NANOMINERALOGY OF THE EL ALI METEORITE: DISCOVERY OF OLSENITE, $KFe_4(PO_4)_3$, THE THIRD NEW MINERAL FROM THIS IAB IRON.

Chi Ma[1,*], Christopher D.K. Herd[2], Andrew J. Locock[2]; [1]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125, USA; [2]Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta T6G 2R3, Canada; [*]E-mail: chima@caltech.edu

Introduction: Nanomineralogy is the study of Earth and planetary materials at nanoscales, focused on characterizing nanofeatures (such as inclusions, exsolution, zonation, coatings, pores) in minerals and rocks, and revealing nanominerals and nanoparticles [1]. Nanomineralogy studies of meteorites with advanced analytical techniques, in particular using high-resolution analytical scanning electron microscopy (SEM), have led to the discovery of more than fifty new minerals and phases since 2007 [e.g., 2-3]. Each and every new mineral has a voice and a story to tell, providing insights on conditions of formation.

The El Ali meteorite, found in 2020 in Somalia, is an IAB Complex iron meteorite. During our initial study of this iron, two new phosphate minerals elaliite ($Fe^{2+}_8Fe^{3+}(PO_4)O_8$, IMA 2022-087) and elkinstantonite ($Fe_4(PO_4)_2O$, IMA 2022-088) have been discovered [4]. Our further nanomineralogy investigation of the same sample (El Ali block section MET11814/2-1/EP1) has revealed a third new phosphate mineral olsenite ($KFe_4(PO_4)_3$, IMA 2022-100) [5]. In a companion abstract [6], we consider elaliite and elkinstantonite. Here, we present olsenite and discuss its origin and significance.

Olsenite, $KFe_4(PO_4)_3$, is a K-Fe-phosphate with an orthorhombic *Pnnm* structure. The mineral has been approved by the IMA-CNMNC. The name is in honor of Edward J. Olsen, the former Curator of Mineralogy and Meteorites at the Field Museum of Natural History in Chicago, who helped describe a few new minerals from meteorites: brianite, buchwaldite, galileiite, krinovite, and panethite, and was the first to find phosphate minerals in iron meteorites [7].

Electron probe microanalyzer, field-emission SEM and electron backscatter diffraction have been used to characterize olsenite and associated phases. Synthetic $KFe_4(PO_4)_3$ with the orthorhombic *Pnnm* structure is well known [8].

Occurrence, chemistry, and crystallography: Olsenite occurs as irregular crystals, 1 to 5 μm in size, in contact with graftonite ($Fe^{2+}Fe^{2+}_2(PO_4)_2$), elaliite, and troilite (FeS) within several phosphate-sulfide inclusions (Figs. 1-3). Other inclusions consist of symplectitic intergrowths of wüstite, troilite, magnetite, and other phosphates including sarcopside and/or graftonite, elaliite, elkinstantonite. The mineral intergrowth with sarcopside and/or graftonite extends from

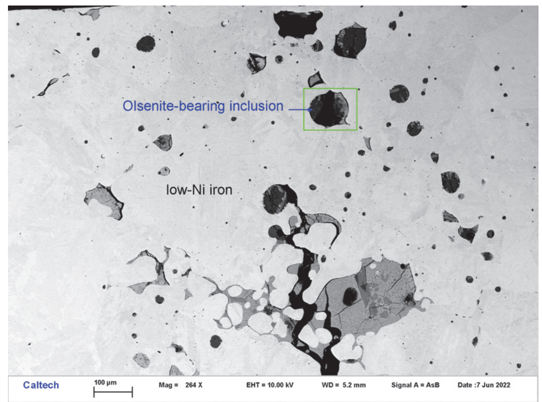

Fig. 1. Back-scatter electron (BSE) image showing phosphate and sulfide inclusions in low-Ni iron. Rectangle outlines the olsenite-bearing inclusion shown in Fig. 2.

