Regolith particles on the asteroid Itokawa were recovered by the Hayabusa mission. Their three-dimensional (3D) structure and other properties, revealed by x-ray microtomography, provide information on regolith formation. Modal abundances of minerals, bulk density (3.4 grams per cubic centimeter), and the 3D textures indicate that the particles represent a mixture of equilibrated and less-equilibrated LL chondrite materials. Evidence for melting was not seen on any of the particles. Some particles have rounded edges. Overall, the particles’ size and shape are different from those seen in particles from the lunar regolith. These features suggest that meteoroid impacts on the asteroid surface primarily form much of the regolith particle, and that seismic-induced grain motion in the smooth terrain abrades them over time.

The Hayabusa mission recovered at least 1534 particles from the smooth terrain of MUSES-C Regio on asteroid 25143 Itokawa (1, 2). These grains are less than a few hundred micrometers in diameter (3). These samples can be compared with the other extraterrestrial regolith to have been sampled, that of the Moon, which was sampled by the Apollo and Luna missions (4).

It is accepted that most meteorites originate from asteroids, as, for example, demonstrated by orbital determination from observed meteorite falls. Ground-based telescope observation (5) and remote-sensing observation by the Hayabusa spacecraft (6) indicate that the materials on S (IV)–type asteroid Itokawa are similar to LL5 or LL6 chondrites. Itokawa samples allow a direct validation of the relation between asteroidal and meteorite mineralogy. In addition, the properties of Itokawa particles allow studies of regolith formation on an asteroid. Here, we describe the three-dimensional (3D) structures of Itokawa particles by using x-ray microtomography to understand their textures, mineralogy, and shapes in comparison with those seen in meteorites and in lunar samples and use the results to infer how Itokawa’s regolith formed.

Our imaging tomography experiments were made at beamline BL47XU of SPring-8 (7). We obtained 40 particles ranging from 30 to 180 μm in size from sample catcher A by tapping it (tapping samples). These particles were collected during the spacecraft’s second touchdown on the asteroid (2). These particles were imaged with effective spatial resolutions of ~200 or ~500 nm, which is sufficient for comparisons with the textures of ordinary chondrites. Successive 3D computed tomography (CT) images (Fig. S1), which show quantitative 3D mineral distribution, were obtained. Mineralogy of the particle was derived by comparing a set of CT images taken at dual x-ray energies (7 and 8 keV) (fig. S2). In addition to the tapping samples, we swept 1534 particles from sample catcher A surface by using a Teflon (Dupont) spatula (spatula samples). We used a scanning electron microscope (SEM) to measure the size of 1469 particles larger than 0.5 μm (3).

The CT images of different particles show substantial textural variations (Fig. 1). None of the textures is consistent with in situ melting caused by the impact of meteoroids, such as seen in the lunar agglutinates. The textures are also different from those of porous interplanetary dust particles and Stardust particles of cometary origin. Eighteen of the 40 particles are polymetallic, mainly composed of olivine, low-Ca pyroxene, high-Ca pyroxene, plagioclase, and/or troilite (e.g., Fig. 1A), whereas 22 particles are almost (~80 volume [%] monomineralic and are dominated by olivine (Fig. 1B), low-Ca pyroxene (Fig. 1C), or plagioclase. Most of the particles seem to have equilibrated chondritic textures, suggesting thermal metamorphism (petrologic type of 5 and/or 6), whereas a few of them have less-equilibrated textures, such as a chondrule fragment where mesostasis and pyroxene with Ca zoning are seen (Fig. 1D). Some less-equilibrated materials are also present (3), suggesting that the Itokawa material is representative of a breccia. Voids, both spherical and elongated, are common in 15 of the particles (Fig. 1B). Seven particles contain cracks showing partially healed impact-generated fractures (Fig. 1A).

The total volume of the 40 particles obtained from CT image analysis (7) is 4.23 × 10^6 μm^3. This corresponds to a sphere 201 μm in diameter (typical chondrule diameter in LL chondrites is ~900 μm). The modal mineral abundances (vol. %) of the entire 40-particle sample were obtained from the relative volumes of crystalline minerals in the 3D data of individual particles (64% olivine, 19% low-Ca pyroxene, 3% high-Ca pyroxene, 11% plagioclase, 2% troilite, ~0.02% kamacite, ~0.2% taenite, ~0.1% chromite, and ~0.01% Ca phosphates). These are similar to those of LL chondrites, although the abundance of troilite and metals is ~2% lower than those in the average LL chondrite (8) (table S1). The chemical and oxygen isotope data of Itokawa materials (3, 9) also show a similarity to LL chondrites.

