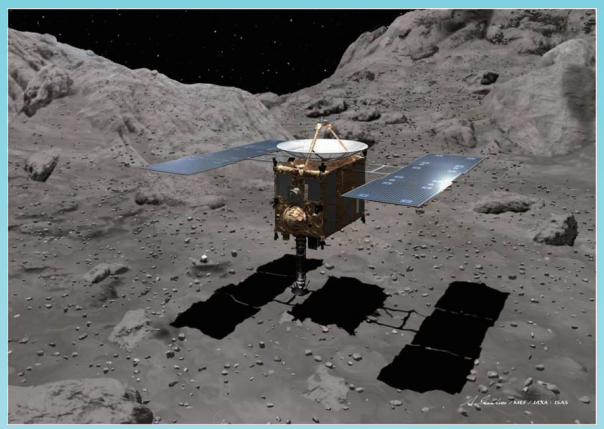
Earth, Planets and Space

Science of solar system materials examined from Hayabusa and future missions



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PREFACE Open Access

The *Earth, Planets and Space* Special Issue: "Science of solar system materials examined from Hayabusa and future missions"

Tatsuaki Okada[1*], Michael E. Zolensky[2], Trevor R. Ireland[3] and Toru Yada[1]

It is our great pleasure to present the special issue of the journal *Earth, Planets and Space*, entitled "Science of solar system materials examined from Hayabusa and future missions." We would like to start with a brief introduction of the Hayabusa mission and its story of sample collection on the asteroid, followed by the curation and delivery of returned samples to researchers. All of the 14 manuscripts published in this special issue are also reviewed here.

Hayabusa was the Japan Aerospace Exploration Agency (JAXA) engineering mission to explore and return a sample from a near-Earth asteroid. It was launched in 2003 by 5th M-V launch vehicle, visited and explored asteroid 25143 Itokawa in 2005, and finally returned surface materials from there to Earth in 2010. The purpose of this mission was an engineering experiment of a round-trip journey to the asteroid, as well as scientific experiments for understanding the origin and evolution of the early solar system by exploring a primitive body. The S-type, sub-kilometer-sized asteroid Itokawa was found to be chondritic in composition and low-density rubble-pile in structure (e.g., Fujiwara et al. 2006). Its surface was basically rough and covered with boulders, but smooth terrains such as MUSES-C Regio also existed where the first and second touchdown operations were conducted for sample collection (see Fig. 1).

The returned samples have been curated in JAXA's Extraterrestrial Sample Curation Center. These samples are of small amount and very fine grained, because the impact-sampling method failed to shoot projectiles for sample acquisition and only floating dust grains entered into the sample catcher (see Fig. 2). Thousands of micron-sized silicate-dominated grains other than artificial contaminants were found by scraping them from the inside wall of the catcher with a Teflon spatula and tapping on the chamber. These samples are consistent with chondritic composition as shown by scanning electron microscopy (SEM) with energy-dispersive X-ray spectroscopy (EDS). The removal of tens of micron-sized particles (up to 300 μm) in the catcher was started using the newly developed electrostatic control manipulator. So far, about 500 particles have been catalogued for initial description about size, shape, SEM images, and representative elemental and mineral composition from EDS spectra (e.g., Yada et al. 2014), and part of those catalogued particles have been delivered for more advanced research including preliminary examinations and through an international announcement of opportunity.

The preliminary examination of Hayabusa-returned samples has successfully unveiled the mineralogical, petrographic, chemical, and isotopic relationships between an S(IV)-type asteroid and ordinary LL chondrite meteorites as predicted by ground-based observation (e.g., Binzel et al. 2001, 2010) and provided the first direct evidence that meteorites originate from asteroids (Ebihara et al. 2011; Nakamura et al. 2011; Noguchi et al. 2011; Tsuchiyama et al. 2011; Yurimoto et al. 2011). The particle-size distribution and existence of rounded grains (Tsuchiyama et al. 2011) as well as the noble gas isotopic compositions (Nagao et al. 2011) have also recorded asteroid surface processes such as meteoroid impacts, possible granular flow, and solar wind irradiation on the asteroid surface, which were not observed in meteorites. Organic analyses have been also performed (Kitajima et al. 2011; Naraoka et al. 2012), but indigenous organic compounds have not been identified from the samples to date.

Investigation of Hayabusa-returned samples has expanded to any interested researchers by applying to the International Announcement of Opportunity, and the successful winners started their advanced and sophisticated research. Hayabusa 2013: 1st Symposium of Solar

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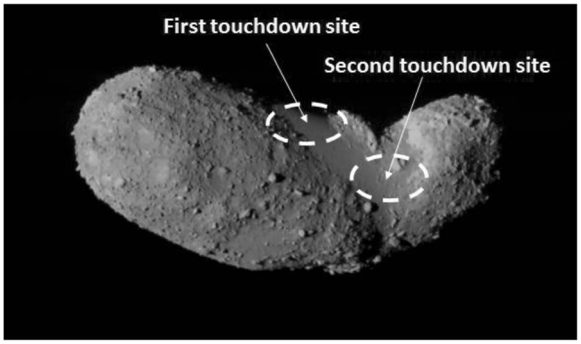

Fig. 1 Digital image of asteroid 25143 Itokawa and the estimated first (high-latitude region) and second (equatorial region) touchdown sites. Both sites are inside a flat terrain MUSES-C Regio. The image was taken from Home Position with ONC-T imager on 10 October 2005. (ST_2448357351_v, http://darts.isas.jaxa.jp/planet/project/hayabusa/amica.pl)

System Materials was held for these researchers to come together and discuss their latest results, giving new prospects to understanding the asteroid-meteorite connection and the early solar system origin and evolution. All the papers presented in the symposium were invited for submission to this *EPS* special issue, and any papers related to the topics were also welcomed. In the end, 14 manuscripts were successfully completed for publication in this special issue.

