COMPARISONS OF MARTIAN AND ANTARCTIC ALTERATION: A TRANSMISSION ELECTRON MICROSCOPE STUDY OF MIL 090032.
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Introduction: Miller Range (MIL) 090032 was collected during the 2009 field season of the Antarctic Search for Meteorites Program (ANSMET). Petrological and geochemical analyses of MIL 090032 and its three paired meteorites (MIL 090030, 090136 and 03346) indicate they originated from the same augitic cumulate layer(s) as the nakhlite martian meteorites [1-3]. As with the other nakhlites, MIL 090032 contains iddingsite-like alteration veins in the olivine phenocrysts that reportedly originated on Mars[4]. These 'iddingsite' veins have been analysed in a number of the nakhlite meteorites[5], and the presence of hydrous silicate gel, smectite clays, siderite, Fe-oxides, gypsum and carbonate have been reported. The presence and proportion of these phases in the different nakhlites appears to relate to the composition and concentration of the martian brine that flowed through each, thus supporting the theory that the nakhlite secondary alteration phases were produced by an evaporation sequence on the surface of Mars[6].

Compared with most other nakhlite samples, thin-sections of the Miller Range nakhlites contain relatively wide (~50-100 µm) and abundant martian 'iddingsite' veins within their olivine phenocrysts [2]. In addition, MIL 090032,25 – a thin-section originating from the exterior of the meteorite - contains three areas of terrestrial alteration at its externally exposed surfaces. The relative abundance of both terrestrial and martian alteration phases in this one thin-section makes it an ideal sample for high-precision, small scale, mineralogical comparisons. The aim of this study was to compare the chemistry and mineralogy of the martian and terrestrial alteration phases at sub-micrometer scales. These comparisons will help determine how close an analogue to the martian surface the Antarctic really is, in addition to revealing more about the martian paleoenvironment at the time the nakhlite 'iddingsite' veins formed (<1.3 Ga [7,8]).

Methodology: The JEOL JSM-5900LV scanning electron microscope and the JEOL JXA-8500F electron microprobe at UH produced high resolution backscattered electron and elemental X-ray images of the areas of interest. The electron microprobe was subsequently used to determine the major- and minor-element chemistry of each mineralogical phase.

We utilised the 80-300 kV aberration-corrected FEI Titan (Scanning) Transmission Electron Microscope (S-TEM) system at Lawrence Livermore National Laboratory to analyse two ~15×8µm Focused Ion Beam (FIB) sections from MIL 090032,25. One of these FIB sections (FIB 1) was cut from an area of martian alteration and the other was cut from an area of terrestrial alteration (FIB 2).

Results: The martian alteration vein FIB section (FIB 1) contains hydrous amorphous silicate gel towards the center, with areas of phyllosilicate (possibly nontronite) interspersed within this central zone (Fig. 1). Hydrated Fe-oxides were also observed within this zone. The Mg/(Mg+Fe) ratio of the amorphous silicate gel varies from 0.24 to 0.20. This range is between the average ratios previously measured in Nakhla (0.24) and Y000593 (0.15) [5]. Previous measurements indicate that this ratio is related to the depth of each nakhlite beneath the surface on Mars, where Lafayette was deepest and Nakhla and Y000593 were closest to the surface [5,6]. Our measured ratios would therefore place MIL 090032 close to the martian surface, in agreement with Mikouchi et al. [9]. This result is supported by the presence of jarosite (an Fe,K-sulphate evaporite) towards the outer edges of the alteration vein. On a plot of Fe vs. Si wt% both MIL 090032,25 phyllosilicate and silicate gel data plot close to similar phases in Lafayette, but form a different slope gradient (Fig. 2). Therefore, it appears MIL 090032 was involved in a different fluid fractionation pathway to Lafayette, Governador Valadares (GV) and Nakhla (which all show a gradient of -1.2), and Y000593 (which shows a gradient of -1.6) [5].

Terrestrial alteration areas in MIL 090032,25 mostly consist of gypsum and jarosite, the latter of which is commonly intergrown with an Fe-rich clay-like phase. FIB section 2 was taken from a region encompassing all three of these phases (Fig. 3). S-TEM data indicate the Fe-rich phase actually consists of two amorphous silicate layers. The outer layer (layer 1) contains more Fe, Mg, Al, Ca, S and Cl, and less Mn and K than the inner layer (layer 2). The jarosite layer (layer 3) proved to be a mixture of jarosite and amorphous Si-Fe-O bearing phases (probably hydroxides or gels), plus minor Fe-Mn-S oxide.

Conclusions: Our S-TEM data reveal a mixture of phyllosilicate and silicate gel (at a ratio of ~1:1) in the central zone of MIL 090032 martian alteration veins.

