# WIDESPREAD HYDROTHERMAL ALTERATION MINERALS IN THE FINE-GRAINED BLACK MATRIX OF THE TIESCHITZ UNEQUILIBRATED ORDINARY CHONDRITE.

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**Introduction:** Tieschitz is an unequilibrated ordinary chondrite (UOC) classified as a type H/L3.6 [1]. This meteorite contains two types of matrix, termed white and black matrix [2]. The white matrix is a distinctive matrix material enriched in Na, K and Al, the most abundant phases being nepheline and albite [3-6]. This white matrix has been interpreted as representing a component of the chondrules, i.e. mesostasis glass which had been leached out and redeposited by a fluid phase. This conclusion is consistent with previous studies that have provided significant evidence that Tieschitz has experienced metasomatic alteration on the ordinary chondrite parent body [3, 7-9].

In this study, we have focused on determining the effects of metasomatism on the fine-grained material in the black matrix of this meteorite. The texture and mineralogy of Tieschitz matrix were characterized using Scanning Electron Microscopy (SEM), electron microprobe (EMPA) and Focused Ion Beam/Transmission Electron Microscopy (TEM).

**Methods:** Fragments of Tieschitz and one polished thin section were initially studied on a FEI Quanta 3D FEGSEM/FIB operating at 30 kV, using backscattered electron (BSE) imaging. Elemental distribution maps were made by energy dispersive X-ray spectroscopy (EDS) for initial identification of different mineral phases. Quantitative mineral analyses were determined using a JEOL 8200 Superprobe electron microprobe (EMPA), operating at an acceleration voltage of 15 kV. Two TEM sections of selected regions of matrix were prepared using the focused ion beam technique, with a FEI Quanta 3D FEGSEM/FIB instrument. Bright field and scanning transmission electron microscopy images, electron diffraction and EDS X-ray analyses were carried out at 200 kV on the JEOL 2010 high resolution TEM (HRTEM) and JEOL 2010F FEG TEM/Scanning TEM (STEM).

**Results:** The fragment of Tieschitz that was analyzed in this study contains one large dark clast (4.7 x 5 mm), several chondrules and regions of both black and white matrix. In the clast and the black matrix we observed micron-sized, irregularly-shaped voids containing a fibrous mineral extending inwards from the void walls (Figure 1a). These geode-like voids are widespread at the surface of the Tieschitz polished section. The bulk compositions of the adjacent areas are similar to the black matrix described by [10] and are characterized by their low abundances of Na, K and Al (Table 1). Sometimes the voids contain elongated (up to 20 μm in length) iron-rich olivines (Figure 1, b) with morphologies similar to those in the matrix of the Allende CV3 carbonaceous chondrite.

| | $SiO_2$ | $Al_2O_3$ | FeO | MgO | CaO | $K_2O$ | $Na_2O$ |
|---|---|---|---|---|---|---|---|
| **Black mx*** | 43.3 | 4.6 | 26.7 | 19.6 | 3.4 | 0.3 | 2.1 |
| ***Black mx*** | ***49.4*** | ***3.3*** | ***24.7*** | ***19.2*** | ***1.9*** | ***0.2*** | ***1.3*** |
| **White mx*** | 58.3 | 23.9 | 5.0 | 2.4 | 3.7 | 0.1 | 6.5 |
| **White mx*** | 66.5 | 19.0 | 4.9 | 2.6 | 4.2 | 0.3 | 2.5 |

**Table 1.** Bulk compositions of the black matrix (mx) and white matrix measured in Tieschitz; *compositions from [10] and italic compositions are from this study (EDS quantification of one elemental map – 70 x 90 μm).

