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THE ORIGIN OF IDDINGSITE VEINS IN OLIVINE FROM THE NAKHLITE METEORITES: NEW INSIGHTS FROM ANALOGY WITH CM CARBONACEOUS CHONDRITES AND TERRESTRIAL BASALTS.

M. R. Lee, P. Lindgren, H. Breton and T. Tomkinson, School of Geographical and Earth Sciences, University of Glasgow, Gregory Building, Glasgow G12 8QQ. E-mail: Martin.Lee@glasgow.ac.uk.

Introduction: The nakhlite meteorites are samples of a ~1300 million year old martian clinopyroxenite lava flow or sill [1, 2]. These rocks contain secondary minerals including hydrous silicates, carbonates, sulphates and Fe-(hydr)oxides that formed by water-mediated alteration of the igneous body [3, 4]. A prerequisite for understanding the nature of the aqueous system from which these minerals formed, including water/rock ratio, the provenance of solutes and its longevity, is knowing whether the secondary minerals formed by replacement of primary igneous components (minerals and glasses), or by cementation of pores that were opened by fracturing. A replacive origin would suggest low water/rock ratios with solutions being close to saturation with respect to secondary minerals, and does not require a pre-existing network of pores for fluids to gain access to mineral grain interiors. An origin by cementation would suggest that solutes had been sourced by dissolution of other parts of the nakhlite parent rock or the martian crust and were introduced by fluid flow under relatively high water/rock ratio conditions; a means of fracturing the rock is also required.

Here we have sought to answer the question of whether olivine-hosted veins in the nakhlites formed by cementation or replacement by comparing the microstructures of veins in the nakhlite Lafayette with veins in olivine grains from type I chondrules in Murchison (CM2 carbonaceous chondrite). We also draw on previously published work on ‘iddingsite’ veins in olivine from terrestrial basalts.

Methods: This study used a polished block of the Murchison (CM2) carbonaceous chondrite, and a thin section of Lafayette. The olivine grains and their alteration products were characterised by backscattered electron imaging using a Zeiss Sigma field-emission SEM operated at 20 kV.

Results: The key characteristics of secondary mineral veins in Murchison and Lafayette olivine grains are as follows.

Murchison olivine-hosted veins. As it is one of the least aqueously altered of the CM carbonaceous chondrites, secondary minerals are scarce within the forsterite-rich olivine grains of Murchison type I chondrules. Nonetheless they can host secondary mineral veins, which are a maximum of 10 μm in width and typically extend only part way into grains from their edges. These veins have a fine-scale layering that is identified by differences in Z between successive generations of their fill. The axial layer is straight and parallel sided, ~0.2-0.5 μm in width, and may have a relatively high Z. Flanking layers have serrated interfaces with each other, and typically increase in Z towards vein margins (Fig. 1); this sequence can, however, differ significantly even within a single olivine grain. Vein walls may be planar and parallel to the vein axis, serrated or irregular.

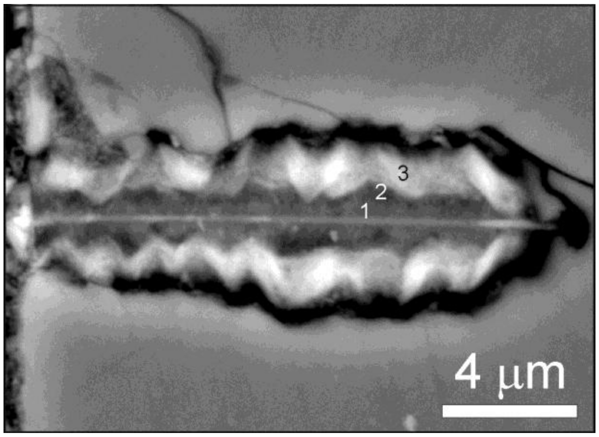

Figure 1. Backscattered electron SEM image of a vein in a type I chondrule olivine grain from the Murchison CM carbonaceous chondrite. The axial layer is straight and narrow, and is flanked by 3 layers that increase in Z overall (labelled 1-3). The interfaces between layers 1 and 2, and between layers 2 and 3 are finely serrated.

Lafayette olivine-hosted veins. Lafayette has the greatest abundance of secondary minerals among the nakhlites, and they occur mainly as olivine-hosted veins and irregular patches within the mesostasis [4, 5]. The veins have an average width of 13 μm; some crosscut grains but the majority extend only part way into olivine from intergranular boundaries. The axes of most veins lie parallel to olivine (001).