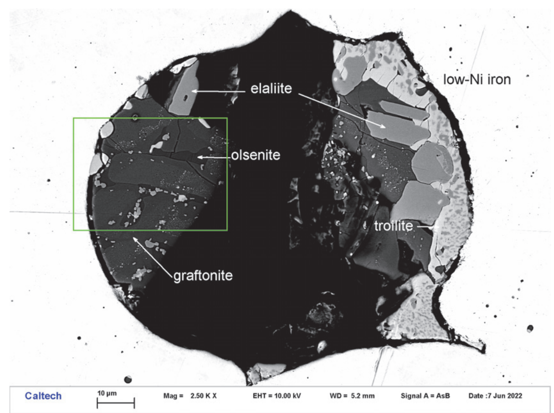

Fig. 2. BSE image showing type olsenite, elaliite, graftonite and troilite in one inclusion.

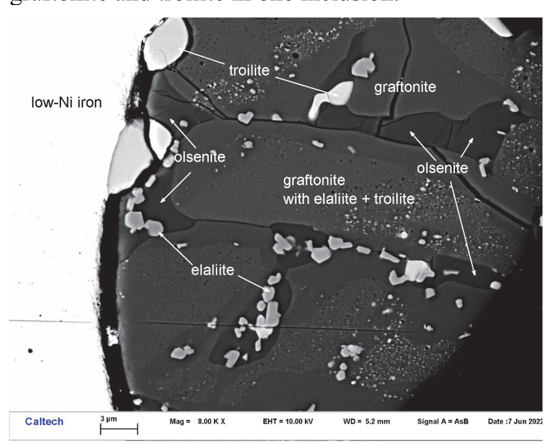

Fig. 3. Enlarged BSE image revealing type olsenite, elaliite, graftonite and troilite.

the margins of iron sulphide-wüstite symplectites. The inclusions occur within low-Ni iron (kamacite) containing 9.4 wt% Ni.

The chemical composition of type olsenite by low-voltage electron probe microanalysis (Table 1) yields an empirical formula (for 12 O atoms *pfu*) of $(K_{0.74}Na_{0.13})_{\Sigma 0.87}(Fe_{3.99}Mn_{0.06})_{\Sigma 4.06}(P_{2.88}S_{0.10}Si_{0.01})_{\Sigma 2.99}O_{12}$ on Point #109. The empirical formula of the mean of 5 points (based on 12 O atoms *pfu*), is $(K_{0.82}Na_{0.14})_{\Sigma 0.96}$ $(Fe_{3.83}Mn_{0.05})_{\Sigma 3.88}(P_{2.97}S_{0.06}Si_{0.02})_{\Sigma 3.05}O_{12}$. The simplified formula is $(K,Na)(Fe,Mn)_4P_3O_{12}$. The ideal formula is $KFe_4(PO_4)_3$, which requires: K_2O 8.60**,** FeO 52.50, P_2O_5 38.90, Total 100 wt.%.

Conventional X-ray studies could not be carried out because of the small crystal size. Electron back-scatter diffraction (EBSD) revealed that olsenite has the orthorhombic *Pnnm* $KFe_4(PO_4)_3$-type structure. Its EBSD patterns give a good fit to the unit cell of synthetic $KFe_4(PO_4)_3$ of [8] (Fig. 4), with a mean angular deviation of 0.44º-0.48º, showing the unit cell parameters: a = 9.81(1) Å, b = 16.51(1) Å, c = 6.27(1) Å, V = 1016(2) Å^3, Z = 4. Olsenite has a calculated density of 3.52 g/cm^3. The Gladstone-Dale relationship gives n = 1.66 (based on the normalized measured composition and calculated density).

Origin and significance: Olsenite, $KFe_4(PO_4)_3$ with orthorhombic *Pnnm* structure, is not closely related in a structural sense to other minerals to our knowledge, but it is isostructural with at least nine synthetic compounds like $KMg_4(PO_4)_3$ [e.g., 9]. In the Dana classification, olsenite belongs to the *Anhydrous Phosphates* $(A^+B^{2+})_5(PO_4)_3$, and its sodium analogue is galileiite, $NaFe_4(PO_4)_3$ with a trigonal *R*-3 structure, which is a member of the fillowite group [10].

