Asteroid Itokawa
A Source of Ordinary Chondrites and A Laboratory for Surface Processes

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Launched on May 9, 2003, the Hayabusa spacecraft travelled 300 million kilometers to reach its target less than half a kilometer across in September 2005. Artist's conception of the Hayabusa spacecraft deploying one of the target markers used to guide the spacecraft's descent to the surface of asteroid Itokawa. Image from JAXA

The Japanese spacecraft Hayabusa returned samples from the surface of an asteroid (near-Earth S-type asteroid 25143 Itokawa) for the first time in human history. This article describes the results of the initial analysis of the mineralogy, micropetrology, and elemental and isotopic compositions of regolith particles from Itokawa measuring 30–180 µm in diameter. The results show a direct link between ordinary chondrites and S-type asteroids. The regolith particles provide evidence of space-weathering rims and grain abrasion, and the information obtained has elucidated various processes on the airless surface of Itokawa, such as the impact of small objects, grain motion, and irradiation by solar wind.

Keywords: Hayabusa mission, regolith, space weathering, solar wind, impact, S-type asteroids

HAYABUSA: SAMPLE-RETURN MISSION

The spacecraft Hayabusa of the Japan Aerospace Exploration Agency (JAXA) arrived at the near-Earth S-type asteroid 25143 Itokawa in September 2005 and made remote sensing observations of the asteroid (Fujiwara et al. 2006). Fine particles on Itokawa's surface were recovered and successfully returned to Earth in June 2010. This material was the first sample recovered from an asteroid and returned to Earth. Furthermore, Itokawa's surface was only the second extraterrestrial surface to have been sampled (the first being the Moon's, which was sampled by the Apollo and Luna missions, e.g. Heiken et al. 1991). A preliminary examination of these samples was carried out in Japan in 2011 (Nakamura et al. 2011; Nakamura et al. 2012), and more detailed investigations are now being performed in laboratories around the world.

Asteroids are small celestial bodies in our Solar System that have not grown to planets, and thus hold valuable information about conditions during the formation of the Solar System. It is known from images acquired by spacecraft that the surfaces of relatively large asteroids (a few tens to a hundred kilometers in size), such as asteroid 433 Eros (Veverka et al. 2001), are roughly similar to the Moon's surface. They are covered with sand-sized particles, called regolith, formed mainly by crushing of material during the impact of celestial objects onto the asteroids, and they have a large number of impact craters. In contrast, Itokawa is a small asteroid (535 × 294 × 209 m) with low gravity and thus a low escape velocity (~0.2 m/sec) (Fujiwara et al. 2006). Observations by the Hayabusa spacecraft revealed that its surface morphology is different from that of larger asteroids: the surface is mostly covered by boulders, with a maximum size of about 50 m, and in some areas by regolith (Fig. 1a). The porosity of Itokawa is estimated to be about 40% based on its low bulk density (1.9 g/cm^3). The presence of a large number of boulders and the high porosity imply that Itokawa is a rubble-pile asteroid that was formed by the early collisional breakup of a preexisting large parent body followed by the reagglomeration of a small fraction of the original fragments (Fujiwara et al. 2006).

It has long been accepted wisdom that most meteorites originate from asteroids, as demonstrated by orbital determinations from observed meteorite falls (Cloutis et al. 2014 this issue). Primitive meteorites called chondrites constitute more than 80% of observed meteorite falls. They are divided into three major classes based on chemical composition: ordinary, carbonaceous, and enstatite chondrites. As discussed below, Itokawa materials are thought to represent ordinary chondrites. Ordinary chondrites comprise three groups, H, L, and LL, which vary in the amounts and forms of iron they contain. "Ordinary" refers to their prevalence; they constitute 74% of observed meteorite falls. Another criterion for chondrite classification is rock texture, which correlates with metamorphic or alteration history (petrologic type). Increasing thermal metamorphism corresponds to types 3 to 6, while increasing hydrous alteration is observed in types 3 to 1.