The porosities of individual particles range from 0 to 11%. The mean porosity of 1.4% is lower than the average porosity of LL chondrites (8.2 ± 5.5%) (standard deviation) (10). This is because most porosity in LL chondrites is in cracks between grains, and these cracks are not represented in the Itokawa samples because of a size effect: LL chondrites are bigger than the particles.
analyzed here. The mass of each mineral (table S1) was obtained from the modal abundances, and the density calculated from its mean chemical compositions (3). The total mass of our examined particles is 14.5 μg. From the mineral mass and the porosity, we obtained an average density of 3.4 g/cm^3. This corresponds to grain density and is comparable to the measured grain density of LL chondrites (3.54 ± 0.13 g/cm^3) (10).

If the collected sample is representative of Itokawa and has the average porosity of LL chondrites, its bulk density would be 3.1 ± 0.2 g/cm^3. The macroporosity of Itokawa would then be 39 ± 6% on the basis of the bulk density of Itokawa (1.9 ± 0.13 g/cm^3) (1). This is consistent with a rubble-pile asteroid model of Itokawa (1).

The sphere-equivalent diameters of tapping sample particles calculated from their volumes range from 14 to 114 μm (median 36.8 μm), whereas the diameters of spatula sample particles range from 0.5 to 32 μm (median 3.5 μm). These particles are smaller than the size-sorted, mm- to cm-sized particles observed in close-up images of MUSES-C Regio (2). The mm- to cm-sized particles were not comminuted by the pressure of the spacecraft during touchdown [−0.02 MPa (7)] if they are coherent (11), and the collected small particles should be original regolith particles from the smooth terrain. Three sampling mechanisms are possible (7): (i) impact by the sampler horn, (ii) electrostatic interaction between charged particles and possibly charged sampler horn, and (iii) levitation by thruster jets from the ascending spacecraft. Some mechanisms may have caused some size sorting. However, because details concerning the touchdown conditions are not known, we cannot specify the mechanism(s) and such effect.

The cumulative size distribution of the tapping samples has a log slope of about −2 in the range of 30 to 100 μm (Fig. 2). Large particles might have been selectively picked up from the tapping samples. The spatula samples have a log slope of −2.8 in the range of 5 to 20 μm (Fig. 2). However, sweeping by the spatula would have pulverized some of the particles, and the slope is an upper limit to the original slope. Thus, the slope for the fine particles (~5 to 100 μm) in the smooth terrain should be shallower than −2.8 and probably around −2. This slope is shallower than that of Itokawa boulders of 5 to 30 m (−3.1 ± 0.1) (12). If transition of the slope from about −3 to −2 occurs at the mm- to cm-sized region, then we can explain the observation of abundant mm- to cm-sized regolith (2). The lack of mm-sized particle in the Hayabusa samples might be explained by a small probability of collecting these small particles. However, the possibility of size selection biases during sampling from Itokawa or agglomerations of small particles (11) cannot be excluded. In contrast, abundant sub-mm regolith powder was observed on the Moon, and the size distribution from lunar samples has a steep slope (−3.1 to −3.3 in the range of 20 to 500 μm) (4), suggesting repeated fragmentation on this relatively large celestial body.

The lower abundance of ~10- to 100-μm particles in the smooth terrain can potentially be explained by (i) smaller grains having higher ejection velocity and therefore higher loss rates from Itokawa after impacts (13), (ii) selective electrostatic levitation of smaller grains (13), and/or (iii) size-dependent segregation by vibration [the Brazil-nut effect (14)].

Figure 3A shows the shape distributions of the tapping samples. The mean b/a and c/a ratios are 0.71 ± 0.13 and 0.43 ± 0.14, respectively [a, b, and c are longest, middle, and shortest axial diameters, respectively, of a best-fit ellipsoid (7)]. The distribution among polymineralic and monomineralic particles does not have any significant difference based on the Kolmogorov-Smirnov test. Some voids define a 3D plane (arrows). (7 keV, X = 431 cm\(^{-1}\)). Sample RA-QD02-0063 (7 keV, X = 431 cm\(^{-1}\)). Concentric structure is a ring artifact. Bright edges of particles and voids are artifacts resulting from refraction contrast. Ol indicates olivine; LPx, low-Ca pyroxene; HPx, high-Ca pyroxene; Pl, plagioclase; CP, Ca phosphate; Tr, troilite; and Meso, mesostasis.

