Experimental study on the collisional disruption of core-mantle targets: implications for the impact fragmentation of rocky planetesimals

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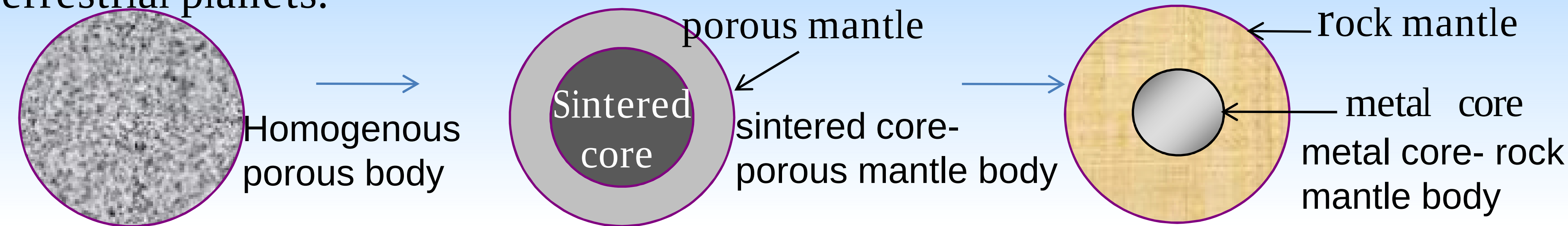
➢Collisional growth of planetesimals in the solar nebula

The collisional process in the Solar System is important to clarify the evolution of planetary system. Protoplanets were formed by collisional disruption and re-accumulation of small planetesimals in the solar nebula. Impact experiments and numerical simulations regarding the collisional disruption have been performed as for homogeneous targets such as simple rock or porous synthetic matter.

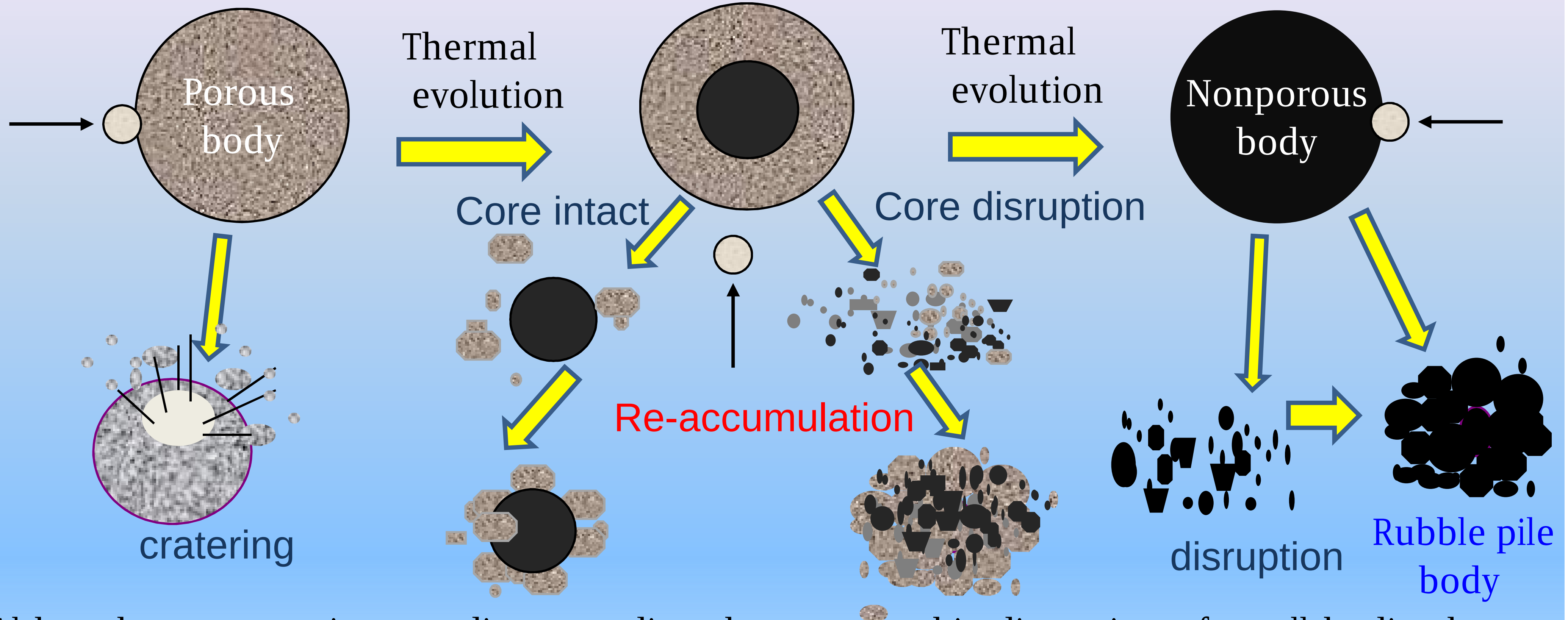
➢ Thermal evolution of planetesimals

There could be many core-mantle bodies in planetary accretion process as a consequence of thermal evolution. In the initial stage, small silicate bodies with a sintered core-porous mantle structure were formed as a consequence of pressure sintering. A differentiated body could be formed as a result of internal thermal evolution by potential heat sources such as ^{26}Al, and the thermal evolution may establish a layered structure with a metallic core and rock mantle similar to terrestrial planets.



Disruption and reaccumulation of core-mantle body

Here, we notice core-mantle bodies with sintered cores covered with porous mantle in order to study the collisional disruption process of thermally evolved rocky planetesimals.



Although many previous studies regarding the catastrophic disruption of small bodies have been performed for porous and nonporous bodies with a homogeneous internal structure, the layered structures may be very common in small rocky bodies as a result of internal thermal evolution. The collisional disruption of core-mantle bodies may cause the diversity of collisional outcomes such as core disruption or core intact. Furthermore, rubble pile bodies with various internal structures may be formed by re-accumulation of disrupted fragments in both cases of core intact and disruption. Thus, we need to consider not only homogenous bodies but also core-mantle bodies in order to the study the collisional disruption process of rocky planetesimals.

