Topography of large craters of 162173 Ryugu. N. Namiki[1,2], T. Mizuno[2,3], H. Senshu[4], H. Noda[1,2], K. Matsumoto[1,2], N. Hirata[5], R. Yamada[5], Y. Ishihara[6], H. Ikeda[3], H. Araki[1,2], K. Yamamoto[1], S. Abe[7], F. Yoshida[4], A. Higuchi[1], S. Sasaki[8], S. Oshigami[1], S. Tsuruta[1], K. Asari[1], S. Tazawa[1], M. Shizugami[1], H. Miyamoto[9], H. Demura[5], J. Kimura[8], T. Otsubo[10], N. Hirata[11], F. Terui[3], S. Watanabe[12], T. Saiki[3], S. Nakazawa[3], M. Yoshikawa[3], and Y. Tsuda[3], [1]National Astronomical Observatory of Japan (2-21-1 Osawa, Mitaka, Tokyo, Japan 181-8588, nori.namiki_AT_nao.ac.jp), [2]SOKENDAI (The Graduate University for Advanced Studies), [3]Japan Aerospace Exploration Agency, Institute of Space and Astronautical Science, [4]Chiba Institute of Technology, [5]The University of Aizu, [6]National Institute of Advanced Industrial Science and Technology, [7]Nihon University,[8]Osaka University, [9]The University of Tokyo, [10]Hitotsubashi University, [11]Kobe University,[12]Nagoya University.

Introduction: High-velocity impact and ejction of surface materials are important processes which governs dynamical evolution of not only asteroid belt, but also debris disk in the early solar system [1, 2]. An efficiency of disruption and surface alteration of C-type rubble pile asteroids are of particular significance in the view of transportation of water and organic materials to the early Earth, Mars, and icy satellites, and needs to be understood by in situ observation from spacecrafts [2-4]. 25143 Itokawa is the first rubble pile body ever identified via remote sensing and returned samples of Hayabusa mission [5]. 253 Mathilde and 21 Lutetia are C-type asteroids visited by NEAR [6] and Rosetta [7]. Craters on these asteroids, however, are widely different, and impact processes occurring on the C-type rubble pile bodies has not been understood well yet. The target of Hayabusa2, 162173 Ryugu, is a rubble pile asteroid of C-type [8] and possesses a key to link variable cratering records on Itokawa, Mathilde, Lutetia, and Bennu which was recently visited by OSIRIS-REx spacecraft.

Ryugu is the second asteroid whose topography is measured accurately by laser altimeter (LIDAR) [9] after 433 Eros [10]. Compared with photoclinometry and stereogrammetry, LIDAR is straightforward and less constrained by solar lightning conditions and photometric properties of surface. While precise orbit reconstruction and accurate pointing information are required to study areal topography, along-track profile can be promptly implemented independently from these uncertainties of the spacecraft [9, 11].

Crater Topography: In LIDAR topography data, 3 circular depressions are found on near the equatorial bulge [*8, 12*]. All of these circular depressions are identified as craters and have been given names approved by IAU, namely Urashima, Kolobok, and Brabo craters (Fig. 1). After careful calibration for different passes, consistent and precise cross sections of the craters are derived.

For Urashima crater, topography data of 4 passes are merged. While there exist other passes which go through Urashima crater, only passes which go through near the center of the crater are chosen in Fig. 1. Because these passes are taken in different days of operation, altitude of the spacecraft and sampling rate vary widely from 6 to 21 km and from 1/32 Hz to 1 Hz, respectively. Nonetheless, the cross sections in Fig. 1 show a good match. Similarly, three passes are merged for Kolobok and Brabo craters in Fig. 1. The match among different passes is very good for these craters, too, except for topography over large boulders.

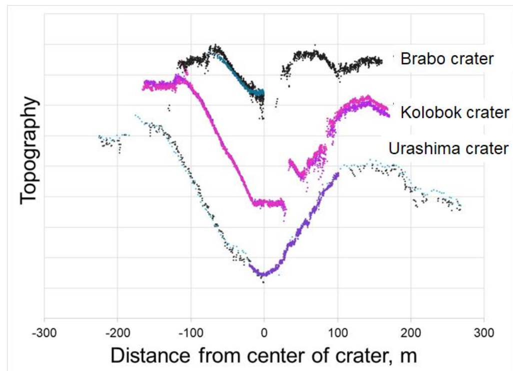

Fig. 1. East-west cross sections of large craters of Ryugu.