**Fig. 1.** Slice images of Itokawa particles obtained by microtomography with a gray scale showing the linear attenuation coefficient (LAC) values (from 0 to X cm\(^{-1}\)), where X is the maximum LAC value in the CT images. (A) Sample RA-QD02-0063 (7 keV, X = 431 cm\(^{-1}\)). (B) RA-QD02-0014 (7 keV, X = 287 cm\(^{-1}\)). Some voids define a 3D plane (arrows). (C) RA-QD02-0042 (7 keV, X = 575 cm\(^{-1}\)). (D) RA-QD02-0048 (7 keV, X = 431 cm\(^{-1}\)). Concentric structure is a ring artifact. Bright edges of particles and voids are artifacts resulting from refraction contrast. Ol indicates olivine; LPx, low-Ca pyroxene; HPx, high-Ca pyroxene; Pl, plagioclase; CP, Ca phosphate; Tr, troilite; and Meso, mesostasis.

**Fig. 2.** Cumulative size distribution of Itokawa particles. Sphere-equivalent diameters of the tapping samples and diameters of the spatula samples are shown.
(K-S) test (probability, $P = 0.84$) probably because the monomineralic particles are polycrystalline and not affected by anisotropy, such as cleavage. The mean axial ratio ($a:b:c$) of fragments generated in laboratory impact experiments is $-2: \sqrt {2}: 1$ ($b/a = 0.71$ and $c/a = 0.5$) over a broad size range ($-0.4$ to $-10$ cm) (15, 16) (Fig. 3). The mean ratios, $b/a$, for boulders on Itokawa (0.68, range from 0.1 to 5 m) and asteroid (433) Eros (0.71 to 0.73, range from 0.1 to 150 m) have similar values (17). The K-S test indicates that the shape distribution of the Itokawa particles is not significantly different from that of the laboratory experimental fragments (16) ($P = 0.17$). The Itokawa particles are probably the results of mechanical disaggregation, primarily as a response to impacts. However, other processes, such as disaggregation of larger particles by thermal cycling (18), cannot be excluded. The edges of 30 of the tapping particles are angular (Figs. 1, A, B, and D, and 4, A and B, and movie S1), suggesting that they are fragments of mechanically crushed precursors, whereas some edges of remaining particles are rounded (Figs. 1C, 4, C and D, and movie S2). Their 3D shapes are also more spherical than the particles with angular edges (Fig. 3A). In contrast to the Itokawa particles, the shapes of lunar regolith particles are more spherical (4, 19) than experimental impact fragments (Fig. 3B) ($P = 0.00$ in the K-S test).

Two types of terrains are observed on the surface of Itokawa: boulder-rich rough terrain and smooth terrain (2). It has been proposed that Itokawa is a rubble-pile asteroid that was formed by an early collisional breakup of a preexisting large parent body followed by a re-agglomeration of some of the original fragments (I). It has been also proposed that mm to cm particles formed by impact processing and selectively migrated into the smooth terrains of gravitational potential lows by granular processes (14) induced by seismic vibration (13). Smaller Itokawa particles would have formed in situ by impact processing on Itokawa’s surface, although a possibility of direct re-accumulation from the catastrophic impact that formed Itokawa cannot be excluded. Even though Itokawa has a low escape velocity

![Fig. 3. The 3D shape distributions of (A) Itokawa particles and (B) lunar regolith (19, 26). Fragments of impact experiments (16) are also shown in both graphs. Large circles in (A) shows particles with rounded edges.](www.sciencemag.org)

![Fig. 4. The 3D external shapes of Itokawa particles. (A) Stereogram (box size 232 µm by 232 µm by 203 µm) and (B) SEM micrograph of RA-QD02-0023. (C) Stereogram (box size, 112 µm by 112 µm by 93 µm) and (D) SEM micrograph of RA-QD02-0042.](www.sciencemag.org)
(−0.2 m/s), some amount of small particles (~cm) should have low enough impact ejection velocities (20) to allow them to reaccumulate onto the surface. An in situ origin seems to be consistent with the residence time of Itokawa particles in the regolith deduced from galactic cosmic ray noble gas analyses (~10 million years) (21), which is younger than the lower limit of Itokawa’s age (>−75 million years) (22).

