27 | 13.9 | II |
| 72 | 52.43 | 100.93 | 12.6 | II |
| 73 | 23.18 | 141.89 | 12.5 | II |
| 74 | 17.15 | 137.76 | 11.4 | II |
| 75 | 19.01 | 224.05 | 11.2 | II |
| 76 | -35.88 | 231.29 | 10.5 | II |
| 77 | 3.40 | 314.61 | 10.0 | II |
| | Clá | assification | IV | |
| 78 | -31.21 | 341.74 | 223 | IV |
| 79 | -45.92 | 334.99 | 133 | IV |
| 80 | -30.64 | 284.23 | 112 | IV |
| 81 | -58.37 | 198.43 | 112 | IV |
| 82 | 38.21 | 298.88 | 55.8 | IV |
| 83 | 31.87 | 15.43 | 53.0 | IV |
| 84 | 10.26 | 69.87 | 46.7 | IV |
| 85 | -10.59 | 316.99 | 35.0 | IV |
| 86 | -25.36 | 189.21 | 11.4 | IV |

*1 Number in descending order of diameter. Ryugu has 7 named craters:
Urashima (No.1), Cendrillon (No.2), Kolobok (No.3), Momotaro (No.4),
Kintaro (No. 6), Brabo (No. 8), and Kibidango (No.10).

³⁵⁶ ^{*2} Classification shown in Table 2.

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