The Complexity of Aqueous Alteration Veins in Nakhlites

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Introduction: Nakhlites are a group of basaltic meteorites originating from the mid-Amazonian igneous crust of Mars [1]. They represent an interesting set of samples to study the aqueous alteration at the Martian subsurface, as they contain aqueous alteration phases in olivine called "iddingsite" (e.g. [2]). Studying iddingsite in nakhlites can reveal the water-crust interactions and the hydrothermal physico-chemical conditions that prevailed at the Martian subsurface, with implications for the past habitability of Mars, and in particular for microbial life during the Amazonian period. We studied iddingsite in Caleta el Cobre (CeC) 022, a nakhlite that contains a high amount of alteration products, and compared this meteorite to 7 other nakhlites.

Methods: A serie of analyses were conducted on eight nakhlites polished sections: CeC 022, Governador Valadares, Lafayette, Miller Range (MIL) 03346, Nakhla, North-West Africa (NWA) 817, NWA 998 and Yamato (Y) 000953 to assess the mineralogy, the chemical and the isotopic composition of the alteration products in nakhlites: electronic microscopy (FEG-SEM and TEM), EDX microanalyses and chemical maps, LA-ICPMS major elements analyses, Raman spectra, and finally, hydrogen isotopic measurements by SIMS.

Results: In all nakhlites, the alteration veins show at least two types of iddingsite (Fig. 1A): (i) a coarse iddingsite in contact with olivine at the border of the alteration veins, showing 50-200 nm crystals, composed of a mixture of 1:1 phyllosilicates of greenalite-cronstedtite composition, and Fe-oxyhydroxides ; (ii) a fine iddingsite, in the inner part of the alteration veins, with <10 nm crystals, with a composition close to saponite (2:1 phyllosilicate). Complex chemical zoning of Mg, Ca, Mn, S, P and Al, has been observed on EDS-TEM mappings in NWA 10153. In most nakhlites, olivine grains also display planes of secondary inclusions, composed of pyroxene, magnetite and a void potentially filled by a fluid (Fig. 1B). In most nakhlites, magnetite-pyroxene symplectites are found in olivine grains, often at the border of the secondary inclusion planes. Those secondary inclusions and symplectites can also be observed at the center of the iddingsite veins (Fig. 1A). Also, sulfide-magnetite veinlets are observed at the center of the iddingsite veins, and also crosscutting olivine and pyroxene grains and mesostasis. Finally, organic matter is observed on Raman spectra in the iddingsite of many nakhlites, and is located in coarse iddingsite, as shown by TEM observations of NWA 10153.

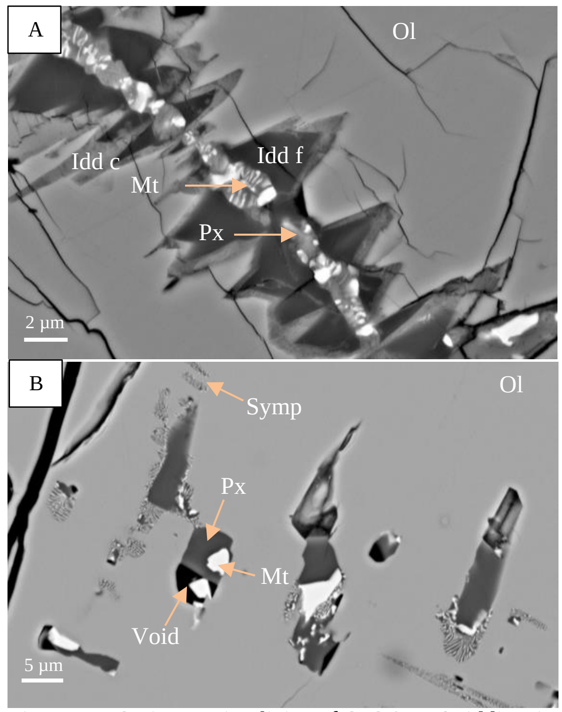

Figure 1: BSE images in olivine of CeC 022. A: iddingsite veins with magnetite-pyroxene symplectites as center of vein. B: symplectites of magnetite and pyroxene, and secondary inclusions composed of magnetite, pyroxene and a void. Idd c: coarse iddingsite; Idd f: fine iddingsite; Mt: magnetite; Ol: olivine; Px: pyroxene; Symp: symplectite.

Discussion and conclusion: Our favored scenario is that the secondary inclusions and the symplectites are formed by a first fluid alteration event triggered by late magmatic fluids, prior to the iddingsite formation event,. These secondary inclusions represent weakness planes that facilitate the circulation of the alteration fluid forming the iddingsite inside the olivine grains. The composition and texture of both types of iddingsite is suggestive of a crystallization by filling of existing fractures, with an alteration fluid enriched in elements from basaltic glass and host olivine dissolution, and changes in the alteration conditions or fluid composition. The sulfide-magnetite veinlets represent either the late stage of the same alteration event as the iddingsite formation, or a different later fluid injection. With the two types of iddingsite, the complex centers of veins and the chemical zoning in the fine iddingsite, we suggest that fluid alteration in the nakhlites has a complex multistage history of fluid injections.

References: [1] Nyquist, L. E., et al. (2001) *Chronology and evolution of Mars.* 105-164, [2] Changela, H. G., and J. C. Bridges. (2010) *Meteoritics & Planetary Science* 45 .12:1847-1867.