The composition of asteroids has been estimated by comparing their reflectance spectra in visible to near-infrared light with those of meteorites. Ground-based telescope observation (Binzel et al. 2001) and remote sensing images obtained by the Hayabusa spacecraft (Abe et al. 2006) indicated that the materials on S-type asteroid Itokawa are probably similar to thermally metamorphosed LL chondrites belonging to petrologic type 5 or 6 (i.e. LL5 or LL6). However, the spectral features of S-type asteroids and ordinary chondrites do not exactly match: the reflectance of the asteroids in the shorter-wavelength (blue) region is lower than that of the meteorites (Cloutis et al. 2014). It has been determined that such spectral darkening and reddening occurred on the Moon by "space weathering" (e.g. Heiken et al. 1991), and similar phenomena are expected on the surfaces of asteroids. Itokawa samples allow a direct validation of the relation between asteroid observations and meteorite samples, and they can also be compared with lunar regolith. Thus, in addition to providing information about composition, Itokawa regolith

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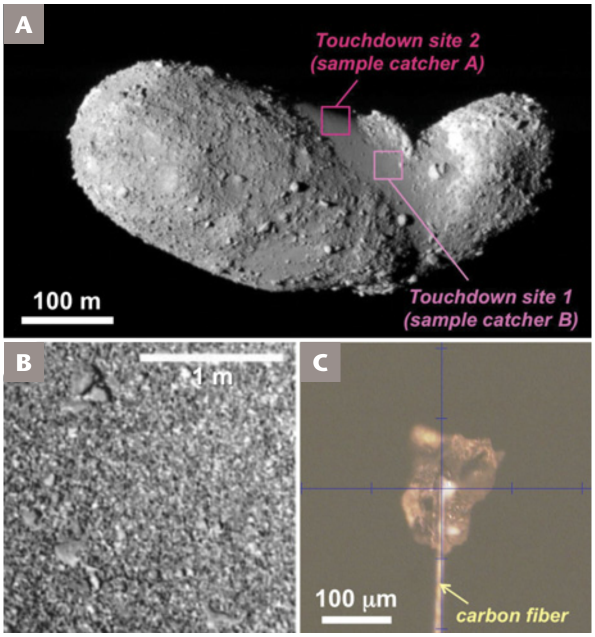

Figure 1 Asteroid Itokawa and an Itokawa particle. (**A**) Image of Itokawa taken by the Hayabusa aircraft. Samples stored in catchers A and B were collected from two touchdown sites, 2 and 1, respectively (modified from a JAXA image, http://spaceinfo.jaxa.jp/hayabusa/photo/itokawa04.html). (**B**) Close-up image of touchdown site 1 (modified from Yano et al. 2006). (**C**) Optical microscope image of particle RA-QD02-0010 collected by the Hayabusa spacecraft.

samples can be studied to understand surface processes on an asteroid, such as regolith formation, micrometeorite bombardment, and irradiation by cosmic rays. Exotic materials, including organic-rich matter provided by impacts on the asteroid's surface, might also be included in the samples. The returned samples from Itokawa are ideal for such examination because they come from a known source and they have experienced minimal contamination from the Earth's atmosphere and organic materials.

SAMPLE COLLECTION AND CURATION

In the original sampling plan, a bullet was to have been shot from the spacecraft into Itokawa's regolith at the time of spacecraft touchdown on the surface, and particles were then to have been collected and placed in a sample capsule (Yano et al. 2006). Unfortunately, no bullets were shot during the two touchdowns and only a limited number of small particles were recovered in the two sample catchers, A and B, which correspond to the second and first touchdowns, respectively (Figs. 1a, b) (Nakamura et al. 2011). The sample capsule was opened at JAXA's curation facility.

In total, more than 2000 returned particles have been identified by preliminary elemental analysis to date, and more remain to be identified. Two methods were used to obtain sample particles (Nakamura et al. 2011). The first involved sweeping the inner wall of sample catcher A with a Teflon spatula. However, most of the particles collected on the spatula were too small (smaller than 10 µm) to be safely handled without losing them. The other method was to collect particles that fell from sample catchers A and B onto a silica glass plate after physically tapping the catcher. Larger particles (maximum size about 300 µm) were safely picked up from the quartz plates (these are called "tapping samples").

SAMPLE ANALYSIS

Sixty-eight particles 30–180 µm in size from the tapping samples (64 and 4 particles from sample catchers A and B, respectively) (Fig. 1c) were allocated to researchers for initial analysis. The total volume of 48 particles examined by X-ray microtomography was approximately 4×10^6 µm^3, corresponding to a sphere about 200 µm in diameter or 15 µg in mass (Tsuchiyama et al. 2013a).