Among the important topics discussed here are the surface processes discovered in the ultrafine structures of Hayabusa-returned samples, influenced by space weathering or shock or thermal alteration mechanism. This was enabled by advanced analytical techniques for ultrafine grains using transmission electron microscopy after preparing ultrathin-sectioned specimens using ultramicrotomy and focused ion beam techniques.

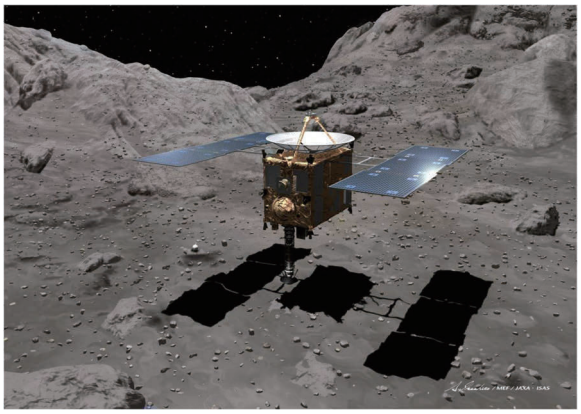

Fig. 2 An artist view of the Hayabusa spacecraft just a moment before the touchdown on the surface of asteroid 25143 Itokawa for sampling with the horn-shaped sampler (Ikeshita/MEF/JAXA-ISAS). Actual result was that the impact sampling failed to shoot the projectile for excavating the surface materials and collecting part of them into the sample catcher, but only the dusts floating around there were obtained and consequently returned to Earth

Keller and Berger (2014) report on their detailed structural and elemental analysis by scanning and transmission electron microscopy of two particles returned by Hayabusa, which have a 50- to 100-nm-thick disordered olivine rim surrounding the particles. This evidence of space weathering by irradiation of solar wind ions and the number density of ion particle track in the rim suggest the short exposure age of 10^3 to 10^4 years. Noguchi et al. (2014) report results of detailed mineralogical investigation of four Itokawa particles collected from the first touchdown site by micro-Raman spectroscopy, scanning electron microscopy, electron microprobe analysis, X-ray absorption spectroscopy, and transmission electron microscopy and conclude that those particles are consistent with LL6 and that space weathering (space-weathered rim and number densities of solar flare tracks) at this site was less severe than at the second touchdown site reported in the initial analysis (Noguchi et al. 2011), which suggests uncertainty in the previously reported exposure history of the surface, and 10^3 years rather than 10^4 years of exposure age. Thompson et al. (2014) report detailed microchemical and microstructural features indicative of space weathering in a Hayabusa-returned particle using transmission electron microscopy of the microtomed ultrathin section of rim regions. They suggest that solar wind irradiation is likely responsible for the surface amorphous regions and the multi-layered rims with a nano-crystalline outer layer underlain by an amorphous inner layer are derived both from micrometeorite impacts and solar wind irradiation, indicating multiple surface-processing events on the asteroid. Langenhorst et al. (2014) report detailed analytical scanning and transmission electron microscopic investigations on one olivine-dominated Itokawa particle, which suggests that the particle is of LL-chondrite origin as previously reported and that even regolith particles lacking visible microcraters on their surfaces might have still experienced shock metamorphism and were involved in collisional fragmentation. In Harries and Langenhorst (2014), analysis of another Itokawa particle suggests a lower abundance of shock metamorphism relative to the one by Langenhorst et al. (2014), indicating heterogeneity of shock events on Itokawa or on its parent body. A thin polycrystalline olivine rim on one face of the particle may have originated by solar wind irradiation, followed by annealing and recrystallization, which may have occurred due to the warmer surface temperature of Itokawa near perihelion distances by dynamical orbital evolution.

New analyses and discussion also strengthen the previous results and contribute to building the new prospects of asteroid and solar system science. Mikouchi et al. (2014) report the results of a mineralogical investigation

of seven Itokawa particles collected from the first touchdown site of Itokawa through field emission secondary electron microscopy, synchrotron radiation X-ray diffraction, and X-ray absorption near-edge structure analysis and concluded that the particles are slightly shocked equilibrated LL chondrite, as suggested in the preliminary examination. Connolly et al. (2015) discussed the formation of rounded shape grains included in the samples returned by Hayabusa (e.g., Tsuchiyama et al. 2011) and argued that the Itokawa surface was in a high-energy environment possibly caused by the YORP effect to raise a continuous granular flow. In their hypothesis, the portion of rounded to angular grains is higher for C-type relative to S-type asteroids, which could be verified by samples returned by Hayabusa 2 or OSIRIS-REx. Takeda et al. (2015) report on the mineralogy of three LL chondrites (possibly related to Itokawa) that partial melts found in them indicate that even a primitive solar system parent body of such as LL chondrites experienced partial melting and suggests that granulitic materials may have been formed at depths within their parent body by an impact event.

