A Modified Asteroids Resurfacing Model Induced by Regolith Convection

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Abstract

Regolith convection generated by impact-induced global seismic shaking could cause resurfacing process on asteroids. Because it has not been clear whether the regolith convection can resurface asteroids within their lifetimes even under microgravity condition, a model for the asteroid resurfacing resulting from regolith convection is built to estimate its timescale, in this study. In our previous paper (*Yamada et al., Icarus **272** pp. 165 - 177, 2016*), we have developed a simple model of the asteroid resurfacing. Here, we report a slightly improved version of the model and re-evaluate the resurfacing timescale. The re-estimated resurfacing timescale T as a function of various sized-target asteroid D_a is much smaller than mean collisional lifetime for both the main belt asteroids and near earth asteroids in the range of $D_a < 10$ km. This means that the convective resurfacing occurs much more frequently than the catastrophic disruption of asteroids. Moreover, the re-estimated timescale is much shorter than that estimated by our previous study. By allowing small convective migration, $T(D_a)$ can be very short.

1. Introduction

Hayabusa's observation

Surface fluidization [1, 2]

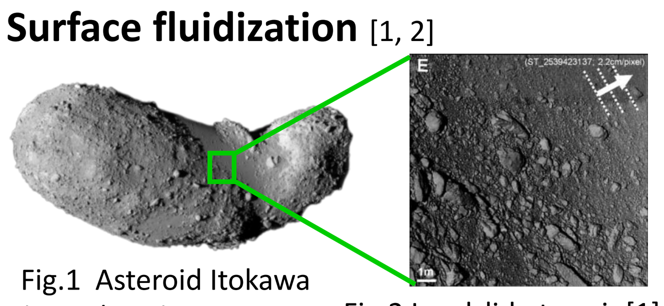
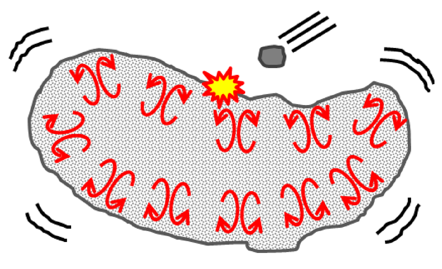


Fig.1 Asteroid Itokawa (JAXA/ISAS)
Fig.2 Landslide terrain[1]
Very vague craters on the surface of Itokawa[2]

Relatively young surface [3, 4]

Cosmic-ray exposure (CRE) age : 1.5 Myr ~ 8 Myr (Sample returned from Itokawa)

Regolith Convection



Regolith migrates as a part of convective motion due to the impact induced global seismic shaking [1].

Granular Convection

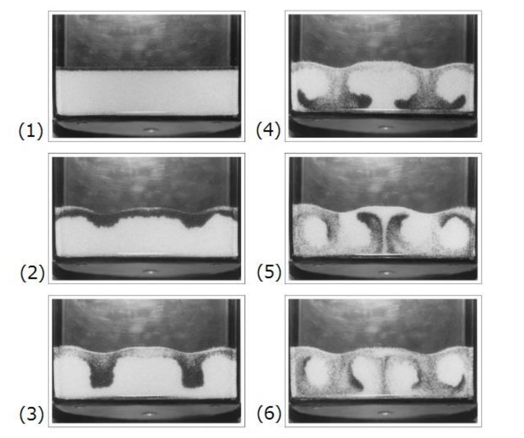


Fig. 3 Convective motion observed in a vertically vibrated glass beads bed on the ground experiment [5]

Onset criterion: $\Gamma = \frac{a_{max}}{g} > 1$

a_{max}: Maximum shaking acceleration [m/s²]
g: Gravitational acceleration

In general, the surface on the small asteroids is an extreme microgravity condition (Itokawa: $g \sim 10^{-4}$ m/s²).

If we assume that granular convection is generated on the surface of asteroid, convective velocity would become very small under microgravity condition. Can the regolith convection really resurface the **various-sized asteroids** covered with regolith within their lifetimes?