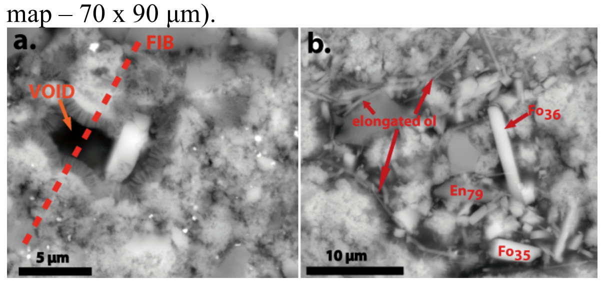


**Figure 1.** Backscattered electron images of the mineral phases in the clast and black matrix of Tieschitz showing the presence of voids (a) and elongated FeO-rich olivines (b). A fibrous mineral is present lining the walls extending inwards into the geode-like void. The dashed line across the void shows the position of one Focused Ion Beam section prepared for TEM analysis.

TEM studies show that the fibrous mineral extends from the wall of the void filled with C-rich material into a vein in the interior of the sample (red dashed line – Fig. 2). The individual fibers are not single crystals, but polycrystalline, consisting of multiple subparallel fibers (up to 1 μm in length and 200 nm in width). Using quantitative EDS analysis and electron diffraction, the mineral was identified as a Ca-bearing amphibole (Figure 3), with an elemental composition close to that of actinolite. Compositionally the grains are homogeneous with only small variations in $Al_2O_3$ and CaO (~3 wt%). The possibility of the presence of amphibole in Tieschitz was noted by Alexander et al. (1989) [9]. They identified a FeO and CaO silicate phase in Tieschitz white matrix which they suggested was a pyroxene or amphibole, but were unable to confirm either identification based on their electron diffraction data. Our data demonstrate a new and confirmed widespread occurrence of amphibole in Tieschitz.

Olivine ($Fo_{37-45}$) is the dominant mineral phase on the edges of the voids and in the adjacent matrix. Low-

Ca pyroxene ($En_{58-97}$) and taenite ($Fe_{77-56}Ni_{23-44}$) are the others phases identified in the regions of matrix of Tieschitz studied so far. No sulfides or phyllosilicates have been identified.

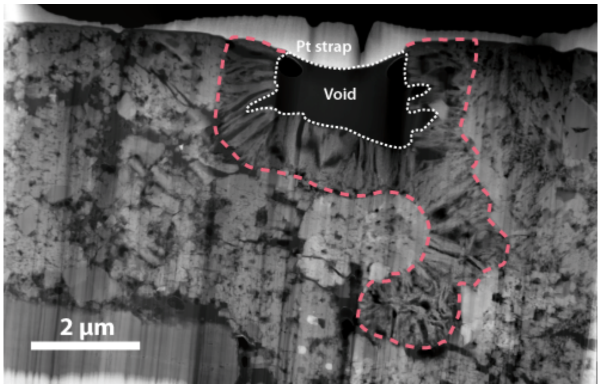


**Figure 2.** Dark-field STEM image of a FIB section of Tieschitz. The position of the section is shown in Fig. 1. The protective platinum (Pt) strap is at the top of the image. The red dashed line shows the region of the fibrous phase filling the void and extending to form a vein in the interior of the sample.

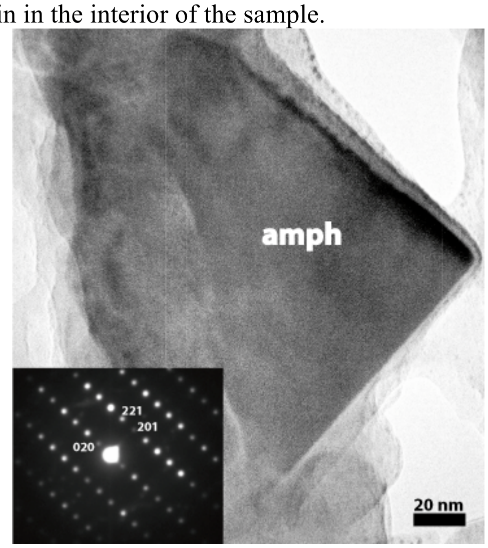


**Figure 3.** TEM bright field image and diffraction pattern (inset) of the Ca-bearing amphibole identified in the voids and veins in the black matrix of Tieschitz.