The inclusions in El Ali contain at least five phosphate phases (graftonite, sarcopside, elaliite, elkinstantonite and olsenite) along with wüstite, troilite, and magnetite, whereas silicate, phosphide, carbide, and

Table 1. EPMA data for olsenite in El Ali.

Constituent (wt%)	Olsenite (n=5)	Olsenite (Point #109)
Na_2O	0.74	0.73
SiO_2	0.18	0.15
P_2O_5	37.32	37.53
SO_3	0.83	1.42
K_2O	6.83	6.39
CaO	0.04	0
MnO	0.63	0.74
FeO	48.67	52.61
Total	**95.24**	**99.57**

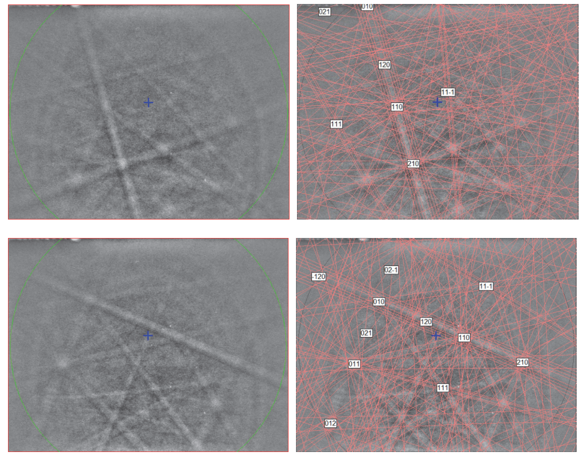

Fig. 4. (left) EBSD patterns of two olsenite crystals at different orientations, and (right) the patterns indexed with the *Pnnm* $KFe_4(PO_4)_3$-type structure.

carbon phases are absent. Phosphate minerals such as sarcopside $(Fe^{2+}_3(PO_4)_2)$ and/or graftonite $(Fe^{2+}Fe^{2+}_2(PO_4)_2)$ are not uncommon in IAB irons. In El Ali, olsenite $(KFe^{2+}_4(PO_4)_3)$ contains only ferrous iron, whereas associated elaliite $(Fe^{2+}_8Fe^{3+}(PO_4)O_8)$ has both ferrous and ferric iron. In this case, the inclusions crystallized under more oxidizing conditions, resulting in an assemblage with variable iron valence state. A more O- and P-rich and S-poor melt with high Fe and K likely resulted in the formation of olsenite and elaliite.

Elaliite, elkinstantonite and olsenite in El Ali are the latest new minerals found in iron meteorites. Other recently-identified new minetrals from iron meteorites include joegoldsteinite $(MnCr_2S_4)$ in Social Circle [11], edscottite (Fe_5C_2) in Wedderburn [12], and colomeraite $(NaTi^{3+}Si_2O_6)$ in Colomera [13]. The ongoing nanomineralogy research is revealing more new meteoritic minerals – stay tuned.

References: [1] Ma C. (2008) Eos Trans. *AGU 89th*, Abstract MR12A-01. [2] Ma C. (2018) *Am. Mineral*., 103, 1521–1522. [3] Rubin A. E. and Ma C. (2021) *Meteorite Mineralogy*. [4] Herd C. D. K. et al. (2022) *Eur. J. Mineral.*, 34, 599–600. [5] Ma C. et al. (2023) *Eur. J. Mineral.*, 35, in CNMNC Newsletter 71. [6] Herd C. D. K. et al. (2023) *LPSC*, 54, Abs 2220. [7] Steele I. M. and Hutcheon V. (2020) *Am. Mineral.*, 105, 583–584. [8] Matvienko E. N. et al. (1981) *Doklady Akademii Nauk SSSR*, 259, 591–595. [9] Tomaszewski P. E. et al. (2005) *Solid State Sci.*, 7, 1201–1208. [10] Olsen E. J. and Steele I. M. (1997) *Meteorit. Planet. Sci.*, 32, A155–A156, [11] Isa J. et al. (2016) *Am. Mineral*., 101, 1217–1221. [12] Ma C. and Rubin A. E. (2019) *Am. Mineral.*, 104, 1351–1355. [13] Ma C. (2021) *Eur. J. Mineral.*, 33, 644.