The lack of in situ melting textures in Itokawa particles can be explained by relatively low-impact velocities of the type expected among asteroids (~5 km/s) (23). Greater quantities of melt-containing ejecta would be expected with impact velocities of >10 km/s, of the type that produce agglutinates on the Moon.

Particles with rounded edges were probably formed from particles that were originally more angular. Sputtering by solar-wind particles is unlikely to explain the rounded morphology because of the short residence time on the uppermost regolith layer deduced from solar-wind noble gas analyses (~150 years) (21). The rounded particles may be a result of abrasion as grains migrate during impacts. The spherical shapes of lunar regolith particles (Fig. 3B) are due to their longer residence time in the regolith, which allows more thorough sputtering by solar-wind particles.

The size and 3D shape of collected 10- to 100-μm-sized Itokawa particles suggest that they were primarily formed on Itokawa’s surface by impact and suffered abrasion by seismic-induced grain motion in the terrain together with minor repeated solar-wind particle implantation (21) and space weathering (24). Because these processes are mechanical and substantial melting did not occur during impacts, the particles collected by the Hayabusa spacecraft may not have suffered a large degree of chemical fractionation and are thus largely representative of the surface materials of Itokawa.

References and Notes
7. Materials and methods are available as supporting material on Science Online.
11. Some of the mm- to cm-sized particles might be agglomerations of smaller particles weakly bound by cohesive forces (25). We cannot exclude a possibility that the collected particles are these smaller particles broken apart by the sampling mechanism(s).
19. The 3D structures of lunar regolith particles (105 to 250 μm) at Apollo 16 landing site were measured by microtomography (bia = 0.79 ± 0.10 and cla = 0.61 ± 0.10) (26).
23. Few amounts of melting products were reported in ejecta in laboratory impact experiments with silicate rocks at impact velocities of ~4 to 5 km/s (27).
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Supporting Online Material
www.sciencemag.org/cgi/content/full/333/6046/1125/DC1
Materials and Methods
SOM Text
Figs. S1 to S4
Table S1
References (28–38)
Movies S1 and S2
2 May 2011; accepted 5 August 2011 10.1126/science.1207807
Supporting Online Material for

Three-Dimensional Structure of Hayabusa Samples: Origin and Evolution of Itokawa Regolith

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This PDF file includes:

- Materials and Methods
- SOM Text
- Figs. S1 to S4
- Table S1
- References

Other Supporting Online Material for this manuscript includes the following:
available at www.sciencemag.org/cgi/content/full/333/6046/1125/DC1

- Movies S1 and S2
Materials and Methods

Microtomography Imaging and Samples

X-ray tomography is the method to obtain internal structures by using signals that are obtained when an X-ray beam passes through an object. Tomography using X-ray absorption is a conventional method to give spatial distribution of X-ray linear attenuation coefficients (LACs) in a slice of an object as a digital image (CT image). Synchrotron radiation (SR) X-ray beams with high flux density and high coherence gives CT images of high spatial resolution and high S/N ratio. High flux X-ray beams are easily monochromated, and this gives quantitative LAC values in CT images, which can be used for identification of minerals and their rough chemical compositions. In addition, nano-scale resolution can be obtained by X-ray microscope optics that uses a Fresnel zone plate (FZP) for the imaging tomography.

The forty sample particles (RA-QD02-0009, 10, 11-1, 11-2, 13, 14, 16, 19, 21, 23, 24, 25-01, 25-02, 27, 28, 30, 31, 32, 34, 36, 38, 39, 41, 42, 43, 47, 48, 50, 54, 55, 57, 58, 60, 61, 62-1, 62-2, 63, 66, 67, 68) of the tapping samples analyzed in Hayabusa preliminary examination (3) were imaged using an absorption imaging tomography system (28,29) at BL47XU of SPring-8 in Hyogo, Japan (30). Each particle was attached to the end of a carbon fiber of 5 μm in diameter with epoxy resin (Embed 812, Electron Microscopy Sciences, USA). The particle was also covered entirely with a thin layer of the same resin to avoid oxidation of the sample.

