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Summary: *Longitudinal dichotomy seen on Ryugu. The sharp ridge of the western bulge. Likely rotationally induced deformation feature.*

Background: 162173 Ryugu, the target of Hayabusa2, has a round shape with an equatorial ridge, known as a top-shape [1, 2]. Although Ryugu's top shape is axisymmetric in general, it is not strictly so (Figure 1). The ridge angle, which defines an angle between the surfaces in the northern and southern hemispheres at the equatorial ridge, or Ryujin Dorsum, varies when seen from different views. The eastern and western regions are divided by Tokoyo and Horai Fossae, a trough system that is widely placed in the southern hemisphere and possibly spreads towards the northern hemisphere. The ridge angle on the west side, or the western bulge (160˚ E – 70˚ W), is sharper than that on the eastern side (Figure 1). Also, the surface of the bulge is less cratered than that in other regions [1]. Note that while the boulder distribution is being argued to characterize the east-west dichotomy, further discussion is necessary [1, 3].

Formation of a top shaped asteroid: Top shaped asteroids are likely to be common in Near-Earth Asteroids (NEAs) [4]. They usually rotate near their critical spin periods, ~2.3 hr [e.g., 5, 6], while Ryugu's spin period is 7.6 hr [2]. A key issue is how a top shaped asteroid has formed. It is generally agreed that such a shape results from rotationally induced deformation [7, 8, 9] while reaccumulation at the formation stage may also be plausible [10].

Ryugu's top shape, which has the east-west dichotomy, may provide additional clues on the formation process of top-shaped asteroids. Here, we investigate the formation process of the western bulge, assuming that it might have occurred when Ryugu was spinning at a fast spin period.

Asymmetric trend of structurally failed regions in Ryugu: We use a finite element model (FEM) technique, applying the ANSYS FEM solver [11, 12, 13]. This technique describes deformation of a pile of regolith in a rubble pile asteroid assumed to be behave like a uniform continuum medium. The deformation of an element consists of elastic and plastic modes without material softening and hardening. A three-dimensional 10-node FEM mesh is generated from a stereophotoclinometry (SPC)-derived polyhedron model (SHAPE_SPC_3M_v20180731.obj) [2], which has 1,579,015 vertices and 3,145,728 facets. The derived FEM mesh has 8,305 triangular elements and 15,033 nodes. We investigate the variations in structurally failed regions, or areas that experience irreversible deformation, in Ryugu.

At a spin period at 3.75 hr, Ryugu starts to experience structural failure in the interior (Figure 2a). As the spin period becomes shorter, the central region is more sensitive to structural failure (Figure 2b).

Importantly, there are structurally intact regions (the green regions) on the equatorial plane at any spin periods shorter than 3.75 hr. These regions are located in the subsurface of the western bulge and may not disappear unless large deformation occurs in the structurally failed regions (the yellow regions).

We attribute this structural failure mode to the deformation process that Ryugu had in the past. Consider that a rubble pile asteroid experiences an irreversible deformation process. Such a process settles into a new configuration for which the potential of the deformed elements becomes minimum [14]. Elements that experienced such deformation are likely to relax structurally while other elements do not. Therefore, when the asteroid encounters a fast-rotation condition once again, only the elements that did not experience structural failure previously become sensitive to failure. Given this consideration, we infer that the western bulge result from an internal deformation process at fast rotation in the past.

Spin period at which the circularity of Ryujin Dorsum formed: If the western bulge is developed due to a rotationally induced deformation process, that region should grow further and thus have a high topographic feature shortly after the deformation. However, some materials may be weakly bonded and therefore fluidized. In this case, when the centrifugal force exceeds the gravity force, these materials are likely to be lofted; in other words, it is difficult for the edge of the western bulge to resist the strong centrifugal force during the deformation process.