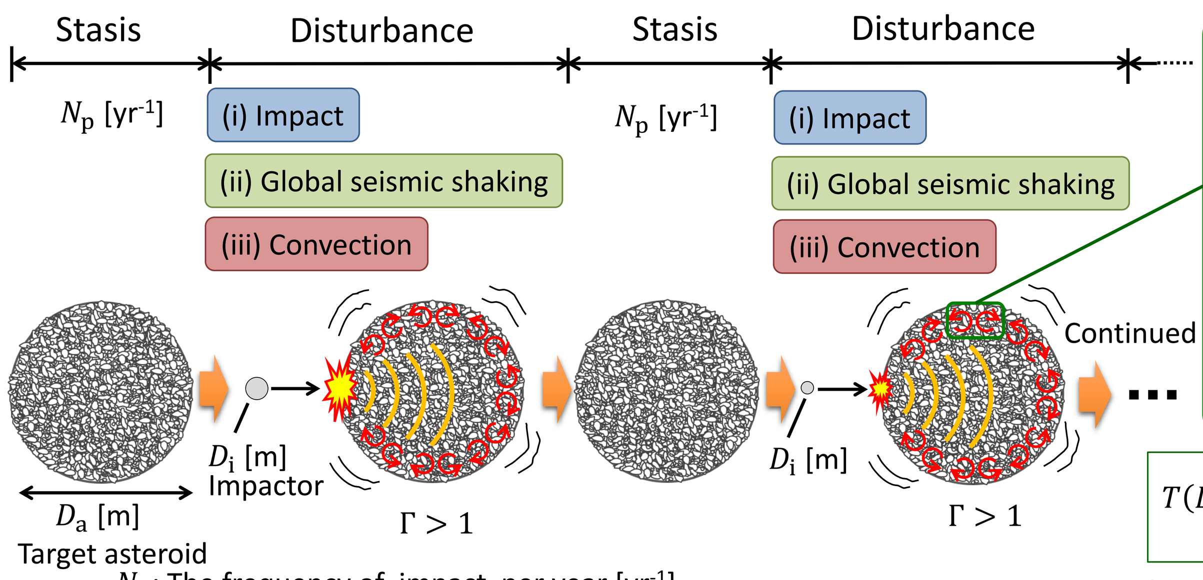
Purpose

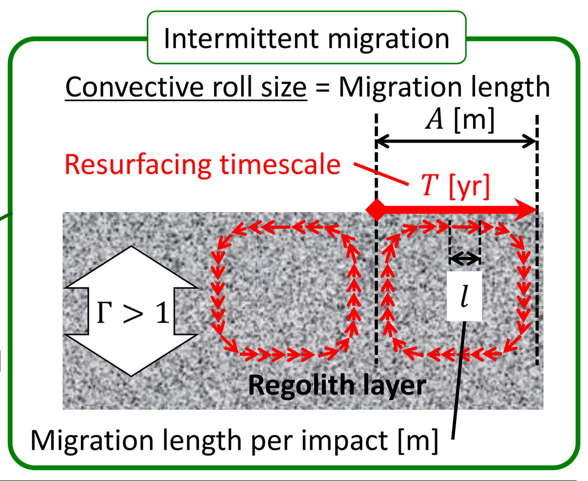
① Developing the model of asteroidal resurfacing process induced by the granular convection mainly using the experimental scaling

② Evaluating the possibility of resurfacing process by comparing the asteroidal resurfacing timescale with other timescales such as the mean collisional lifetime or CRE age

2. Model

Intermittent and repetitive migration by regolith convection results in the asteroidal resurfacing.





N_p: The frequency of impact per year [yr⁻¹]
Γ: Maximum dimensionless shaking acceleration

$$T(D_a) = \frac{A}{\int_{D_{imin}}^{D_{imax}} l(D_i, D_a) N_p(D_i, D_a)\, dD_i} \cdots (1)$$

A is assumed as $100d$ based on the experimental observation of splitting convective roll [5].

