Overview of S-type asteroid Itokawa, based on the studies on samples returned by Hayabusa.

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Introduction: Hayabusa spacecraft, which was launched in May 2003, reached near-Earth S-type asteroid 25143 Itokawa in September 2005. It landed onto the surface of the smooth terrain called "MUSES-Sea" of Itokawa twice in November 2005, even though its touchdown sampling system had not fully functioned [1]. Hayabusa spacecraft had overcome a series of troubles happened after the 2nd sampling and during its returning cruise back to Earth, and return its reentry capsule including its sample container to the Woomera prohibited area in South Australia in June 2010. After a series of procedures in the curation facility in JAXA, sub-mm sized mineral grains were recovered from its sample canister [2, 3]. A series of preliminary examination analyses on those grains revealed that they originated from surface regolith of asteroid Itokawa and that were comparable to equilibrated LL chondrites [4-9].

Initial descriptions and distributions of Itokawa samples: The sample canister is separated into two rooms, room A and B, and those from the 1st touchdown should be recovered into the room A and those from the 2nd one should be in the room B, even though the gap of the division plate between the two rooms sizes around 0.5mm and those smaller than the size of gap might be mixed up between the two rooms. The sample container was introduced into the clean chamber and opened in static vacuum condition in order to recover gas sample in the container even though it did not contain detectable amount of sample gas. The sample canister was extracted from the container in purified nitrogen condition and samples grains inside the sample canister were recovered onto quartz glass or aluminum plates due to compulsive fall by tapping the canister in upside down orientation. Individual sample grains were handpicked and handled with an electrostatically controlled micro-manipulation system developed for Hayabusa returned samples and installed in the clean chamber of purified nitrogen condition [10]. They were transferred to the sample chamber of the field emission secondary electron microscope equipped with the energy dispersive X-ray spectrometer (FE-SEM/EDS) Hitachi S-4300SE/N or SU6600 without exposing to the air and examined for their backscattered electron images and qualitative chemical composition. After sent back to the clean chamber, they were placed onto gridded quartz glass slides, lately individual quartz glass containers, to be stored in its purified nitrogen condition and given individual identification numbers. So far, 1344 of individual Hayabusa grains have been described and given sample IDs. The sample IDs start from "RA" are from room A, which comprise 605 grains, "RB" from room B, 404 grains, "RC" from a rotation cylinder situated between the two rooms, 86 grains, and "RX" are from both rooms, 249 grains [11]. All the initial description information of Hayabusa sample grains are also published on the sample catalog website (https://curation.isas.jaxa.jp/curation/hayabusa/index.html). Among them, 20 of grains and one Teflon spatula containing fine Itokawa grains have been distributed to NASA, based on Memorandum of Understanding between JAXA and NASA for the Hayabusa mission. On the other hand, international announcement of opportunity of Hayabusa samples have been conducted since 2012, and 254 of individual Hayabusa grains have been distributed to 69 of research plans of AO so far, which result in various kind of scientific achievements mentioned below.

Equilibrated chondritic body Itokawa: Modal abundance, average fayalite content in olivine and ferrosilite content in low-Ca pyroxene, and oxygen isotopic compositions of Itokawa grains match those of LL chondrites [4, 5, 12, 13], and distribution of fayalite contents in olivine and petrologic observation indicated its petrologic type ranges from type 4 to type 6 [4]. Olivine-spinel geothermometer and plagioclase geothermometer have been applied for Itokawa mineral grains, indicating that peak temperature they experienced during thermal metamorphism in asteroid should have reached 800˚C and it slowly cooled down to 600˚C, which corresponds to petrologic type <5 [4, 14, 15]. The thermal metamorphism it experienced should have occurred in a body predate asteroid Itokawa. Assuming ^{26}Al as a heat source of such body, the size of the precursor body of asteroid Itokawa should have sized 20km in radius based on numerical simulation [16]. Concerning about its shock stage, detailed studies on olivine and plagioclase in Itokawa grains indicate they experienced shock stage 2, moderately shocked, which corresponds to 5-10 GPa in shock pressure. Thus, Itokawa is an LL chondritic breccia body of various petrologic type ranging from type 4 to 6. The U-Pb chronology obtained from phosphates found in Itokawa grains show a single isochron age of 4.64 ± 0.18 Ga, indicating the precursor body should have formed in the early solar system [17]. Also a lower intersection age of the U-Pb system is 1.51 ± 0.85 Ga, indicating catastrophic break-up event should have occurred for the precursor body of Itokawa at this age. This age is consistent with a result of complete degas age estimated from ^{40}Ar-^{39}Ar system as 1.3 ± 0.3 Ga [18], whereas it is inconsistent with the degas age by ^{40}Ar-^{39}Ar system as 2.3 ± 0.1 Ga [19]. It seems that further confirmation is needed for the chronological study.