Discussions concerning the category 3 particles are specially featured topics in this special issue. Hayabusa-returned samples are classified into four categories. Category 1 and 2 particles consist of silicate minerals without or with a metallic component, respectively, and most of them are considered to have been indigenous to Itokawa. Category 4 includes artificial materials from inside the sample catcher or from the sampling tools. Category 3 particles from Itokawa represent a number of samples that are predominantly composed of carbon or carbon compounds. The lack of carbon in any of the type I or II grains that have been proven to originate on Itokawa has raised suspicion that the category 3 particles are contaminants of possibly terrestrial origin or are materials that may have originated from the surface of the Hayabusa spacecraft. In a series of five studies in this issue, the possible origins of category 3 particles are addressed.

Uesugi et al. (2014) report preliminary results of the analyses of five category 3 (carbonaceous) materials removed from the Hayabusa spacecraft sample catcher and conclude that differences in their microstructure and elemental distributions suggest multiple origins. They also inform the summary of damage occurring on those samples by each analytical process as lessons learned for future sample return analysis of carbonaceous materials expected by the Hayabusa 2 and OSIRIS-REx missions. Ito et al. (2014) have measured H, C, and N isotopic compositions of three category 3 particles with ion imaging on a nanoSIMS ion microprobe. Isotopic compositions of these elements are quite variable in extraterrestrial samples; however, they have found that the isotopic compositions are all within error of terrestrial. Kitajima et al. (2015) performed micro-Raman and infrared analysis of the same three particles as measured by Ito et al. (2014). They found that the Raman spectra show disordered parameters associated with a low-maturity level, and hence, the particles are not associated with the Itokawa asteroid particles. Naraoka et al. (2015) report TOF-SIMS analysis of three category 3 particles [only one in common with Ito et al. (2014) and Kitajima et al. (2015)] in order to determine elemental compositions. These analyses have proven to be difficult because the particles have been part of an extended analytical program, and in particular, the Cs primary ion beam used in the nanoSIMS analysis has pervaded the grain. Nevertheless, Naraoka et al. (2015) found organic carbon associated with nitrogen, fluorine, and silicon, which are uncommon in nature but quite common in man-made materials. They concluded that the category 3 particles are likely man-made rather than natural organic matter. Based on these studies, it appears that the category 3 particles are not associated with Itokawa but their specific site of origin is difficult to determine. On the other hand, Yabuta et al. (2014) report results of analyses by scanning transmission X-ray microscopy using carbon-, nitrogen-, oxygen-, fluorine-, and calcium-X-ray absorption near-edge structure (XANES) spectroscopy for different kinds of two carbonaceous particles removed from the Hayabusa spacecraft sample catcher. These were distinct from commercial or biologic fresh materials, but they were unable to rule out an extraterrestrial origin for some of these particles.

Additional featured topics discussed in the symposium and also in this special issue are instrumentation and methods for sample analysis, as well as remote sensing or ground-based observations for asteroids, comets, and meteors. The only such manuscript published in this special issue is by Mediedo (2014), which reports the newly developed ground robotic spectroscopic observation system for determining the composition of fireballs, the solar system materials ablating during atmosphere entry. The derived physico-chemical data are expected to contribute to a systematic characterization of materials coming from different comets and asteroids.

All the 14 manuscripts in this special issue are fruitful and constructive for discussion about the asteroid-meteorite connection and the early solar system origin and evolution. Detailed analysis of Hayabusa-returned samples is not yet complete and will continue with more sophisticated and more statistically significant analyses and techniques. In the near future, sample returns from C-type asteroid 1999JU3 by Hayabusa 2 in 2020 and from B-type asteroid Bennu by OSIRIS-Rex in 2023 are expected to advance asteroid and solar system science, and we believe that the developed methodology and lessons learned from the analysis of the Hayabusa-returned samples will play a significant role in these missions.

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FRONTIER LETTER Open Access

Mineralogy and crystallography of some Itokawa particles returned by the Hayabusa asteroidal sample return mission

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Abstract

We studied seven Itokawa particles provided by the Japan Aerospace Exploration Agency (JAXA) as first International Announcement of Opportunity (AO) study mainly using electron and synchrotron radiation X-ray beam techniques. All the analyzed particles were collected from the first-touchdown site and composed of olivine and plagioclase with traces of Ca phosphate and chromite, and do not contain pyroxenes. Optical microscopy of these particles shows minor undulatory extinction of olivine and plagioclase, suggesting minor shock metamorphism (shock stage: S2). The electron microprobe analysis shows that olivine is $Fo_{70\text{-}73}$ and plagioclase is $An_{13\text{-}10}Or_{5\text{-}7}$. The synchrotron radiation X-ray diffraction (SR-XRD) analysis of olivine crystals gives cell dimensions of $a = 4.708$ to 4.779 Å, $b = 10.271$ to 10.289 Å, $c = 6.017$ to 6.024 Å, corresponding to the Fo content of $Fo_{\sim 70}$ by Vegard's law. This composition matches the result obtained by the electron microprobe analysis. The olivine compositions of the analyzed particles are consistent with those of LL chondrites. The cell dimensions of two plagioclase crystals ($a = 8.180$ to 8.194 Å, $b = 12.53$ to 12.893 Å, $c = 7.125$ to 7.23 Å, $\alpha = 92.6°$ to 93.00°, $\beta = 116.36°$ to 116.75°, $\gamma = 90.03°$ to 90.17°) indicate that their equilibration temperatures are 800°C ± 10°C. This temperature is near the peak metamorphic temperature recorded by equilibrated ordinary chondrites. The size of plagioclase crystals and the homogeneity of olivine compositions indicate that their petrologic type is ≥5. We also analyzed plagioclase by SR iron X-ray absorption near-edge structure (SR-XANES) and found that its $Fe^{3+}/(Fe^{2+} + Fe^{3+})$ ratio is approximately 0.5. Such high Fe^{3+} abundance indicates the formation under a relatively oxidizing environment. Thus, all these analyses have reconfirmed that the Itokawa particles returned by the Hayabusa spacecraft are very weakly shocked equilibrated LL chondrites, which matches the results of the preliminary examination team.