It was important to prepare a systematic sample-analysis program, where different analyses were made grain by grain, to obtain as much information as possible from the small amount of tiny particles. The 68 particles were divided into two groups for analysis. One group followed an analytical protocol designed for the characterization of space weathering, noble gases, and carbonaceous and organic materials, while minimizing contamination. For the analysis of space weathering, ultrathin sections were made across the surfaces of twelve particles mainly using an ultramicrotome in a purged nitrogen atmosphere to avoid oxidation of Fe nanoparticles, and these were examined by transmission electron microscopy (TEM) (Noguchi et al. 2011, 2013). The isotopic compositions of noble gases in three particles, which were handled in a nitrogen-purged atmosphere, were measured by laser ablation mass spectrometry (Nagao et al. 2011). The surfaces of five particles were examined nondestructively by micro-Raman and micro-infrared spectroscopy to seek carbonaceous materials possibly present on the surfaces (Kitajima et al. 2011). These particles were then rinsed with a small amount of dichloromethane/methanol solution, and the extracts were examined using high-precision liquid chromatography to seek amino acids or using time-of-flight secondary ion mass spectrometry (TOF-SIMS) to analyze other organic compounds, including a search for polycyclic aromatic hydrocarbons (Naraoka et al. 2012). Neutron activation analysis of one particle was done after the rinse to determine major and minor element abundance (Ebihara et al. 2011). The residual samples from all of the above treatments, except for those analyzed for noble gases, were then added to the mainstream analytical protocol described below.

Particles of the mainstream group, including the remaining portion of the 48 particles, were sequentially examined by progressively more destructive analytical methods (Nakamura et al. 2011; Tsuchiyama et al. 2013a). First, synchrotron radiation (SR)–based microtomography was used to obtain three-dimensional structures of the Itokawa grains (Tsuchiyama et al. 2011, 2013a). This was followed by SR-based X-ray diffraction (XRD) to identify mineral phases (Nakamura et al. 2011). The use of microtomography together with XRD for nondestructive analysis is one of the key features of the Hayabusa preliminary examination strategy involving sequential studies. The three-dimensional mineral distribution, together with the external shape of each particle, provides critical information concerning where a particle should be cut to ensure that the subsequent destructive analyses examine the best areas of the minerals exposed in the cross sections of these small particles. Then, the particles were polished or sectioned by an ultramicrotome or a focused ion beam (FIB). Ultrathin sections were analyzed by TEM to examine the micro- and nanostructures (Nakamura et al. 2011, 2012). The polished cross sections of the particles were examined using an optical microscope and a field-emission scanning electron microscope (FE-SEM) (Zolensky et al. 2012), and the chemical compositions of minerals were measured using an electron probe microanalyzer (EPMA) (Nakamura et al. 2011). Subsequently, oxygen and magnesium isotope compositions of minerals together with some minor element compositions were determined using secondary ion mass spectroscopy (SIMS) (Yurimoto et al. 2011a, b). The surface nanomorphologies of eight particles were also observed by FE-SEM before sectioning (Matsumoto et al. 2012).

Five different particles were independently studied by another examination team (Nakamura et al. 2012). First, the surface nanomorphologies of these particles were observed by FE-SEM, and then the particles were sectioned using FIB. The FIB sections were observed using an optical microscope and FE-SEM; the elemental and oxygen isotope compositions of minerals were measured by EPMA and SIMS, respectively.

WHAT WAS LEARNED FROM THE SAMPLE ANALYSES

Materials on Itokawa's Surface

A list of minerals identified in Hayabusa samples (Nakamura et al. 2011) is shown in Table 1, and typical particle cross sections are shown in Figure 2. The isotopic compositions of minerals can give information about their formation and later history. The oxygen isotope compositions of Hayabusa samples are different from those of terrestrial materials and are consistent with those of LL chondrites (Table 1), although the possibility of an L chondrite affinity cannot be excluded by the isotope ratios alone (Yurimoto et al. 2011a). Subsequently, more accurate data on the oxygen isotope compositions showed that the Itokawa particles resemble equilibrated LL chondrites (Nakashima et al. 2013).