We investigate the locations of the dynamical equilibrium points where the gravitational and centrifugal forces are balanced, as well as the energy levels, in the rotating frame (Figure 3). If an equilibrium point touches the surface at a given spin period, then materials at that location should be shed. We find that when the spin period is 3.5 hr, the equilibrium points reach the surface. This result indicates that if Ryugu had the deformation producing the western bulge at a spin period shorter than 3.5 hr, the size of Ryujin Dorsum would be smaller than the currently observed size. This condition implies a cohesive strength of Ryugu as ~4 Pa.

Conclusion: Assuming that materials are uniformly distributed within Ryugu, our FEM model showed that the longitudinal variation in the structurally failed regions appears at a spin period shorter than 3.75 h. Structurally intact regions spread in the western bulge while other areas are sensitive to structural failure. We inferred that this variation is indicative of the deformation process that made the western bulge. We also showed that because of the size of Ryujin Dorsum, this deformation process might have occurred at a spin period of ~3.5 hr, implying a cohesive strength of ~4 Pa. The physical properties derived for Ryugu are consistent with those by earlier work. [2].

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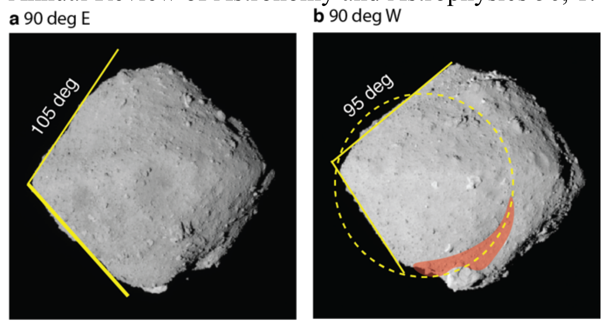

Figure 1. Ryugu's shape seen from different views. a. View from 90 deg E (image: hyb2 onc 20180630 140543 tvf l2a). b. View from 90 deg W (image: hyb2 onc 20180630 101759 tvf l2a). The red region is the observed trough [1]. The dashed yellow circle describes the western bulge. Each panel also describes the ridge angles.

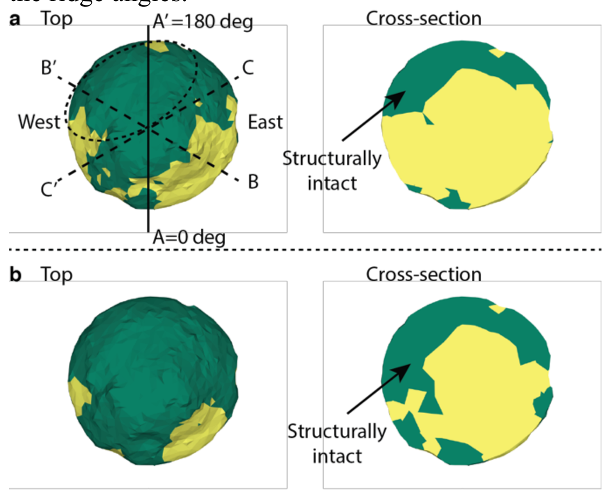

Figure 2. Ryugu structural failures at spin periods of 3.75 hr (panel a) and 3.5 hr (panel b). The yellow regions indicate the locations of elements that experience structural failure at cohesive strengths of 1.5 Pa (3.75 hr) and 4 Pa (3.5 hr).

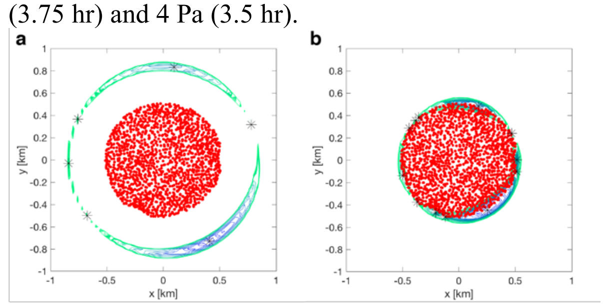

Figure 3. Locations of the equilibrium points. a. Case of a spin period of 7.6 hr (the current spin period). b. Case of a spin period of 3.5 hr. The red dots describe the shape of Ryugu. The contours describe the energy levels near those of the equilibrium points in the rotating frame. It is viewed from the spin axis.