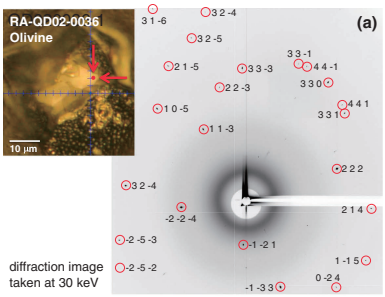

Figure 1

Keywords: Itokawa; Hayabusa; Olivine; Plagioclase; SR-XRD; SR-XANES; LL chondrites

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FRONTIER LETTER Open Access

Microchemical and structural evidence for space weathering in soils from asteroid Itokawa

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Abstract

Here we report microchemical and microstructural features indicative of space weathering in a particle returned from the surface of asteroid Itokawa by the Hayabusa mission. Space weathering features include partially and completely amorphous rims, chemically and structurally heterogeneous multilayer rims, amorphous surface islands, vesiculated rim textures, and nanophase iron particles. Solar-wind irradiation is likely responsible for the amorphization as well as the associated vesiculation of grain rims. The multilayer rims contain a nanocrystalline outer layer that is underlain by an amorphous inner layer, and both have compositions that are distinct from the underlying, crystalline orthopyroxene grain. The multilayer rim features could be derived from either radiation-induced sputter deposition or vapor deposition from micrometeorite impact events. The amorphous islands on grain surfaces have a distinctive morphology and composition suggesting that they represent surface deposits of melt derived from micrometeorite impact events. These observations indicate that both irradiation damage and micrometeorite impacts play a role in surface modification and space weathering on asteroid Itokawa.

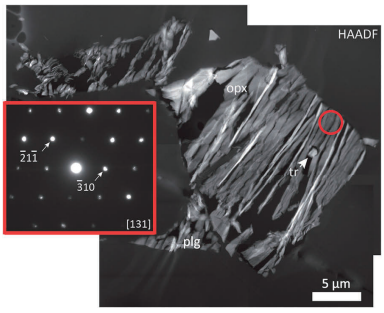

Figure 1

Keywords: Hayabusa; Itokawa; Space weathering; Irradiation; Micrometeorite impact; Airless body; Transmission electron microscopy; Sample return analysis

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FRONTIER LETTER Open Access

Mineralogy and defect microstructure of an olivine-dominated Itokawa dust particle: evidence for shock metamorphism, collisional fragmentation, and LL chondrite origin

Falko Langenhorst*, Dennis Harries, Kilian Pollok and Peter A van Aken

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Abstract

We report here detailed analytical scanning and transmission electron microscopic investigations on an olivine-dominated dust particle (RB-QD04-0042) from the surface of asteroid 25143 Itokawa. The dust particle was returned to Earth by the Hayabusa spacecraft and was made available in the context of the first announcement of opportunity for Hayabusa sample investigation. Multiple thin slices were prepared from the precious particle by means of focused ion beam thinning, providing a unique three-dimensional access to its interior. The 40×50 μm sized olivine particle contains a spherical diopside inclusion and an intimate intergrowth of troilite and tetrataenite. The compositions of olivine ($Fo_{69}Fa_{31}$) and diopside ($En_{48}Wo_{42}Fs_{10}$), as well as the high Ni content of the sulfide-metal alloy, indicate a *LL* ordinary chondrite origin in accord with previous classifications. Although no impact crater exists at the surface of RB-QD04-0042, transmission electron microscopy revealed the presence of various shock defects in constituent minerals. These defects are planar fractures and [001] screw dislocations in olivine, multiple {101} deformation twins in tetrataenite and basal (0001) stacking faults in troilite. These diagnostic shock indicators occur only in a small zone on one concave side of the dust particle characterized by a high fracture density. These observations can be explained by a collisional event that spalled off material from the particle's surface. Alternatively, the dust particle itself could be a spallation fragment of an impact into a larger regolith target. This suggests that Itokawa dust particles lacking visible microcraters on their surfaces might have still experienced shock metamorphism and were involved in collisional fragmentation that resulted in the formation of regolith.

