A MODIFIED ASTEROID RESURFACING MODEL INDUCED BY REGOLITH CONVECTION. Tomoya M. Yamada, Kosuke Ando, Tomokatsu Morota, Hiroaki Katsuragi, Department of Earth and Environmental Sciences, Nagoya University, Furocho, Chikusa, Nagoya 464-8601, Japan (yamada.tomoya@a.mbox.nagoya-u.ac.jp).

Introduction: Regolith convection could be one of the potential mechanisms to explain size-segregated terrains and resurfacing processes on asteroid. The idea was proposed to explain the surface-boulders distribution on the asteroid Eros that cannot be explained by only impact scattering [1]. Even on the asteroid Itokawa observed by *Hayabusa*, regolith convection is a possible mechanism to explain size-segregated surface terrain [2]. Besides, the cosmic-ray exposure (CRE) age of the grains returned from Itokawa was estimated as 1.5 - 8 Myr [3, 4]. This relatively young CRE age might also stem from the resurfacing process such as regolith convection.

The convective motion of regolith could be caused by the impact-induced global seismic shaking. In the laboratory experiment, granular convection is readily induced when the granular bed is subjected to vertical vibration of $\Gamma \gtrsim 1$ (Γ is dimensionless vibration strength defined by the ratio between the maximum vibrational and gravitational accelerations (e.g. [5])). Granular convection is one of the principal reasons for size-segregation in the vibrated granular bed [6]. However, extremely slow convective motion has been predicted under the microgravity condition such as small asteroids [7]. In order to evaluate the contribution of granular convection to the asteroidal resurfacing, it is necessary to estimate the timescale of asteroidal resurfacing by regolith convection and to compare it with other timescales such as CRE age and/or collisional lifetime.

As a first step to solve this problem, we have proposed a model of convective resurfacing for asteroids, based on the laboratory experiment of granular convection [8]. Although the convective resurfacing is extremely simplified in the model, the model has allowed us to estimate the timescale of asteroidal resurfacing. In this paper, we report a slightly improved version of the model and re-evaluate the resurfacing timescale.

Model: Here, we briefly mention the structure of resurfacing model [8]. We divide the resurfacing process into three phases as follows.

(i) Impact: Impactors intermittently collide with a target asteroid.
(ii) Vibration: The collision results in a global seismic shaking.
(iii) Convection: The global seismic shaking induces the regolith convection on the asteroid.

The entire process from (i) to (iii) is schematically shown in Fig. 1. For more details, see Ref. [8].

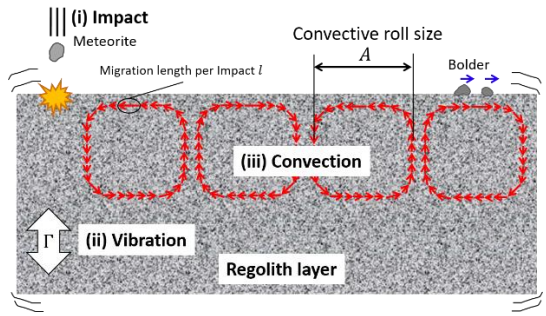

Figure1: A schematic diagram of the asteroidal resurfacing model. Asteroidal resurfacing by regolith convection is intermittently attained by repeating three phases: (i) impact, (ii) vibration, and (iii) convection. Each red arrow's length schematically shows regolith migration length per impact l.

At the impact phase (i), we estimate the frequency of impact events per year N_p by using the mean collision probability P_i ($= 2.9 \times 10^{-24}$ m^{-2}yr^{-1}) and population model of the main belt asteroids (MBAs) [9]. To compute the value of Γ induced by each impact, we utilize the global seismic shaking model [10] at the vibration phase (ii). At the convection phase (iii), we use the scaling of granular convective velocity obtained by the laboratory experiment [11] which enables us to compute the convective velocity v_c from Γ. By integrating v_c, the convective migration length per impact event l can be computed. Moreover, we assume a convective roll of size $A = 100d$, where d is regolith particle diameter ($d = 10$ mm [12]), on the basis of laboratory experiment.