The mineral assemblage of the Itokawa samples is consistent with that of ordinary chondrites. The chemical compositions of minerals fall within the compositional range of LL chondrites (Table 1) (Nakamura et al. 2011; Nakamura et al. 2012). The modal abundances of minerals are also consistent with LL chondrites (Table 1) (Tsuchiyama et al. 2011, 2013a). Slight differences of the mineral abundances between the Itokawa sample and LL chondrite might be due to a statistically insufficient amount of Itokawa sample. Based on the abundances and the chemical compositions of minerals, the bulk density (3.4 g/cm^3; Tsuchiyama et al. 2011, 2013a) and the bulk chemical composition (Nakamura et al. 2011) were obtained. The Fe/Sc and Ni/Co ratios are consistent with those of ordinary chondrites. Depletion of Ir, which may be the result of condensation in the early solar nebula before chondrite formation, was also noted (Ebihara et al. 2011).

The above results clearly show that the materials making up Itokawa's surface correspond to ordinary chondrites, in particular LL chondrites. This provides the first direct link between asteroids and meteorites based on sample analysis.

Itokawa's Parent Body

About 90% of the Itokawa particles examined exhibit triple junctions at the boundaries between coarse silicates (Fig. 2a) or almost monomineralic features (Fig. 2c, d); the particles show an almost homogeneous chemical composition of minerals, indicating that they have been thermally annealed, and thus they are similar to LL5 and/or LL6 chondrites (Nakamura et al. 2011; Tsuchiyama et al. 2011, 2013a). The maximum temperature estimated from the chemical compositions of an equilibrated Itokawa mineral pair of Ca-poor and Ca-rich pyroxenes is about 800 °C. If a small body like Itokawa was heated to 800 °C, even its interior would have cooled very fast. Based on a heating model calculation using the extinct nuclide ^{26}Al as a heat source, the original Itokawa parent body radius should have been larger than 20 km (Nakamura et al. 2011) (Fig. 3). The remaining Itokawa particles (~10%), which are made up of fine silicate grains and have more heterogeneous chemical compositions, are similar to LL4 chondrites (Fig. 2b). Such less-equilibrated material should have formed near the original parent-body surface. A relative age determination, using the ^{26}Al–^{26}Mg isotope system, indicates that the maximum age of thermal metamorphism is 4.562 billion years (Yurimoto et al. 2011b).

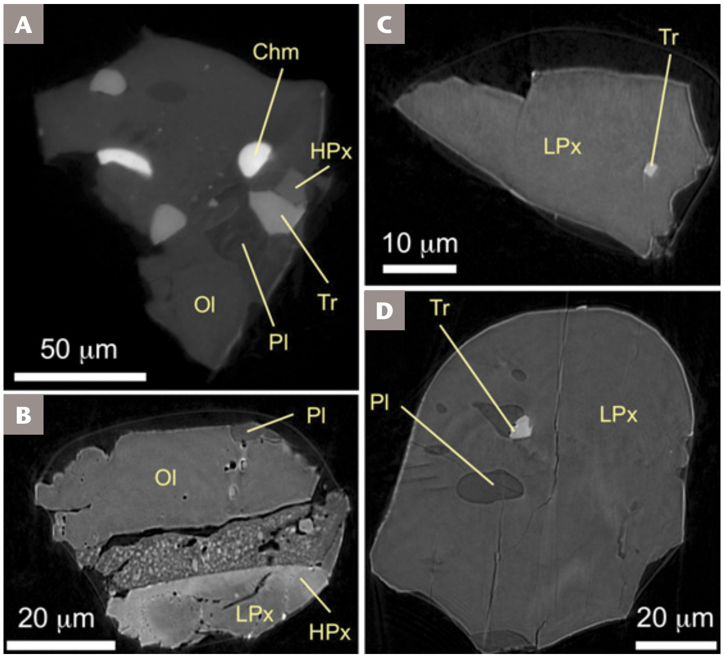

Figure 2 Slice images of Itokawa particles obtained by microtomography for samples RA-QD02-0031 (**A**), RA-QD02-0048 (**B**), RA-QD02-0038 (**C**), and RA-QD02-0042 (**D**). The image contrast corresponds to the X-ray linear attenuation coefficient of the material. Elements heavier than Mg and lighter than Fe (e.g. S, Ca, and Cr) give bright tones in images taken at 7 keV. The bright edges of objects are artifacts resulting from refraction contrast. Mineral abbreviations are given in Table 1. B and D modified from Tsuchiyama et al. (2011)

Some of the Itokawa particles have minerals with impact shock features (Zolensky et al. 2012). Optical microscope observations suggest mild impact at the S2 meteorite shock stage, which corresponds to a shock pressure of 5–10 GPa. It is not yet known how these features are related to impacts on the Itokawa parent body and/or to Itokawa's formation.