Keywords: Hayabusa; Itokawa; Shock metamorphism; Collisional fragmentation; Ordinary chondrite; Olivine; Tetrataenite; Troilite; Diopside

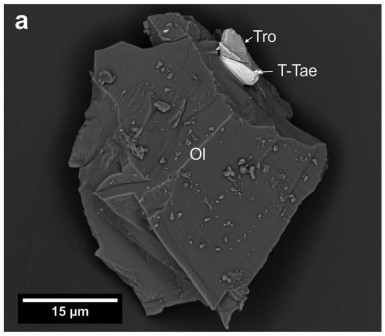

Figure 1

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FULL PAPER Open Access

Mineralogy of four Itokawa particles collected from the first touchdown site

Takaaki Noguchi*, John C Bridges, Leon J Hicks, Steven J Gurman, Makoto Kimura, Takahito Hashimoto, Mitsuru Konno, John P Bradley, Ryuji Okazaki, Masayuki Uesugi, Toru Yada, Yuzuru Karouji, Masanao Abe, Tatsuaki Okada, Takuya Mitsunari, Tomoki Nakamura and Hiroyuki Kagi

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Abstract

Four Itokawa particles collected from the first touchdown site were mineralogically investigated by optical microscopy, micro-Raman (μ-Raman) spectrometry, scanning electron microscopy (SEM), electron microprobe analysis (EPMA), X-ray absorption spectroscopy (XAS), and transmission electron microscopy (TEM). Their mineralogy has an affinity to that of LL6 chondrites based on micro-Raman spectroscopy, EPMA, and XAS analyses. However, the space weathering rims on them are less developed than those observed on the Itokawa particles collected from the second touchdown site. Solar flare tracks are rarely observed in the four particles, whose number densities were lower than those observed in the Itokawa particles from the second touchdown site.

Keywords: Itokawa; XANES; EPMA; TEM; Space weathering; Solar flare tracks

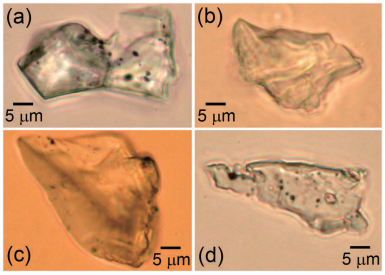

Figure 1

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LETTER Open Access

Robotic systems for the determination of the composition of solar system materials by means of fireball spectroscopy

José M Madiedo

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Abstract

The operation of the automated CCD spectrographs deployed by the University of Huelva at different observatories along Spain is described. These devices are providing information about the chemical nature of meteoroids ablating in the atmosphere. In this way, relevant physico-chemical data are being obtained from the ground for materials coming from different bodies in the Solar System (mainly asteroids and comets). The spectrographs, which work in a fully autonomous way by means of software developed for this purpose, are being employed to perform a systematic fireball spectroscopic campaign since 2006. Some examples of meteor spectra obtained by these devices are also presented and discussed.

Keywords: Meteors; Meteoroids; Meteorites; Asteroids; Comets

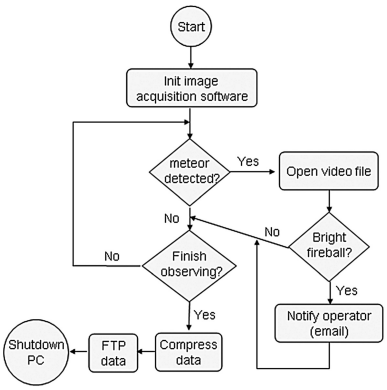

Figure 1

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LETTER Open Access

A transmission electron microscope study of Itokawa regolith grains

Lindsay P Keller* and Eve L Berger

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Abstract

Analyses of two olivine-rich particles from asteroid 25143 Itokawa returned by the Hayabusa mission (RA-QD02-0125 and RA-QD02-0211) show evidence for space weathering processes that occurred in the Itokawa regolith. Submicrometer impact-derived crystalline and glassy grains are observed adhering to the surfaces of the particles, including albite, orthopyroxene, olivine, augite, pyrrhotite, troilite, melt splashes, and melt spherules. Both particles are surrounded by 50- to 100-nm-thick disordered rims that are nanocrystalline, not amorphous, and compositionally similar to the grain cores. A pyrrhotite grain attached to RA-QD02-0125 also shows a disordered rim that is sulfur-depleted with nanophase Fe metal grains decorating the outermost surface. The structurally disordered rims on the Hayabusa particles likely result from atomic displacement damage from solar wind ions given the similarity of the rim thickness compared to the implantation depth of solar wind ions. The outermost few nanometers of the disordered rims are more Si-rich and Mg- and Fe-depleted relative to the cores of the grains and likely represent a minor accumulation of impact-generated vapors or sputter deposits. Nanophase Fe metal particles are present in the rim on RA-QD02-0211 but were not detected in the rim on RA-QD02-0125. Solar flare particle tracks are observed in RA-QD02-0211 but were not observed in RA-QD02-0125, suggesting short surface exposure times for the particles, on the order of approximately 10^3 to 10^4 years. This result implies that the optical effects of space weathering develop far more rapidly than was previously recognized.