Those veins that are less than ~5 μm in width are composed mainly of a Fe- and Mg-rich hydrous silicate containing nanocrystalline smectite, hematite and ferrihydrite [4]. The vein fills commonly have a very fine-scale compositional layering. Typically the axial layer is straight and parallel-sided, whereas flanking layers tend to have serrated interfaces with each other (Fig. 2) and with the host olivine. The wider veins in Lafaytte are mineralogically and microtexturally more complex. Their axial Fe-Mg silicate is commonly flanked by a narrow selvage of Fe-(hydr)oxide, and the interface between these two vein constituents is often finely serrated. Towards the vein margin the Fe-(hydr)oxide passes into siderite that has been variably replaced by coarsely crystalline phyllosilicates. The siderite formed by crystallographically controlled replacement of olivine [5].

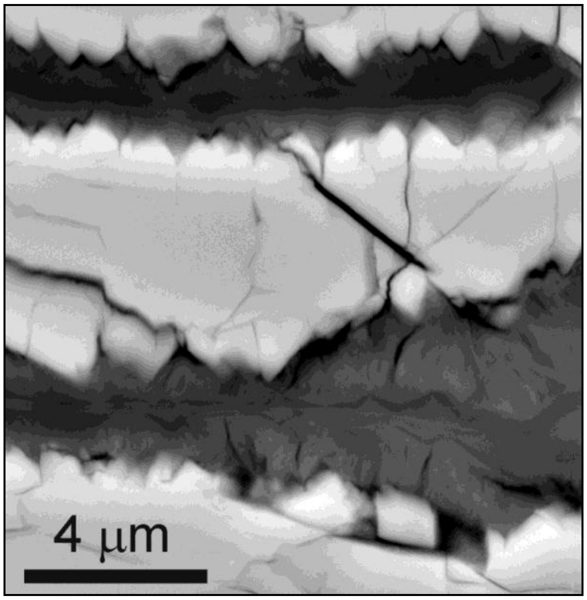

Figure 2. Backscattered electron SEM image of a pair of olivine hosted veins in the nakhlite Lafayette. The axes of both veins are oriented parallel to (001) olivine. A layering of the vein fill is revealed by subtle differences in mean atomic number (Z). The axial layers tend to be narrow and parallel sided whereas flanking layers have serrated margins.

Iddingsite veins in terrestrial basalts. Previous work on iddingsite veins in olivine grains from terrestrial basalts [6, 7] has shown that they start from (001) parallel cracks, and then develop a sawtooth texture as they are widened by replacement. The cross-sectional shapes of teeth and notches in serrated vein walls are very similar to etch pits produced by dissolution of terrestrial olivine [8]. Etch channels parallel to (001) in naturally weathered terrestrial fayalite form by the preferential protonation of M1 octahedral cations [9, 10].

Discussion: Despite obvious differences in alteration environments between Murchison and Lafayette (i.e., interior of a C-complex asteroid *vs* the shallow crust of Mars), conditions of water-rock interaction are likely to have been similar (e.g., low temperature, low Eh, high pH, with solutions being available for a relatively short period of time). Thus a comparison of vein microstructure between the two meteorites is a valid approach to obtain new insights into mechanisms of their formation.

Vein formation in Murchison. The microstructure of Murchison veins is consistent with an origin by replacement of olivine, which progressed outwards from the vein axis (i.e., centripetal replacement). The remarkably straight axial layer demonstrates a strong crystallographic control on its development; although the orientation of the vein axis has not been determined yet, it is likely to be parallel to (001). As the replacement front then moved into the olivine grain parallel to [001] its trajectory was crystallographically controlled, and probably by olivine {111} planes. Our conclusion that Murchison veins have formed by centripetal replacement is in good agreement with recent work on serpentinisation of the QUE 93005 CM carbonaceous chondrite [11].

Vein formation in Lafayette. Olivine-hosted veins in Lafayette have several microstructural similarities with those in Murchison, which points towards a comparable origin by centripetal replacement: (i) they often penetrate only a short distance into olivine grains from their edges; (ii) they have a preferred crystallographic orientation; (iii) they have an axial band that is straight and parallel sided; (iv) interfaces between layers, and between the vein fill and the host olivine, are commonly serrated and defined by {111} planes.

Conclusions: Centripetal replacement is a key mechanism by which olivine is converted to secondary minerals (i.e., phyllosilcates, carbonates, Fe-(hydr)oxides). The microstructural fingerprints of this process (e.g., a straight axial layer and serrated flanking layers) are the outcome of a control on vein initiation and widening by the olivine crystal structure.

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