

**AN ABSENCE OF SEISMIC SHAKING ON RYUGU INDUCED BY THE IMPACT EXPERIMENT ON THE HAYABUSA2 MISSION.** G. Nishiyama<sup>1</sup> (gaku.nishiyama@eps.s.u-tokyo.ac.jp), T. Kawamura<sup>2</sup>, N. Namiki<sup>3</sup>, B. Fernando<sup>4</sup>, K. Leng<sup>4</sup>, T. Saiki<sup>5</sup>, H. Imamura<sup>5</sup>, Y. Takagi<sup>6</sup>, K. Shirai<sup>5</sup>, M. Hayakawa<sup>5</sup>, C. Okamoto<sup>7</sup>, H. Sawada<sup>5</sup>, Y. Tsuda<sup>5</sup>, K. Ogawa<sup>5</sup>, M. Arakawa<sup>7</sup>, <sup>1</sup>The University of Tokyo, <sup>2</sup>Institut de Physique du Globe de Paris, <sup>3</sup>National Astronomical Observatory of Japan, <sup>4</sup>University of Oxford, <sup>5</sup>Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, <sup>6</sup>Aichi Toho University, <sup>7</sup>Kobe University.

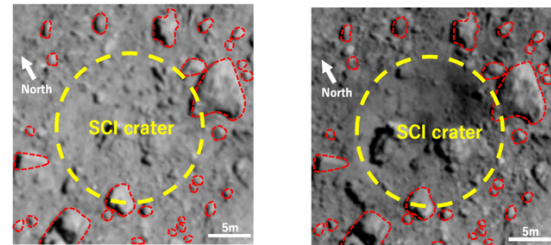
**Introduction:** Recently, multiple space exploration missions have revealed that asteroids have complex and variable surfaces. For example, Eros and Itokawa are covered with a loose regolith layer and show direct evidences of downslope motions such as flat-floored sediments ponds in craters, a deficit of small craters, and large blocks surrounded by debris aprons [1] [2]. Similar geomorphology has been observed on 162173 Ryugu by Hayabusa2 [3], indicating mass movements on the asteroid's surface.

While there are several processes that can account for both lateral and vertical mass transport of asteroid regolith, the most plausible one is global vibration, that is, impact-induced seismic shaking [2]. The low gravity on asteroids as well as the concentration of seismic energy inside their small volume have been suggested as causes of global surface renewal. Numerical simulations and laboratory experiments are supporting this hypothesis. However, it should be noted that it remains unclear whether the loose regolith under microgravity can be sufficiently elastic for seismic wave propagation to occur, because the behavior of such powdery materials can be either elastic or plastic according to circumstances.

The Japanese spacecraft Hayabusa2, which explored the near-earth asteroid Ryugu from June 2018 to November 2019, was expected to observe impact-induced seismic shaking. Included in the payload was a Small Carry-on Impactor (SCI) to generate an artificial impact crater and enable active seismic experiment on Ryugu [4]. Although there were no conventional seismometers placed on the asteroid itself, measurement of boulder movement distances with the Optical Navigation Camera (ONC) was anticipated to yield constraints on elasticity of the rubble-pile asteroid Ryugu.

In April 2019, the SCI operation was successfully conducted and provided surprising images of crater ejecta taken by a Deployable CAMera 3 (DCAM3). Later, the Hayabusa2 ONC took an image of the periphery of the SCI crater in order to contrast it with the image taken prior to the SCI impact (Fig.1). Whilst the impactor made a crater of about 13 m in diameter, boulders located around the edge of the crater appear unmoved by the seismic waves produced by the SCI impact. Aiming to explain this unexpected observation, we conduct seismic wave propagation modelling with

a wide range of parameters. Consequently, we show that the low yield strength of the Ryugu regolith would reduce its elasticity for the seismic waves to propagate.



**Figure 1:** Pre-SCI (left) and post-SCI (right) images around the SCI crater. This comparison implies that the boulders' hopping was little excited by seismic waves, and horizontal movement is smaller than 1 m at greatest. (Image credit: JAXA, U. Tokyo, Kochi U, Rikkyo U, Nagoya U, Chiba Institute of Technology, Meiji U, U. Aizu, AIST)

**Modelling methods:** Using a fast modelling code for 3D seismic wave propagation, AxiSEM3D [5], we numerically simulate seismic shaking on asteroids with a wide range of rigidities, quality factors and seismic efficiencies (the conversion ratio of impactor's kinetic energy to seismic wave energy). To evaluate the influence of inner structure on boulder movement, we adopt the following inner structural models: (a) a homogeneous, (b) a rigid shell with soft core, and (c) a soft surface with rigid core. The thickness of surface layer is set to be 50 m. This layer of depth is chosen because even the largest crater with depth ~45 m doesn't have a floor with terraced structures [3]. Following previous studies, an isotropic seismic moment tensor of explosion form is assumed and is calculated by taking the scaling function of [6]. The source function is a gaussian with 100 ms half-width. Note that the non-spherical shape of Ryugu was not taken into consideration because this study focusses on the near-field around the SCI crater.