Keywords: Hayabusa; Itokawa; Space weathering; Irradiation; Micrometeorite impact; Solar flare tracks; Transmission electron microscopy

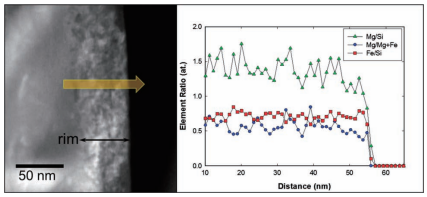

Figure 1

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LETTER Open Access

H, C, and N isotopic compositions of Hayabusa category 3 organic samples

Motoo Ito*, Masayuki Uesugi, Hiroshi Naraoka, Hikaru Yabuta, Fumio Kitajima, Hajime Mita, Yoshinori Takano, Yuzuru Karouji, Toru Yada, Yukihiro Ishibashi, Tatsuaki Okada and Masanao Abe

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Abstract

Since isotopic ratios of H, C, and N are sensitive indicators for determining extraterrestrial organics, we have measured these isotopes of Hayabusa category 3 organic samples of RB-QD04-0047-02, RA-QD02-0120, and RB-QD04-0001 with ion imaging using a NanoSIMS ion microprobe. All samples have H, C, and N isotopic compositions that are terrestrial within errors (approximately ±50‰ for H, approximately ±9‰ for C, and approximately ±2‰ for N). None of these samples contain micrometer-sized hot spots with anomalous H, C, and N isotopic compositions, unlike previous isotope data for extraterrestrial organic materials, i.e., insoluble organic matters (IOMs) and nano-globules in chondrites, interplanetary dust particles (IDPs), and cometary dust particles. We, therefore, cannot conclude whether these Hayabusa category 3 samples are terrestrial contaminants or extraterrestrial materials because of the H, C, and N isotopic data. A coordinated study using microanalysis techniques including Fourier transform infrared spectrometry (FT-IR), time-of-flight secondary ion mass spectrometry (ToF-SIMS), NanoSIMS ion microprobe, Raman spectroscopy, X-ray absorption near edge spectroscopy (XANES), and transmission electron microscopy/scanning transmission electron microscopy (TEM/STEM) is required to characterize Hayabusa category 3 samples in more detail for exploring their origin and nature.

Keywords: H, C, and N isotopes; Ion imaging with NanoSIMS; Hayabusa organic samples

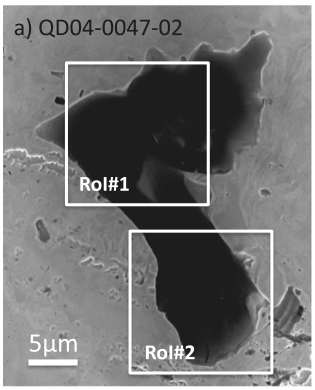

Figure 1

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LETTER Open Access

Sequential analysis of carbonaceous materials in Hayabusa-returned samples for the determination of their origin

Masayuki Uesugi*, Hiroshi Naraoka, Motoo Ito, Hikaru Yabuta, Fumio Kitajima, Yoshinori Takano, Hajime Mita, Ichiro Ohnishi, Yoko Kebukawa, Toru Yada, Yuzuru Karouji, Yukihiro Ishibashi, Takaaki Okada and Masanao Abe

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Abstract

Preliminary results of the analyses of five carbonaceous materials (particle size of approximately 50 μm) from the Hayabusa spacecraft sample catcher, including their texture, chemistry, and chemical/isotopic compositions, are summarized. The carbonaceous particles underwent sequential analysis using a series of microanalytical instruments located at several research institutes and universities. Collected particles were initially classified into four categories: two categories containing extraterrestrial silicate particles, one category containing metal and quartz particles consistent with contamination from the sample catcher or sample manipulation tools, and a final category containing carbonaceous particles. Analysis of this final category was the main focus of this study. Through examination of the carbonaceous materials, the appropriate analytical processes for sample transportation and handling were optimized to minimize sample damage and terrestrial contamination. Particles were investigated by transmission electron microscopy/scanning transmission electron microscopy, and Ca-carbonate inclusions were found in one particle. In a different particle, a heterogeneous distribution of silicon in a uniform C, N, and O matrix was found. Though further analysis is required for a strict determination of particle origin, the differences in the microstructure and elemental distribution of the carbonaceous particles suggest multiple origins.

Keywords: Hayabusa; Carbonaceous material; Sequential analysis; Microstructural observation by TEM/STEM

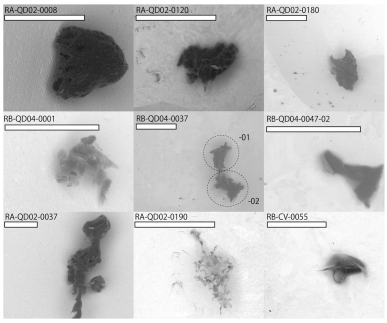

Figure 1

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LETTER Open Access

X-ray absorption near edge structure spectroscopic study of Hayabusa category 3 carbonaceous particles

Hikaru Yabuta*, Masayuki Uesugi, Hiroshi Naraoka, Motoo Ito, A L David Kilcoyne, Scott A Sandford, Fumio Kitajima, Hajime Mita, Yoshinori Takano, Toru Yada, Yuzuru Karouji, Yukihiro Ishibashi, Tatsuaki Okada and Masanao Abe

Earth, Planets and Space 2014, **66**:156 doi:10.1186/s40623-014-0156-0
Received: 30 April 2014, Accepted: 12 November 2014, Published: 3 December 2014

