Iron nano-particles in brown olivine in Yamato 984028 shergottite

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Introduction

Martian meteorites, in particular shergottites, often contain darkened olivine. The coloration of olivine is black in hand specimen and brown under plane polarized light (PPL) of optical microscope, therefore such olivine is called as "brown olivine". Brown olivine in NWA 2737 chassignite has been well studied (Treiman et al., 2007; Van de Moortèle et al., 2007; Bläß et al., 2010) and they reported that the brown color is induced by the presence of iron metal nano-particles precipitated in olivine due to a strong shock event. Although only iron metal has been reported as nano-particles in brown olivine in NWA 2737 chassignite, brown olivine in shergottites, such as LEW 88516, NWA 1950 and LAR 06319, were reported to contain magnetite nano-particles (Kurihara et al., 2009). Formation processes of iron metal nano-particles have been suggested (e.g., Takenouchi et al., 2017), however, formation processes and formation conditions of magnetite nano-particles were not enough considered (Mikouchi et al., 2013). In order to reveal the relations between iron metal and magnetite nano-particles, the species of nano-particles and the shock textures of the meteorite should be compared in many shergottites. In this study, brown olivine in Yamato 984028 (Y984028) shergottite is analyzed because species of nano-particles has not been reported in spite of the presence of brown olivine.

Sample and Method

Y984028,80 (a small chip) and Y984028,31 (a thin section) are analyzed in this study. Y984028 is a poikilitic shergottite and contains abundant shock melt veins. We picked up brown olivine crystals from a chip of Y984028 and then crashed it to prepare powdered olivine sample. The powdered sample is observed by transmission electron microscopy (TEM) at the University of Tokyo (JEOL JEM-2100). TEM-EDS analysis is performed to measure chemical composition of olivine and nano-particles. The Y984028,31 thin section was observed by scanning electron microscopy (SEM) at NIPR (JEOL JSM-7100F).

Result

Observation of the thin section reveals that the shock melt glassy veins occupied about 7 vol.% of this meteorite. No high-pressure phases were found as reported in Takenouchi et al. (2015). Olivine around shock melt glassy veins looks colorless due to recrystallization by partial melting. Part of olivine, which is far from the thick shock melt veins, shows brownish coloration and characteristic features of brown olivine (Takenouchi et al., 2015). TEM observation of powdered brown olivine sample reveals that brown olivine in Y984028 contains iron nano-particles (Fig. 1) similar to brown olivine in the other shergottites. Iron nano-particles are present in defect-rich lamellar areas similar to those in NWA 1950 (Takenouchi et al., 2017). The size of nano-particles is ~30 nm in diameter. TEM-EDS analysis indicates that the nano-particles are not magnetite but iron metal because no enrichment of oxygen is detected by EDS analysis when we compared EDS spectra of the host olivine and nano-particles (Figure 2).

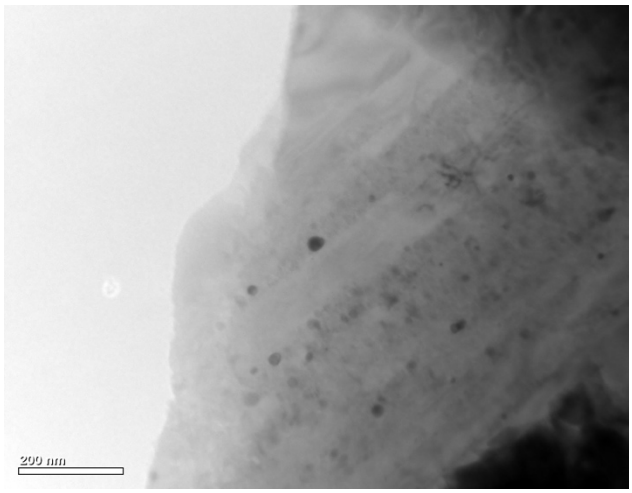

Figure 1 TEM bright field image of brown olivine fragment. Black spherules are iron nano-particles.