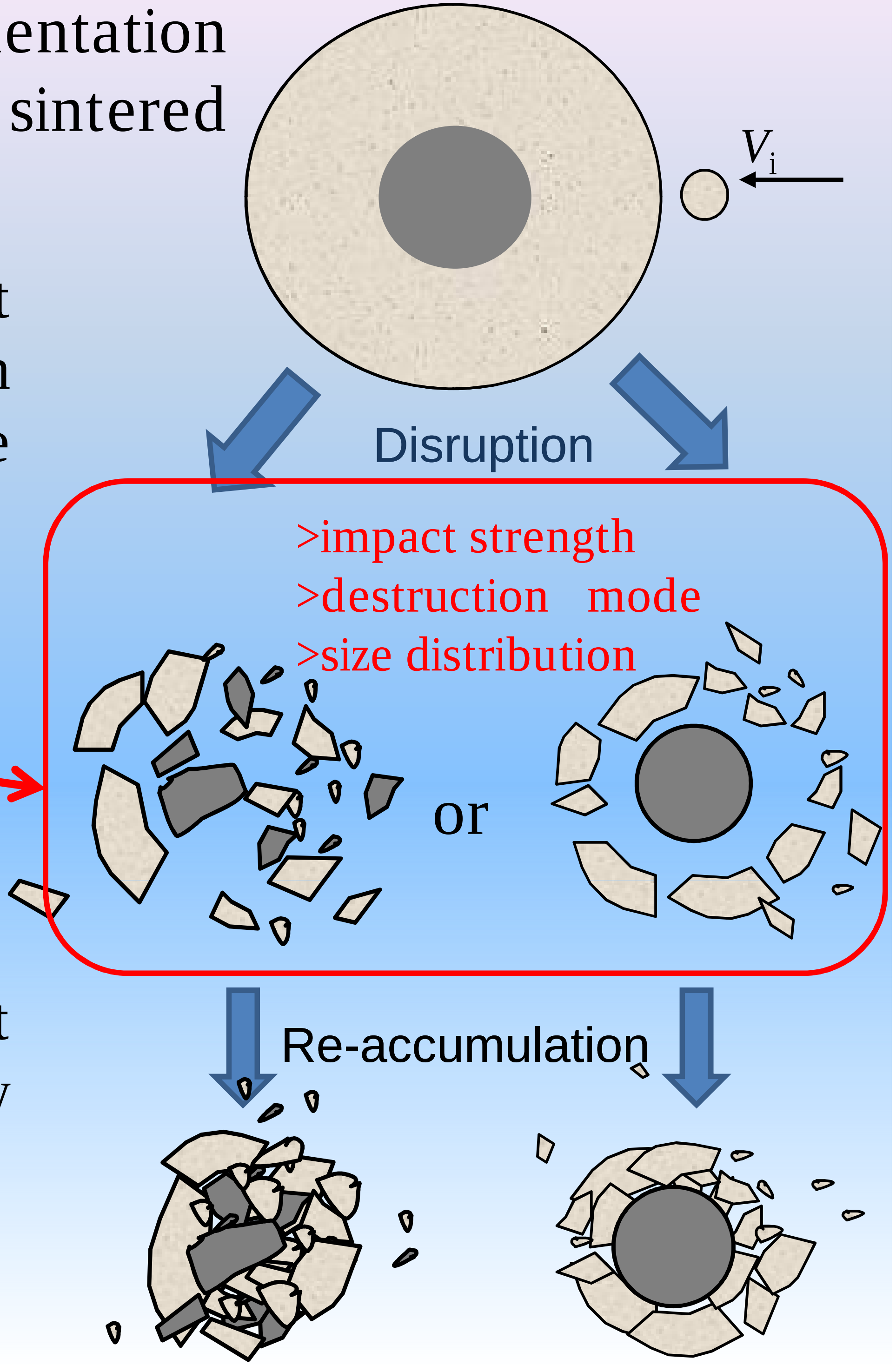
Purpose of this study

Therefore, we clarify the impact fragmentation of thermally evolved bodies with sintered rock core-porous rock mantle.

⇒In this study, we performed impact experiments using core-mantle targets with different core/target size ratios to simulate the various degrees of internal evolution.

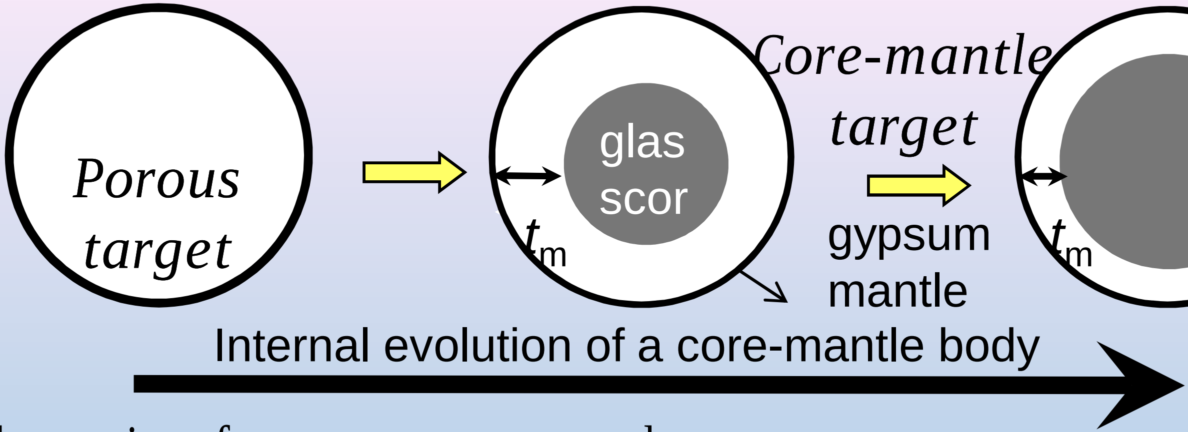
>We investigated the impact strength, destruction mode and size distribution of impact fragments as a result of the collision.

