DYNAMICAL EVOLUTION OF ITOKAWA INFERED FROM IMPACT EXPERIMENTS ON RUBBLE-PILE TARGETS.

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Introduction: Close-up images by Hayabusa revealed that a probable rubble-pile asteroid Itokawa possesses the crater-like morphologies (Fig.1) [1]. As resurfacing ages of other planetary bodies are estimated based on crater statistics, craters on asteroids would provide valuable information on their evolution. Because crater-retention age is influenced sensitively by crater size scaling, accurate age estimation requires an accurate crater scaling law. For example, a previous study shows the crater retention age based on the strength scaling would yield 75 Myr – 1 Gyr for Itokawa [2], but it is not obvious if cratering on rubble-pile asteroids, whose surface is composed of coarse-grains, are controlled by material strength. If gravity controls crater size instead, crater retention age on Itokawa would be younger by an order of magnitude.

Moreover, recent extensive radiometric analysis of samples returned from Itokawa have yielded a number of age estimations, such as cosmic ray exposure (CRE) ages [3, 4] and a ^{40}Ar/^{39}Ar degassing age [5]. Accurate understanding of such radiometric ages would require more accurate crater size scaling on rubble-pile structures with possible mechanical stratification. Although crater experiments on coarse-grained targets have been conducted [6, 7], their results are not necessarily consistent to each other. Furthermore, there is a possibility that Itokawa and other asteroids may have a boulder-rich layer superimposed on a finer regolith-rich substrate because of Brazil-nut effect, as suggested by the distribution of boulders [8]. Such mechanical stratification may have a significant effect, such as armoring from small projectiles [9], on crater size as well. The purpose of this study is to examine what crater scaling rule should apply for estimating crater age on Itokawa. In order to answer this question, we conduct impact experiments on coarse-grain targets and mechanically stratified targets with a coarse-grain layer on a fine-regolith substrate.

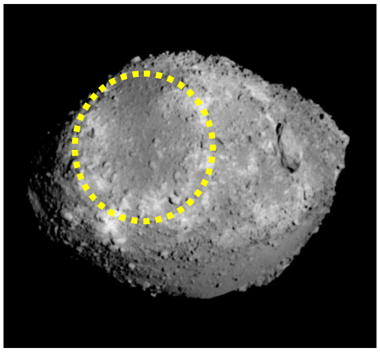

Fig. 1 *A circular depression on Itokawa. This is the second largest depression, Arcoona: 161m x 128m [1].*

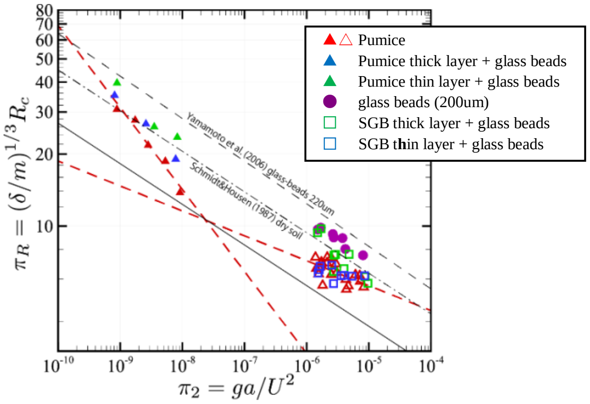

Fig. 2 *Crater sizes on targets composed of coarse grains (comparable to projectile size). For low-impact energy, craters on coarse grain target are significantly smaller than the gravity scaling. As impact energy increases, crater sizes on targets composed of coarse-grains approach the gravity scaling on dry soils. The slope of the scaling rule for coarse-grained targets steepens as impact energy increases. The black line is the possible minimum line of crater sizes on coarse-surface targets.*

Experiments & Results: The impact experiments were conducted with an one-stage gas gun in the Univ. of Tokyo at low velocities (70-190 m/s) and ISAS two-stage vertical gun for high velocities (1.5-5.3 km/s). When a cm-sized projectile hits a m-sized boulder on an asteroid surface at the mean impact velocity (~5.3 km/s) in the asteroid main belt, the boulder would be easily disrupted. To achieve the disruptions at low impact energy, we used pumice and weakly sintered-glass-beads blocks (SGB) of 8 – 15 mm size as boulder simulants [10]. We also used loose 200 μm glass beads as regolith simulant. Three types of targets were used: (1) two-layer targets with a block layer on a regolith substrate, (2) a uniform block layer, (3) a uniform regolith layer. For two-layer target (1), we changed the block layer thickness with 20 mm and 40 mm. We used two types of polycarbonate impactors: 10-mm diameter projectiles for low velocities and 4.6-mm diameter projectiles for high velocities. We measured the rim-to-rim (crest) diameters of craters.