**Discussion:** Our SEM and TEM observations of the black matrix of Tieschitz UOC show the presence of widespread voids and veins that have not been recognized or described before. These voids are partially to completely filled by a polycrystalline fibrous mineral that we have identified as a Ca-bearing amphibole. The occurrence and morphology of the amphibole strongly suggests that it was precipitated from an aqueous fluid in voids in the matrix, forming the micron-sized geode-like voids. The development of these pores could have occurred during the same event that caused extensive leaching of mesostasis glass and development of porosity in Tieschitz chondrules. Leached elements (Na, Al, Si) from mesostasis are generally considered to have been redeposited outside the chondrules to form the white matrix [3, 7]. However, one of the outstanding issues related to this model is the fate of Ca, a highly mobile element that was also leached along with Na, Al and Si from chondrule mesostasis. The occurrence of calcic amphibole provides a plausible mineralogical sink for Ca, leached from chondrule mesostasis during this metasomatic event. The occurrences of amphibole minerals in the clast and in the black matrix of Tieschitz further support the idea that high temperature hydrothermal processes have locally affected the H chondrite parent body. Based on experimental studies of amphibole stability, formation of Ca amphibole could have occurred during hydrothermal alteration at temperatures below ~450ºC at 1 bar [11].

Micron-sized Fe-rich olivines with a distinct, euhedral elongated texture often occur in the same voids, coexisting with the amphibole. This association provides evidence that the olivine and amphibole formed during the same hydrothermal event, providing further support for the hypothesis that olivines with this distinct morphology can form by crystallization from a hydrothermal fluid. Hydrothermal growth has been proposed previously as a mechanism for the formation of elongated Fe-rich olivines in carbonaceous chondrites during fluid-assisted metamorphism [12-14]. However, in these cases, no hydrous phases are associated with the olivine. Our new data establishes an important link between the formation of a high temperature hydrous phase and distinct olivine morphologies.

**Conclusions**: The presence of calcic amphibole in a distinct textural occurrence indicative of the involvement of fluids provides definitive evidence of the importance of hydrothermal processes in the metamorphic evolution of Tieschitz. These observations further underline the importance of understanding the significant effects of fluids on the mineralogical behavior of low petrologic type ordinary chondrites during parent body metamorphism.

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**References:** [1] Sears D.W., *et al.* (1980) *Nature* **287**, 791. [2] Ashworth J.R. (1981) *Royal Soc. of London Proc. Series A* **374**, 179. [3] Christophe Michel-Levy M. (1976) *Earth Planet. Sci. Lett.* **30**(1), 143-150. [4] Ashworth J.R. (1977) *Earth Planet. Sci. Lett.* **35**, 25. [5] Nagahara H. (1984) *Geochim. Cosmochim. Acta* **48**, 2581. [6] Hutchison R., *et al.* (1979) *Nature* **280**, 116. [7] Hutchison R., *et al.* (1998) *Meteorit. Planet. Sci.* **33**, 1169-1179. [8] Alexander C.M.O, *et al.* (1986) *Meteorit. Planet. Sci.* **21**, 328. [9] Alexander C.M.O., *et al.* (1989) *Earth Planet. Sci. Lett.* **95**, 187. [10] Christophe-Michel-Lévy M. (1975) *Meteorit. Planet. Sci.* **10**, 381. [11] Jenkins D.M, *et al.* (1991) *Am. Mineral.* **76**, 458. [12] Krot A.N., *et al.* (2004) *Antarctic Met. Res.* **17**, 153. [13] Brearley A.J. (2009) *Lunar Planet. Sci.* XL, 1791. [13] Krot A.N., *et al.* (2000) *Meteorit. Planet. Sci.* **35**, 1365-1386.