Three-dimensional structures of Hayabusa samples using X-ray microtomography

Asteroids are small objects that have not grown into planets and that contain information on the formation of the solar system. Particles of Asteroid Itokawa were successfully recovered by the Hayabusa mission of JAXA (Japan Aerospace Exploration Agency). They are the first samples recovered from an asteroid, and the second extraterrestrial regolith (sandy particles) to have been sampled, the first being the Moon, which was sampled by the Apollo and Luna missions.

It is accepted that most meteorites originate from asteroids, as demonstrated by orbital determination from observed meteorite falls. The materials on asteroids have been estimated by comparing reflectance spectra between asteroids and meteorites. Itokawa has an S-type spectrum, which is one of the major types and similar to those of ordinary chondrites, particularly LL5 or LL6 chondrites. However, there is a spectrum discrepancy between the asteroid and meteorites, which is considered to result from space weathering. Itokawa samples allow a direct validation of the relation between asteroids and meteorites. In addition, the properties of Itokawa particles allow studies of regolith formation and evolution.

About 2000 recovered particles (< ~300 μm and most of them are <~10 μm) have been identified as having an Itokawa origin by curation at JAXA. About fifty particles were allocated for preliminary examination (PE) [1]. Our team examined three-dimensional (3D) structures by non-destructive X-ray microtomography as the first analysis in a sequential PE analytical flow [2]. The purposes are to understand their materials in comparison with meteorites and the 3D shape features in connection with regolith formation and evolution, and to provide information for the design of later destructive analyses. The latter is one of the key features of the Hayabusa PE strategy.

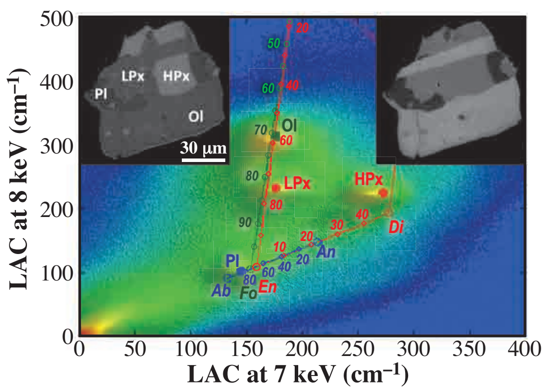

Fig. 1. A two-dimensional histogram of linear attenuation coefficient (LAC) values at 7 and 8 keV for an Itokawa particle (RA-QD02-0024) (original figure in [3] was changed). Solid symbols correspond to the mean chemical compositions of the minerals in Hayabusa samples [1]. Ol: olivine, *Fo*: forsterite, LPx: low-Ca pyroxene, *En*: enstatite, HPx: high-Ca pyroxene, Pl: plagioclase, *Ab*: albite, *An*: anorthite. Numbers along olivine, pyroxene, and plagioclase solid solutions are the forsterite, enstatite, wollastonite, and albite contents (in mol.%). Inserted images are CT images at 7 keV (left) and 8 keV (right).

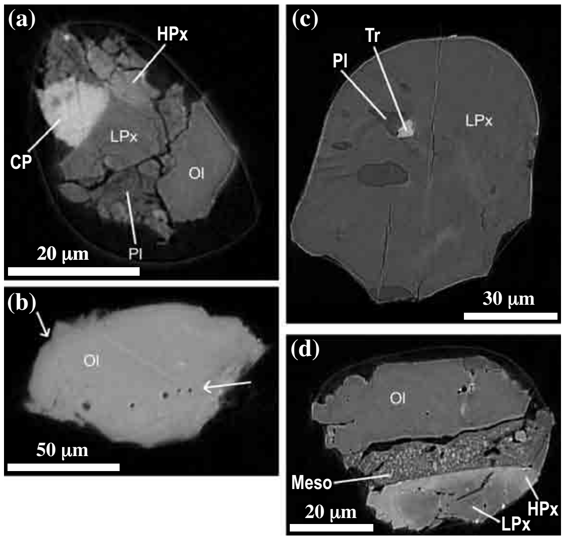

Fig. 2. Representative CT images of Itokawa particle [2]: samples **(a)** RA-QD02-0063, **(b)** RA-QD02-0014, **(c)** RA-QD02-0042, and **(d)** RA-QD02-0048. Concentric structure is a ring artifact. Bright edges of particles and voids are artifacts resulting from refraction contrast. CP indicates Ca phosphate; Tr, troilite; and Meso, mesostasis. The other abbreviations are the same as those in Fig. 1.

Forty particles (~30 to 180 μm) were imaged at beamline **BL47XU** with an effective spatial resolution of ~200 or ~500 nm by absorption imaging tomography [2]. Imaging at two X-ray energies of 7 and 8 keV made the identification of minerals in CT images possible (analytical dual-energy microtomography [3]) since the *K*-absorption edge of Fe (7.11 keV) is present between the two energies (Fig. 1). Chemical compositions of olivine [$(Mg,Fe)_2SiO_4$], low-Ca pyroxene [$(Mg,Fe)SiO_3$], high-Ca pyroxene [$(Ca,Mg,Fe)SiO_3$], and plagioclase [$(Na,Ca)(Al,Si)AlSi_2O_8$] can be obtained by this method. A successive set of 3D CT images, which shows quantitative 3D mineral distribution, was obtained for each particle.

