Electron holography observation of presudo-magnetites and metallic iron nanoparticles in space weathered Ryugu sample

Yuki Kimura[1], Takeharu Kato[2], Satoshi Anada[2], Ryuji Yoshida[2], Kazuo Yamamoto[2], Toshiaki Tanigaki[3], Tetsuya Akashi[3], Hiroto Kasai[3], Kosuke Kurosawa[4], Tomoki Nakamura[5], Takaaki Noguchi[6], Masahiko Sato[7], Toru Matsumoto[6], Tomoyo Morita[5], Mizuha Kikuiri[5], Kana Amano[5], Eiichi Kagawa[5], Toru Yada[8], Masahiro Nishimura[8], Aiko Nakato[9], Akiko Miyazaki[8], Kasumi Yogata[8], Masanao Abe[8], Tatsuaki Okada[8], Tomohiro Usui[8], Makoto Yoshikawa[8], Takanao Saiki[8], Satoshi Tanaka[8], Fuyuto Terui[10], Satoru Nakazawa[8], Hisayoshi Yurimoto[11], Ryuji Okazaki[12], Hikaru Yabuta[13], Hiroshi Naraoka[12], Kanako Sakamoto[8], Sei-ichiro Watanabe[14], Yuichi Tsuda[8], and Shogo Tachibana[6,8]

[1]Institute of Low Temperature Science, Hokkaido University, Sapporo 060-0819, Japan.
[2]Nanostructures Research Laboratory, Japan Fine Ceramics Center, Nagoya, 456-8587, Japan.
[3]Research & Development Group, Hitachi, Ltd., Hatoyama, Saitama, 350-0395, Japan.
[4]Planetary Exploration Research Center, Chiba Institute of Technology, Narashino 275-0016, Japan.
[5]Department of Earth Sciences, Tohoku University, Sendai 980-8578, Japan.
[6] Division of Earth and Planetary Sciences, Kyoto University; Kyoto 606-8502, Japan.
[7]Department of Earth and Planetary Science, The University of Tokyo, Tokyo 113-0033, Japan.
[8]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara 252-5210, Japan.
[9]National Institute of Polar Research, Tashikawa 190-8518, Japan.
[10]Kanagawa Institute of Technology, Atsugi 243-0292, Japan.
[11] Department of Natural History Sciences, Hokkaido University, Sapporo 060-0810, Japan.
[12] Department of Earth and Planetary Sciences, Kyushu University, Fukuoka 819-0395, Japan.
[13] Graduate School of Advanced Science and Engineering, Hiroshima University, Higashi-Hiroshima 739-8526, Japan.
[14] Department of Earth and Environmental Sciences, Nagoya University, Nagoya 464-8601, Japan.

The traces resulting from space weathering could provide a detailed understanding of interplanetary processes. However, most meteorites are composed of materials produced in the interior of the asteroid and have not undergone space weathering on its surface. Analysis of samples gently collected from the surface of extraterrestrial bodies by spacecraft is therefore useful for studying the details of space weathering [1,2].

Here, we focused on the space weathering of magnetite in samples brought back from the C-type asteroid Ryugu by the *Hayabusa2* spacecraft. Magnetite is an important mineral to record the nebular magnetic field, but studies on its space weathering are limited. Magnetite is universally found in carbonaceous meteorites as a major product of aqueous alteration of asteroids during the early stages of solar system formation. In particular, since most of the samples recovered by the *Hayabusa2* spacecraft were collected from the surface of the asteroid, it is important to understand the degree of space weathering influence on magnetite in order to interpret the origin of remanent magnetization. We have previously studied the magnetic domain structure of framboidal magnetite in recovered samples using electron holography [3,4]. In this study, we report on our newly discovered flamboids, which does not show a typical magnetic domain structure of magnetite.

From an area with relatively abundant Fe and containing many spherical particles similar to framboidal magnetite was selected from the surface of particle A0064-FO007 and an ultrathin section was prepared by focused ion beam (FIB) machining without applying magnetic field greater than that of the Earth. The ultrathin section contained about a dozen framboidal magnetite particles with sizes ranging from 500-900 nm (Fig. 1A). The magnetic domain structures of these particles were observed by electron holography (HF-3300EH; Hitachi High-Tech Corp., Tokyo), and it was found that the magnetic domains of each particle had a concentric magnetic structure typical of submicrometer-sized magnetite particles (Fig. 1B) [5-8].

Ultrathin sections taken from neighboring locations of the same particles also contained flamboidal particles of 400-800 nm in diameter, similar to Fig. 1A (Fig. 1C). The scanning transmission electron microscopy–energy-dispersive X-ray spectrometry analysis of this particle confirmed that it was iron oxide, consistent with magnetite, but electron holography showed no magnetic domain structure. This suggests that the particle is a nonmagnetic mineral and not magnetite. We analyzed the bonding state of iron and oxygen using electron energy loss spectroscopy and found that this nonmagnetic particle exhibited characteristics of both magnetite and wüstite in terms of the bonding state of iron and oxygen. We named such particles that exhibit both features of magnetite and wüstite, and do not show a magnetic domain structure "pseudo-magnetite".

Around the pseudo-magnetite particles, there was a decrease in signal intensity of various light elements in the region of about 2 μm below the surface. In addition, the elemental mapping of iron shows many small iron particles that may have been released or diffused from the pseudo-magnetite (Fig. 1E). More than 100 metallic iron particles of 30-400 nm were easily counted in an alteration region 2 μm deep, 10 μm long, and 0.1 μm thick from the surface. Assuming that this reduction is due to a micrometeoroid impact and that a 10-μm diameter region is altered to a depth of 2 μm in a single impact, the total number of iron particles produced would be ~10^4, which could acquire remanent magnetization during an event involving the formation of iron nanoparticles by a micrometeoroid impact. Therefore, the iron particle precipitation associated with a micrometeoroid impact could play an important role as the remanence acquisition event.