Surface Processes on Itokawa

Examination of regolith particles from Itokawa provides valuable information on surface processes that cannot be obtained from existing meteorites. The shape distribution of Itokawa particles with respect to their three axial ratios is not statistically different from that of fragments formed by high-speed impact in laboratory experiments, indicating that the Itokawa particles resulted from mechanical disaggregation, primarily as a response to impacts (Tsuchiyama et al. 2011, 2013a). The particle size distribution has a cumulative log slope of about –2, which is more gradual than that of boulders (about –3), indicating a lower abundance of 10–100 µm particles than of millimeter- to centimeter-sized regolith particles (Tsuchiyama et al. 2011, 2013a); this conclusion is consistent with the close-up image of regolith taken by the Hayabusa spacecraft (Fig. 1b) (Yano et al. 2006). This size distribution may be explained by smaller particles having higher ejection velocities and thus higher loss rates as a result of impacts

TABLE 1 MINERALS IN ITOKAWA PARTICLES AND LL4-6 CHONDRITES: ABUNDANCES AND COMPOSITIONS

Mineral	Abbreviation	Formula	Crystal system[a]	Mineral abundance (wt%)[b]		Chemical composition[c,d]		Oxygen isotope composition, $\delta^{17}O_{SMOW}$ (‰)[e,f]		
				Itokawa	LL4-6	Itokawa	LL4-6	Itokawa	LL[g]	Terrestrial[h]
Olivine	Ol	$(Mg,Fe)_2SiO_4$	Orth	67.2	51.1±2.2	Fa28.6±1.1	Fa26–32	1.46±0.41	1.32±0.50	-0.01±0.37
Low-Ca pyroxene	LPx	$(Mg,Fe)SiO_3$	Orth, Mono	18.1	21.1±2.0	Fs23.1±2.2 Wo1.8±1.7	Fs22–26	1.57±0.62	1.06±0.45	
High-Ca pyroxene	HPx	$(Ca,Mg,Fe)SiO_3$	Mono	2.6	7.4±0.9	Fs8.9±1.6 Wo43.5±4.5				
Plagioclase	Pl	$(Na,Ca)Al(Al,Si)Si_2O_8$	Mono, Tri	8.5	9.7±0.8	Ab83.9±1.3 Or5.5±1.2		1.15±0.51	1.61±0.70	0.07±0.21
Troilite	Tr	FeS	Hex	2.9	5.7±1.5					
Kamacite	Kam	α-(Fe,Ni)	Cub	0.0	3.5±2.0	3.8–4.2 wt% Ni 9.4–9.9 wt% Co	~5.0 wt% Ni 1.4–37 wt% Co			
Taenite	Tae	γ-(Fe,Ni)	Cub	0.5		42–52 wt% Ni 2.0–2.5 wt% Co				
Chromite	Chm	$FeCr_2O_4$	Cub	0.1	1.6±0.1					
Apatite	Cp[i]	$Ca_5(PO_4)_3(F,Cl,OH)$	Hex	0.1						
Merrillite		$Ca_9NaMg(PO_4)_7$	Tri							

[a] Cub: cubic, Hex: hexagonal, Orth: orthorhombic, Mono: monoclinic, Tri: triclinic

[b] Data from Tsuchiyama et al. (2013a)

[c] From Nakamura et al. (2011)

[d] Fa: Fe/(Mg+Fe), Fs: Fe/(Mg+Fe+Ca), Wo: Ca/(Mg+Fe+Ca), Ab: Na/(Ca+Na+K), Or: K/(Ca+Na+K) in mol%

[e] From Yurimoto et al. (2011a)

[f] $\Delta^{17}O_{SMOW} = \delta^{17}O_{SMOW} - 0.52\ \delta^{18}O_{SMOW}$, where $\delta^{N}O = 1000[\{(^{N}O/^{16}O)_{sample} - (^{N}O/^{16}O)_{SMOW}\} / (^{N}O/^{16}O)_{SMOW}]$; (N = 17 or 18, SMOW: terrestrial standard

[g] Measurements of Ensisheim LL6 chondrite

[h] Measurements of terrestrial olivine from San Carlos and plagioclase from Miyake-jima (theoretically, $\Delta^{17}O_{SMOW} = 0$)

[i] Apatite and merrillite are abbreviated together as Cp (Ca phosphate)

on Itokawa. In contrast, abundant submillimeter-sized fragments in regolith are observed on larger bodies such as the Moon (Heiken et al. 1991).