>As a result, we clarified that the impact fragmentation strongly depends on energy partition coefficient into mantle and core.



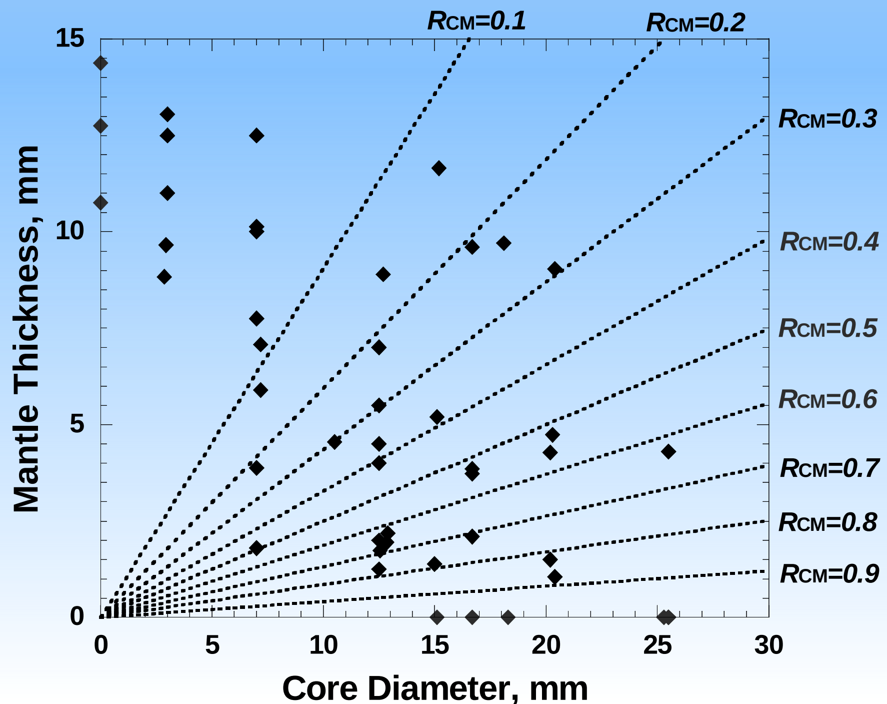
Next, we explain the sample preparation.

Sample preparation



Density	Porosity
Gypsum mantle	
$1.1 g/cm^3$	~55%
Glass core	
$2.5 g/cm^3$	~0%

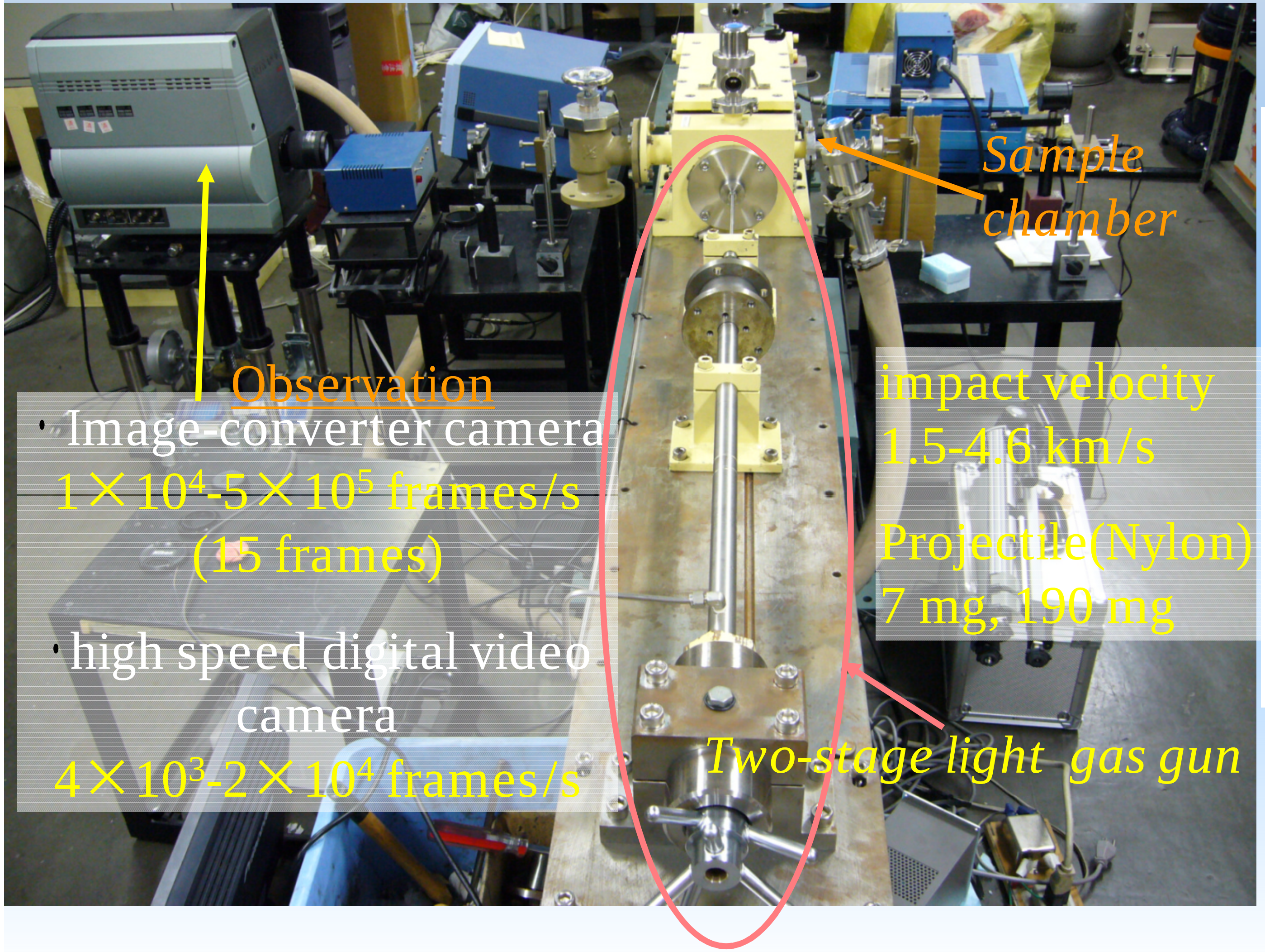
The ratio of core mass to total target mass (Core Mass Ratio, R_{CM}) is an important parameter characterizing the internal structure. We changed the R_{CM} from 0 to 1 by varying core diameter (0-26 mm) and mantle thickness (0-15 mm) systematically.