Micrometeoroid impacts are thought to have occurred frequently within protoplanetary disks. However, the traces left behind by these impacts are found only on the topmost surfaces of asteroids, so previous studies using meteorites have had limited opportunities to study these traces. Even if a meteorite fell to Earth leaving behind pseudo-magnetite and iron particles, these particles would be oxidized by weathering on the ground afterward. In addition to the samples obtained by the *Hayabusa2* spacecraft, the samples brought back from the asteroid Bennu by OSIRIS-REx will also have a chance to be analyzed. In this process, it is necessary to avoid changes in remanent magnetization due to oxidation of pseudo-magnetite and metallic iron nanoparticles. Although pseudomagnetite may represent only a small percentage of total magnetite, its presence should be considered when analyzing extraterrestrial samples recovered from an asteroid surface. In our presentation, the event and timing of the micrometeorite impact and other suspect magnetite particles will be discussed.

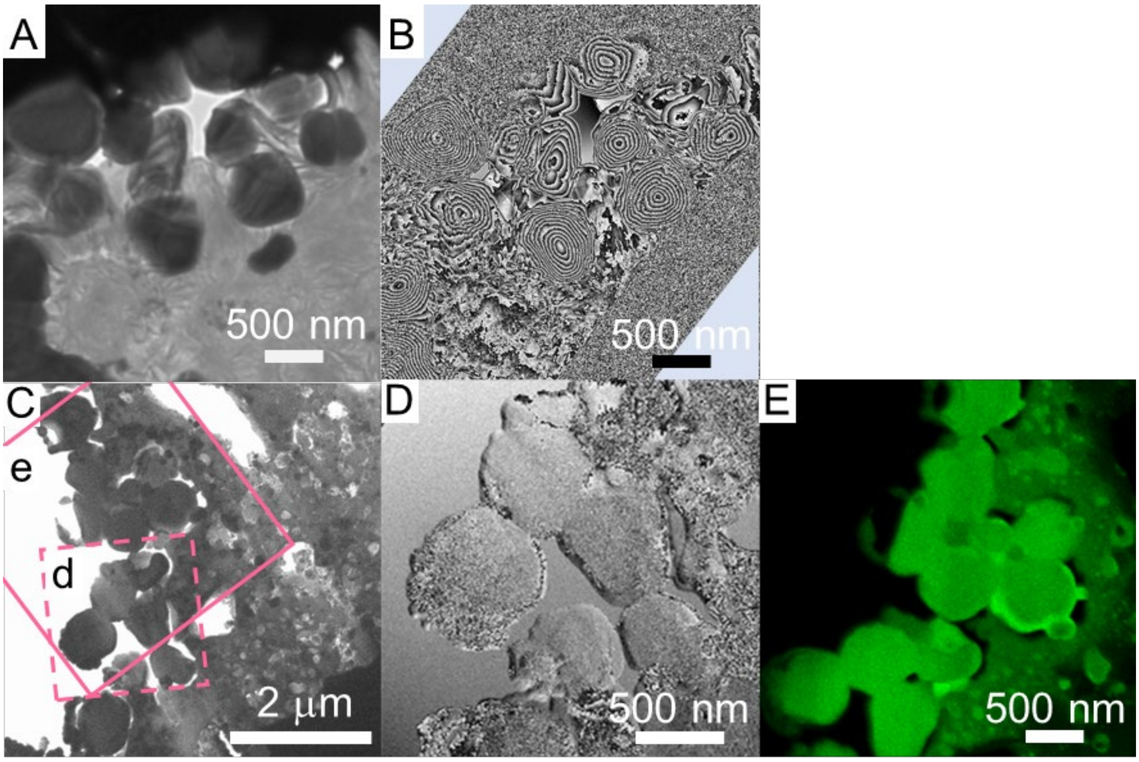

Figure 1. Framboids with and without magnetic domain structures characteristic to magnetite. A and **B**. Bright field TEM and the corresponding magnetic-flux-distribution images, respectively, of framboidal magnetite particles in a thin section prepared from the A0064–FO007 sample of asteroid Ryugu. **C**. Bright field TEM image of pseudo-magnetite particles in a thin section prepared from neighboring region of A. **D.** Magnetic-flux-distribution image, corresponding to the box d in C, observed by electron holography. **E**. Elemental mapping of iron corresponding to the box e in C.

The authors thank the Ministry of Education, Culture, Sports, Science and Technology (MEXT) (grants JPMXS0450200421, JPMXS0450200521) for financial support and JEOL for providing access to the tabletop SEM (JCM-7000, NeoScope). We thank the developers of iSALE, including G. Collins, K. Wünnemann, B. Ivanov, J. Melosh, and D. Elbeshausen. We also thank Tom Davison for the development of pySALEPlot.

References

[1] Noguchi T. et al. 2011. Science 333:1121. [2] Noguchi T. et al. 2023. Nat. Astron. 7:170. [3] Nakamura T. et al. 2022. Science 379: eabn8671. [4] Kimura Y. et al. 2023 Scientific Reports 13:14096. [5] Kimura Y. et al. 2013. Nat. Commun. 4:2649. [6] Almeida T. P. et al. 2014. Nat. Commun. 5:5154. [7] Almeida T. P. et al. Geophys. Res. Lett. 41:7041. [8] Kimura Y., Yamamoto K. & Wakita S. 2021. Astrophys. J. Lett. 917:L5.