The surfaces of regolith particles can be regarded as an interface with the space environment, where the impacts of small objects and irradiation by the solar wind and galactic cosmic rays have been recorded (FIG. 3). Two kinds of surface modification have been recognized on Itokawa particles. One is the formation of space-weathering rims: thin layers of amorphous silicates a few to 80 nm in thickness contain a large amount of iron-rich nanophase (FIG. 4A) (Noguchi et al. 2011, 2013). The presence of the nanophase is the cause of the reddening and darkening of the reflectance spectrum, known as space weathering (FIG. 4C). In the amorphous layer, vesicles about 100 nm across are sometimes observed (FIG. 4B) (Noguchi et al. 2013). These rim structures can be explained by (1) amorphization, (2) in situ reduction of iron, and (3) blistering due to the implantation of solar wind particles, particularly He, as deduced from the penetration depth of helium (about 50 µm) and rim textures. In fact, noble gases (He, Ne, and Ar) from the solar wind were detected in Itokawa particles (Nagao et al. 2011). The timescale for the rim formation, which was roughly estimated from the solar flare density recorded in particles, is only about one thousand years (Noguchi et al. 2013). This is consistent with the residence time spans of grains in the uppermost surface, 150–550 years, estimated from the solar Ne concentrations (Nagao et al. 2011). The present results provide the first direct evidence of space weathering on an asteroid. The cause of the space weathering is significantly different from that on the Moon, where the process involves vapor deposition of amorphous materials containing Fe nanophase mainly caused by bombardment of micrometeoroids (e.g. Pieters et al. 2000). This difference might be due to the much larger residence timescales for regolith on the Moon (typically over 400 million years).

The other observed surface modification that has taken place on Itokawa grains is grain abrasion (Tsuchiyama et al. 2011, 2013b). The edges of Itokawa particle surfaces observed by microtomography are usually angular (FIG. 2C), but some are rounded (FIG. 2D). Similar features were also observed with higher resolution by FE-SEM; sharp steps formed by fracturing were observed on angular surfaces (FIG. 5A), while faint or no steps were observed on rounded surfaces (FIG. 5B) (Matsumoto et al. 2012). These results indicate that some mechanically crushed fragments were abraded later. The degree of rim development due to space weathering is not related to the abrasion (Tsuchiyama et al. 2013b). Thus, the abrasion process can be regarded as a different type of space weathering with a longer timescale, and should be called “space erosion.” This abrasion may be the result of grain migration, which is caused by seismic waves repeatedly reflecting off the surface of Itokawa after impacts (Tsuchiyama et al. 2011). Release profiles of solar noble gases from Itokawa particles are consistent with grain motion in the regolith layer, and observed He losses suggest preferential abrasion of the space-weathering rim from the particle surfaces (Nagao et al. 2011).

Galactic cosmic rays can reach much deeper levels (several tens of centimeters below the surface) in an asteroid. However, no measurable cosmic ray–produced Ne was detected beyond experimental errors (Nagao et al. 2011).

This result permits estimation of the upper limit of the residence timescale of grains in the regolith layer, namely, about 8 million years. This is much shorter than the nominal exposure ages of over 400 million years for mature lunar regolith (Wieler 2002). The short duration of cosmic ray exposure and solar wind implantation indicates that the loss of surface materials from this small asteroid with low gravity through impacts occurred at a rate of several tens of centimeters per million years (Fig. 3) (Nagao et al. 2011).

Submicrometer-sized impact craters were observed on the surface of one grain (Fig. 5c) (Nakamura et al. 2012). They may have been created by the impact of high-speed secondary nanoparticles produced by the impact of an object into Itokawa's regolith. Tiny, flattened glass objects, which seem to be melt splash (Fig. 5d) (Nakamura et al. 2012; Matsumoto et al. 2012), probably also formed as a result of small-scale impacts. Large-scale melting features, such as the agglutinates found in lunar regolith, have not yet been observed among the Itokawa samples (Tsuchiyama et al. 2011). This can be explained by the differences between the mass and representative impact velocities for asteroids and the Moon (about 5 km/sec and over 10 km/sec, respectively).