The experimental results characterized by two dimensionless parameters, the gravity-scaled event size $\pi_2 = (ag/U^2)$ and the scaled crater size $\pi_R = (\delta/m)^{1/3}(R_c/a)$, are shown in Fig. 2. Our results indicate that the crater scaling on coarse-grain targets is closer to the gravity scaling than the strength scaling especially at high velocities, where target grains would be disrupted upon impact. When the top coarse-grain layer is thinner, the lower energy is needed for crater size to approach the gravity scaling. This result is consistent with a prediction based on impact experiments on gravels at high enough velocities to cause gravel disruption [7].

Mechanism of armoring: Apparently, the slope of the crater scaling on coarse-pumice targets (red triangles) at high velocities have a steeper slope than that at low velocities, suggesting the presence of multiple mechanisms controlling crater size. More specifically, there may be three mechanisms of armoring depending on impact energy. First, if impact energy is low enough that the target grains are rarely disrupted, target grains move as receiving momentum from a projectile, as discussed by [6]. As impact energy increases, the projectile penetrates into the target deeper by disrupting target grains. When the projectile disrupts only the surface grains, fragments are ejected without transferring momentum efficiently to grains deeper in the target and crater size increases only gradually. However, when impact energy becomes large enough for the projectile to penetrate into a certain depth, the fragments from disrupted surface grains can also transfer their momentum to surrounding grains very efficiently, and resulting crater size approaches the gravity scaling.

Extrapolations from both high and low velocity ranges we experimented (red dashed lines in Fig. 2) would predict the minimum size for craters formed on coarse surfaces. In this case, the minimum value is ~60% of the gravity scaling on dry soils (black solid line in Fig. 2); the armoring effect suppresses the excavation energy by ~40% at most. We call this suppressed scaling as "gravity scaling with armoring".

Crater retention age of Itokawa: The mean time interval for objects with diameter larger than D_p to hit a asteroid with diameter D_a is $\Delta\tau = 4/[P_i {D_a}^2 N(> D_p)]$, $(D_p \ll D_a)$, where the intrinsic collision probability P_i that a single member of the impacting population will hit a unit area of the target body in a unit time is derived as $2.86 \times 10^{-18} \mathrm{km}^{-2} \mathrm{yr}^{-1}$ among main belt asteroids [11]. Our experimental results show that the crater sizes formed on the coarse surfaces are in between the gravity scaling and the gravity scaling with armoring (the 40% suppressed from the gravity scaling). Thus, the age estimation based on the gravity scaling with armoring gives an upper estimate for the time to produce a given size of crater.

We choose large craters on Itokawa to estimate the crater retention age to avoid the effect of seismic shaking or other erasure processes. On Itokawa, there are five circular depressions with minor axis diameter larger than 100 m [1]. If the gravity scaling applies to the real Itokawa surface, a 100-m-sized crater would be formed in 0.1 Myr. And if the gravity scaling with armoring applies, it would be 1.1 Myr, respectively. Consequently, the formation of five of 100-m sized craters on Itokawa would take 0.4 - 8.4 Myr including statistical error of 50%.

Discussion: The crater retention age is younger than the age estimate based on the strength scaling law [2] by more than an order of magnitude. Our age is rather close to the CRE ages of the returned samples which suggest as young as < 10 Myr [3,4]. Age estimates obtained in a variety of studies on Itokawa so far are summarized in Fig. 3. There is a trend between the depth and their ages; isotopic clocks or morphologic clocks for deeper layers exhibit older ages. More recently an old ^{40}Ar/^{39}Ar age (1.26±0.24 Gyr) was reported [5]. This age probably corresponds to a much older event, such as a catastrophic disruption of Itokawa's parent body. Because the collisional lifetime of Itokawa is only a few million years [12], Itokawa might be disrupted more than once since this event and the current shape of Itokawa could be formed upon the second or third impact disruption. Our crater age may reflect such an event age. Apparent inconsistency between our crater age and boulder distribution age by [13] for similar depth scales may hold important information about the dynamical history of Itokawa; and more detailed investigation on the time scales of these features may be of great importance.

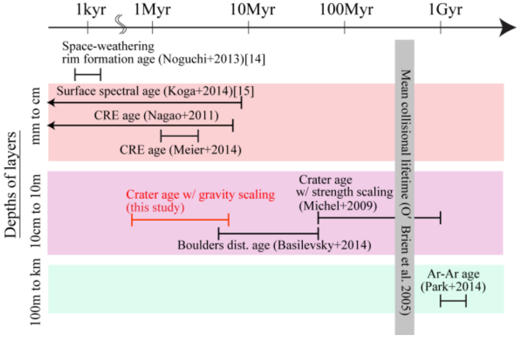

Fig. 3 *A variety of age estimates for different depths of layers on Itokawa.*

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