We prepared spherical samples with a dense core-porous mantle structure as shown in the upper left, and we changed the core and mantle sizes (see the left figure) to simulate internal evolution of core-mantle bodies. Soda-lime glass (or crystalline quartz) and porous gypsum were used as the core and mantle, respectively. Porous gypsum is frequently utilized as an analogue of low-density bodies such as small asteroids and satellites in impact experiments (e.g., Nakamura et al., 1992; Kawakami et al., 1990). We used soda-lime glass and crystalline quartz to simulate the sintered core because they are typical silicate representing homogenous material without porosity.

Impact experiment

We performed impact experiments on both core-mantle and homogenous samples by using a two-stage light gas gun set at Nagoya University. We used two sizes of nylon projectiles with the same density of 1100 kg/m^3. They have a cylindrical shape with masses of 7 mg and 190 mg. A head-on collision was caused between the projectile and the spherical target for all runs. The impact velocities (V_i) ranged from 1 to 5 km/s. The target was suspended by threads in a target chamber.



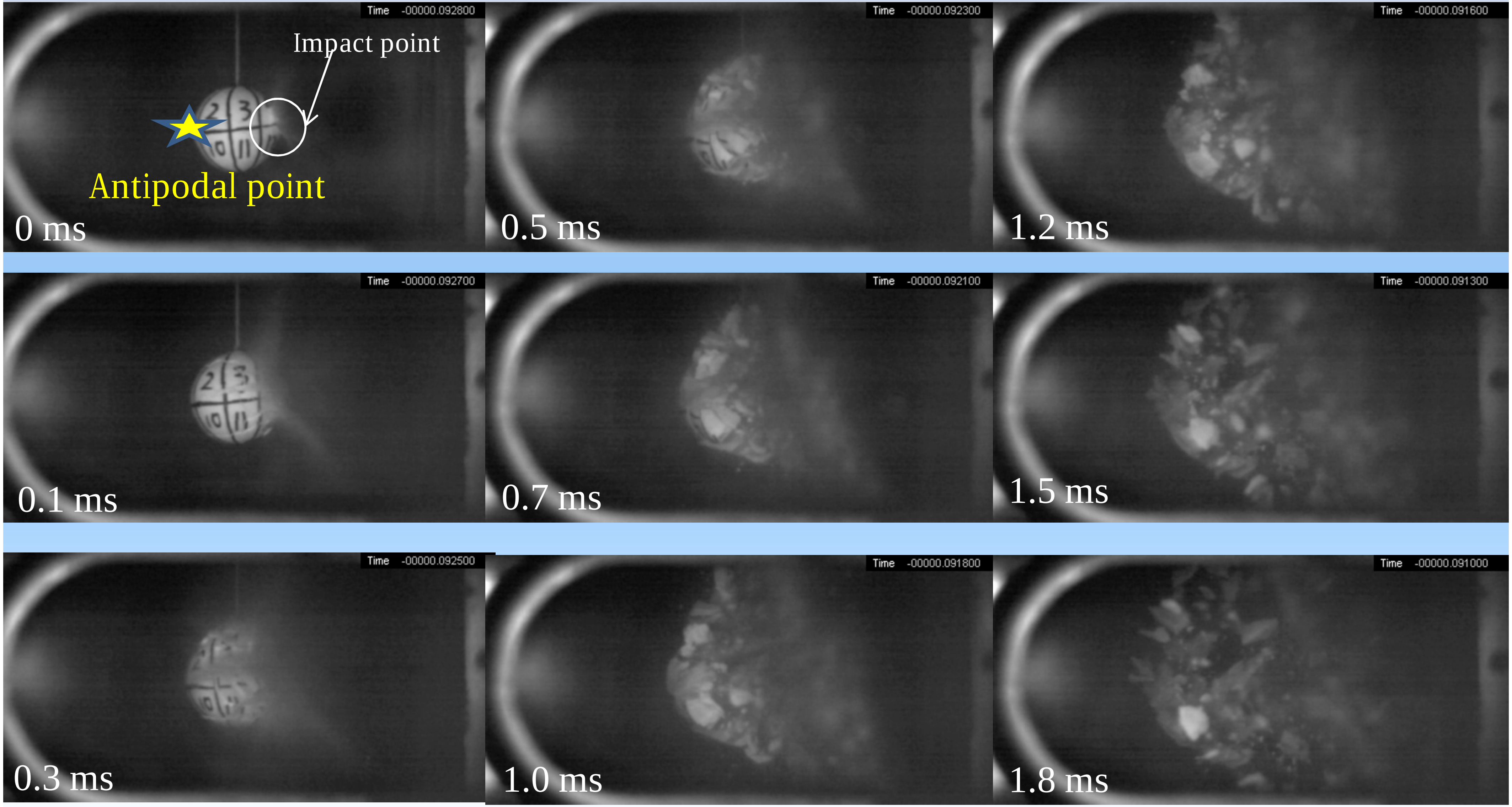
The collisional disruption was observed by using an image-converter camera to take successive images of 15 frames up to 5×10^5 frames per second with an exposure time of 50ns or a high-speed digital video camera at 4×10^3-2×10^4 frames per second with the shutter speed of 1μs.

