

**SECONDARY MINERALS IN NAKHLA: A 3D RECONSTRUCTION OF ALTERATION SEQUENCES.**

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**Introduction:** Nakhilites are pyroxenites that sample a shallow ~1.3 Ga intrusion or lava flow on Mars [1]. They host amorphous and/or nanocrystalline Fe,Mg-silicate gel and a range of salt and clay minerals that clearly formed via reactions with fluids on Mars [e.g., 2,3,4]. As such, the nakhilites bear information on liquid present as recently as ~680 Ma, [5] in the Martian subsurface and it is broadly accepted that the fluid represented a low-T hydrothermal brine [6]. However, limited data on the chemistry of salt minerals [2,3], mineral assemblages they form [3], and their textural relationship to primary igneous minerals [4] and fracture systems [7] leave uncertainties with regard to the timing, duration and nature of aqueous events, and their implications for habitability. This study is concerned with the relationship of secondary to primary minerals and fractures in the Nakhla to gain a better insight into their formation and replacement history, and subsequently fluid flow sequence(s) within the parent intrusion or lava pile.

**Method:** We have conducted a non-destructive 3D survey of secondary minerals in 8 fragments of Nakhla (50–400 mg in size) by combining computed X-ray microtomography and FEG-SEM/EDX imaging of unprepared meteorite surfaces. A spatial resolution in  $\mu$ -CT reconstructions (~5  $\mu$ m/voxel) was sufficient to visualize primary igneous minerals and fracture systems. It was not possible to produce a complete 3D reconstruction for the alteration minerals owing to their small size and similar attenuation coefficient with the mesostasis. Alteration minerals have been successfully identified and analysed by FEG-SEM/EDX qualitative element mapping of oriented surfaces of the fragments (sub-micron resolution). These element maps were then overlain on the 3D  $\mu$ -CT reconstructions.

**Results:** 7 fragments studied reveal a typical cumulative texture [8] and modal composition, while one reveals to be significantly enriched in mesostasis (up to 45 vol%). The alteration record differs for the two lithologies.

*Secondary to primary mineral relationships:* Mg,Mn-siderite and Ca-sulfate are spread across all the primary minerals and do not differ significantly in chemical composition between various locations. Fe,Mg-silicate ‘gel’ is preferentially related to olivine. For halite, two different relationships are distinguished. When associated with large mesostasis patches, it forms anhedral crystals up to 500  $\mu$ m and often is associated with Mg-sulfate. Elsewhere it forms small, subhedral or cubic crystals, commonly associated with gypsum.

*Secondary mineral relationships to the fracture system:* All fragments are pervasively fractured with cracks cutting through all the primary minerals. 3D reconstruction of fractures in olivine show they form a complicated network, with many being wedge-shaped cracks continuing in augite and mesostasis. When olivine is split along surfaces of these cracks, they often exhibit dissolution pits and host secondary minerals. Fe,Mg-silicate ‘gel’ forms a continuous or patchy cover on the split surfaces of fractures, commonly associated with carbonates. Halite is close to olivine margins and always connected to the fracture system continuing in the whole rock. Elsewhere, siderite, sulfate and halite assemblages occur, always connected to the whole-fragment crack system. The exceptions are, however, large halite crystals associated to mesostasis patches.

**Discussion:** Chemistry of secondary minerals in Nakhla and their common association with fracture systems suggest that the alteration is related to fluid percolation through the rock. Morphology of olivine fractures confirms that dissolution of olivine contributes to the deposition of secondary minerals [4]. The alteration sequence from olivine infilling may be reconstructed as: 1) Siderite crystallization in open/partly open fractures; 2) Dissolution of olivine, siderite corrosion and replacement by Mg,Mn-rich siderite perhaps simultaneous with 3) Fe,Mg-silicate ‘gel’ deposition; 4) Crystallization of sulfates and halite at the margins of cemented grains. This sequence agrees with the model of fluid evolution and alteration due to evaporation of hydrothermal brine [4,6]. Questions remain with regard to the origin of the halite associated to mesostasis patches. Large halite crystals may have formed in a separate, earlier episode. It has previously been suggested that halite may have formed via high temperature crystallization from silicate melt [3], when Cl was supplied via either volatile metasomatism or sediment entrapment [3]. Association of halite with Mg-sulfates strengthens the role of entrapment, but more research is required to exclude terrestrial influence in forming the Mg-sulfates. It is likely that in the event of hydrothermal alteration, earlier formed halite was dissolved and remobilized to crystallize cubic crystals across the whole fractured rock. More research, especially on trace elemental signatures of salt minerals, is planned to confirm that.

**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] Needham A.W. et al. 2013. *Geochimica et Cosmochimica Acta* 116: 96–110. [8] Corrigan C.M. et al. 2015. *Meteoritics and Planetary Science* 50: 1497–1511.