We used two different X-ray energies, 7 and 8 keV, for the imaging. Multiple projection images (either 1800 or 1200) through a sample were taken by rotating each sample in small steps through a total of 180 degrees (0.1 or 0.15 deg./projection, respectively). CT images were reconstructed from projection images by a convolution back-projection algorithm (31). Three-dimensional (3D) structure was obtained by stacking successive CT images taken of different slices through the particle (Fig. S1).

Two different Fresnel zone plates were used to change the magnification factor on the detector because the sample size must be smaller than the field of view to obtain quantitative LACs of materials. The magnification factor is also changed by the X-ray energy; the sizes of voxel (pixel in 3D) are 85.7 and 98.6 nm at 7 and 8 keV, respectively, for small samples (<~100 μm), and 213 and 252 nm at 7 and 8 keV, respectively, for large samples (>~100 μm). The resulting effective spatial resolution is ~200 and ~500 nm for the small and large samples, respectively.

The LAC values in CT images were obtained using calibration, in which the LAC values of standards have been already measured at SPring-8 (32). It should be noted that characteristic artifacts in CT images are sometimes seen. They are (1) a concentric structure (ring artifact) (e.g., Figs. S1 334.tif and 1A), (2) a pair of bright and dark contrasts at the edge of an object due to refraction of the X-ray beams (e.g., upper left edges of particle in Fig. S1, and Figs. 1A,C,D), and (3) a shadow from an object with high absorption (e.g., arrow in Fig. S2B).

Since the K-absorption edge of Fe (7.11 keV) is present between the two energies used in the imaging experiments, K-, Ca-, and Cr-rich minerals (minerals with elements heavier than Si but lighter than Fe) have relatively large LAC values at 7 keV, while Fe-rich minerals have large LAC values at 8 keV (c.f., K-absorption edge of Ni at 8.33keV). The order of brightness in CT images, which is proportional to the LAC value, is as follows: chromite > taenite > kamacite ~ troilite ~ apatite > high-Ca pyroxene > olivine ~ low-Ca pyroxene > plagioclase at 7 keV, while kamacite > taenite > troilite > chromite > olivine ~ apatite > high-Ca pyroxene ~ low-Ca pyroxene > plagioclase at 8 keV (Figs. S3). Thus, we can distinguish most minerals in meteorites easily from pairs of CT images taken at both energies. As a result, 3D mineral distribution maps could be successfully obtained from the scanned particle. The mineral phases determined by the tomography are consistent with those by X-ray diffraction measurements and SEM/EDX and EPMA analysis (3).
The 3D CT images were processed and analyzed using a software package for basic 3D analysis, “Slice” (33). A solid object was extracted three-dimensionally by binarization of the CT images. Three-dimensionally closed pores were easily recognized in the binary images. However, cracks and most pores are three-dimensionally connected outward in the small Itokawa particles – such pores were originally part of larger mineral grains and grain aggregates before they were broken up. These “open pores” were recognized using a wrapping method (34). Then, the volumes of a solid object, closed pores and open pores were obtained respectively by counting the number of voxels in each domain. The porosity was calculated as $\frac{V_{CP} + V_{OP}}{V_S + V_{CP} + V_{OP}}$, where $V_S$, $V_{CP}$, and $V_{OP}$ are the volumes of solid object, closed pores and open pores, respectively. The sphere-equivalent diameter, $d$, was calculated from the total volume of a particle, $V_p = V_S + V_{CP} + V_{OP}$, as $d = \left(\frac{6V_p}{\pi}\right)^{1/3}$. The external shape of a particle can be recognized from the binary images for the solid object. Bird’s eye views of the particles from different observing angles were created (e.g., Figs. 4A,C and Movies S1 and S2). The shape of each solid object was approximated by an ellipsoid (35). The longest, middle, and shortest axial lengths, a, b, and c, respectively, of each object were obtained from the ellipsoid.

