Space environment of an asteroid preserved on micro-grains returned by the Hayabusa spacecraft.

Eizo Nakamura[1], A. Makishima[1], T. Moriguti[1], K. Kobayashi[1], R. Tanaka[1], T. Kunihiro[1], T. Tsujimori[1], C. Sakaguchi[1], H. Kitagawa[1], T. Ota[1], Y. Yachi[1], T. Yada[2], M. Abe[2], A. Fujimura[2], M. Ueno[2], T. Mukai[2], M. Yoshikawa[2], and J. Kawaguchi[2], [1]The Pheasant Memorial Laboratory, Okayama University, Misasa, Tottori 682-0193, Japan (eizonak@misasa.okayama-u.ac.jp), [2]Japan Aerospace Exploration Agency

Introduction: The Japan Aerospace Exploration Agency (JAXA) conducted the Hayabusa mission with the goal of better understanding solar system evolution through direct sampling of an asteroid and return of the samples to Earth for detailed analytical work. A target was set to the near-Earth asteroid 25143 Itokawa, an example of a spectral type-S asteroid common in the inner part of the asteroid belt. As a part of the mission, initial analyses of returned grains were carried out by several teams of researchers (see http://www.jaxa.jp/press/2011/01/20110117_hayabusa_e.html).
One team reported on the general properties of the grains and concluded that the building blocks of the rubble pile were identical to those of equilibrated LL ordinary-chondrites (OC) with mild overprinting by "space weathering" [1, 2, 3, 4]. This conclusion is consistent with the spectroscopic observations made from Earth and by the Hayabusa spacecraft [5, 6]; however, some key questions remain. What record of the environment at the asteroid exterior exists on the surface of grains deposited there and, more broadly, what were the most important processes shaping the post-accretion appearance of this asteroid? Nanometer-scale investigation of the surfaces of these micro-grains can help us characterize the space environment of this and other asteroids, an important step toward more general understanding of impact phenomena in the inner solar system. In this paper, we report highlights of our initial analysis.

Experimental: All analyses were undertaken at the Pheasant Memorial Laboratory with nm-scale sample handling capability in part demonstrated by Nakamura et al. (2003) [7]. During this study, we (1) determined optical properties, (2) described surface textures and identified constituent phases using a field-emission-type scanning electron microscope (SEM), (3) produced slabbed samples of the grains using a focused-ion beam methods (FIB), (4) investigated major-element compositions by electron-microprobe techniques, and (5) performed in-situ analyses, including measurements of O-isotope composition, by secondary-ion mass-spectrometry (SIMS).

Mineralogical features: The grains were 40–110 μm-sized, mono- or poly-phase fragments. All grains exhibit angular outlines and high surface relief. The abundant mineral phases observed in the grains are olivine, low-

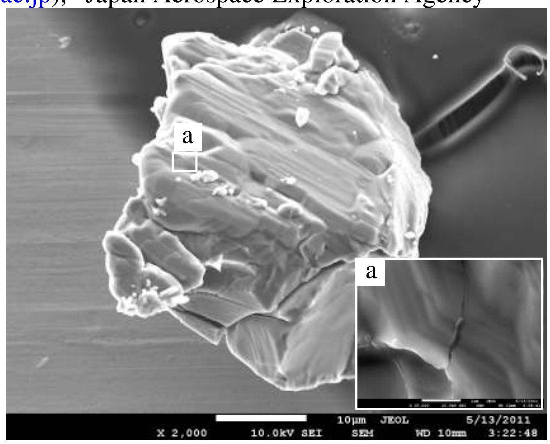

Figure 1: **Surface images obtained by SEM of the entire grain RA-QD02-0121. Shock lamellae are developed on olivine substrate. (a) Quenched melt on and along a crack.**

Ca pyroxene, diopside, and plagioclase. This finding is consistent with that of another recent study of the mineralogy of 1534 grains from Itokawa [1]. As a representative, mineralogical properties of RA-QD02-0121 is described here. The grain (40×30 μm) consists of olivine and low-Ca pyroxene (Figure 1a), with the olivine showing sets of sharply defined lamellae with widths at the sub-μm scale (Figure 1b). These lamellae could reflect high strain rates and high shear stresses associated with shock compression and have previously been referred to as shock lamellae [8]. An object with a ropey fabric, observed on and along a crack cross-cutting the lamellae, appears to have originated from melt (Figure 1c).

Chemical properties: In-situ O isotope analyses were carried out by SIMS. The analytical uncertainty is estimated from the spot-to-spot reproducibility (±1SD, standard deviation), typically 0.5‰ both for δ^{18}O and δ^{17}O. The analyses demonstrate variation in O isotope compositions within and among phases, with these compositions scattering around those of whole-rock samples of OC and forming a cluster elongated with a slope of ∼0.5. The means of ten analyses are 5.2, 4.1, and 1.4‰ for δ^{18}O, δ^{17}O, and Δ^{17}O, respectively. The averages estimated from all grains show Δ^{17}O >0. Based on these observations, we confirmed that the grains are extraterrestrial and derived from the asteroid Itokawa.

