STRUCTURAL AND CHEMICAL MICROANALYSIS OF ANOMALOUS ENSTATITE ACHONDRITES VIA ELECTRON BACKSCATTER DIFFRACTION (EBSD)

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Introduction: Enstatite chondrites are undifferentiated meteorites that sample the same region of the solar nebula as the precursors of Earth [1]. Enstatite achondrites that have similar mineralogy and bulk compositions to the enstatite chondrites but have undergone significant metamorphism. The most abundant enstatite achondrites are the aubrites, a group of differentiated meteorites resulting from extensive igneous processing. There are, however, a small subset of enstatite rich meteorites that differ mineralogically and texturally from the aubrites. [e.g., 2-4]. In previous studies [5,6], mineral chemistry was used to compare various anomalous enstatite achondrites in order to investigate the possible formative processes, in highly reducing conditions. A low oxygen fugacity environment allowed normally lithophile elements to become chalcophile and form the exotic sulfide species that are commonly seen in enstatite meteorites. To follow up, investigation of silica polymorphs in these meteorites may provide insight about the thermal history experienced during their formation [7]. The aim of this study is to explore the evolutionary history of anomalous enstatite achondrites via chemical and structural mineral analysis. It also demonstrates the applicability of EBSD in structural phase identification in meteoritic materials.

Methods: Anomalous enstatite achondrites NWA 4301, Zaklodzie and NWA 8173 (in two samples with differing lithologies “a” and “b”) [5,6] were used for this study, in the form of slabs and probe mounts. Sample surfaces were prepared using a vibratory polisher and 0.05 µm colloidal silica for two hours and subsequently carbon coated with a thickness of (150-200 Å). EDS and EBSD analysis were done using the Oxford Xmax 80mm^2 silicon drift EDS detector, and an HKL, Nordlyis EBSD detector. Oxford INCA and HKL Channel5 software suites were used to process EDS and EBSD data respectively. These detectors were attached to a Hitachi SU6600 FE-SEM at the Zircon and Accessory Phase Laboratory (ZAPLab) at Western University and operated at 20 kV, and ~2.5 nA. Samples were tilted 70° and a working distance of 19 mm was used for EBSD analysis. Phase indexing with EBSD used band centers (minimum 5, maximum 7 bands), and 30 milliseconds per frame.

Results:

NWA 4301: The dominant silica polymorph found was tridymite (Fig 1a). It occurs as irregular, small (10-30 µm) grains entrenched in metal or iron oxide (due to weathering). Tridymite was predominantly located in a 4 mm, sulfide rich, plagioclase-depleted area in one of the slabs. Troilite was the main sulfide mineral found in this sample. Rounded to sub-rounded amorphous silica grains with minor Fe content were also present in this area (Fig 1b) and were mainly associated with kamacite. The sulfide-metal-silica rich area also contains large (hundreds of microns) laths of graphite associated with metal.

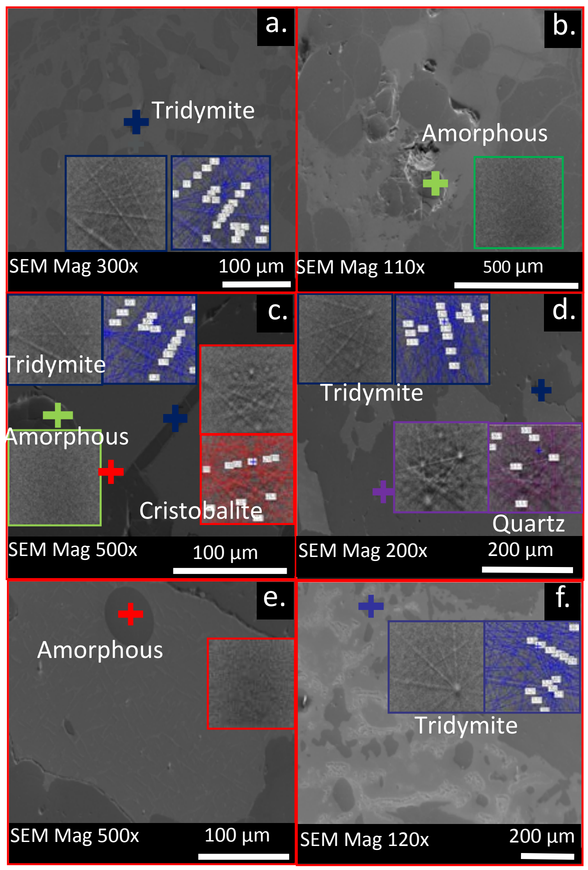

Fig 1. EBSD of silica polymorphs in (a,b) NWA 4301, (c) Zaklodzie, (d,e) NWA 8173a, and (f) NWA 8173b.

The enstatite grains occur as both ortho- and clinoenstatite as were also detected with µXRD [6]. Previously described as polysynthetic twinned enstatite, EBSD revealed alternating bands of ortho- and clinoenstatite, the latter occurring as small (~5-10 µm) bands. A large semi-tabular grain of sinoite (Si_2N_2O), previously identified in other meteorites [8] was also identified by EBSD in one of the NWA 4301 slabs at the edge of a kamacite grain.