(i) Impact

$\langle P_i \rangle$: Mean collisional probability per cross section per year [6]

$\langle P_i \rangle$ for Main Belt Asteroids (MBAs): 2.86×10^{-24} [m⁻² yr⁻¹]

$\langle P_i \rangle$ for Near Earth Asteroids (NEAs): 15.3×10^{-24} [m⁻² yr⁻¹]

$$N_p(D_i, D_a) = \langle P_i \rangle \times \underbrace{N_i(D_i)}_{\text{Population}} \times \underbrace{\left(\frac{D_a}{2} + \frac{D_i}{2}\right)^2}_{\text{Cross section}} \cdots\cdots (2)$$

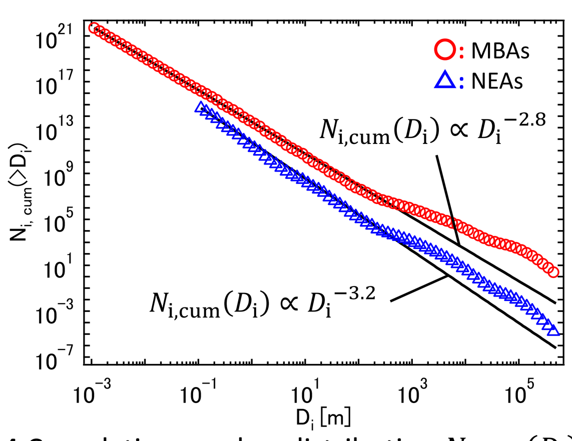
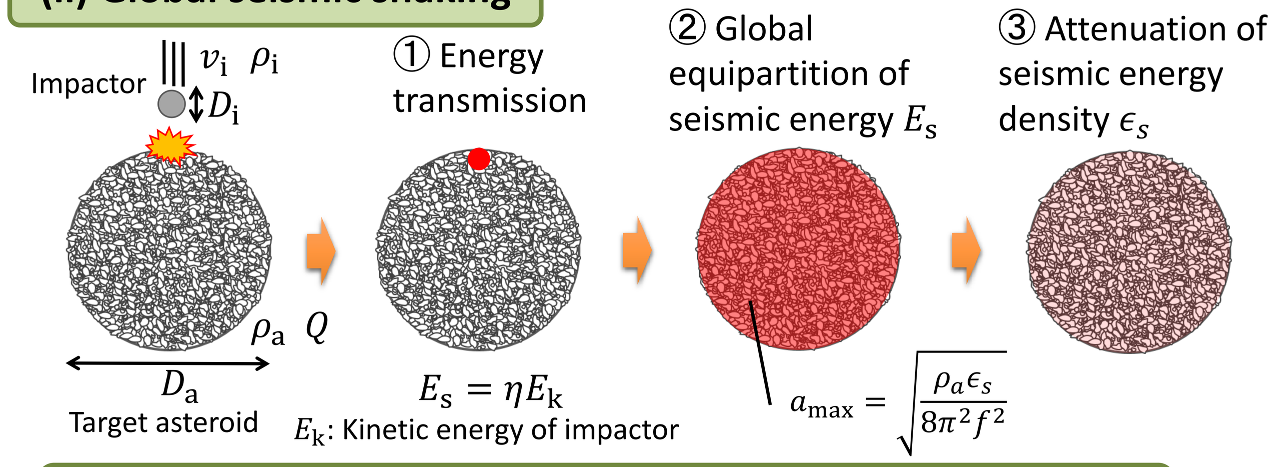


Fig. 4 Cumulative number distribution $N_{i,cum}(D_i)$[6]