High-Speed Photography

high speed digital video camera

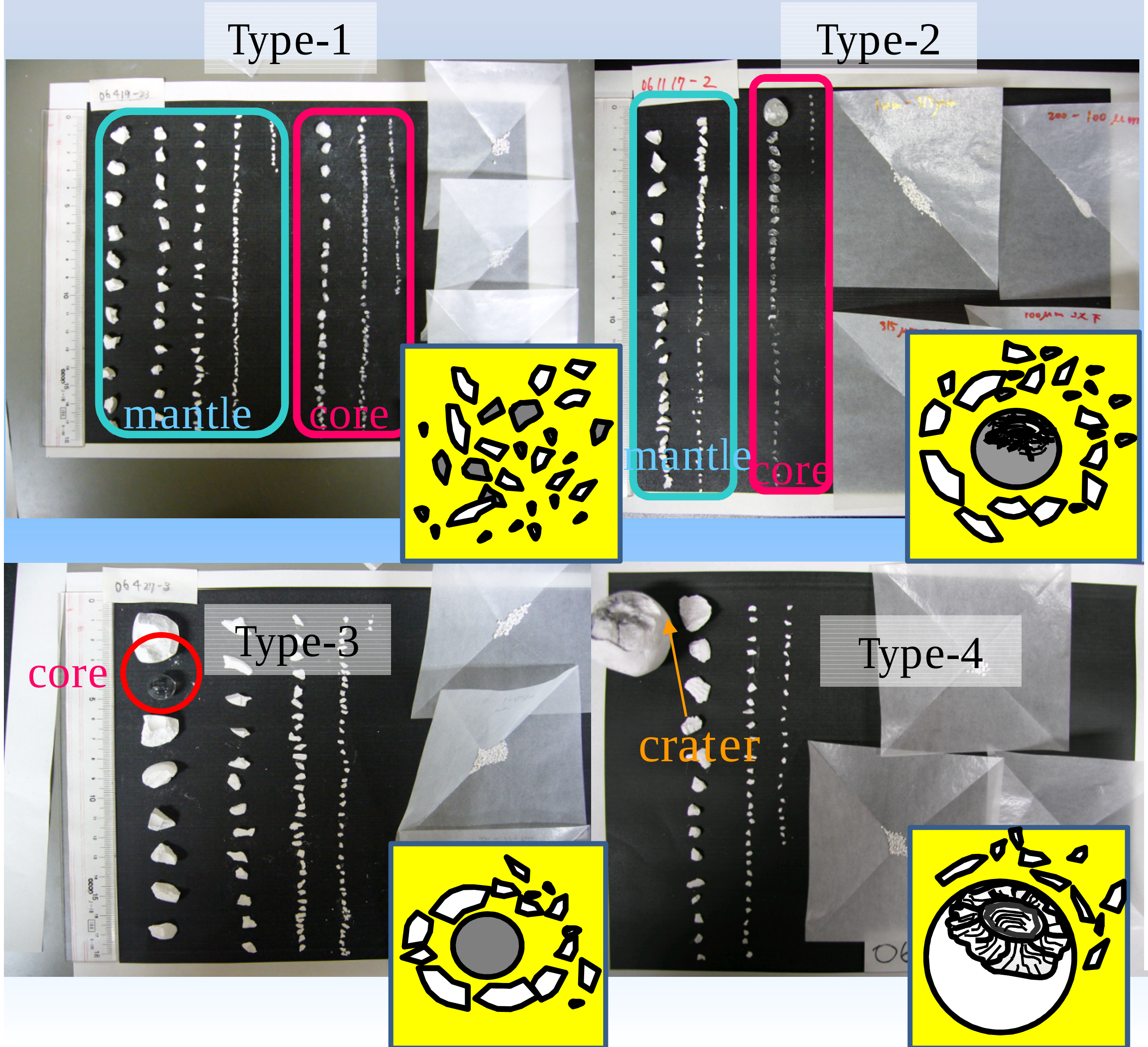
Q_t= 7300 J/kg

These pictures show the process of collisional disruption. We observed the process using a high-speed digital video camera by lighting from the forward of the target using two metal-halide lamps. We can observe the behavior of fragments at various positions from an impact point.



Destruction mode of core-mantle target

The figures show photographs of recovered targets. Recovered targets were categorized into four types of destruction modes according to the degree of mantle and core disruption.



Type 1 shows both core and mantle were completely disrupted so that the maximum fragment of the core was less than half of the initial core mass.

