Elucidation of aqueous alteration of the Yamato 000749 nakhlite based on multi-probe microscopy

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Motivation

No liquid water present on the Martian surface today. Through the Mars explorations and researches of Martian meteorites for many years, evidence for liquid water in the past Mars has been found. It's suggested that there once was a large amount of water on Martian surface (e.g., Sekine, 2012). A Martian meteorite is one of the important clues for restoring the past Martian surface environment that cannot be unveiled by the Mars surface survey alone using Rovers and satellites. It is expected that a group of Martian meteorites nakhlites has evidence for a rock-fluid reaction occurred on the past Mars. One of the representative evidence for the rock-fluid reaction is a unique texture iddingsite, which is an alteration texture formed in and around olivine grains of nakhlites. Many kinds of secondary minerals such as clay minerals occur in the iddingsite through the rock-fluid reaction. They have recorded the water-rock reaction in the era when liquid water present on Mars, and have important implications for understanding the evolutionary process of Mars. In particular, the mineral assemblages, chemical compositions, and chemical species of the secondary minerals depend on the varied chemical parameters such as temperature and pH-Eh of the fluid.

Suga et al. (2017) described the secondary minerals in the iddingsite of nakhlite the Yamato (Y) 000593. Another Martian meteorite, the Yamato (Y) 000749 nakhlite is also a member of Yamato 000 nakhlites like Y 000593, containing pervasive iddingsite. Based on $^{40}Ar/^{39}Ar$ and cosmogenic exposure dating by Cohen et al. (2017), Y 000749 was located at the lower portion of the same nakhlites source compared to Y 000593. We expect that these nakhlites have different modes of alteration even in the same source. Such heterogeneity on the mode of aqueous alteration will be related to the past hydrothermal environment on Mars. Hence, we will describe the secondary minerals occurring in the iddingsite of Y 000749.

Methods

We polished the allocated Y 000749 chip sample using a lapping film (3M^{TM}) to avoid the loss of any soluble materials first under dry condition. We clarified the secondary mineral species, chemical compositions, and chemical species of the iddingsite in Y 000749 using a combined SEM-Raman-FIB-TEM-STXM technique that we developed. Pervasive iddingsite textures were observed along with the fractures and grain-boundaries of the olivine grains in Y 000749 through FE-SEM observation and Raman spectroscopy analysis. We extracted and processed several portions including iddingsite to be thin foils by FIB for TEM/STEM and STXM analyses.

Results and Discussion

We identified laihunite, ferrihydrite, goethite, poorly-crystallized silica minerals, and the minor amounts of iron sulfates in the iddingsite through the combined analysis. Laihunite was identified both by the Raman spectrum and selected-area electron diffraction (SAED) patterns. Ferrihydrite and goethite were confirmed by Raman spectra, O- and Fe-XANES spectra, and SAED patterns. Raman spectrum and STEM-EDS analysis indicated the existence of poorly-crystallized silica minerals. The minor amount of iron sulfate was identified by the S-XANES spectrum. As for the poorly-crystallized silica minerals, we have tried to identify in detail them again by analyzing the newly prepared FIB thin films.

Figure 1 shows the representative TEM image of the iddingsite of Y 000749. Based on the detailed TEM observation and XANES analysis, the secondary minerals in the iddingsite of Y 000749 arrange in a layer along with the fractures of the olivine grains: laihunite, ferrihydrite (and goethite) containing a trace amount of iron sulfate, and poorly-crystallized silica minerals from the outside of the iddingsite vein towards the center of the vein (Fig. 1). Considering the layered occurrences of the secondary minerals, we propose that the formation sequence is as follows: i) laihunite, ii) ferrihydrite and lesser amounts of goethite and iron sulfates, iii) poorly-crystallized silica minerals.

Based on the occurrences and formation conditions of the secondary minerals, we expect that Y 000749 experienced three different alteration events at least. We propose that Y 000749 has the following aqueous alteration history: At the first alteration event, Mg and Fe coordinated in the olivine structure were dissolved into the fluid and a part of Fe-bearing olivine was oxidized, thus leading to form laihunite. In the second alteration event, Fe dissolved in the fluid was precipitated as ferrihydrite (and/or goesite). Then, at the third alteration event, Si dissolved in the fluid was precipitated as poorly-crystallized silica minerals.

Suga et al. (2017) reported that the iddingsite of Y 000593 includes laihunite, opal-A, jarosite, natrojarosite, goethite, and ferrihydrite. Comparing their results with our results of Y 000749, the species and quantity ratio of secondary minerals are different from each other although Y 000593 and Y 000749 are regarded as a paired meteorite. The alteration was initiated by the formation of ferrihydrite subsequent to the formation of laihunite both in Y 000593 and Y 000749, which would occur under high-temperature and high-pH conditions (Treiman, 2005). The mode of subsequent alteration changed in between Y 000593 and Y 000749 because there is difference in the species of secondary minerals formed next to laihunite in the iddingsites. Sulfates were formed in Y 000593, while few amounts of sulfates were observed in Y 000749. Alternatively, poorly-crystallized silica minerals were pervasively formed in Y 000749. As described above, based on Cohen et al. (2017), the burial depths of Y 000749 and Y 000593 are different in the same nakhlites complex. We expect that the alteration condition depends on the burial depth even in the same source. Hence we plan to investigate another nakhlite to verify this hypothesis.

Conclusions

From the mineral species and layered structure of secondary minerals in the iddingsite of Y 000749, the fluids involved in the alteration of Y 000749 were hot and oxidative, and Y 000749 have experienced three aqueous alteration events at least. In addition, by comparing each secondary mineral in the iddingsite of Y 000749 and Y 000593, we found that both meteorites, which were considered a paired meteorite, had experienced alteration at different places (depths). Based on our results, and the stratigraphic model of nakhlites by Cohen et al. (2017), we expect that the fluid reacted with nakhlites originated from Mars's underground.

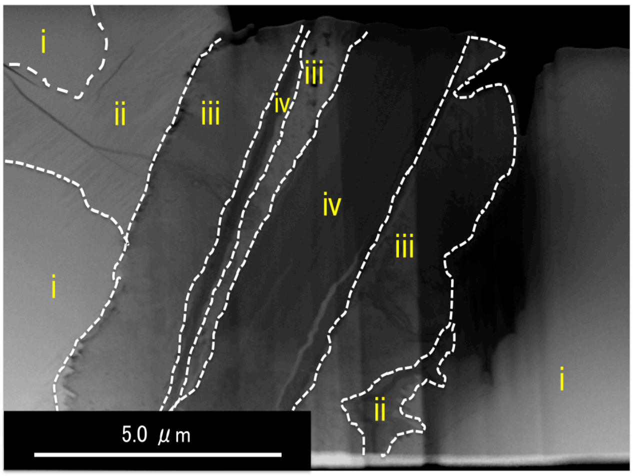

Figure 1. HAADF-STEM image of representative iddingsite (ii, iii, and iv) next to original olivine (i) in Y 000749.

References

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