SUMMARY AND FUTURE OUTLOOK

Figure 3 illustrates Itokawa's history and regolith evolution as elucidated from a preliminary examination of the returned samples. This history is summarized as follows: (1) Formation of the Itokawa parent body, which was larger than 20 km in diameter and composed of LL chondrite materials. (2) Thermal metamorphism (up to about 800 °C), probably slightly less than 4.562 billion years ago. (3) Catastrophic impact and formation of the rubble-pile asteroid Itokawa by reaccumulation of some fragments. (4) Formation of regolith by impacts of small objects, with selective escape of the finest-scale particles. (5) Implantation of solar wind into the uppermost particle surfaces and formation of space-weathering rims with a timescale of ~10^3 y. (6) Grain abrasion, probably due to seismic-induced particle motion, with time periods significantly longer than 10^3 y. Processes (5) and (6) might have been repeated. (7) Final escape of particles from the asteroid by impact within the past 8 million years.

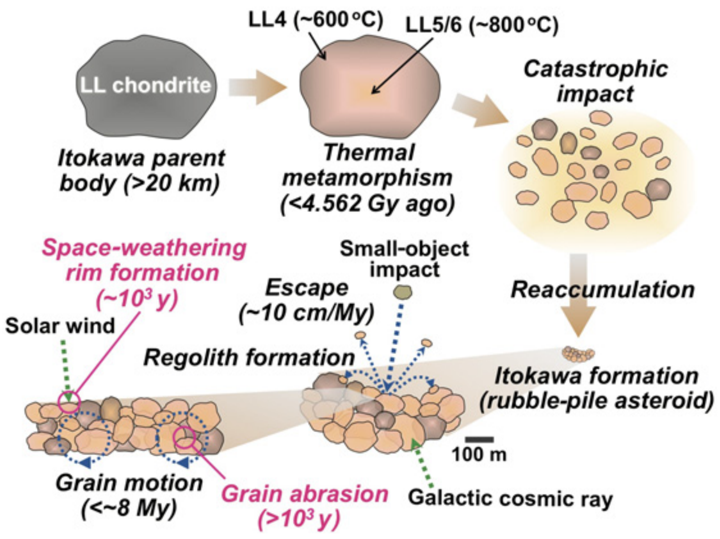

Figure 3 Outline of Itokawa's history and regolith evolution. Modified from an original illustration by Dr. S. Tachibana of Hokkaido University

As the size and amount of the collected Itokawa samples are very limited, some basic information has not yet been obtained. For example, we do not know the absolute formation age of Itokawa material. The nature of the catastrophic impact on the parent body is not well understood, nor is the age of this impact, which corresponds to Itokawa's formation age. We have not found any unmetamorphosed chondritic materials (LL3 chondrites) that might have been present on the surface of the original parent asteroid. The cause of grain abrasion should be confirmed. It will be critical to make comparisons with the lunar regolith by analyzing particles from each body using the same methods, which will eventually lead to a comprehensive understanding of surface processes on airless bodies.

It is expected that exotic materials that originated from other celestial bodies and fell on Itokawa are included in the Hayabusa samples. Carbonaceous materials, including