The individual constituent minerals, in the different grains, have nearly identical major-element compositions. The 1SD in the (Fe/Mg) atomic ratios of olivine and pyroxenes are less than 1%. The (Fe/Mg) ratios of the phases decrease in the order of olivine (highest), low-Ca pyroxene, and diopside (lowest), and (Fe/Mn) is higher in olivine than in pyroxenes. These observations are consistent with the grains having been at an equilibrium condition and, applying two-pyroxene thermometry [9], indicate a temperature of $\sim$860 °C. Ratios of (Fe/Mg) and (Mn/Fe) in olivine and pyroxenes in the Itokawa grains fall within the range for LL-OC [10]. The major element compositional variations and the record of shock-induced deformation preserved in the grains are similar to those noted for equilibrated LL-OC [11]. Thus, together, our observations indicate that the uppermost layer of Itokawa's surface is dominantly composed of equilibrated LL-OC-like material, a conclusion consistent with that of [2, 1] based on study of other grains from Itokawa.

Physical properties: Surfaces of the grains from Itokawa retain textures reflecting the environmental conditions that influenced the physical evolution of the asteroid exterior. The grain surfaces are dominated by fractures, and the fracture planes contain sub-μm-sized craters and adhered objects. The occurrences of sub-μm-scale craters (100–200 nm in diameter) provide a record of bombardment by nm-scale projectiles. Assuming that the projectile diameters were an order of magnitude smaller than the diameters of the pits [12] results in estimated projectile sizes of 10–20 nm.

The adhered objects are another prominent feature of the grain surfaces (Figure 2). We categorize the adhered objects based on morphology as follows: (1) common adhered particles (CAP) making up 90% of the adhered object population, (2) molten splash-shape glasses (MSG), (3) dome-outline objects (DOO; Figure 2a), and (4) particularly irregularly-shaped clots (PIC; Figure 2b), aggregates of several lithic materials.

Discussion: Most of adhered objects were formed during impacts and are likely representative of the asteroid's surface. We examined 914 adhered objects, randomly chosen from the five grains. Based on semi-quantitative analyses, modal abundances of the silicates were estimated to be 32, 23, 16, 3.9, 1.2, and 25 vol.% for olivine, low-Ca pyroxene, plagioclase, diopside, K-feldspar, and glass. Onboard X-ray fluorescence spectroscopy inferred that the element ratios of (Mg/Si) and (Al/Si) of Itokawa's exterior are 0.78$\pm$0.09 and 0.07$\pm$0.03, respectively [6], and these ratios are similar to our ratios of 0.72 and 0.08. Near-infrared spectroscopy (NIRS) provided an olivine/(olivine + pyroxene) modal ratio of 0.7 to 0.8 for the average surface material of Itokawa [5], and this is significantly higher than the estimate of 0.5 resulting from our analysis. A laboratory simulation using OC suggested that impact melting and subsequent crystallization can modify the spectra [13]. In this study, a considerable number of glassy particles were observed on the grain surfaces and the absorption effect of these glassy materials is likely underestimated in the previous model based on NIRS results.

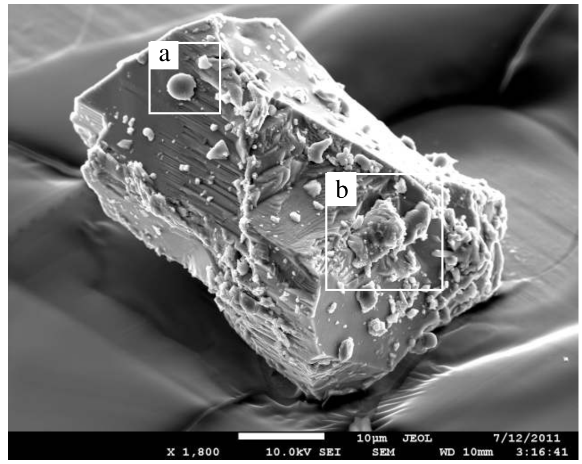

Figure 2: **RA-QD02-0116 with abundant adhered objects. (a) DOO and (b) PIC are sticked on the surface.**

Because of the low escape velocity on Itokawa and on other similar bodies, it is likely that such asteroids are major sources of interplanetary dust particles. Further surface observations on grains returned by Hayabusa will add statistical significance to the insights regarding solid-to-solid interactions fundamental to our understanding of asteroid accretion and, more broadly, the formation and evolution of interplanetary objects.

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