(ii) Global seismic shaking



η : Seismic efficiency
Q : Seismic quality factor
f : Seismic frequency [Hz]
v_i: Impact velocity [m s⁻¹]
G: Gravitational constant [kg⁻¹m³s⁻²]
ρ_i: Impactor density [kg m⁻³]
ρ_a: Target density [kg m⁻³]
t : Time [s]
ϵ_s: Shaking energy density [J/m³]

$$\epsilon_s = \frac{(Shaking\ energy)}{(Asteroid\ volume)}$$

$$\Gamma(t, D_i, D_a) = \frac{a_{max}(D_i, D_a)}{g(D_a)} \cdot \exp\left(-\frac{\pi f}{Q} t\right) = \frac{3 f v_i}{G} \sqrt{\eta \frac{\rho_i D_i^3}{\rho_a^3 D_a^5}} \cdot \exp\left(-\frac{\pi f}{Q} t\right) \cdots\cdots (3)$$ [1, 7]

(iii) Convection

Granular convective velocity v_c can be scaled by the product of power laws among gravitational velocity, vibrational velocity, and dimensionless convective roll size (system size) [8].

$$v_c(\Gamma(t, D_i, D_a)) = C_0 \left(\sqrt{gd}\right)^{1-2\alpha} \left(\frac{\Gamma(t, D_i, D_a) g}{2\pi f}\right)^{2\alpha} \left(\frac{A}{d}\right)^{\beta} \cdots\cdots (4)$$

Eq. (3) is obtained by laboratory experiment using spherical glass beads. The values, $C_0 = 3.6 \times 10^{-3}$, $\alpha = 0.47$ and $\beta = 0.82$, are also determined from the analysis of convective velocity data [8]. Using Eqs. (3) and (4), the velocity of regolith convection can be estimated.

We assume that regolith migrates during global seismic shaking of $\Gamma > 1$. The global seismic shaking starts at $t = t_{diff}$ (the diffusion timescale of ϵ_s to whole asteroid) and ends at $t = t_{atten}$ (the time when Γ decays to be 1). By integrating Eq. (3) from t_{diff} to t_{atten}, l can be estimated.

$$l(D_i, D_a) = \int_{t_{diff}}^{t_{atten}} v_c\left(\Gamma(t, D_i, D_a)\right) dt \cdots\cdots (5)$$

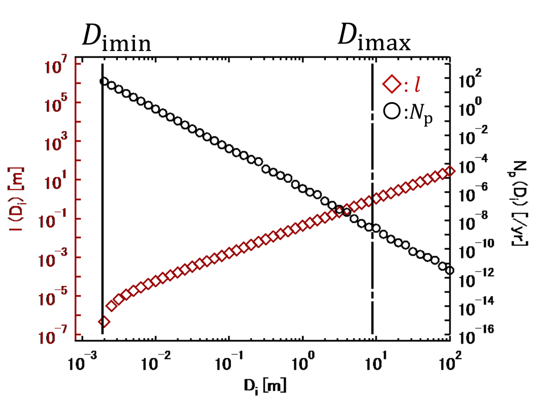


Fig. 5 $l(D_i)$ and $N_p(D_i)$ for Itokawa-sized asteroid (D_a = 400 m).

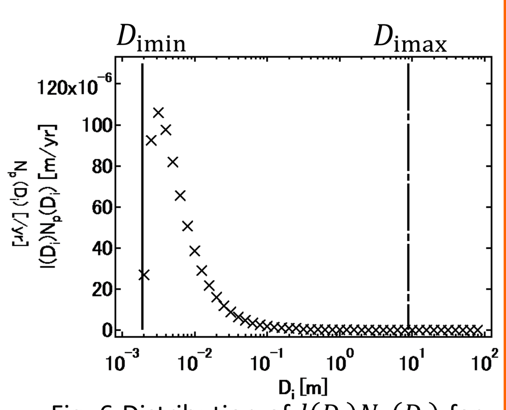


Fig. 6 Distribution of $l(D_i)N_p(D_i)$ for Itokawa-sized asteroid (D_a = 400 m).