Depth-to-diameter ratios (d/D) of Urashima, Kolobok, and Brabo craters are 0.2, 0.14, and 0.155, respectively, and are consistent with previous in situ observations of asteroid topography [3, 7., 13, 14], while there seems marked difference from craters on Itokawa [15] and Bennu. Both Itokawa and Bennu are comparable in size and surface gravity to Ryugu, and these 3 asteroids are regarded as rubble pile bodies. On the contrary, the d/D of Itokawa craters, 0.08 ± 0.03 [15], is significantly shallower than that of Ryugu and other asteroids. The d/D of Bennu is apparently shallower, too. In addition, craters on Ryugu have topographically distinctive raised rim (Fig. 1) while those on Itokawa do not [15].

The low d/D of Itokawa is regarded as a result of either an influence of curvature of small body, a lack of raised rim, or fine grains infilling the craters [15], but has been unsolved. On the other hand, craters of Mathilde have characteristics much alike to those on Ryugu; the d/D ranging from 0.12 to 0.25, prominent

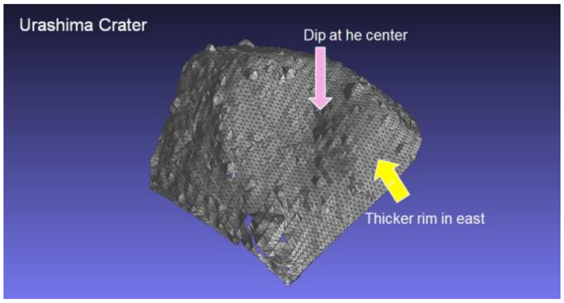

Fig. 2. 3D topography model of Urashima crater.

raised rim, and a lack of ejecta blanket. While Mathilde is 50 times larger than Ryugu, the bulk density of Mathilde is only 1.34 ± 0.2 g cm^{-3} [6]. Such low density is likely suggesting that Mathilde is as porous as 50 % [6].

The shapes of the four craters are neither bowl-shaped like 951 Gaspra and Eros [13, 16, 17] nor flat like Itokawa [15]. It is notable that slopes of inner wall of Ryugu craters are linear rather than paraboloidal, and that Kolobok and Brabo craters are flat-bottomed (Fig. 1). In Fig. 2, we show 3D topography model of Urashima crater which is derived from LIDAR topography data taken on Oct. 30, 2018. Fig. 2 shows a central cavity on Urashima crater [12] indicating an agreement with impact cratering experiments into porous targets [4], while the d/D of Ryugu crates is lower than experimental results which is between 0.2 and 0.5 [18]. It is interesting that slopes of the 3 craters are almost identical (Fig. 1). Such nearly identical conical shape indicates that either the crater shape is well relaxed, or in the contrary, is holding initial shape.

The slopes of inner walls are measured with respect to local gravity estimated by taking GM of 30.0 m^3s^{-2} [8] and assuming a constant density inside of Ryugu Fig. 3). The mode of the slopes of inner wall of Urahisma, Kolobok, and Breabo craters are between 16º and 20º, 7º and 15º, 16º and 18º, respectively. The mode of slopes is shallower than the repose angle of regolith which is between 30º and 35º. The shallow slopes and flat bottom may indicate that morphology of Ryugu craters is sufficiently relaxed. However, preservation of entire conical shape as well as central cavity of Urashima crater instead suggest that modification of crater topography on Ryugu is limited volumetrically and is less effective than Itokawa.

Asymmetry in East-West Profile: A close examination of Fig. 1 and 2 reveals an interesting characteristics of Ryugu craters. Width of rim is wider on eastern wall than western wall. The cause of this east-west asymmetry is difficult to explain, and we consider three hypotheses. First, oblique impact from west could produce wider and thicker rim by either enhanced compaction or thicker ejecta deposits on eastern side. Because TIR observation does not show any variation of thermal properties of crater walls from surrounding area, compaction is unlikely. This hypothesis requires angular momentum of projectiles aligned with rotation axis of Ryugu. Such alignment would be possible if the projectiles which used to be boulders launched from the surface when Ryugu's rotation was decelerated. Apparently the craters postdate rotation deceleration because their morphology is little influenced by subsequent mass wasting from equatorial bulge. The projectiles could be last remnants of re-accumulation of rubble piles.

Second, similar asymmetry is found for Stickney crater on Phobos. Thomas [19] proposes that Coriolis force acting on low velocity ejecta leads ejecta to accumulate on east side of Stickney crater.

Third, dusts could accumulate on western inner walls. When levitating dusts fall to the surface at the dusk, it is possible that dusts would be flown by solar wind and accumulate more on western side than eastern side. If this is the case, any difference of eastern and western sides in TIR observation is expected. To date, observation data are insufficient to prove or disprove this hypothesis [20].

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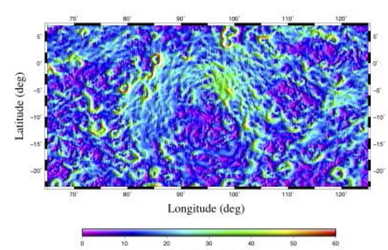

Fig. 3. Slope map of Urashima crater.