Magnetite and non-magnetite framboids in Ryugu sample

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There are many magnetite (Fe_3O_4) particles found in chondrites together with clay minerals [1,2] suggesting that they were formed by aqueous alteration [3]. Magnetite can record magnetic field environment at the time of its formation as natural remanent magnetization [4]. Therefore, it is important to know when and how magnetite particles formed in order to estimate the magnetic field environment of the early solar system and to understand the physical evolutionary processes that have a relationship with the magnetic filed. A large amount of magnetite is also found in Ryugu samples [5] and it has been confirmend that submicron-scale magnetite is a main carrier of the natural remanent magnetization [6]. We conducted electron holography to visualize the magnetic domain structure of the flamboidal magnetite and found that the magnetite particles have a concentric circular magnetic field (vortex structure) and an external leakage of the magnetic field that could be a carrier of remanent magnetization [5,6]. In addition to the typical framboidal magnetite, here we report the discovery of a flamboidal magnetite-like mineral that does not exhibit a magnetic field in a sample.

Figure 1 shows a part of a typical flamboidal magnetite in an ultrathin section extracted from a Ryugu sample A0064-FO007 using a cryo-focused ion beam (FIB; NB5000, Hitachi High-Tech) under -90ºC at Japan Fine Ceramics Center (JFCC). The bright-field transmission electron microscope (TEM) image shows at least eight magnetite particles of ~1 μm in diameter surrounded by phyllosilicates at the bottom part. The upper side of the image corresponds to the surface of the parent sample before they were extracted. The strong contrast area marked with W on the upper side is tungsten that was deposited before processing to prevent damage by FIB machining. Figures 1 i and ii show magnetic flux distribution images corresponding to two boxes observed by electron holography using a specially designed TEM (HF-3300, Hitachi High-Tech) at JFCC. The concentric stripes inside the particles represent the phase change due to magnetization, because the internal potential has been subtracted by taking images from the back and front. Namely, magnetite particles have a vortex magnetic domain structure. In addition, an external magnetic field can be seen on the outside of the particle. Magnetite particles are thought to have formed by aqueous alteration between 3.1-6.8 million years after the formation of first mineral, calcium–aluminium-rich inclusion, at the beginning of the Solar system [7]. The external magnetic field is a result of the magnetic field environment that existed when magnetite formed by aqueous alteration in the parent body of Ryugu [6].

Figure 2 shows a high-angle annular dark field scanning TEM (STEM-HAADF) image of an ultrathin section of a portion of a flamboid from a different fragment in the Ryugu sample A0064-FO007, which was broken into several pieces when fixed to the indium plate for easier handling, extracted using the cryo-FIB. Similar to the Fig. 1, several spherical particles of ~1 μm can be seen. Corresponding magnetic flux distribution image has been shown in Fig. 2B. Unlike i and ii in Fig. 1, the contrast within the particles is flat and there is no magnetic domain structure characteristic of magnetite. Elemental composition analysis using an energy dispersive X-ray spectroscopy (EDS) confirms that the particles are iron oxide (Fig. 2C). Although it looks like typical framboidal magnetitee, electron energy-loss spectroscopy analysis indicated that the bonding states of oxygen and iron were clearly different from that of magnetite. The observed bonding state was consistent with wüstite ($Fe_{1-y}O$), which is antiferromagnetic and does not acquire remanent magnetization.. Although particles appeared to be framboidal magnetite based on a micrograph, these particles were actually wüstite. We refer to this particle as framboidal pseudo-magnetite.

The framboidal pseudo-magnetite is present on the top surface of the host sample, and the bottom is a matrix composed mainly of phyllosilicates. TEM-EDS mapping showed iron-rich region that may be leached from the pseudo-magnetite into the matrix. Magnetite with porous surface texture and metallic iron has been found in the analysis by Sand team [8]. Sample analysis in the first Hayabusa mission has reported the formation of iron particles on a silicate grain by space weathering [9]. In case of our pseudo-magnetite, although the presence of metallic iron particulates was also confirmed, they appear to be coarser than those found in previous studies and are We expect that framboidal pseudo-magnetite may also have formed by space weathering of magnetite, but different mechanisms from other two samples. Similar pseudo-magnetite particles have also been found in other FIB thin sections. We will discuss the formation process of framboidal pseudo-magnetite at the symposium.

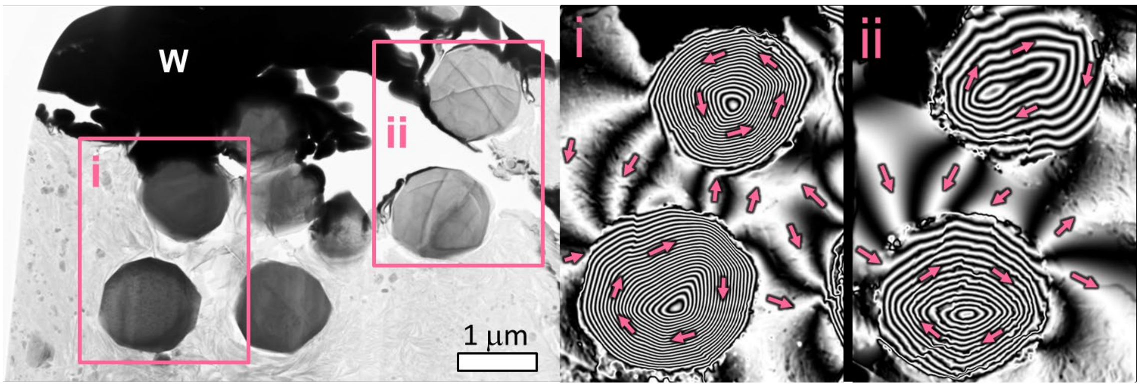

Figure 1. TEM image of a thin section of a typical magnetic framboid extracted from the sample A0064-FO007 and its characteristic magnetic structure observed by electron holography. Arrows show the direction of the magnetic flux.

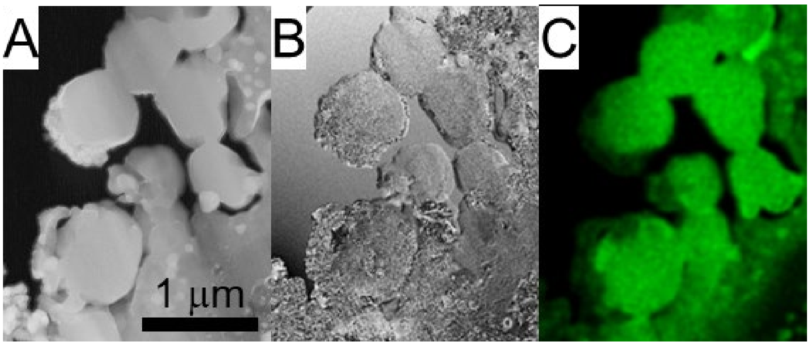

Figure 2. Framboidal pseudo-magnetite. A. STEM-HAADF image of a thin section of a fragment from the sample A0064-FO007 prepared by FIB. B. Magnetic flux distribution image obtained from the reconstruction of remanent magnetic state of magnetites observed by electron holography. Uniform contrast indicate that the particles are not magnetic minerals. C. Corresponding elemental mapping of iron.

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References

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