The modal abundances of minerals were obtained mainly from histograms of LAC values in CT images at 7 and 8 KeV (Figs. S2C,D). The number of voxels that correspond to each mineral was counted to obtain the volume of the mineral, as the voxel size is known (36). We adopted the LAC values at the minimal counts between the peaks of minerals as thresholds. To check the accuracy of this approach, the number of voxels for each mineral was counted manually on the 3D CT images. The difference for each mineral is less than ~8 vol.%, and the LAC values by the histograms were calibrated against the values by the manual painting. Finally, the modal abundances for the whole samples were obtained by considering the volumes of solid particles (Table S1). The errors could not be evaluated qualitatively. However, the errors of olivine, low-Ca and high-Ca pyroxenes, plagioclase and troilite are low (on the order of 10%) while those of minor elements are relatively large (on the order of 50%). Modal abundances of ordinary chondrites (7,37) are also shown in Table S1. The densities of minerals were calculated from the mean chemical compositions of the minerals (3). When the mineral forms solid solutions, the density was calculated using an empirical relation between the density and the Mg/(Mg+Fe) ratio for olivine (38) and linear interpolation between the densities of end members (Vegard’s law) for pyroxenes, plagioclase, chromite, and Fe-Ni metal. The mass of each mineral was calculated from the volume and density, and then the total mass (14.5 μg) and bulk density was obtained (3.4 g/cm³). The bulk chemical composition for the whole sample was also calculated from the mass abundances of the minerals and their chemical compositions in (3).

SOM Text

The Role of Microtomography in Preliminary Examination

Use of microtomography together with XRD (3) for non-destructive analysis can provide key information for the design of later destructive analyses of the same particle. This is one of the key features of the Hayabusa preliminary examination strategy for the analytical flow sequential studies of tapping sample particles. 3D mineral distribution maps, together with the measured external shape of each particles, provides critical information concerning where a particle should be cut to ensure later destructive analyses examine the best areas of specific minerals in cross sections of these small particles.

As a first step, we use the tomographic information to determine an optimal direction for embedding a sample particle into a resin to obtain the best cross section. The particle was then embedded into a resin according to the optimal direction. Then, the resin with the embedded sample was polished manually before obtaining a small cross sectional area of the particle. A cross sectional CT image
closest to the optical microscopic image of the real sectional area was searched by examining CT images cutting from different directions from the original 3D CT images. Thus, we know the exact cutting direction in the 3D coordinate and the depth of the best sectional position from the current position resulting from the previous polishing. Then, the resin was polished again to obtain the desired section of the particle. The final SEM and corresponding CT images are shown in Figures S4A and S4B, respectively. The vertical and horizontal CT images are also shown in Figure S4C and S4D, respectively. The largest cross sectional areas of grains of chromite, one of the important accessory minerals, were obtained in this cross section. The chemical compositions of chromite were effectively measured by EPMA to compare the sample with the ordinary chondrites (3).

In addition to searching specific mineral phases, carbonaceous materials in a particle can be identified by the microtomography if they are present since they have very low LAC values at both 7 and 8 keV (e.g., carbon in Figs. S3A,B). In this case, we would cut the particle to obtain the best cross section for the carbonaceous materials, and analyses using PEEM/XANES for carbon and TOF-SIMS would be used. Unfortunately, we have not found any carbonaceous materials in the tapping sample particles examined so far.

Estimation of the pressure of the spacecraft during the second touchdown and possible sampling mechanisms

Although detailed conditions for the spacecraft’s second touchdown are not known, the pressure at the tip of the sampler horn, which had a radius of 85 mm and a width of 5 mm, is estimated to have been ~0.02 MPa during touchdown (lasting 1 sec). The spacecraft mass was ~500 kg at the time of touchdown and the velocities of approach and take off were ~0.05 m/s (2). The pressure of the spacecraft on the surface was therefore significantly lower than the particle strengths (> 1MPa).

There are three possible models for the mechanism by which small particles made it into the sample container: (1) impact model, where particles were lifted up when the sampler horn hit Itokawa’s surface, (2) electrostatic model, where charged particles were lifted up by electrostatic interaction with the sampler horn if the horn was charged with the same sign as the particles, and (3) thruster model, where particles were lifted up by thruster jet plumes from the ascending spacecraft after the touchdown. Since we do not know the detailed conditions of the touchdown and the charging state of the sample horn, we cannot specify which mechanism(s) are probable.