Zaklodzie: Tridymite and cristobalite were the main silica polymorphs identified through EBSD (Fig 1c). Tridymite is present as small irregular grains, associated with metal, sulfides (troilite) and in interstitial silica-plagioclase areas. Cristobalite also occurs as small, irregular grains and is mainly situated around metal grains and interstitial silica-plagioclase areas. Amorphous semi-rounded silica grains similar to those previously discussed for NWA 4301 were also found in Zaklodzie; these appear to contain iron, and occur within large kamacite grains (Fig 1c). Small laths of graphite are mostly associated with metal grains within the meteorite. Both ortho- and clinoenstatite were present in Zaklodzie, as was previously reported by Uribe et al. [6] using µXRD.

Troilite was identified as one of the main sulfides present in Zaklodzie using EBSD. A sulfide mineral of cubic structure was also indexed, using mineral chemistry data, given that most sulfides present in enstatite achondrites are isostructural. From chemical compositions obtained previously with EPMA, the cubic sulfide present is keilite, whose composition is reported in [6].

Acicular grains of sinoite within troilite were identified in Zaklodzie and appear to have a fan-out texture. This texture is indicative of a single episode of crystallization during heating at high temperatures.

NWA 8173a: The main silica polymorph found in this meteorite was tridymite (Fig 1d). Tridymite occurs as small (10-30 µm), irregular grains located around kamacite, sulfide grains and as inclusions within both phases. Quartz was also identified in this sample and it was seen in proximity to a sulfide grain and around enstatite grains (Fig 1d). Amorphous silica occurs as round droplets embedded in a sulfide matrix (Fig 1e). The chemical composition of this inclusion contained some feldspathic impurities (Na 2.3 wt%, Al 4.9% S 0.4% and K 1.9 wt %) compared with the quartz and tridymite grains found elsewhere in NWA 8173.

The exsolution lamellae hosted in the cubic monosulfide, keilite grains were identified as troilite. The host sulfide is defined as keilite based on chemical composition from [5] given that adequate indexing was not possible due to multiple isostructural sulfide species being matched by EBSD.

The pyroxene grains in this sample were mostly orthoenstatite. Dendritic carbon inclusions in metal, diffracted enough to discard it as amorphous carbon, but not enough to be accurately indexed with EBSD.

A grain of about 80 µm, low relief in surface electron imaging (SEI), and associated with sulfide was indexed as the mineral fluorphlogopite (Fig 2). EDS analysis revealed the mineral had a composition of 46.3% O, 15.8% F, 1.7% Na, 13.7% Al, 14.3% Si and 3.5% K, a similar composition to chemical data obtained previously in [5] via EPMA analysis.

NWA 8173b: Only tridymite was identified in this sample (Fig 1f). Similar assemblages of graphite and pyroxene occur in the NWA 8173 “a” lithology. However, BSE images reveal that the NWA 8173b fragment is coarser grained, and has larger, more localized metal and sulfide grains than the NWA 8173a fragment.

Conclusions: EBSD analysis of various anomalous enstatite achondrites resulted in identification of silica polymorphs, sulfides, graphite and it also identified unique textures and minerals, which we are using to reconstruct the high-temperature metamorphic history and formation mechanisms of this class of meteorites.

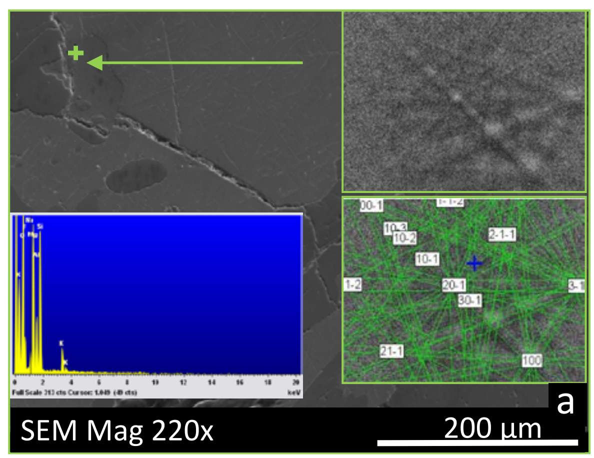

Fig 2. a) BSE image, EBSD and EDS spectra of fluorphlogopite beside sulfide in NWA 8173a.

References: [1] Javoy et al. 2010., EPSL 29, 259-268; [2] Boesenberg et al. 2014 LPSC XLV abstract # 1486; [3] Keil and Bishoff, 2008, MAPS 43, 1233-1240; [4] Izawa et al., 2010 MAPS 46, 1742-1753; [5] Uribe et al. 2016 LPSC XLVII abstract #2797; [6] Uribe et al. 2016 LPSC XLVII abstract #3071; [7] Kimura et al. 2005., MAPS 40,855-868; [8] Rubin, 1997. American Mineralogist, 82,1001-1006.