Multiplying l by N_p and integrating the product by D_i, the mean migration length per year can be estimated. Dividing A by the mean migration length per year, we can numerically compute the resurfacing timescale T as a function of asteroid diameter D_a. The above-mentioned process is mathematically expressed as follows,

$$\mathrm{T}(D_\mathrm{a}) = \frac{A}{\sum_{Di=Di,\mathrm{min}}^{Di,\mathrm{max}} l(D_\mathrm{i}, D_\mathrm{a}) N_\mathrm{p}(D_\mathrm{i}, D_\mathrm{a})}. \quad (1)$$

In the summation of Eq. (1), the upper limit $D_\mathrm{i,max}$ and the lower limit $D_\mathrm{i,min}$ are determined by the collisional disruption limit [13] and the minimum migration length limit, respectively. In the previous model, we have assumed that $D_\mathrm{i,min}$ is determined by the minimum migration length per impact event l_min. Specifically, $l_\mathrm{min} = 0.1A$ has been assumed in Ref. [8]. Although we have considered that the well-ordered (reproducible) convective motion should have such a lower limit, this assump-

tion is more or less arbitrary.

Modified point: Therefore, in this paper, we improve this lower limit. In the previous work [8], we assumed that l must be large enough to follow the reproducible convective roll of size A. This means that the minimum limit $l_{\min}$ should be related to A. However, it has been confirmed by the experiments (e.g. [14]) that even extremely small l can follow the reproducible convective roll. Thus, $D_{\mathrm{i,min}}$ is simply re-defined by only using a criterion $\Gamma = 1$ (This criterion roughly corresponds to $l_{\min}\sim 10^{-5}$ m for Itokawa-sized asteroid ($D_{\mathrm{a}} = 400$ m)). $D_{\mathrm{i,min}}$ computed by this criterion and $D_{\mathrm{i,min}}$ used in Ref. [8] are shown in Fig. 2 as a function of D_{a}. The impact events which can generate regolith convection correspond to the hatched area (gray or light red).

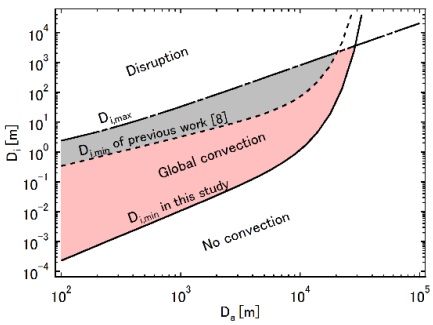

Figure2: Regimes of impact events which can generate the global convection on MBAs (hatched by gray or light red). The chain line shows disruption limit $D_{\mathrm{i,max}}$ [13]. The solid line shows $D_{\mathrm{i,min}}$ used in this study and the dashed line shows $D_{\mathrm{i,min}}$ used in Ref. [8].

Result: The computed $T(D_{\mathrm{a}})$ is shown in Fig. 3. Red circles represent $T(D_{\mathrm{a}})$ computed in this study. In contrast, gray triangles represent $T(D_{\mathrm{a}})$ in the previous work [8]. We also obtain a corresponding approximated scaling form of $T(D_{\mathrm{a}})$ as,

$$T(D_{\mathrm{a}})\sim \frac{A^{0.18} f^{0.09} d^{0.79} G^{0.88} \rho_{\mathrm{a}}{}^{1.81}}{Q\eta^{0.93} v_{\mathrm{i}}{}^{1.85} \rho_{\mathrm{i}}{}^{0.93} P_{\mathrm{i}} C_1} D_{\mathrm{a}}{}^{1.66} \exp\left(\frac{1.9\pi f D_{\mathrm{a}}{}^2}{Q K_{\mathrm{s}} \pi}\right), \quad (2)$$