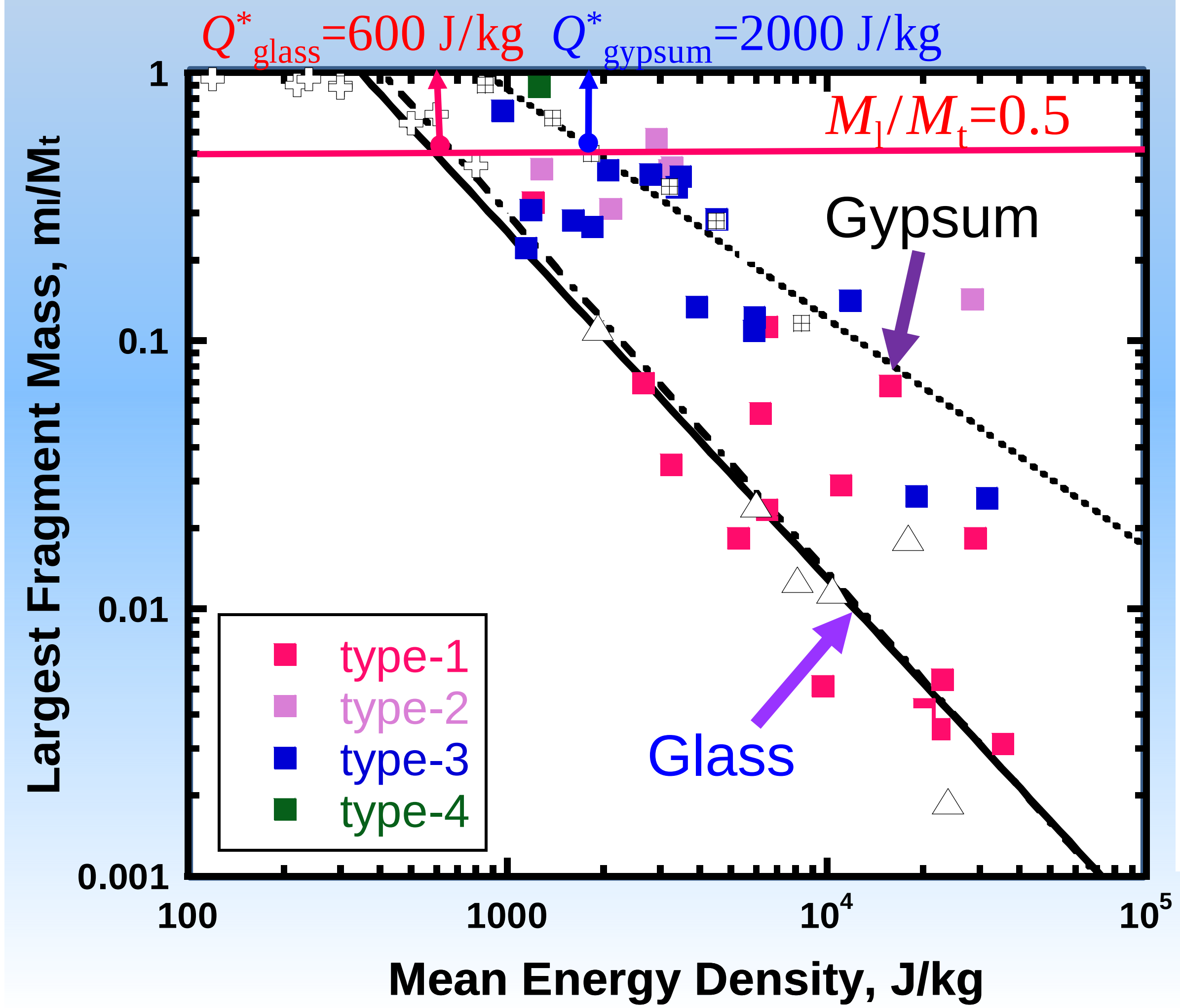
Type 2 shows the recovered fragments showing a large core remnant, but the mantle is completely disrupted. The mass of the largest core fragment is larger than half of the initial core mass.

Type 3 shows an intact core and broken mantle. The mantle was completely disrupted, and the largest fragment mass of the mantle was less than half of the initial mantle mass.

Type 4 shows a recovered target with a crater on the mantle. There was an intact core inside of this target.

Impact strength of core mantle target

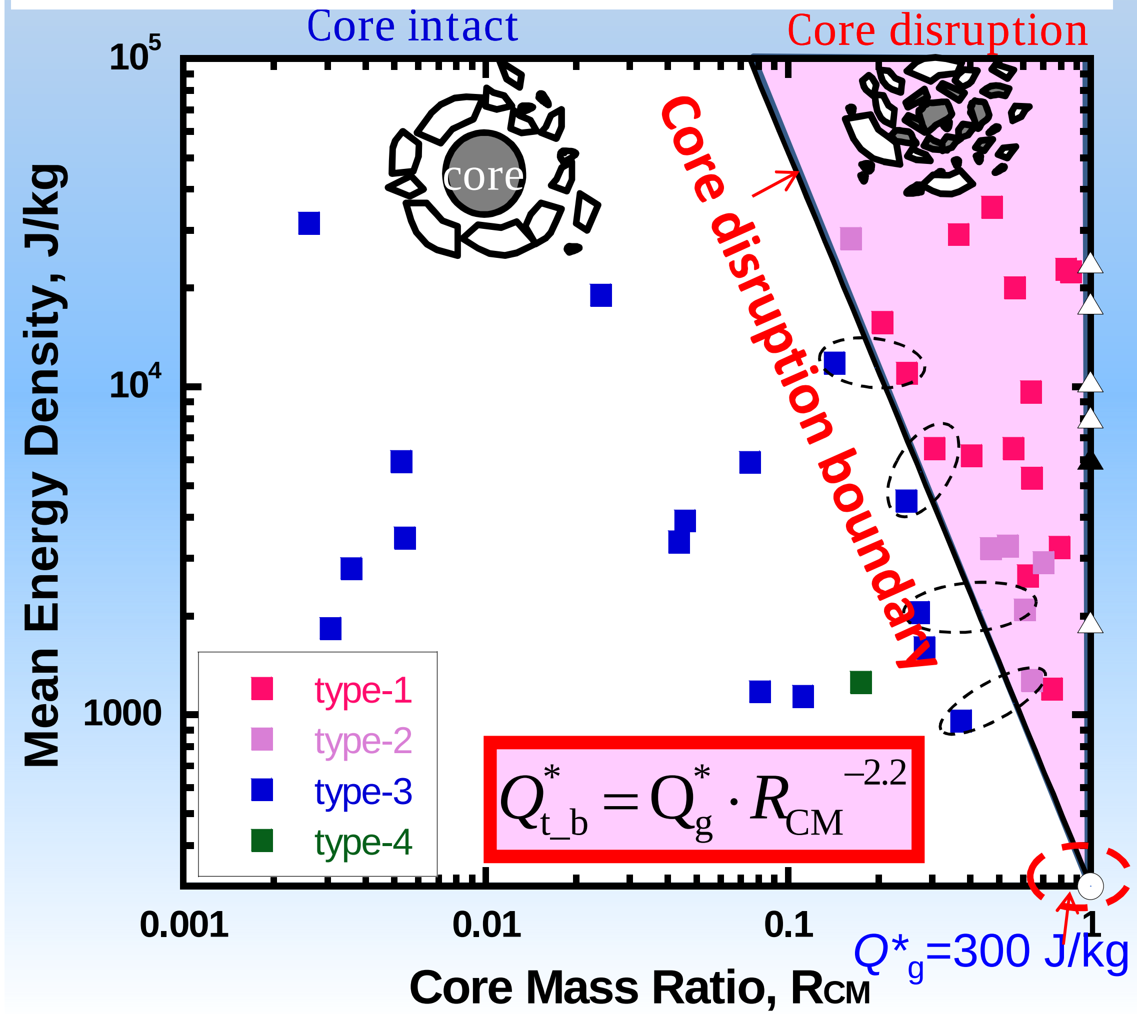
The largest fragment mass normalized by the original target mass (m_l/M_t) is a useful parameter to denote the degree of impact disruption. Previous authors showed that in the case of homogenous targets such as basalt and glass, the m_l/M_t simply decreases with the increase of the mean energy density.



