CORRELATIVE 4D TOMOGRAPHIC STUDY OF ALTERATION VEINS IN NAKHLITES TO NON-DESTRUCTIVELY DETERMINE FLUID FLOW SEQUENCES IN THE MARTIAN SUBSURFACE

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Introduction: Nakhlites are martian pyroxenites that crystallized as lava flows during the Amazonian period, ~1.3 Ga [1]. They host a range of fluid alteration minerals: carbonates, sulfates, halides and clay minerals, that clearly formed via water-rock interactions in the subsurface of Mars [e.g., 2,3,4], possibly as recently as ~680 Ma [5]. The nature of the aqueous alterations, mechanisms by which the secondary minerals formed, and source of fluids are however all a matter of extensive debate [2-4]. Alteration minerals may have been deposited from a single, episodic low-temperature fluid [4], but more complex scenarios are also proposed that include multiple events of ingress of surface-deirved waters [2,6], or serpentinisation and carbonation of olivine via reaction with atmospheric-derived CO_2 [3]. To address the question of whether nakhlites were altered by a single or multiple fluid(s), we performed non-destructive chemistry- and phase-resolved (i.e. four-dimensional) studies of the secondary minerals in alteration veins in nakhlites in situ. The specific questions we addressed were: 1. What is the spatial distribution of the secondary minerals to the primary minerals, to each other, and the fracture systems and 2. Which fracture system(s) relate(s) to which alteration phases and how the chemical composition of the phases changes spatially.

Methods: To provide a full understanding of the textural details, we designed a multi-method correlative study of alteration veins. The samples of Nakhla and Lafayette in their as-received state were first scanned with absorption tomography at micron- and sub-micron-scale modes. The reconstructions allowed us to visualize the fracture system and alteration veins. Analysis was supplemented with non-destructive low-current SEM/EDX analysis of alteration minerals, as observed on split fracture surfaces [6]. Such qualitative elemental distribution with sub-micron resolution was sufficient to identify intimate textures in 2D. Reconstruction of the fracture system correlated with chemical information was used to identify volumes hosting a range of alteration phases. From those regions of ineterst, 'house-shaped' samples up to 80 µm in size were extracted by plasma FIB sectioning using a Xe ion beam [7]. The extracted volumes were imaged using element-specific X-ray fluorescence tomography combined with phase-specific X-ray diffraction tomography. The tomographic imaging was performed with a monochromatic beam of 18 keV and 6.7 keV (below Fe K-edge), performing 362° rotation and collecting projections with steps of 2°. Fluorescence and diffraction signals were collected simultaneously and the voxel size after reconstruction is 2 µm.

Results: Transmission of X-rays from the extracted volumes was enough to receive fluorescence signal of Fe, Mn, Ca, and in most cases of K and Cl. This allowed us to image the spatial distribution of alteration phases (Fig. 1) such as: Mn-carbonates (based on Mn signal), Ca-sulfates (Ca) and Fe,Mg-phyllosilicate (K). Distinguishing the Fe,Mg-carbonates from the host olivine is more challenging and requires correlation with the phase-resolved XRD.

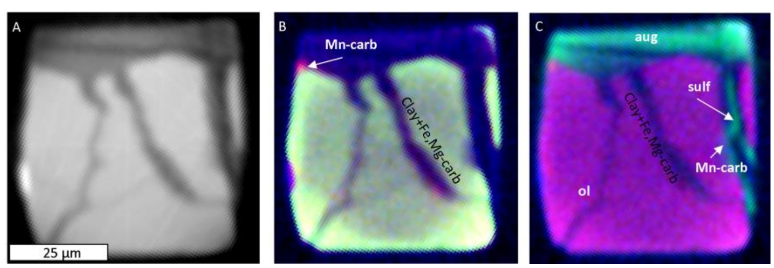

Fig. 1. Example XRF-CT slices of Nakhla showing mineral assemblages in alteration veins. **A**. Absorption contrast image at E=18 keV. **B**. Composite elemental map: R-Mn, G-Fe, B-K. **C**. Composite elemental map: R-Mn, G-Ca, B-K at E=6.7 keV.

Fe,Mg-carbonates are hosted within wedge-shaped veins, intimately overgrown with Fe,Mg-phyllosilicates (Fig. 1B). Unlike the carbonates, sulfates are contained in thick fractures, and usually fill these fractures completely. The amount of Fe,Mg-phyllosilicates largely varies in these fracture systems (Fig. 1C). Sulfates tend to infill separate fractures systems to the Fe,Mg-carbonates. Mn-rich carbonates (or Ca,Mn-carbonates in Lafayette) occur related to fracture systems that are separate from those of the Fe,Mg-carbonates, but most often associated with sulfates.

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