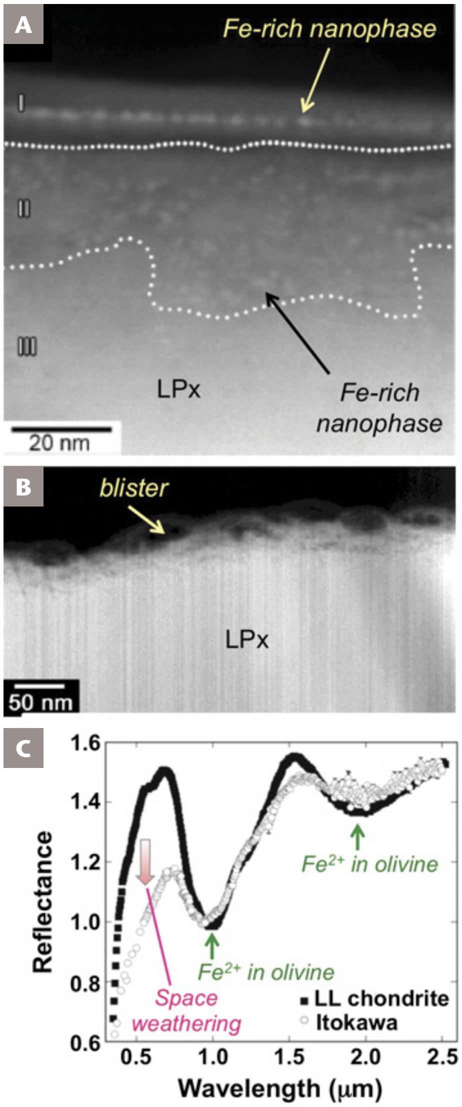

Figure 4 Space-weathering rims on Itokawa particle surfaces. (**A**) Sample RA-QD02-0042 observed using a scanning transmission electron microscope. Zone I is an amorphous surface layer, zone II is a partially amorphized area, and zone III is the crystalline substrate. Modified from Noguchi et al. (2011). (**B**) Sample RA-QD02-0009 observed using a transmission electron microscope. Courtesy of Dr. T. Noguchi of Ibaraki University. (**C**) Reflectance spectra of Itokawa (open circles) and LL chondrite (solid squares). Absorptions at 1.0 and 2.0 μm caused by Fe^{2+} in olivine are seen in both spectra. Space weathering causes reduction of the reflectance (darkening) and steepening of the slope (reddening) of the asteroid spectra. LPx: low-Ca pyroxene. Modified from Watanabe et al. (2008)

organic materials, are being actively sought but have not been detected thus far (Kitajima et al. 2011; Naraoka et al. 2012). The safe handling of tiny grains less than 10 µm across is difficult at present. Unique materials may be present in these tiny particles.

We do not completely understand how the Hayabusa spacecraft collected the samples without shooting a bullet. Three sampling mechanisms are possible (Tsuchiyama et al. 2011): (1) ejection by impact with the sampler horn, (2) levitation by electrostatic interaction among charged particles, and (3) ejection by thruster jets from the ascending (or descending) spacecraft. Some of these mechanisms might have caused the fractionation of particle sizes and/or mineral abundances. As all the particles analyzed show solar noble gas implantation and space-weathering rims, they must have been sampled from the outermost surface of the asteroid. More detailed analysis may elucidate the mechanism.

The detailed-analysis phase for Hayabusa samples started in mid 2012. The analysis team looks forward to many new discoveries and to sharing them with the scientific community and the world.

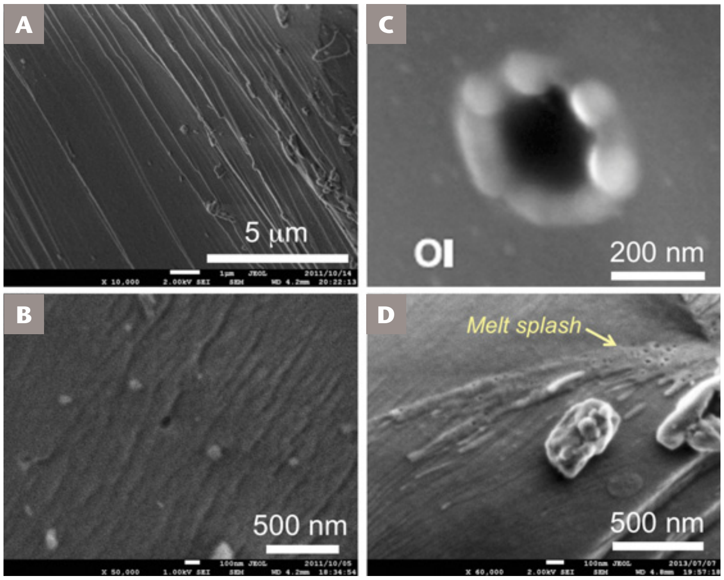

FIGURE 5 Surface micro/nanomorphologies of Itokawa particles observed using a field-emission scanning microscope. (**A**) Sharp steps on a fractured surface (sample RB-QD04-0049). (**B**) Faint steps on a rounded surface (RB-QD04-0023). (**C**) A pit with ornaments resembling a crater (sample RA-QD02-0093). (**D**) Flattened glass with bubble, like melt splash (sample RB-QD04-0043). Substrates of all the images are olivine. IMAGES A, B, AND D COURTESY OF T. MATSUMOTO OF OSAKA UNIVERSITY; C MODIFIED FROM NAKAMURA ET AL. (2012)

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