Abstract

Analyses with a scanning transmission x-ray microscope (STXM) using x-ray absorption near edge structure (XANES) spectroscopy were applied for the molecular characterization of two kinds of carbonaceous particles of unknown origin, termed category 3, which were collected from the Hayabusa spacecraft sample catcher. Carbon-XANES spectra of the category 3 particles displayed typical spectral patterns of heterogeneous organic macromolecules; peaks corresponding to aromatic/olefinic carbon, heterocyclic nitrogen and/or nitrile, and carboxyl carbon were all detected. Nitrogen-XANES spectra of the particles showed the presence of N-functional groups such as imine, nitrile, aromatic nitrogen, amide, pyrrole, and amine. An oxygen-XANES spectrum of one of the particles showed a ketone group. Differences in carbon- and nitrogen-XANES spectra of the category 3 particles before and after transmission electron microscopic (TEM) observations were observed, which demonstrates that the carbonaceous materials are electron beam sensitive. Calcium-XANES spectroscopy and elemental contrast mapping identified a calcium carbonate grain from one of the category 3 particles. No fluorine-containing molecular species were detected in fluorine-XANES spectra of the particles. The organic macromolecular features of the category 3 particles were distinct from commercial and/or biological 'fresh (non-degraded)' polymers, but the category 3 molecular features could possibly reflect degradation of contaminant polymer materials or polymer materials used on the Hayabusa spacecraft. However, an extraterrestrial origin for these materials cannot currently be ruled out.

Keywords: Hayabusa; Category 3 carbonaceous particles; STXM; XANES; Organic macromolecule

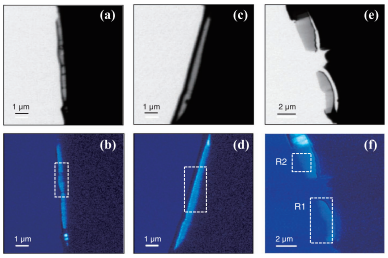

Figure 1

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LETTER Open Access

The mineralogy and space weathering of a regolith grain from 25143 Itokawa and the possibility of annealed solar wind damage

Dennis Harries* and Falko Langenhorst

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Abstract

We report the results of detailed mineralogical investigations by analytical scanning and transmission electron microscopy of particle RA-QD02-0115 recovered from the surface of asteroid 25143 Itokawa. We divided the 65 μm × 50 μm small particle into eight individual subsample slices via the focused ion beam method. The particle dominantly consists of olivine and contains inclusions of merrillite, tetrataenite/taenite, troilite, chromite, kamacite, and Cl-bearing apatite (in approx. decreasing order of frequency). The composition of olivine (fayalite 29.8 ± 1.1 mol% and molar Fe/Mn ratio of 57 ± 2) as well as the Ni-rich metal assemblage indicates an LL-type affinity in accord with previous classifications. The particle shows effects of solar wind irradiation on one of its principal faces. Olivine developed an approximately 34 nm wide rim composed of low-angle misoriented, nanometer-sized crystallites accompanied by a small amount of amorphous material. Exposed troilite developed a 4 to 8 nm wide polycrystalline rim with large-angle misorientations of the iron sulfide nanocrystallites. Merrilite shows marginally discernable surface damage but was too unstable under the electron beam for a detailed study. Cl-bearing apatite was found fully crystalline with no discernable rim structure. We discuss the unusual polycrystalline nature of the olivine rim in terms of possible annealing and recrystallization effects, which may have occurred during periods of time when Itokawa's surface temperature may have been warmer due to closer perihelion distances. Model calculations show that the dynamical orbital evolution of near-Earth asteroids could lead to complex space weathering processes, arising from the competing interplay between irradiation-induced damaging and thermally driven annealing.

Keywords: Hayabusa; Itokawa; Olivine; Troilite; Phosphates; Space weathering; Orbital evolution; Irradiation; Annealing; Recrystallization

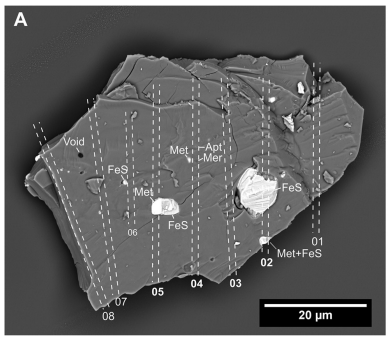

Figure 1

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LETTER Open Access

Mineralogy of some evolved LL chondrites with reference to asteroid materials and solar system evolution

Hiroshi Takeda*, Hiroshi Nagaoka, Akira Yamaguchi, Yuzuru Karouji and Yuuki Yazawa

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Received: 13 February 2014, Accepted: 4 December 2014, Published: 13 January 2015

Abstract

Mineralogy of three LL chondrites including Y-981971, Y-793214, and Y-790782 indicates that granulitic materials may have been formed in some depth of their parent body by an impact event. This process of high-temperature episodes is different from the records in the differentiated achondrites (howardite-eucrite-diogenite (HED)) possibly from the Vesta-like asteroid.