3. Modified Points

D_{imax} and D_{imin}

The upper limit D_{imax} and the lower limit D_{imin} for Eq. (1) are determined by the collisional disruption limit [9] and the minimum migration length limit, respectively.

Previous model [10]

It has been assumed that D_{imin} is determined by the minimum migration length per impact event l_{min}. Specifically, $l_{min} = 0.1A$ has been assumed in Ref. [10]. Although we have considered that the well-ordered (reproducible) convective motion should have such a lower limit, this assumption is more or less arbitrary.

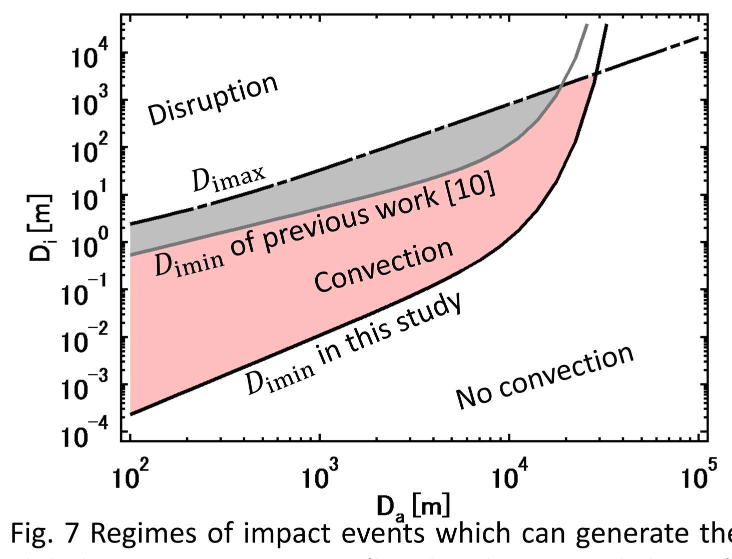


Fig. 7 Regimes of impact events which can generate the global convection on MBAs (hatched by gray or light red).

Modified model

Recently, it has been confirmed by the experiments (e.g. [11]) that even extremely small l can follow the reproducible convective roll. Thus, D_{imin} 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_a = 400 m)). D_{imin} computed by this criterion and D_{imin} used in Ref. [10] are shown in Fig. 7 as a function of D_a. The impact events which can generate regolith convection correspond to the hatched area (gray or light red).