Discussion

Our TEM observation confirms that brown olivine in Y984028 certainly contains nano-particles and the nano-particles are iron metal in our observation. As Mikouchi et al. (2013) suggested, magnetite could form during temperature drop after a shock event. In that case, Y984028 should contain magnetite nano-particles because Y984028 exhibits more abundant shock melt glassy veins and recrystallized polycrystalline olivine indicating post shock annealing for longer time compared to other Martian meteorites with brown olivine, such as LAR 06319 and NWA 1950. The long post shock annealing may result in oxidation of iron metal due to relatively oxidized redox state of Martian meteorite. However, magnetite nano-particles are not found in our observation and magnetite nano-particles are absent. One possible explanation of the absence of magnetite is that both iron metal and magnetite nano-particles form heterogeneously; iron metal nano-particles precipitate and remain in the less affected areas by post shock annealing and magnetite nano-particles form from iron metal in the thermally affected areas by the post shock annealing. Such heterogeneous distribution could result in overlooking of magnetite in our observation, and possibly in the other meteorites. However, thermal heterogeneity after a shock event is not so significant because temperature would be equalized immediately after a shock event. Therefore, small differences in cooling process need to control the species of iron nano-particles. Another possibility is that magnetite forms directly from olivine during a shock event. In this case, maximum shock temperature could control the species of nano-particles because high temperature leads reduced condition while relatively low temperature does oxidized condition. However, this process may be unrealistic because high-temperature (~1700 K) is required to grow iron nano-particles by atomic diffusion, and inconsistent with the observation results in our previous study (Takenouchi et al., 2017).

Therefore, small differences in cooling process may induce variation of nano-particles although the species of nano-particles associated with thermal effects should be revealed by further FIB-TEM works.

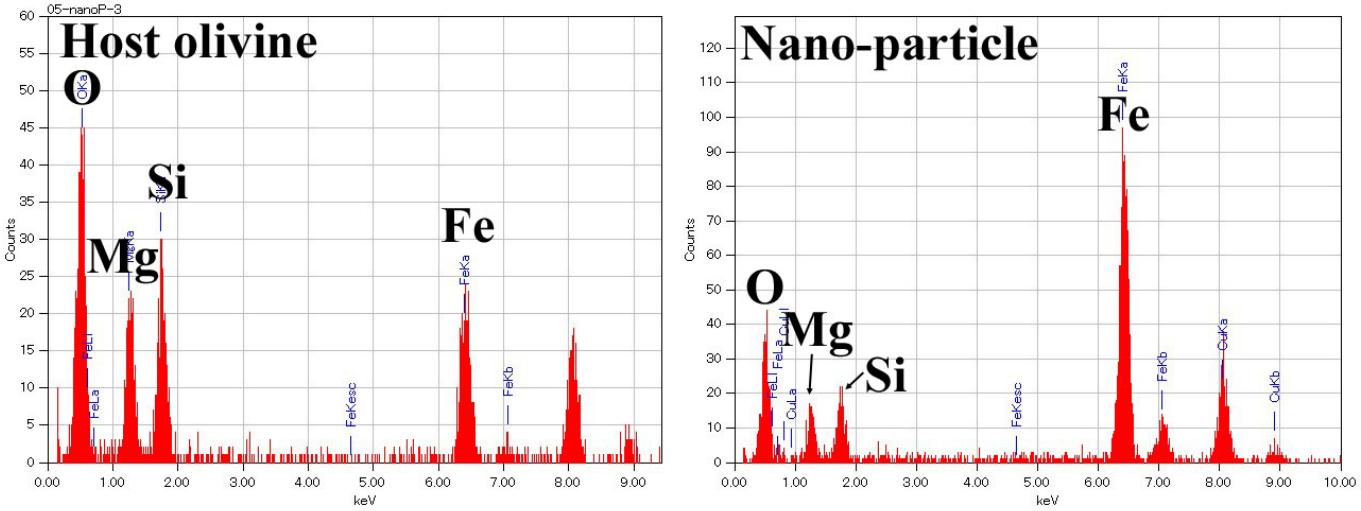

Figure 2 TEM-EDS analysis of the host olivine (left) and iron nano-particle (right). Although iron is enriched in EDS spectra obtained from nano-particle, no enrichment of oxygen is observed (the counts ratio of O, Mg and Si is constant in both analyses).

Summary

This study revealed that brown olivine in Y984028 contains iron nano-particles. Considering thermal history of Y984028, long post shock annealing may induce oxidation of iron metal into magnetite. However, the nano-particles are iron metal. There is a possibility that small differences in cooling process lead heterogeneous oxidation of nano-particles and we overlook the presence of magnetite nano-particles in this meteorite, and also in the other Martian meteorites with brown olivine. In order to confirm the relations between thermal history and species of iron nano-particles, further FIB-TEM works are needed.

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