In our experiment, we examined the m_l/M_t of the homogenous gypsum and glass targets to determine the impact strength of gypsum mantle and glass core. Impact strength is defined as the mean energy density needed to catastrophically disrupt a target. From the results, the impact strength of gypsum and glass are about 2000 J/kg and 600 J/kg. The largest fragment masses of core-mantle targets in the wide range of mean energy density (1 x 10^3-4 x 10^4 J/kg) were spread between those of gypsum and glass targets. It is expected that the core-mantle targets have impact strengths between those of glass and gypsum. We can recognize that m_l/M_t of type 1 are similar to those of glass targets, while type 3 are similar to gypsum.

Mean Energy Density (Q_t) vs. *Core Mass Ratio* (R_{CM})

The figure shows the relationship between mean energy density and core mass ratio. We define the specific energy of the whole target as the mean energy density. The destruction mode of core-mantle targets (type 1,2,3,4) was revealed to depend not only on the mean energy density, but also on the core mass ratio.

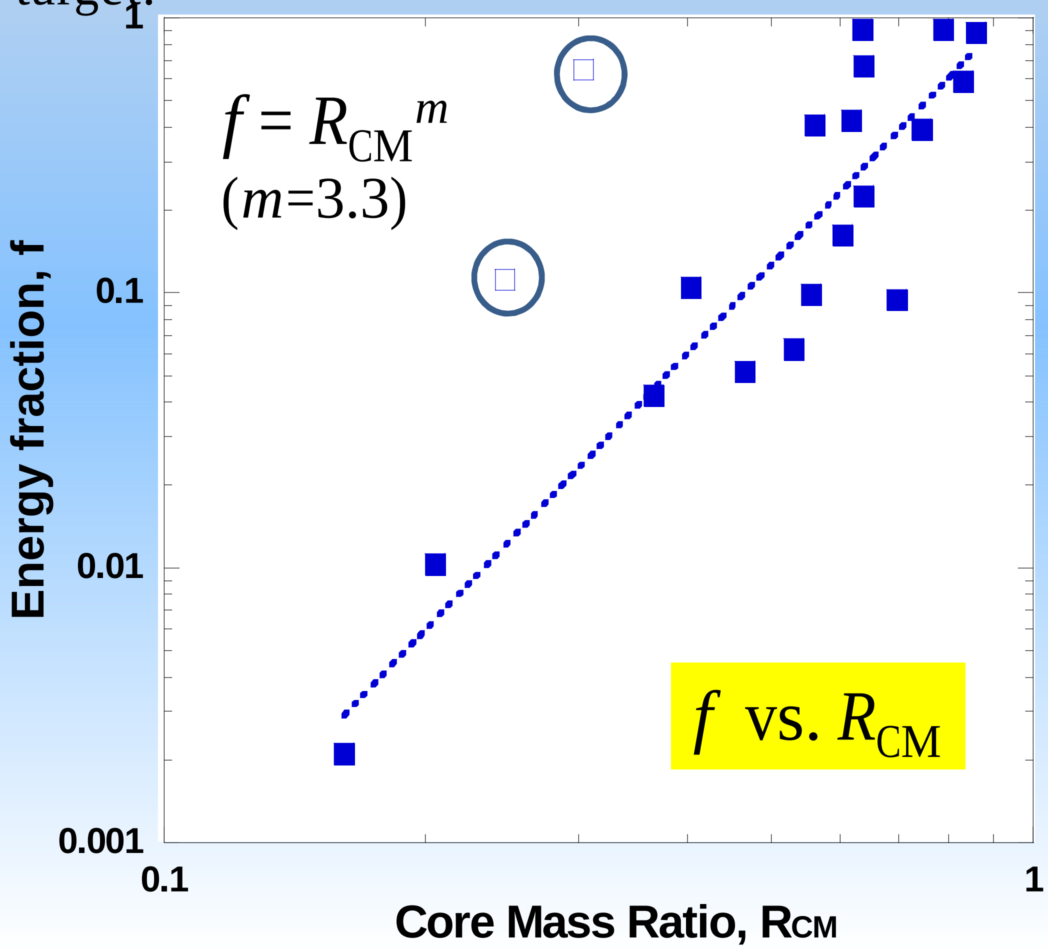


At a constant mean energy density, the destruction mode changed from types 3 and 4 to types 1 and 2 with the increase of R_{CM}. The mean energy density required for the onset of the disruption of a glass target (Q_g^*) was derived to be ~300 J/kg. In contrast, the mean energy density needed to disrupt the core corresponding to the type 1 and 2 modes was larger than 300 J/kg. If we suppose that the effective specific energy achieved in the core at the critical mean energy density required to disrupt the core is the same as Q_g^*, we can expect that the mean energy density of the core-mantle target in the case of the core disruption could be explained by the absorption of the impact energy in the porous mantle.

We can separate the results for the types 1 and 2 from the types 3 and 4. The boundary dividing these modes can be described by the empirical equation in the figure where $Q_{t\_b}^*$ is the mean energy density required to disrupt the glass core, and *n* is found to be -2.2.

Energy partition coefficient (f)

The glass core in a core-mantle target was not damaged at a mean energy density corresponding to the impact strength of bare glass. This means that the effective energy density applied to the glass core was rather smaller than the mean energy density. So, it is important to estimate the impact energy partitioned into the core in order to consider the impact disruption of a core-mantle target.