Tomography gave the total volume of 4.2×10^6 μm^3, which corresponds to a sphere of ~200 μm in diameter (total mass of ~15 μg). The mineral assemblage and their abundances in whole samples (64% olivine, 19% low-Ca pyroxene, 3% high-Ca pyroxene, 11% plagioclase, 2% troilite (FeS), and minor amounts (<0.2%) of kamacite [α-(Fe,Ni)], taenite [γ-(Fe,Ni)], chromite [$(Mg,Fe)(Cr,Al,Fe)_2O_4$], and Ca-phosphates) are similar to those of LL chondrites. A slightly larger amount of olivine and smaller amounts of high-Ca pyroxene, troilite, and (Fe,Ni) in the Itokawa particles can be regarded as statistical errors due to picking up the small sample amount [4]. Other PE data, such as the chemical compositions of minerals [1], also indicate LL chondrites.

The 3D structures of most particles have highly equilibrated textures owing to thermal metamorphism (Figs. 2(a-c)), which correspond to the petrologic type of 5 and/or 6 in ordinary chondrites (LL5 and/or LL6), whereas some of them (~10%) have less-equilibrated textures (LL4) (Fig. 2(d)). SEM observation and the homogeneity of minerals show the same results [1]. Fe-rich nanoparticles observed in thin surface layers (<60 nm) of Itokawa particles show evidence of space weathering [5]. These results showed that the Itokawa surface material is consistent with LL chondrites suffering space weathering, as expected, and brought an end to the mystery of the origin of meteorites.

Sphere-equivalent diameter and three-axial lengths of each particle were obtained from the 3D CT images [2]. The cumulative size distribution of the particles has the log-slope of ~ –2, which indicates a dominance of ~cm size regoliths in the Itokawa smooth terrain by considering the size distribution of boulders (0.1–5 m) with the log-slope of ~ –3. The 3D shape (three axial length ratios) distribution cannot be distinguished from that of fragments produced in impact experiments (Fig. 3(a)), showing that the Itokawa particles are consistent with impact fragments. No particles showing melting were observed, indicating relatively low impact velocities similar to typical relative impact velocities among asteroids (~5 km/s). Most of the particles have sharp edges (Fig. 4(a)), whereas others (~25%) have rounded edges (Fig. 4(b)) and they were probably formed by abrasion from particles that were originally more angular as grains migrated during impact (Fig. 4(c)). The spherical shapes of lunar regolith particles

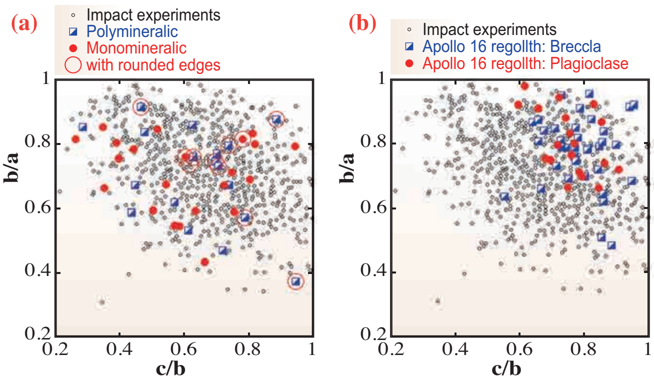

Fig. 3. 3D shape distributions of **(a)** Itokawa particles and **(b)** lunar regolith [2]. Fragments of impact experiments are also shown. Large circles in **(a)** show particles with rounded edges.

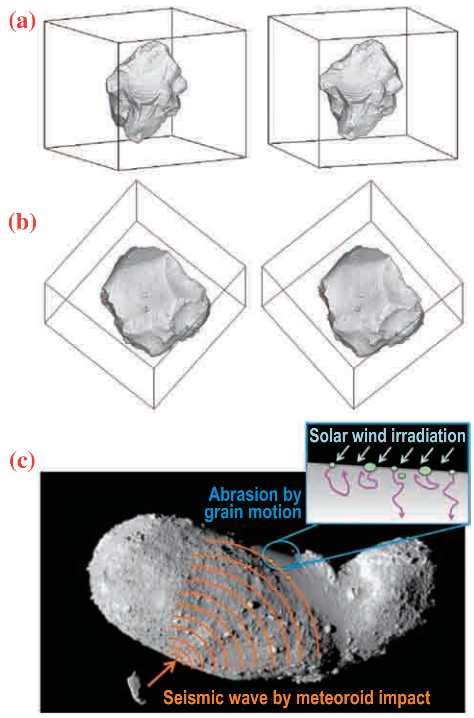

Fig. 4. Stereograms showing the 3D external shapes of Itokawa particles of **(a)** RA-QD02-0023 (232×232×203 μm^3) and **(b)** RA-QD02-0042 (112×112×93 μm^3) [2], and **(c)** an schematic illustration of possible abrasion process of regolith particles on Itokawa by granular processes induced by seismic vibration due to impact of a meteoroid.

(Fig. 3(b)) may be due to their longer residence time in the regolith. Systematic studies on regolith shapes together with micro-structures of particle surfaces, space weathering, and solar wind noble gas analysis will lead to a comprehensive understanding of processes on celestial bodies without atmosphere, such as small steroids and the Moon.

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