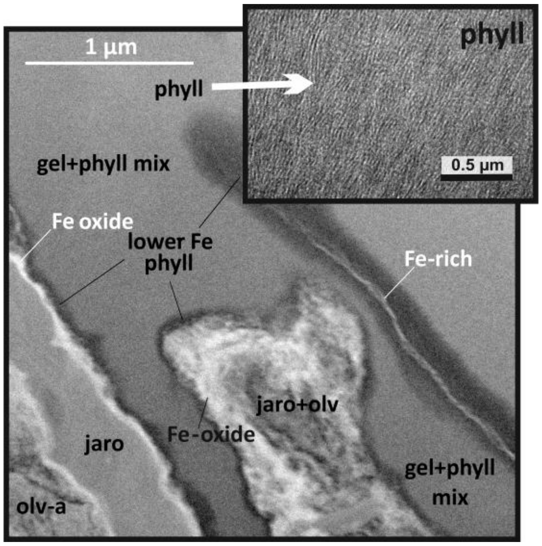

Fig. 1: High angle annular detector (HAAD) S-TEM image of FIB 1 detail (martian 'iddingsite'), showing phyllosilicate (phyll) and Fe-oxides next to jarosite (jaro) and olivine (olv).

Abundant phyllosilicate has only previously been reported in the martian alteration veins of Lafayette – all other nakhlites contain silicate gels. The presence of phyllosilicate suggests MIL 090032, like Lafayette, was altered on Mars by relatively aqueous brine - as silicate gel substitutes for phyllosilicate in low water to rock ratio conditions [9-11]. However, the measured Mg/(Mg+Fe) ratios in gel and phyllosilicate are more in line with the near-surface evaporitic alteration conditions shown in Nakhla and Y000593. The abundance of jarosite sulphate in MIL 090032,25 martian alteration is also indicative of evaporitic conditions, although this particular sulphate has not been reported as pre-terrestrial in the other nakhlites (gypsum was the sulphate produced in Nakhla and GV 'iddingsite'). It is possible that terrestrial weathering produced phyllosilicates from gel in the 'iddingsite' veins of MIL 090032,25, but the absence of phyllosilicates in other nakhlite finds (e.g., Y000593) argues against this. More probably, the MIL 090032 martian alteration veins were formed by a slightly different fluid to those which altered the other nakhlites, as indicated by its different Fe vs. Si (wt%) data slope gradient (Fig. 2).

The absence of phyllosilicates in MIL 090032 terrestrial alteration, and the presence of amorphous silicate 'gel', suggests a low water to rock ratio was present during this meteorites residence in Antarctica. In contrast, as mentioned above, the martian 'iddingsite' alteration veins do contain phyllosilicate. Therefore, it may be that the Antarctic alteration in MIL 090032 formed under water-poor conditions relative to martian 'iddingsite' alteration. In contrast, our data indicate sulphates form readily in this environment, as on Mars.

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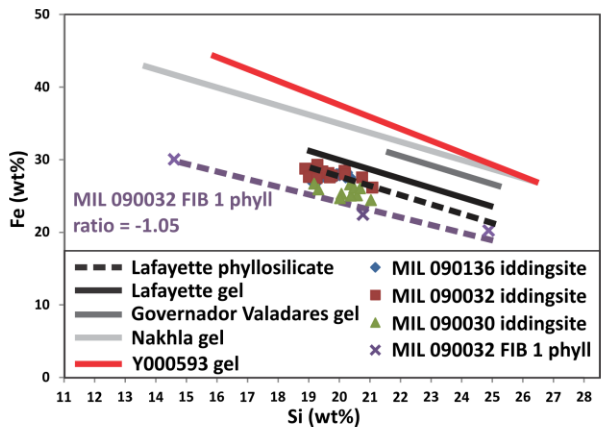

Fig. 2: Plot of Fe vs. Si wt% in nakhlite silicate gels and phyllosilicates. Lines represent previous data [5] with a slope of -1.2, excepting Y000593 data (-1.6). Our data for MIL 090032 phyllosilicate, as well as EMP data for MIL 090032, 090030 and 090136 'iddingsite' show a slope of -1.05.

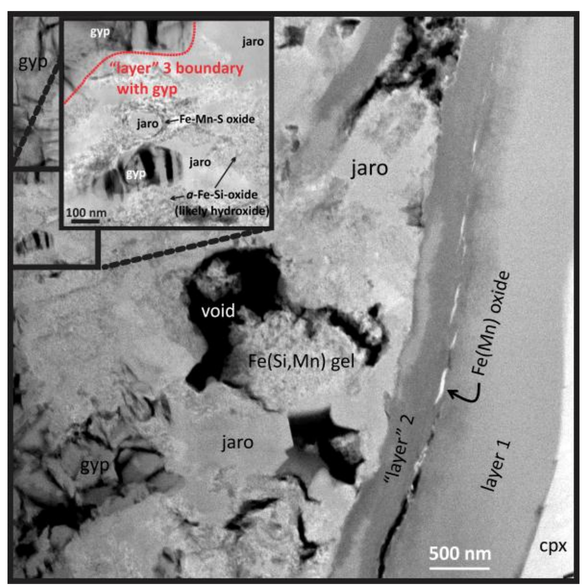

Fig. 3: HAAD S-TEM image of a detail of FIB 2 (terrestrial alteration), showing the two outer layers of amorphous silicate gel (layer 1 and 2), and the inner layer (layer 3) of jarosite, gypsum (gyp) and amorphous silicate gel.