Surface Flows Mechanism on Asteroid Ryugu Inferred from the Azimuthal Direction of Wake-like Features on Regolith Around Large Boulders. N. Takaki[1], T. Morota[1,2], Y. Cho[1], E. Tatsumi[1,3], R. Honda[4], S. Kameda[5], Y. Yokota[4,6], N. Sakatani[6], T. Kouyama[7], M. Hayakawa[6], M. Matsuoka[6], M. Yamada[8], C. Honda[9], H. Suzuki[10], K. Yoshioka[1], K. Ogawa[6,11], H. Sawada[6], S. Sugita[1,8], [1]Univ. of Tokyo (ntakaki@eps.s.u-tokyo.ac.jp), [2]Nagoya Univ., [3]Inst. de Astrofísica de Canarias, [4]Kochi Univ., [5]Rikkyo Univ., [6]JAXA, [7]AIST, [8]PERC, Chiba Inst. of Tech., [9]Univ. of Aizu, [10]Meiji Univ., [11]Kobe Univ.

Introduction: The initial observations of Hayabusa2 found geomorphological and spectral evidence for mass movement on asteroid Ryugu, such as imbricated boulders, regolith run-ups on boulders, and bluer spectra on the equatorial ridge [1]. Furthermore, crater chronology and high-resolution morphology analyses show that the equatorial bluer zone is likely formed by the removal of reddish surface regolith layer due to recent despinning of Ryugu [2]. Subsequently, detailed multi-band imaging analyses have revealed that many large boulders on the flanks of Ryugu's equatorial ridge are associated with blue regions, "wake-like features," toward mid latitudes (i.e., topographical downslope direction), suggesting that surface materials flowed from the equator to mid latitudes [3]. The fact that the wake-like features possess clear color signature supports that they are likely formed by very recently because such color signature can be easily erased by ejecta blanket or landslides. Thus, the wake-like features may preserve the geologic record of flow mechanism the most. The driving mechanism for such surface flows, however, is poorly understood yet.

In this study, we investigate the azimuthal directions of wake-like features based on ONC-T images and those of local topographic slope calculated by Ryugu's shape model to understand the driving mechanism for surface flows on Ryugu.

Survey of blue regions associated with boulders: Based on mid-altitude observation data (~ 0.5 m/pix) or Ryugu [1], we extracted 241 blue regions that are bluer than the Ryugu average spectrum by 1σ and have surface area ≥200 pixels. The blue regions were classified into 3 groups: (A) associated with boulders (76), (B) associated with craters (70), and (C) others (95). The group A includes blue regions adjacent to boulders and blue boulders themselves. Among the group A about a half is located on the higher-latitude sides of the boulders and about a quarter is blue boulder themselves. The other quarter is located on the east, west, or upslope side of boulders.

Flow direction analysis: To estimate flow directions, we manually traced the outlines of the boulders and the blue regions associated with them. The possible flow azimuths were defined as a line connecting the centroid of a boulder outline with that of a blue region (Fig. 1). We also calculated the azimuths of the Ryugu's shape model [4].

Results: The distribution of the possible flow directions is illustrated in Fig. 2. Most of the blue regions associated boulders are located around the equatorial ridge (10 °S~10 °N). Forty boulders with blue regions are on the southern hemisphere.

Analysis result indicates that topographical slopes (<~20°) around the blue regions are flatter than the average slope at the same latitude (Fig. 3a). This trend that blue regions exhibit flatter slopes may be resulted in by mass movement because mass movement would lead to shallower surface slopes through transporting surface materials from geopotential highs to geopotential lows.

The directions of most surface flows inferred from the azimuthal direction of wake-like features exhibit N-S orientation. More specifically, the directions of almost all the wake-like features on the southern hemisphere are southward, but those on the northern hemisphere exhibit greater scatter (Fig. 4). The directions of wake-like features agree with the current downslope directions in their locations (Fig. 5). In some regions, however, the flow direction is perpendicular or opposite to its downslope direction.

Discussion: The above statistical result of azimuth different suggests that most blue regions around boulders were resulted from surface flows consistent with the current geopotential, which was suggested by geomorphological and spectral analyses [1,2].

The consistency between the azimuth of wake-like features and current downslope direction suggests that the surface materials recently moved along the current topographical slope of Ryugu. Similar consistency between the direction of mass movement and current downslope direction was found on Bennu. The mass movement on Bennu may have been caused by spin rate change due to the YORP effect [5]. The YORP effect may also have changed the slope distribution on Ryugu; Ryugu may have been spinning faster in the past than now [4]. When surface slopes exceed the angle of repose during the despinning, surface flows should occur. However, accurate angle of repose of regolith under microgravity and vacuum condition is difficult to estimate. Estimation based on Earth indicates that the angle of repose of dry sand is ~35° [6], but the surface slopes may not have reached ~35° on Ryugu. Calculation results for P= 3.5, 4.5, 5.5, 6.5, 7,6, 8.5, 9.5, and 15.0 hr indicate that the Ryugu surfaces around the equator stay <~20° except in the case of P=3.5 hr. Although the slopes around wake-like features exceed 30° at the spin rate of 3.5 hr, the directions of slopes around the equator are opposite to those of the wake-like features. When we consider only the case of P>4.5 hr, the slopes around wake-like features are lower than ~20° with the highest angle case occurring at P=15.0 hr (Fig. 3b). Note that the local slope around wake-like features increases for larger *P*, but the extent of this increase is very limited. Thus, some mechanisms, such as seismic waves, would have to lower the effective angle of repose of Ryugu surface to form shallow slopes observed on Ryugu. For example, seismic waves reduce the effective angle of repose by lifting surface regolith and reducing friction. In fact, the majority of the Ryugu's surface has slopes <30° at the current spin rate (Fig. 6). Thus, some forces acting on surface layer may have contributed to flows on flatter slopes on Ryugu.