What happens on asteroid Itokawa: Because Itokawa samples are the only surface regolith sample of the S-type asteroid among all kinds of planetary samples, a series of studies for space weathering have been conducted for these samples. Surface of Itokawa grains shows thin (30-60 nm) amorphous layer, containing ~2nm of nano phase Fe particles [7]. The very surface of the amorphous layers are enriched in not only Fe but also S, redeposition of nano phase FeS after micrometeoroids impact should occur and this must redden reflectance spectrum of the asteroid effectively. Solar flare tracks are recognized in olivine in Itokawa grains just below the amorphous phase and its track densities indicate their short surface exposure time on the order of 10^3 to 10^4 years [20]. The fact that the exposure ages of Itokawa grains much shorter than that of Lunar regolith (>several tens million years) are consistent with the result of exposure age estimated from cosmogenic ^{21}Ne concentrations of Itokawa grains as 3 million years, which is much shorter than Lunar regolith as ~400 million years [9]. Short exposure time of Itokawa grains also pointed from little cosmogenic ^{10}B contribution in B isotopic composition observed in Itokawa grains [21]. The short exposure time of Itokawa regolith also indicates that large surface mass loss rate such as several tens of cm per million years, further implied the lifetime of Itokawa as 100 to 1000 million years [9]. Different from silicate minerals, space weathering on the surface of sulfides cause ~1 μm to several hundreds nm of iron whiskers on their surfaces caused by loss of sulfur from sulfide surfaces and deposition onto them due to long exposure to the energetic ions of the solar wind [22]. As mentioned before, surfaces of Itokawa grains also experienced micrometeoroids impact. Microimpact craters are reported on the surfaces of Itokawa grains [23], which results in melt splashes and adhering particles [24] and even secondary submicrometer craters distributed on their surfaces, assuming their exposure time as 10^2 to 10^4 years [25, 26].

New insights of S-type asteroid: Itokawa samples bring us new insights of S-type asteroid. For example, ~1 mole% enrichment of water and hydroxyl on the surface of olivine in Itokawa samples, which is caused by continuous exposure of solar wind to the asteroid surface, indicating ubiquitous presence of such water on airless bodies. They further assume a part of potential sources of Earth's ocean in the early solar system [27]. Concerning about water, euhedral NaCl crystals and KCl, which should have formed by water-rock interaction in Itokawa or its precursor body, were discovered on the surface and interior of Itokawa grains and nanoscale NaCl grains were discovered in an Itokawa grain, indicating S-type asteroid might have once contained certain amount of water and provided water to ancient Earth [28, 29, 30]. S-type asteroids are thought to be poor in organic matters as ordinary chondrites, but indigenous organic matters were discovered from carbon-rich Hayabusa grains [30, 31]. They discovered nanocrystalline graphite and disordered polyaromatic hydrocarbon in carbon-rich grains recovered from the Hayabusa sample canister, showing D- and ^{15}N-enrich isotopic compositions. In another report, they discovered non-protein amino acids, racemic β-aminoisobutyric acid and β-amino-n-butyric acid in carbon-rich grains, indicating their non-biological, non-terrestrial origins.

Concluding remarks: As mentioned above, Itokawa samples continue providing new and striking scientific results. Even though we have (will have) other new returned asteroid samples like Ryugu from C-type asteroid [32] and Bennu from B-type asteroid [33], Itokawa samples remain important because they are still the only S-type asteroid samples for human being.

References:

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