3. Results and Analysis

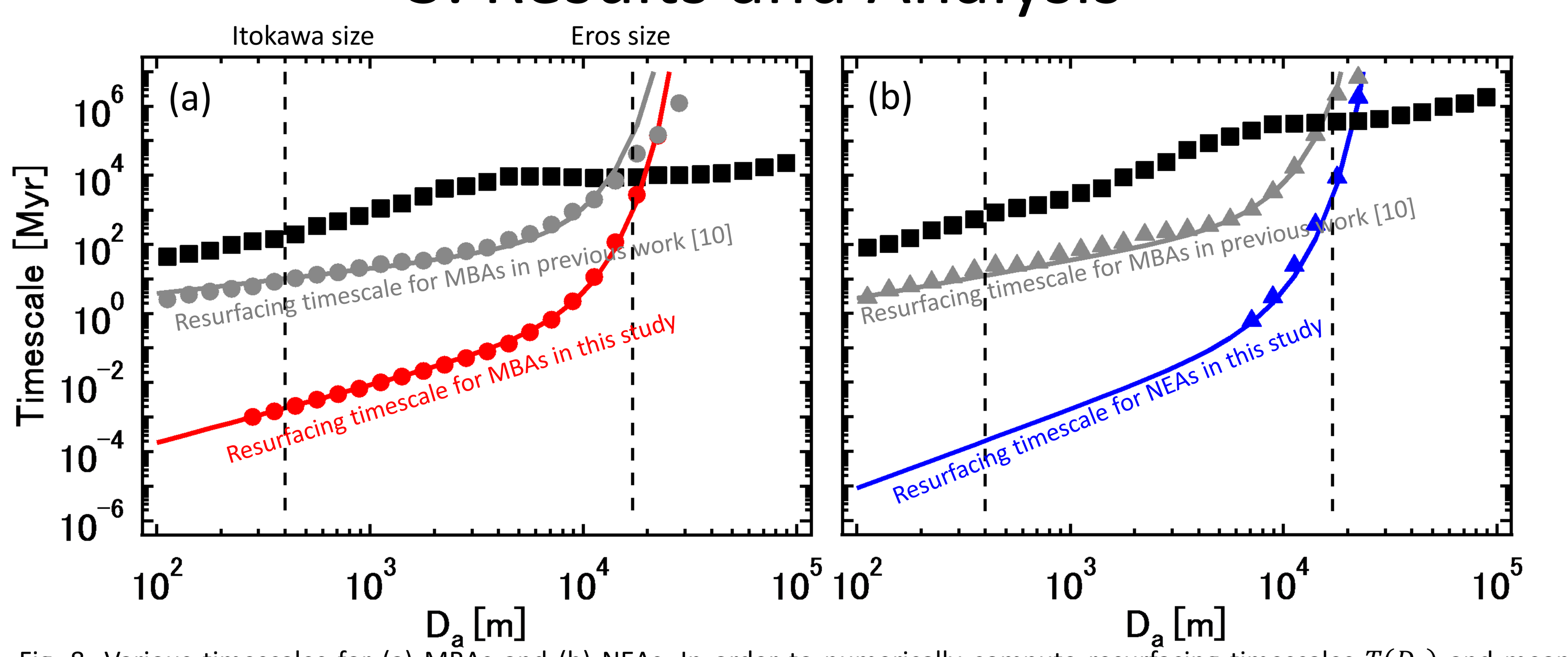


Fig. 8 Various timescales for (a) MBAs and (b) NEAs. In order to numerically compute resurfacing timescales $T(D_a)$ and mean collisional lifetime, standard parameters shown in Table 1 are used. Red and blue solid line represents analytical $T(D_a)$, Eq.(6) for MBAs and Eq.(7) for NEAs, respectively.

$$T(D_a) \approx \frac{C_* G^{0.88} A^{0.18} f^{0.09} d^{0.79} \rho_a^{1.81}}{Q \eta^{0.93} v_i^{1.85} \rho_i^{0.93} P_i C_N} D_a^{1.63} \exp\left(\frac{1.9\pi f}{Q} t_{diff}\right) \cdots (6)$$

$$T(D_a) \approx \frac{C_* G^{1.13} A^{0.18} d^{0.79} \rho_a^{2.15}}{Q \eta^{1.05} v_i^{2.18} \rho_i^{1.05} f^{0.16} P_i C_N} D_a^{2.28} \exp\left(\frac{2.1\pi f}{Q} t_{diff}\right) \cdots (7)$$

Table 1 Parameter values [1, 6, 7].

Q	η	f [Hz]	v_i [km s⁻¹]	ρ_i [kg m⁻³]	ρ_a [kg m⁻³]	A/d
2000	10^{-4}	10	5.3 (MBAs), 15 (NEAs)	2500	1900	100

4. Discussion

Parameter values have uncertainties resulting from asteroidal internal structure and/or surface conditions (Table 2).