**Calculation results:** Because the horizontal movement of boulders is dominated by the largest displacement of seismic waves excited by the SCI, we concentrate only on the peak-simulated velocity in this study. A comparison of calculated maximum acceleration among structure models reveals that the inner

structures do not significantly affect the induced acceleration. The comparison between models with and without an inner core shows that the effect of inner structure on acceleration around the SCI crater is smaller than 15 %. Thus the surface property, not the inner structure, controls seismically-induced boulder movement.

The key implication from our simulation is that physical properties measured in lunar and laboratory experiments (rigidities from  $10^6$  to  $10^9$  Pa, Q factors from 5 to 5000, seismic efficiencies from  $10^{-6}$  to  $10^{-2}$ ) causes such high surface velocities that boulders movement is expected to be more than 1 m. In other words, anelastic effects such as an extremely low quality factor or extremely low seismic efficiency need to be taken into account to reproduce consistent results with observation.

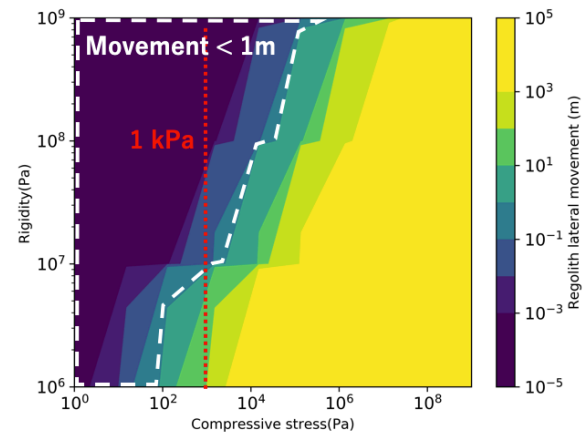
**Interpretations:** To attenuate seismic wave amplitude so rapidly that boulders stay unmoved after the SCI experiment, the quality factor is estimated to be  $\sim 0.5$  or lower. However, such an extremely low quality factor seems unrealistic, considering that a low quality factor is caused by anelastic heat generation and scattering. The absence of a fluid phase such as air or water on Ryugu strongly limits the contribution of heat conversion by viscous friction to low quality factor, whilst for scattering, even if the direct waves effectively attenuate, the amplitude of coda waves remains large enough to move boulders. Therefore, we consider it plausible that the seismic efficiency, in other words the conversion ratio of impactors' kinetic energy to seismic wave energy, is very low.

As is widely known, powdery materials behave plastically under pressures higher than their yield strength, and elastically (i.e. in a manner which may support seismic waves) otherwise. In the plastic regime, the powder behaves as a viscous fluid. As a result, plastic deformation efficiently absorbs wave energy. On the other hand, the deformation propagates as seismic waves in powdery media in the elastic regime. Therefore, the seismic energy that can propagate in regolith on asteroids may be limited by yield strength, possibly making the apparent seismic efficiency extremely low.

The yield strength of a powder is dominated by two effects; interparticle force and porosity. Given that the interparticle force is mainly due to cohesion (on the order of 10 Pa [7]), the yield strength of regolith on Ryugu may be  $\sim 10$  Pa. However, laboratory compressional experiments demonstrate that the yield strengths of irregularly-shaped powders could be as low as than 1 kPa or even lower if the porosity is about 60 % [8].

Assuming that the yields strength is 1 kPa, seismic waves thus propagate only if the elastic stress is lower

than 1 kPa (area to the left of the red dotted line in Fig.2). This may account for the absence of regolith lateral movement observed in the SCI operation during the Hayabusa2 mission.



**Figure 2:** A color map of regolith lateral movement distances as a function of rigidity and seismic stress. The lateral movement distance is calculated from the simulated ground motion velocity assuming that objects on the surface ‘hop’ ballistically along parabolic trajectories. The area enclosed by white dotted line shows the parameters range where the lateral regolith movement is smaller than 1 m. The red dotted line shows the possible yield strength of a powder composition. The seismic waves which can propagate are limited in the area left of the red line by the physical property of highly porous medias such as asteroid regolith.

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