The flatter critical angle suggests that the shape of an asteroid is more deformable than previously thought. Local surface flows may occur at the critical angle flatter than ~20° at least flow of thin surface layer. Local landform changes yield an asymmetry in an asteroid's shape, which changes the magnitude of the YORP effect.

Acknowledgments: This study was supported by JSPS Core-to-Core Program "International Network of Planetary Sciences" and International Graduate Program for Excellence in Earth-Space Science (IGPEES) from the Univ. of Tokyo.

References: [1] Sugita et al. (2019) *Science,* aaw0422. [2] Morota et al. (2020) *Science,* aaz6306. [3] Takaki et al. (2020) *LPSC,* Abstract #1381. [4] Watanabe et al. (2019) *Science,* aav8032. [5] Jawin et al. (2020) *JGR,* 125, e2020JE006475. [6] Carrigy (1970) *Sedimentology,* 14, 147-158.

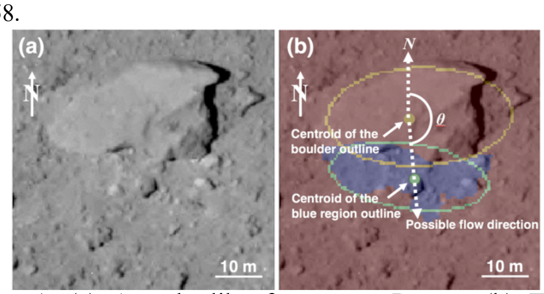

Fig. 1. (a) A wake-like feature on Ryugu. (b) The direction of a wake-like feature, measured as a line connecting the centers (two dots) of the best-fit centroids of boulder and wake-like feature.

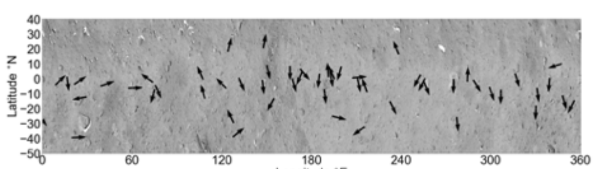

Fig. 2. The distribution of the directions of the wake-like features on Ryugu.

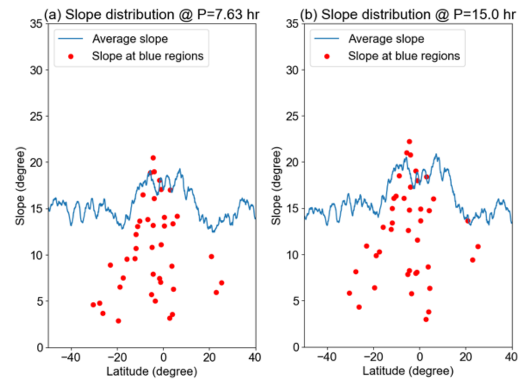

Fig. 3. Comparisons between local topographic slope around wake-like features (red circles) and longitudinally-averaged topography (blue line) at (a) P=7.6 hr and (b) at P=15.0 hr. Most wake-like features are on flatter slopes than the average.

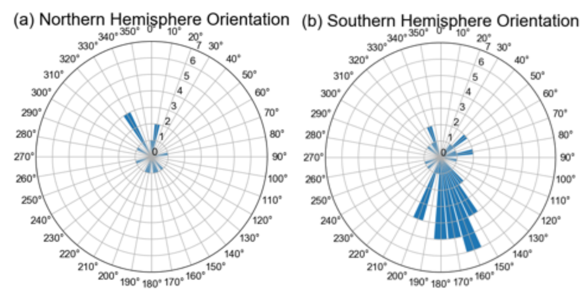

Fig. 4. The azimuths of the wake-like features on Ryugu. Azimuths are measured from north in clockwise direction; 90° is east. The azimuths of the wake-like features on the (a) northern and (b) southern hemispheres.

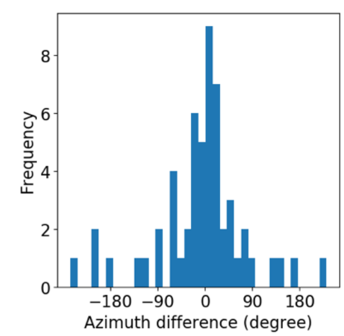

Fig. 5. Histogram of azimuth difference between the directions of flow-like features and current topographic downslope directions.

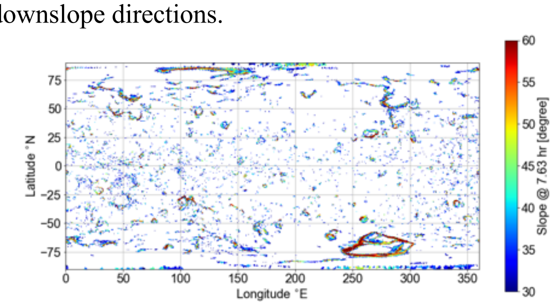

Fig. 6. Distribution map of slopes steeper than 30° on Ryugu. Slopes flatter than 30° are shown with white.