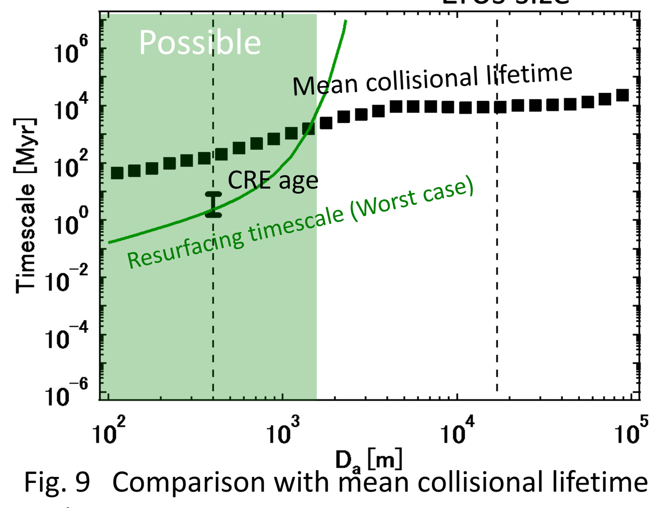


Fig. 9 Comparison with mean collisional lifetime and CRE age.

Table 2 Parameter uncertainties [2, 7].

	Standard case	Worst case
Q	2000	200
f	20 Hz	200 Hz
η	10^{-4}	10^{-6}

The largest energy dissipation
The lowest seismic efficiency

The most difficult conditions to generate regolith convection.

Comparing with mean collisional life time

Even in the worst parameter values case, there are asteroids ($D_a \lesssim 1.0 \times 10^3$ m) in which resurfacing timescale is smaller than mean collision lifetime. This means that convective resurfacing can occur within their lifetimes under microgravity such as small asteroids.

Comparing with CRE age

Resurfacing timescale represents migrating time of regolith grains for horizontal migration while CRE age represents staying time of sample grains on the surface. Therefore, if the relatively large convective roll is assumed, the resurfacing timescale should fall within the range between the CRE age and the mean collisional lifetime of Itokawa. When the parameter values are $Q \approx 200$, $f \approx 200$ Hz and $\eta \approx 10^{-6}$, the resurfacing timescale of Itokawa-sized asteroid is consistent with CRE age of returned sample from Itokawa.

5. Verification

Table 3 Asteroid impact missions and their expected value of l.

Mission	HAYABUSA2	AIDA
Target asteroid	Ryugu	Satellite of Didymos
Impactor mass	2 kg	300 kg
Impactor velocity	2 km/s	6.3 km/s
Energy	4.0×10^6 J	5.9×10^9 J
l	4.0 μm	12 cm

In the future asteroid impact missions, HAYABUSA2 and AIDA, convective regolith migration could be verified. If target asteroids for these missions (see Table 3) are covered with regolith, we can predict the value of l in this study. According to the model, l = 12 cm for AIDA mission is probably large enough to be observed, while l = 4.0 μm for HAYABUSA2 mission is too small to be observed.

6. Conclusions

- The model of asteroidal resurfacing process induced by regolith convection [10] is slightly modified
- By allowing small convective migration l_{min} (as long as $\Gamma \geq 1$ is satisfied), $T(D_a)$ can be very short.
- Regolith convection is a possible mechanism to resurface asteroids of $D_a \lesssim 1.0 \times 10^3$ m within their lifetimes.

Reference: [1] H. Miyamoto *et al.* Science **316**, 1011 (2007); [2] N. Hirata *et al.*, Icarus **200**, 486-502 (2009); [3] K.Nagao et al. Science **333**, 1128 (2010); [4] M. M. M. Meier *et.al.*, LPSC abstract 1247 (2014); [5] K. M. Aoki *et al.*, Phys. Rev. E **54**, 874 (1996); [6] D. P. O'Brien and R. Greenberg, Icarus **178** 179-212 (2005); [7] J. E. Richardson Jr. *et al.*, Icarus **179**, 325-349 (2005); [8] T. M. Yamada and H. Katsuragi, Planetary and Science Science **100**, 7986 (2014); [9] M. Jutzi et al., Icarus **207**, 54-65 (2010); [10] T. M. Yamada et al., Icarus **272**, 165–177 (2016); [11] P. Philippe and D. Bideau (2003) *Phys. Rev. Lett.* **91**, 104302.