Keywords: LL chondrite; Partial melting; Metamorphism; Differentiation; Pyroxene; Olivine

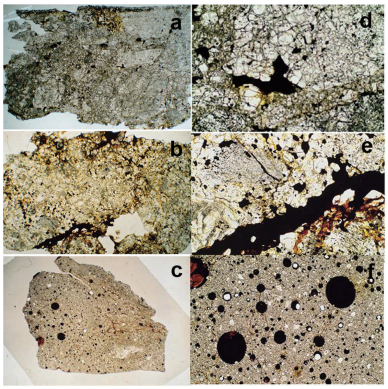

Figure 1

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LETTER Open Access

Towards understanding the dynamical evolution of asteroid 25143 Itokawa: constraints from sample analysis

Harold C Connolly Jr*, Dante S Lauretta, Kevin J Walsh, Shogo Tachibana and William F Bottke Jr

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Abstract

The data from the analysis of samples returned by Hayabusa from asteroid 25143 Itokawa are used to constrain the preaccretion history, the geological activity that occurred after accretion, and the dynamical history of the asteroid from the main belt to near-Earth space. We synthesize existing data to pose hypotheses to be tested by dynamical modeling and the analyses of future samples returned by Hayabusa 2 and OSIRIS-REx. Specifically, we argue that the Yarkosky-O'Keefe-Radzievskii-Paddack (YORP) effect may be responsible for producing geologically high-energy environments on Itokawa and other asteroids that process regolith and essentially affect regolith gardening.

Keywords: Asteroids; Hayabusa; Itokawa; Cosmic-ray exposure ages; Chondrites

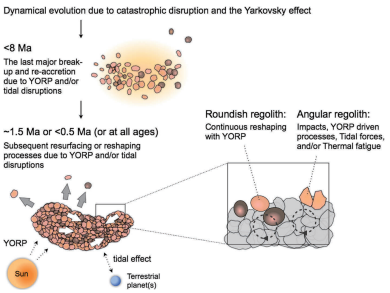

Figure 1

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LETTER Open Access

A micro-Raman and infrared study of several Hayabusa category 3 (organic) particles

Fumio Kitajima*, Masayuki Uesugi, Yuzuru Karouji, Yukihiro Ishibashi, Toru Yada, Hiroshi Naraoka, Masanao Abe, Akio Fujimura, Motoo Ito, Hikaru Yabuta, Hajime Mita, Yoshinori Takano and Tatsuaki Okada

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Abstract

Three category 3 (organic) particles (RB-QD04-0001, RB-QD04-0047-02, and RA-QD02-0120) and so-called 'white object' found in the sample container have been examined by micro-Raman and infrared (IR) spectroscopy. In addition, several artificial substances that could occur as possible contaminants and chondritic insoluble organic matter (IOM) prepared from the Murchison CM2 chondrite were analyzed. The Raman spectra of the particles show broad G-band and weak D-band. The G-band parameters plot in the disordered region and close to the artifact produced from a Viton glove after laser exposure rather than chondritic IOM. The particles were therefore originally at low maturity level, suggesting that they have not experienced strong heating and are therefore not related to the LL4-6 parent body. The IR spectra are not similar to that of chondritic IOM. Furthermore, the particles cannot be identified as some artificial carbonaceous substances, including the white object, which are the possible contaminants, examined in this investigation. Although it cannot be determined exactly whether the three category 3 particles are extraterrestrial, the limited IR and Raman results in this investigation strongly suggest their terrestrial origin. Although they could not be directly related to the artificial contaminants examined in this investigation, they may yet be reaction products from similar substances that flew on the mission. In particular, RB-QD04-0047-02 shows several infrared spectral absorption bands in common with the 'white object.' This may relate to the degradation of a polyimide/polyamide resin.

Keywords: The Hayabusa spacecraft; Carbonaceous material; Category 3 particle; Micro-Raman spectroscopy; Micro-infrared spectroscopy; Insoluble organic matter

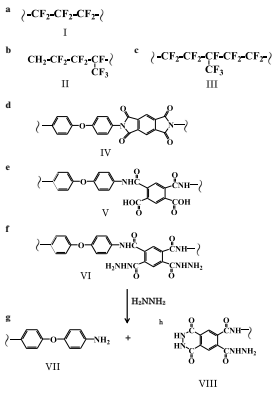

Figure 1

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LETTER Open Access

ToF-SIMS analysis of carbonaceous particles in the sample catcher of the Hayabusa spacecraft

Hiroshi Naraoka*, Dan Aoki, Kazuhiko Fukushima, Masayuki Uesugi, Motoo Ito, Fumio Kitajima, Hajime Mita, Hikaru Yabuta, Yoshinori Takano, Toru Yada, Yukihiro Ishibashi, Yuzuru Karouji, Takaaki Okada and Masanao Abe

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Abstract

Three carbonaceous category 3 particles (RA-QD02-0180, RB-QD04-0037-01, and RB-QD04-0047-02) returned in the sample catcher from the Hayabusa spacecraft were analyzed by time of flight-secondary ion mass spectrometry (ToF-SIMS) to establish an analytical procedure for determination of their origins. By the different analytical schemes, the three particles gave distinct elemental and molecular ions, in which the organic carbons commonly appear to be associated with nitrogen, silicon, and/or fluorine. The particles could be debris of silicon rubber and fluorinated compounds and are therefore man-made artifacts rather than natural organic matter.

Keywords: Hayabusa spacecraft; Category 3 particle; Carbonaceous material; ToF-SIMS analysis

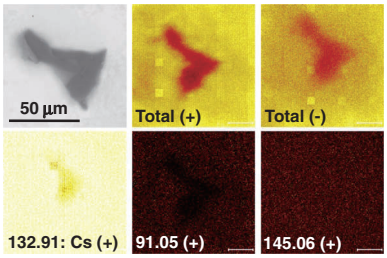

Figure 1

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Correspondence

If you have any questions, please contact editorial@earth-planets-space.com.

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Contents

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