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

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supporting N_2 purge sample preparation at the Institute of Space and Astronautical Sciences of the Japan Aerospace Exploration Agency and Ibaraki University, and for STEM observation at Hitachi High-Technologies. Thanks to H. Hidaka, we could compare the rims of the Itokawa particles and those of space-weathered lunar soil. M. Zolensky was supported by NASA's Muses-C/Hayabusa Program.

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

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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 polymineralic, 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 (vol.) %] 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 less 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

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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

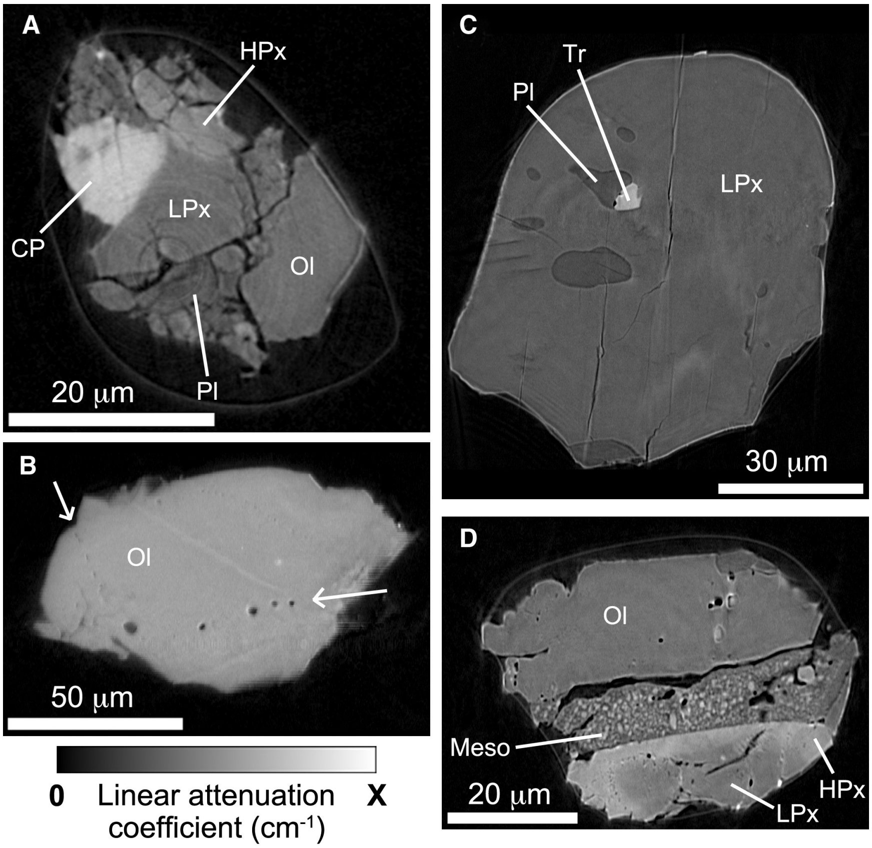
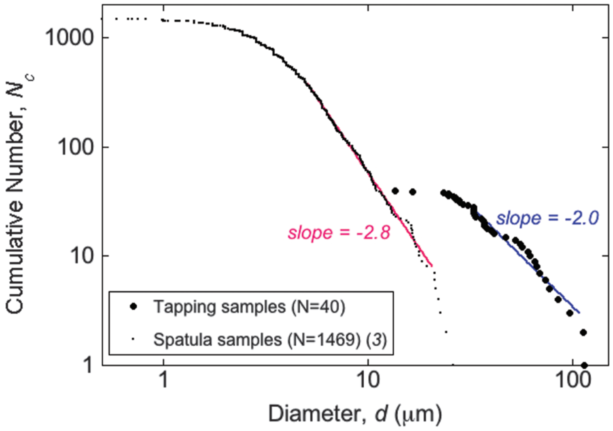


Fig. 1. Slice images of Itokawa particles obtained by microtomography with a gray scale showing the linear attenuation coefficient (LAC) of objects (from 0 to *X* cm^{-1}), where *X* is the maximum LAC value in the CT images. (**A**) Sample RA-QD02-0063 (7 keV, *X* = 431 cm^{-1}). (**B**) RA-QD02-0014 (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:√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).

