

Space environment of an asteroid preserved on micrograins returned by the Hayabusa spacecraft

Eizo Nakamura^{a,1}, Akio Makishima^a, Takuya Moriguti^a, Katsura Kobayashi^a, Ryoji Tanaka^a, Tak Kunihiro^a, Tatsuki Tsujimori^a, Chie Sakaguchi^a, Hiroshi Kitagawa^a, Tsutomu Ota^a, Yusuke Yachi^a, Toru Yada^b, Masanao Abe^b, Akio Fujimura^b, Munetaka Ueno^b, Toshifumi Mukai^b, Makoto Yoshikawa^b, and Jun'ichiro Kawaguchi^b

^aThe Pheasant Memorial Laboratory for Geochemistry and Cosmochemistry, Institute for Study of the Earth's Interior, Okayama University, Misasa, Tottori 682-0193, Japan; and ^bJapan Aerospace Exploration Agency, Yoshinodai 3-1-1, Chuo, Sagamihara, Kanagawa 252-5210, Japan

AUTHOR SUMMARY

Asteroids are intermediate products of the growth of planetary bodies. Similar to what is observed on the Moon, the surfaces of airless bodies such as asteroids retain accumulated histories of solid-to-solid interactions.

Meteorites that fall to Earth are fragments of asteroids; however, their entry into Earth's atmosphere erases much of the evidence for the processes affecting their surfaces in space. For this reason, observations of the surfaces of low-gravity celestial bodies have been limited to those made remotely. In this study, we examined microscopic grains collected from the outermost surface of an asteroid called Itokawa and returned to Earth by the Hayabusa spacecraft. A nanometer-scale study of these grains in our laboratory provides a glimpse of the asteroid surface that is physically and chemically modified by repeated high-velocity collisions with micrometeorites, or tiny meteorites that enter Earth's atmosphere.

In this paper, we report a summary of our initial analysis of the morphology, mineral present, and chemical compositions of five sand-sized (40–110 μm diameter) lithic grains returned from the asteroid Itokawa as a part of the Hayabusa mission. The grains consist of single or multiple mineral phases. The chemical properties of these grains were examined by microbeam techniques. For chemical analyses, each grain was cut into three slabs and the middle slab was analyzed. Oxygen (O) isotope compositions, useful to trace the sources of solar matter, confirmed that the grains cannot be terrestrial in origin and are derived from the asteroid. Considering this O isotope evidence and also the major-element compositions of the grains, we concluded that the building blocks of the asteroid were equilibrated ordinary chondrites, the most abundant type of meteorite falling to Earth. Our observation of the single source of the grains—the ordinary chondrites—is consistent with previous observations of other grains collected from this asteroid (1, 2).

The grain surfaces were characterized using a scanning electron microscope with a 10 nm resolution (Fig. P1A).

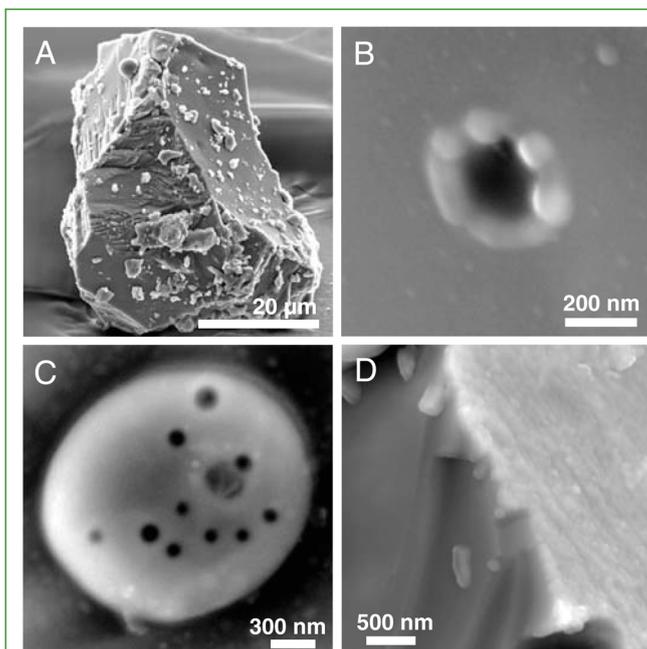


Fig. P1. Landscapes of an asteroid's surface exposed to space. All images were obtained by electron microscopy. (A) A representative grain recovered by the Hayabusa spacecraft. (B) A sub-micrometer-scale crater with chains of spheres slightly overhanging the pit edge. (C) A micrometer-sized material that was molten, quenched, and became glued onto the grain surface. (D) A plane with a scaly fabric eroded on the asteroidal surface.