The energy fraction (f) consumed by the disruption of the glass core is defined by $f=E_c/E_t$, where E_c is the kinetic energy divided into the core and E_t is the initial kinetic energy of the projectile. From the degree of core disruption, we can obtain the specific energy of the core in core-mantle target. Using the values, we clarified that the f varies from below 10^{-3} to close to 1 with R_{CM}. The energy partitioned into the core simply increases with R_{CM}.

The data look quite scattered, but we notice that two data points which are surrounded by circles are the major origins of the scattering because they correspond to the data closest to the boundary between core-disruption and core-intact. Thus, we obtained the empirical equation, $f=R_{CM}^{3.3}$, by fitting the data using the power law relationship, except for the two data points .

Estimation of core disruption boundary

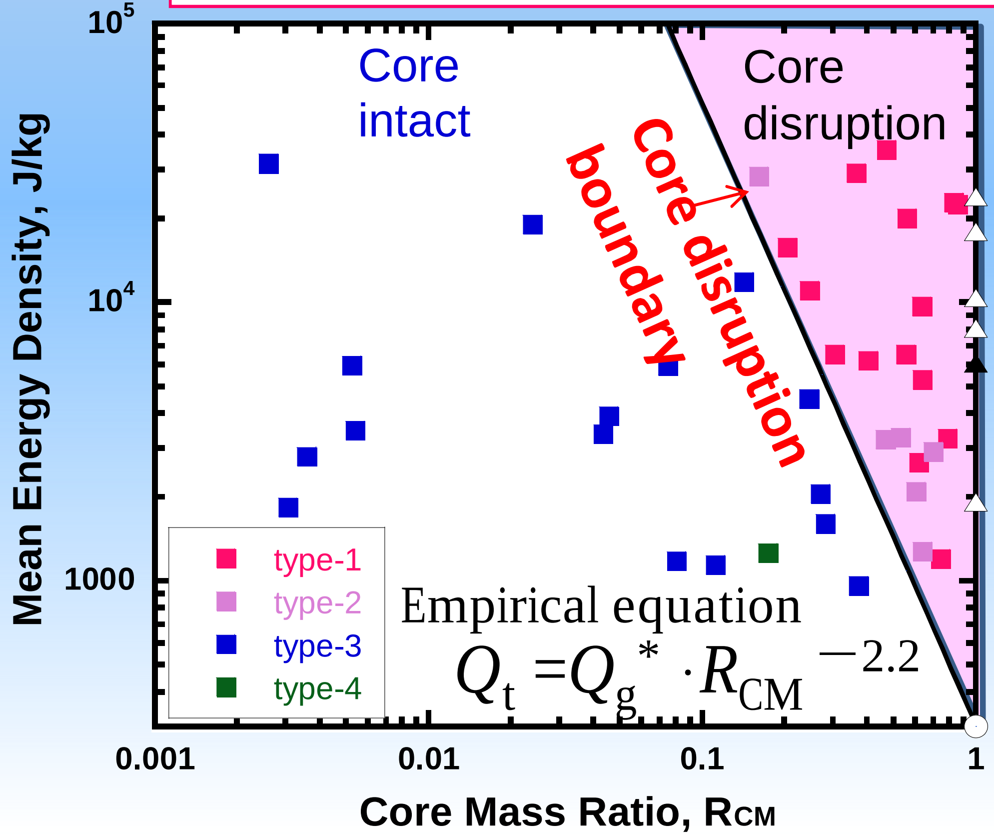
According to the relation between energy fraction and core mass ratio, $f=R_{CM}^{m}$ (1), we can discuss the boundary condition between types 1 and 2 and types 3 and 4 as defined by the glass core disruption.

At the boundary of the core disruption, the specific energy given into the core (Q_c) is equal to or beyond the impact strength of a bare glass target (Q_g^*). Using the energy fraction f, mean energy density Q_t and core mass ratio R_{CM}, we can derive the boundary condition described by $Q_g^*=f \cdot Q_t \cdot R_{CM}^{-1}$ (2) (Okamoto and Arakawa, 2008). From this semi-theoretical equation , we can derive the core disruption boundary condition, $Q_t = Q_g^* \cdot R_{CM}^{1-m}$ (3).

This semi-theoretical equation(3) can explain the empirical equation showing the boundary in the right figure described above. The power law index of Eq. (1), m, was derived to be 3.3, so that the power law index of Eq. (3) is -2.3, which is close to -2.2 in the empirical equation.

Thus, we clarified that the energy fraction consumed by the core disruption is proportional to the power law equation of R_{CM} with the power law index of 1-m.

Therefore, our simple theoretical consideration can explain the collisional outcomes of core-mantle targets obviously depends on the energy fraction of core (and mantle).



Summary

>We conducted impact experiments of inhomogeneous targets such as layered bodies consisting of a dense core and porous mantle to clarify the effect of the layered structure on collisional outcomes.

>We clarified the impact strength of spherical targets composed of soda-lime glass (or quartz) core and porous gypsum mantle as an analog of rocky-layered bodies with porous mantle-sintered cores, which could be formed at an initial stage of thermal evolution.

>The destruction modes of the core-mantle targets depends on the core/target mass ratio (R_{CM}) in the specific energy range from 1×10^3 to 4×10^4 J/kg. We observed two distinct destruction modes characterized by the damage to the core: one shows a damaged core and fractured mantle (types 1 and 2), and the other shows an intact core and broken mantle (types 3 and 4). The boundary condition of the core destruction ($Q_{t\_b}^*$) was experimentally found to be $Q_{t\_b}^*$ [J/kg] $=Q_c^*(R_{CM})^{-2.2}$, where Q_c^* is the specific energy required to disrupt a glass core. From this empirical equation, we can speculate that the impact strength of the body could be significantly reduced with the progress of internal evolution at the initial stage of thermal evolution.

>We estimated the energy partitioned into the glass core. The energy fraction (f) of the glass core depends on the core mass ratio; f simply increases with the increase of core mass ratio. From our simple theoretical consideration, the collisional outcomes of core-mantle targets obviously depends on the energy fraction of core and mantle.