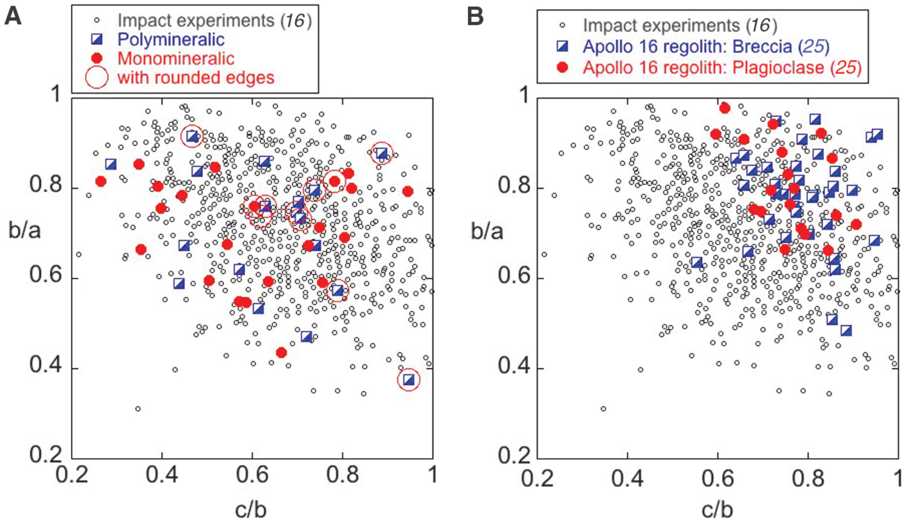


Fig. 3. The 3D shape distributions of (**A**) Itokawa particles and (**B**) lunar regolith (*19*, *26*). Fragments of impact experiments (*16*) are also shown in both graphs. Large circles in (A) shows particles with rounded edges.

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 (*1*). 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