Surfaces of the grains retain textures formed in the space environment and are dominated by fractures containing sub-micrometer-scale craters and adhered objects. The observation suggests the importance, at the asteroid surface, of the destruction of lithic materials by external forces such as repeated collisions. The presence of sub-micrometer-scale craters (100–200 nm in diameter, Fig. P1B) is direct evidence for bombardment by nanometer-scale, high-velocity projectiles. The adhered objects, with a typical size of 1 μm , are another prominent feature of the grain surfaces. It is likely that the adhered objects are fragments of other grains on the Itokawa surface. Most of these objects have subrounded or flake-like shapes and are composed of phases observed on the host grains. The adhered objects are rigidly attached to the grain surfaces with unknown bonding agents. Some of the

objects have subrounded shapes, suggesting that they approached the grain surface with significant velocity before solidification (Fig. P1C). Assuming thermal radiation from a black body; i.e., an idealized physical body that absorbs and emits all incident electromagnetic radiation, the residence time for the melts produced by the collisions is estimated to be 10^{-3} s; therefore, melting occurred within meters of the

Author contributions: E.N. undertook the initial analysis; A.M. and T. Moriguti prepared reference materials; K.K. coordinated the flow of the analytical work through the laboratories and performed the FIB slabbing of the grains; R.T. analyzed oxygen isotopes for the reference materials; T.K. carried out in situ oxygen-isotope analyses; T.T. carried out petrographic and mineralogical investigations; C.S. evaluated adhered objects; H.K. assisted in the electron and ion probe work; T.O. determined elemental compositions; Y.Y. documented the sample status; T.Y., M.A., A.F., M.U., T. Mukai, M.Y., and J.K. worked on sample preparation; and E.N., A.M., T. Moriguti, K.K., R.T., T.K., and T.T. wrote the paper.

The authors declare no conflict of interest.

This Direct Submission article had a prearranged editor.

Freely available online through the PNAS open access option.

¹To whom correspondence should be addressed. E-mail: eizonak@misasa.okayama-u.ac.jp.

See full research article on page E624 of www.pnas.org.

Cite this Author Summary as: PNAS 10.1073/pnas.1116236109.

adhesion sites. We also observed a scaly fabric that can be considered a result of space erosion (Fig. P1D).

Reddening of the surfaces of asteroids and darkening of their remotely obtained infrared spectra have previously been termed space weathering and considered to reflect the existence of nano-phase iron-particles. However, the processes leading to space weathering have remained largely unknown. The surfaces of asteroids, heretofore studied only remotely, are scenes of disaggregation, cratering, melting, adhesion, agglutination (i.e., clumping of particles), and implantation/sputtering. Differences between mineral abundances estimated in our study of microscale grains and those in spectral studies (3) could be explained by the presence of adhered objects that are not accounted for in spectroscopy in the latter. A relatively high temperature (860 °C) estimated in this study from the chemical compositions of minerals in the grains requires equilibration of the minerals in an asteroid significantly larger in size than the modern Itokawa. This observation implies that the genesis of Itokawa is related to a destructive process involving a larger body.

All planetary bodies are believed to have accreted from dust and debris in the early solar nebula, involving repeated collisions among objects, over a very large range in sizes (nanometers to hundreds of kilometers), and related aggregation into growing planetary embryos. Prior to the

return of the grain samples by Hayabusa, it was not possible to directly examine the products of such processes. However, analysis of the surfaces of microscopic grains delivered by this spacecraft has provided evidence for the bombardment of solids, down to the 10-nm scales. A proto-Itokawa asteroid tens of kilometers in diameter was fragmented during a very long collisional history, resulting in the current 100-m-scale Itokawa with its complex surface textures. Although the often “potato-shaped” asteroids appear to float peacefully in space, their shapes, sizes, surface features can reflect hostile collision-related processes, at spatial scales of 10^{-9} to 10^4 m and time scales of up to 10^9 y. Further surface observations of 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 in the space environment.

1. Nakamura T, et al. (2011) Itokawa dust particles: a direct link between S-type asteroids and ordinary chondrites. *Science* 333:1113–1116.
2. Yurimoto H, et al. (2011) Oxygen isotopic compositions of asteroidal materials returned from Itokawa by the Hayabusa mission. *Science* 333:1116–1119.
3. Abe M, et al. (2006) Near-infrared spectral results of asteroid Itokawa from the Hayabusa spacecraft. *Science* 312:1334–1338.