Elucidation of aqueous alteration in the lava units with nakhlites NWA 10153 and NWA 6148

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Introduction

The evidence for liquid water on the past Mars surface is found by the Mars explorations and research about Martian meteorites. Many kinds of phyllosilicate, carbonate, and sulfate minerals occur in Martian meteorite nakhlites [1]. The formation of these alteration minerals depends on temperature, water-rock ratio, dissolved ions species, and pH-Eh. Hence, alteration minerals in nakhlites provide a clue for elucidating ancient Martian surface conditions. Nakhlites are expected to originate from the nakhlite body formed by multiple lava flows on Mars [e.g., 2, 3]. Based on $^{40}Ar/^{39}Ar$ radioisotope ages, the nakhlites body composes of four lava units at least [4]. Alteration minerals occurring in each lava unit have been investigated enthusiastically [e.g., 2, 3]. It is likely that liquid water circulated in the nakhlite body. However, the vertical variation of aqueous alteration in the nakhlite body has not yet been elucidated in detail. NWA 6148 and NWA 10153 are members of nakhlites and their alteration minerals have not been investigated. Jambon et al. (2016) [3] suggest that NWA 6148 originates from the deeper part of the nakhlite body. NWA 10153 is hardly investigated and its position in the nakhlites body is not clear. In this research, we will investigate the petrological and mineralogical features of NWA 6148 and NWA 10153 to add new information about the alteration sequence in a vertical direction in the nakhlite body.

Methods and materials

NWA 6148 and NWA 10153 were embedded into epoxy resin and polished. For petrological and mineralogical descriptions, microtextural observation by an FE-SEM and chemical compositional analysis by an EMPA were conducted. We used an FIB system to prepare the ultra-thin foils of altered portions in the samples. The chemical species of iron, oxygen, carbon, and sulfur in the foils were analyzed by using the BL19A, PF-KEK. The microtextures, chemical compositions, and crystal structures of minerals in the foils were analyzed using an FE-TEM/STEM-EDS.

Results and discussion

NWA 6148 consists mainly of olivine, low-Ca pyroxene, and mesostasis. Plagioclase, K-feldspar, pyrrhotite, and Fe-Ti oxides occur in mesostasis. A quench texture was observed in mesostasis. NWA 6148 has a higher fraction of mesostasis (55.2 vol.%) than other nakhlites (7−24 vol.%) [2]. These features suggest that NWA 6148 does not originate from the deeper part of the nakhlite body; the high fraction of mesostasis is suggestive of a rapid cooling rate near the surface. The low-Ca pyroxene grains of NWA 6148 have Ca zoning. Such Ca zoning is found only in nakhlites NWA 5790 [3] and MIL 03346 [2]. The similarity in Ca zoning suggests that NWA 6148 belongs to the same lava unit as NWA 5790 or MIL 03346. Based on the volume ratio of mesostasis, the stratigraphic sequence is considered to be NWA 6148, NWA 5790 or NWA 6148, MIL 03346 from the top to the bottom of the lava unit. Distinguished alteration texture was not found in NWA 6148. Similarly, alteration minerals are not found in NWA 5790 [5]. On the other hand, iddingsite, one of the alteration textures, is identified in MIL 03346. Most of the alteration minerals in MIL 03346 are iron-rich hydroxy-silicates. Goethite, siderite, gypsum, or anhydrite are not observed in MIL 03346. The total amount of alteration minerals in MIL 03346 is only 0.24 vol% [6]. These features indicate that a part of the nakhlites body, where composes of NWA 6148, NWA 5790, and MIL 03346, would be less affected by aqueous alteration.

NWA 10153 consists mainly of olivine, low-Ca pyroxene, and mesostasis. Plagioclase, K-feldspar, pyrite, and Fe-Ti oxides occur in mesostasis. The compositions of olivine in NWA 10153 is more fayalitic (Fa=86.2±1.5mol%) compared to other nakhlites (Olivine in MIL 03346, NWA 817, and Y 000593 have similar major element compositions [2].). The volume amount of low-Ca pyroxene (~63.4 vol.%) is low compared to other nakhlites (69−84.2 vol.%) [7−9]. The low-Ca pyroxene grains of NWA 10153 have only Fe zoning. The Fe zoning is similar to those of Nakhla and Governador Valarades [10]. The lack of Ca zoning suggests that the lava unit including NWA 10153 is different from that including NWA 6148, NWA 5790, and MIL 03346. The compositions of olivine and the volume amount of low-Ca pyroxene of NWA 10153 do not match any other nakhlites. Accordingly, NWA 10153 may have originated from an unknown lava unit, which is supported by the fact that the initial Nd isotope composition of NWA 10153 is different from any other nakhlites [11].

Many alteration textures were observed around fayalitic olivine, plagioclase, and pyrite grains in NWA 10153. FIB-assisted XANES-TEM/STEM analysis reveals that the alteration textures of fayalitic olivine grains can be divided into four types: i) goethite-, ii) jarosite-, iii) saponite-, and iv) siderite-dominated types. We suggest the following alteration sequence:

first, a neutral to a basic fluid containing CO^{2-} reacted with fayalitic olivine, and most Fe and Mg ions were dissolved into the fluid. The fayalitic olivine was replaced with saponite and siderite precipitated simultaneously. Second, an acidic fluid dissolved pyrite, which reduced the pH of the fluid. Jarosite crystallized from the fluid with very low pH. Subsequently, with increasing the pH again due to the reaction between surrounding minerals and the fluid, goethite precipitated from the fluid finally. The change of alteration environment from neutral−basic to acidic conditions is consistent with those of nakhlites previously studied [12, 13].

We discuss the variation of aqueous alteration in the vertical direction of the nakhlites body based on the stratigraphy of nakhlite body inferred from $^{40}Ar/^{39}Ar$ isotope ages [4] and their assemblages of alteration minerals. Cohen et al. (2017) [4] suggest that the nakhlite body can be divided into four units: Unit I (Lafayette), Unit II (Y 000593 and NWA 5790), Unit III (MIL 03346 and Nakhla), and Unit IV (Y 000749) from the top to the bottom. The location of NWA 10153 in the nakhlites body has not been clarified. Considering the Ca zoning of low-Ca pyroxene, NWA 6148 is located within Unit II or III. Lafayette contains ferroan smectite, magnetite (or maghemite), and ferrihydrite as alteration minerals [14]. Y 000593 includes smectite, saponite, siderite, laihunite, gypsum, opal-A, jarosite, and goethite [15]. NWA 5790 does not contain alteration minerals [5]. The difference in the degree of alteration between Y 000593 and NWA 5790 indicates alteration is heterogeneous even in the same unit. In MIL 03346, iron-rich hydroxy silicates occur although their amount is very limited [6]. Iron-rich silicate (tentatively identified smectite), Ca-carbonate (probable calcite), and Ca-sulfate (possibly gypsum or bassanite) are observed in Nakhla [16]. Shiraishi et al. (2019) [13] identify laihunite, ferrihydrite, goethite, poorly-crystallized silica minerals, and a minor amount of iron sulfates in Y 000749.

Smectite is found in Lafayette (Unit I), Y 000593 (Unit II), Nakhla (Unit III). Smectite seems to occur throughout the nakhlite body. However, there are variations in the assemblage of alteration minerals in each lava unit: Magnetite (or maghemite) is found only in Unit I, Many kinds of alteration minerals are identified in Unit II, and Ca-carbonate is observed only in Unit III. It is unlikely that the same fluid circulated throughout the entire nakhlite body and induced these alterations. The alteration might occur in each lava unit of the nakhlite body.

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