where C_1 is the coefficient of the approximated cumulative number distribution of the MBAs, G is the gravitational constant (6.7×10^{-11} m^{3}s^{-2}kg^{-1}), and K_{s} is seismic diffusivity (2.5×10^{-5} m^{2}s^{-1}). Eq. (2) is shown as a red solid line in Fig. 3. The computational way to obtain Eq. (2) is basically identical to that used in Ref. [8]. For all computations, we use the following standard parameter values: the seismic quality factor $Q = 2000$, the impact seismic efficiency factor $\eta = 10^{-4}$, the seismic vibration frequency $f = 20$ Hz, the mean impactor density $\rho_{\mathrm{i}} = 2500$ kgm^{-3}, the impactor velocity $v_{\mathrm{i}} = 5.3$ kms^{-1}, and the asteroid density $\rho_{\mathrm{a}} = 1900$ kgm^{-3} [9-10].

Discussion: $T(D_{\mathrm{a}})$ estimated in this study is much smaller than the mean collisional lifetime of MBAs (black squares) [9, 13], particularly in the range of $D_{\mathrm{a}} \lesssim 1.0\times 10^4$ m, as shown in Fig. 3. This means that the convective resurfacing occurs much more frequently than the catastrophic disruption of asteroids. Moreover, the estimated timescale is much shorter than that obtained in Ref. [8]. By allowing small convective migration $l_{\min}$ (as long as $\Gamma \geq 1$ is satisfied), the resurfacing timescale can be very short.

The CRE age (1.5 - 8 Myr [4,5]) is much longer than $T = 960$ yr (for MBAs) and $T = 110$ yr (for NEAs: Near Earth Asteroids) at the Itokawa's scale ($D_{\mathrm{a}} = 400$ m). These relatively short resurfacing timescales cannot directly explain the CRE age of returned sample. The CRE age could represent other resurfacing process such as impact erosion or electric levitation of regolith.

At the large D_{a} regime, the value of $T(D_{\mathrm{a}})$ tend to diverge. This means that the estimate of $T(D_{\mathrm{a}})$ in this regime is not very reliable because the target asteroid is too large to cause *global* seismic shaking [10].

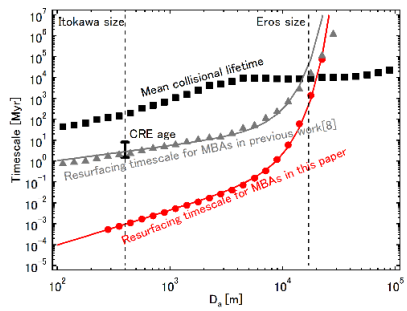

Figure3: Various timescales in the main belt. The red circles show $T(D_{\mathrm{a}})$ obtained in this paper. The gray triangles show $T(D_{\mathrm{a}})$ computed in Ref. [8]. Black squares show the mean collisional lifetime of MBAs [9, 13]. The CRE age of Itokawa's returned samples is indicated by an error bar [4, 5].

References: [1] E. Asphaug et al. (2001) *LPSC XXXII*, Abstract, # 1708. [2] H. Miyamoto et al. (2007) *Science* **316**, 1011-1014. [3] K. Nagao et al. (2011) *Science* **333**, 1128-1131. [4] M. M. M. Meier et al. (2014) *LPSC XLV*, *Abstract*, #1247. [5] A. Garcimartín et al. (2002) *Phys. Rev. E* **65**, 031303. [6] J. B. Knight et al. (1993) *Phys. Rev. Lett.* **70** 3728-3731. [7] C. Güttler et al. (2013) *Phys. Rev. E* **87**, 044201. [8] T. M. Yamada et al. (2016) Icarus **272**, 165-177 [9] D. P. O'Brien and R. Greenberg (2005) *Icarus* **178**, 179-212. [10] J. E. Richardson Jr. et al. (2005) *Icarus* **179**, 325-349. [11] T. M. Yamada and H. Katsuragi (2014) *Planet. Space. Sci.* **100**, 79-86. [12] A. Fujiwara et al. (2006) *Science* **312** 1330-1334. [13] M. Jutzi et al., (2010) *Icarus* **207**, 54-65. [14] P. Philippe and D. Bideau (2003) *Phys. Rev. Lett.* **91**, 104302.