In the impact model, the velocity of collected particles does not depend on the particle size, but the position (distance from the impact point). Hence, size selection probably does not occur for this mechanism. In the electrostatic model, size selection will not occur if the charge on particles is proportional to their mass. However, any non-linear relationship between the charge and mass of particles would lead to some size selection effects. As the electrical condition (charge amount, positive/negative, etc.) of particles and the spacecraft at the time of collection is not known, it is not clear whether this mechanism applies to the collection, and if it did, whether this resulted in any size selection effects. In the thruster model, particles are lifted by gas flow from thruster plumes that hit the surface and size selection would be expected to occur in a manner that favored the collection of smaller, more easily levitated particles.
Fig. S1.
Successional 3D CT images of an Itokawa particle (RA-QD02-0031) at 7 keV. CT images from every 67th slice (14.3 μm interval) are shown. Mineral identifications based on LAC values are labeled as Ol: olivine, Hpx: high-Ca pyroxene, Pl: plagioclase, Tr: troilite, and Chm: chromite.
Fig. S2
CT images and LAC histograms of RA-QD02-0031 (the same particle as in Fig. S1). (A) A CT image at 7 keV. (B) A CT image in the same section of (A) at 8 keV. (C) and (D) show histograms of the LACs for the whole particle at 7 and 8 keV, respectively. Abbreviations for minerals are the same as in Figure S1.
Fig. S3

Linear attenuation coefficients (LACs) of minerals. (A) LAC values at 7 keV plotted against those at 8 keV. (B) A close up of (A) spanning the ranges of silicate minerals. Lines show the ranges of minerals with solid solutions. Points show the mean chemical compositions of the minerals in Itokawa particles (3). Quartz (Qz) and NaCl-KCl, which were found in the spatula sample particles (3) but not found in the tapping sample particles. The position of the LAC values for graphite carbon (Gr) is also shown. Mineral labels are as follows - Fo: forsterite, Fa: fayalite, LPx: low-Ca pyroxene, En: enstatite, Fs: ferrosilite, Di: diopside, Hd: hedenbergite, Ab: albite, An: anorthite, Qz: quartz, Gr: graphite, Ap: apatite, Kam: kamasite, Tae, taenite. Other abbreviations for minerals are the same as in Figure S1.
**Fig. S4**

A final cross section of RA-QD02-0031 (the same particle as in Figs. S1 and S2). (A) An FE-SEM back-scattered electron image. The particle is embedded in a resin. (B) A CT images corresponding to the FE-SEM section shown in (A). (C) A CT image of a vertical section of (B) after the left part was removed by polishing. (D) A CT image of a horizontal section of (B) after the upper part was removed by polishing. Abbreviations for minerals are the same as in Figure S1.
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* (8)
** (37)

# Density of minerals calculated from their average chemical compositions (3).
& Calculated form the volume percent and the density of the minerals and the porosity for mainstream particles.

Table S1.
Modal abundances of minerals of Itokawa particles and ordinary chondrites.

Movie S1
Successional bird’s eye view images of an Itokawa particle (RA-QD02-0023: the same particle as in Figure 4A), box size: 133x137x157 μm.

Movie S2
Successional bird’s eye view images of an Itokawa particle (RA-QD02-0042: the same particle as in Figures 1C and 4C), box size: 66.3x91.0x88.8 μm.

References and Notes

7. Materials and methods are available as supporting material on *Science* Online.


11. Some of the mm- to cm-sized particles might be agglomerations of smaller particles weakly bounded by cohesive forces (25). We cannot exclude a possibility that the collected particles are these smaller particles broken apart by the sampling mechanism(s).


19. The 3D structures of lunar regolith particles (105 to 250 μm) at Apollo 16 landing site were measured by microtomography (b/a = 0.79 ± 0.10 and c/a = 0.61 ± 0.10) (26).


23. Few amounts of melting products were reported in ejecta in laboratory impact experiments with silicate rocks at impact velocities of ~4 to 5 km/s (27).


30. Catcher B, which correspond to the first touchdown (2), has not yet been examined, so we currently do not know whether it contains any additional particles from Itokawa.


36. Strictly speaking, because the histogram peaks of olivine, low-Ca pyroxene, and plagioclase are almost overlapped at 7 keV (e.g., fig. S2C) and those of low-Ca pyroxene and high-Ca pyroxene are almost overlapped at 8 keV, we counted the numbers of voxels for the mineral groups at 7 and 8 keV, respectively. Because we can count the number of voxels for high-Ca pyroxene at 7 keV and those of olivine and plagioclase separately, the number of the voxels for low-Ca pyroxene can be obtained from the mineral group data.