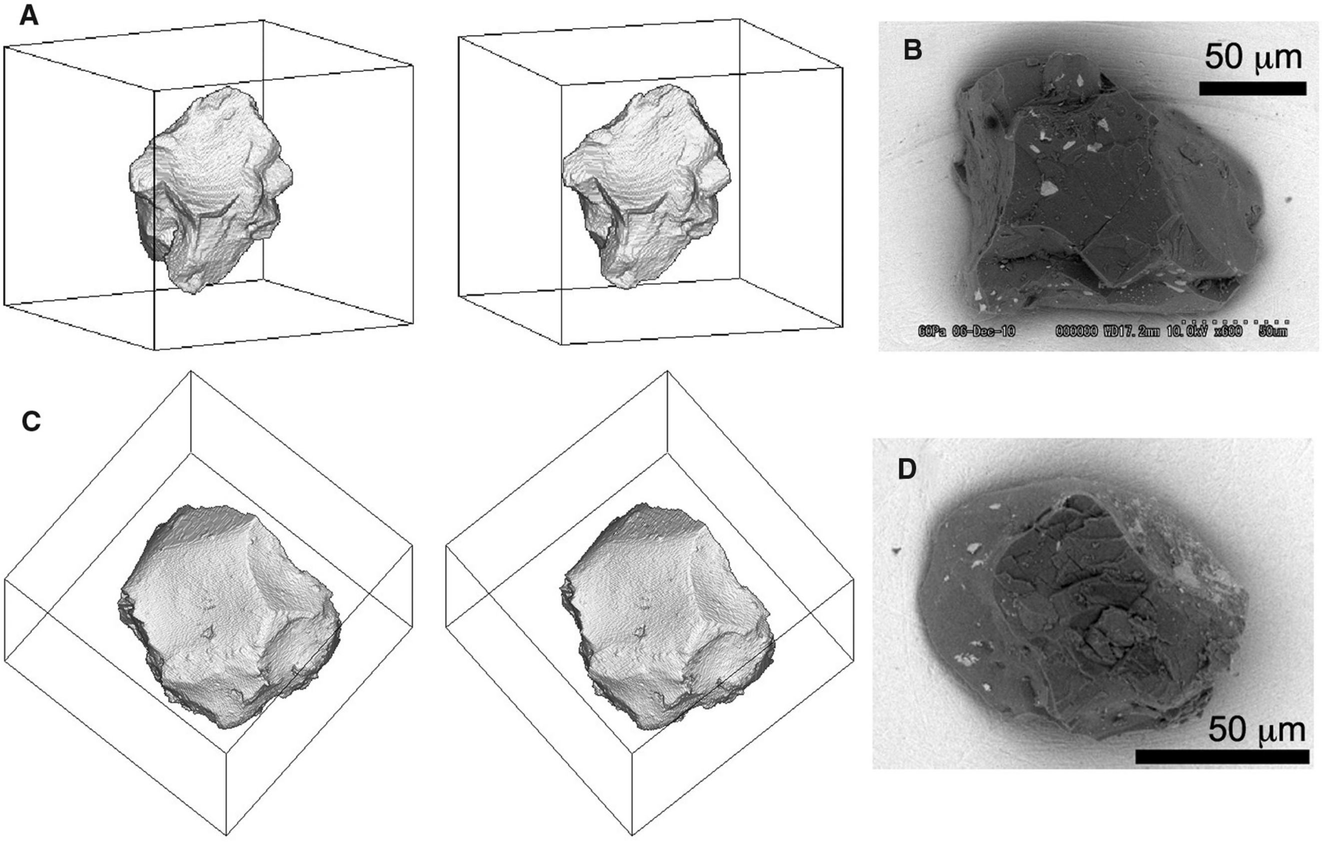


Fig. 4. The 3D external shapes of Itokawa particles. (**A**) Stereogram (box size 232 μm by 232 μm by 203 μm) and (**B**) SEM micrograph of RA-QD02-0023. (**C**) Stereogram (box size, 112 μm by 112 μm by 93 μm) and (**D**) SEM micrograph of RA-QD02-0042.

(~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.

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Supporting Online Material

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Irradiation History of Itokawa Regolith Material Deduced from Noble Gases in the Hayabusa Samples

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Noble gas isotopes were measured in three rocky grains from asteroid Itokawa to elucidate a history of irradiation from cosmic rays and solar wind on its surface. Large amounts of solar helium (He), neon (Ne), and argon (Ar) trapped in various depths in the grains were observed, which can be explained by multiple implantations of solar wind particles into the grains, combined with preferential He loss caused by frictional wear of space-weathered rims on the grains. Short residence time of less than 8 million years was implied for the grains by an estimate on cosmic-ray–produced ^{21}Ne. Our results suggest that Itokawa is continuously losing its surface materials into space at a rate of tens of centimeters per million years. The lifetime of Itokawa should be much shorter than the age of our solar system.

The Hayabusa spacecraft arrived at asteroid 25143 Itokawa in November 2005. Itokawa is a small (535 by 294 by 209 m) (*1*) S-type asteroid with the appearance of a rubble pile. Global remote-sensing observations revealed that there are two geological settings, boulder-rich rough terrains and smooth terrains (*2*–*4*). Hayabusa carried out two touchdowns on a smooth terrain, MUSES-C Regio, and collected regolith particles disturbed by the touching down of the sampler horn (*5*). After the sampling, Hayabusa returned to Earth, and the sample capsule was successfully recovered on 13 June 2010. The sample container was opened at the curation facility of the Japan Aerospace Exploration Agency (JAXA), and a large number of small particles were found. Scanning electron microscope energy-dispersive

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