

MULTIPLE FLUID ALTERATIONS IN THE MARTIAN SUBSURFACE RECORDED BY NAKHLITES

A.M. Krzesińska^{1,2}, P.F. Schofield¹, K. Geraki³, J.R. Michalski⁴, C.L. Smith^{1,5}. ¹Dept. Earth Sciences, Natural History Museum, SW7 5DB, London, UK. ²Institute of Geological Sciences PAS, Wrocław, Poland. ³Diamond Light Source Ltd, Chilton OX11 0DE, UK. ⁴Dept. of Earth Sciences, University of Hong Kong. ⁵School of Geographical and Earth Sciences, University of Glasgow, UK. a.krzesinska@nhm.ac.uk

Introduction: Nakhilites are martian pyroxenites that crystallized in a shallow intrusion or lava flow(s) during the Amazonian period, ~1.3 Ga [1]. They host amorphous and/or nanocrystalline hydrous Fe,Mg-silicates and a range of salt minerals that clearly formed via water-rock interactions in the subsurface of Mars [e.g., 2,3,4] as recently as ~680 Ma [5]. The nature of the aqueous event(s) that triggered the alterations, especially the mechanisms by which the secondary minerals formed are, however, not fully recognized. The most comprehensive model suggests that all the secondary minerals were formed by a single episodic event and were deposited from a brine that was derived from a low-T hydrothermal source [6]. Trace element signatures of some alteration minerals [3] may in turn suggest evaporation of a surface derived brine such as flood waters. Nanostructural studies [4] instead reveal that carbonates may have formed by serpentinization and carbonation of olivine via reaction with atmospheric-derived gas. The majority of interpretations are, however, based mainly on the observation of Fe,Mg-silicates, while the salt minerals, and especially their textures, have been studied far less. Our study is concerned with the reconstruction of fluid flow(s) and alteration/replacement histories recorded by the salt minerals in nakhilites. We focus on their chemical and textural relationships to the primary minerals, each other, the hydrous Fe,Mg-silicates and the fracture systems. Moreover, we have undertaken this study with no (or minimal) invasive or destructive sampling.

Samples and Methods: We have conducted a *non-destructive* 3D survey of secondary minerals in Nakhla (10 fragments, 50–400 mg in size), Governador Valadares (3 fragments, 20-1200 mg) and Lafayette (4 fragments, 35-640 mg) meteorites. We utilized computed X-ray microtomography, SEM-EDX low voltage elemental imaging [7] and synchrotron-based XRF qualitative mapping of REE, Ba Sr, Rb, Cl and Zn in salt minerals. Both SEM-EDX and XRF were performed on unprepared and uncoated surfaces, that is, on salt minerals as identified *in-situ*. A spatial resolution in the μ -CT reconstructions (down to 2 μ m/voxel) was sufficient to visualize fracture and vein systems. SEM/EDX yielded qualitative elemental distribution (at a level of ~1 wt%) with sub-micron resolution, sufficient to identify intimate textures. XRF provided trace element distribution at the ppm level and with a spatial resolution of ~3 μ m. All datasets were linked together to reconstruct in 3D the salt mineral distribution.

Results: The major secondary salt minerals in all the nakhilites we studied are carbonates and sulphates, which are associated with hydrous Fe,Mg-silicates. The textural assemblages they form are different, however, and they rarely co-occur with each other. Two separate groups, Fe,Mg-rich and Mn-bearing, can be identified within the carbonates. Nakhla and Governador Valadares additionally host halite and trace Mg-chloride.

Fe,Mg-carbonates are hosted within size-limited (~100-200 μ m long), wedge-shaped cracks, mostly located in olivine. The carbonates reveal network-like morphologies and indistinct contact with hydrous Fe,Mg-silicates. They are chemically zoned with a significant increase in Mg at the contact with hydrous Fe,Mg-silicates. Fe and Mg contents in carbonates vary between different nakhilites. Unlike the carbonates, sulphates have euhedral shapes and are clearly deposited after the hydrous Fe,Mg-silicates and the Fe,Mg-carbonates. They are deposited in fractures that cut across whole samples. In some cases sulphate-hosting veins that displace carbonate-hosting veins have been observed. Mn-rich carbonates (or Ca,Mn-carbonates in the case of Lafayette) occur as irregular or patchy microcrystalline coatings on Fe,Mg-carbonates, perhaps formed by deposition. When reconstructed in 3D, Mn-carbonates are related to fracture systems that are separate from those of the Fe,Mg-carbonates and are located mainly in proximity to tiny fissures. Unlike Fe,Mg-carbonates, Mn-phases are enriched in Zn and Cl.

Mechanisms of fluid alterations: The differences in morphologies and distribution of Fe,Mg-carbonates and sulphates in nakhilites suggests that these phases formed in separate fluid alteration events. We propose that nakhilites were first altered via carbonation and serpentinization of olivine, as described by [4]. After this event, brittle deformation occurred which was followed by an external fluid flow and deposition of sulphates in open fractures. The precise timing of Mn-carbonate deposition is less clear, but it is likely that they formed in association with the sulphates. Enrichment of Mn-carbonates in Zn may reflect fluid chemistry but may be due to Zn affinity with rhodochrosite and crystal-chemistry [8]. The source fluid for the Mn-carbonates was most reasonably surface derived, as also suggested by association of Cl with the Mn-phases

References: [1] Borg L. and Drake M.J. (2005) *Journal of Geophysical Research* 110: E12S03. [2] Gooding J.L. et al. (1991) *Meteoritics* 26: 135–143. [3] Bridges J.C. and Grady M.M. (2000) *Earth and Planetary Science Letters* 176: 267–279. [4] Lee M.R. et al. (2015) *Meteoritics and Planetary Science* 50: 1362–1377. [5] Swindle T.A. et al. (2000) *Meteoritics and Planetary Science* 35:107–115. [6] Changela H.G. and Bridges J.C. (2011) *Meteoritics and Planetary Science* 45: 1847–1867. [7] Salge t. et al (2017) *80th Annual Meeting of the Meteoritical Society*, abstract submitted. [8] Graf D.L. (1961) *American Mineralogist* 46:1283-1316.