JOEGOLDSTEINITE: A NEW SULFIDE MINERAL (MnCr$_2$S$_4$) FROM THE IVA IRON METEORITE, SOCIAL CIRCLE.

Junko Isa[1], Chi Ma[2], and Alan E. Rubin[1,3]; [1]Department of EPSS, UCLA (jisa@ucla.edu); [2]Division of Geological and Planetary Sciences, Caltech (chi@gps.caltech.edu); [3]IGPP, UCLA.

Introduction: A new sulfide mineral, joegoldsteinite, of end-member formula MnCr$_2$S$_4$, was discovered in the Social Circle IVA iron meteorite. It is a thiospinel, a mineral group that has a general formula of AB$_2$X$_4$ where A is a divalent metal, B is a trivalent metal and X is a 2$^-$ anion, typically S, but in some cases Se or Te. The Fe analogue of joegoldsteinite, daubréelite (Fe^{2+}Cr$_2$S$_4$), is a commonly found thiospinel in enstatite and iron meteorites. Some thiospinels (including synthetic MnCr$_2$S$_4$) are known to be magnetic semiconductors and have been studied extensively by materials scientists [e.g., 1-2]. Although joegoldsteinite is not abundant, tiny grains were also identified in the Indarch EH4 enstatite chondrite. Joegoldsteinite was approved as a new mineral by the International Mineralogical Association (IMA2015-049) in August 2015.

IVA iron meteorite and naming of the mineral: Joegoldsteinite is present in the Social Circle IVA iron meteorite. The meteorite itself was found as a single ~100-kg mass in Georgia, USA in 1926 during ploughing [3]. Group IVA constitutes the third largest "magmatic" iron-meteorite group; each magmatic group is modeled as having formed by fractional crystallization in the metallic core of a differentiated asteroid [4]. IVA iron meteorites are fine octahedrites showing Widmanstätten patterns [3]. Studies of the metallographic cooling rates in IVA iron meteorites have been controversial for several decades [5-6]. The mineral was named in honor of Joseph (Joe) I. Goldstein (1939-2015) who was well known for his fundamental contributions to research on iron meteorites, metallographic cooling rates, Fe-Ni phase equilibria, electron microscopy and microanalysis. He was Distinguished Professor Emeritus of Mechanical and Industrial Engineering and former dean of the College of Engineering at the University of Massachusetts, Amherst. Before arriving at Amherst, Goldstein was the T. L. Diamond Distinguished Professor of Metallurgy and R. D. Stout Professor of Materials Science and Engineering at Lehigh University; he served as vice president for graduate studies and research and as director of Lehigh's Electron Optical Laboratory.

Samples and analytical methods: A polished thick section of Social Circle (TK 724) was made from a 2×3×5-mm-size aliquot from the UCLA meteorite collection. It was examined in reflected light with an Olympus BX60 petrographic microscope and by backscattered-electron (BSE) imaging using a VEGA Tescan SEM at UCLA and a Zeiss 1550VP field-emission SEM at Caltech. Phases were analyzed by energy-dispersive X-ray spectroscopy (EDX) with the SEM and by a JEOL 8200 electron microprobe (EPMA) at UCLA. A synthesized FeCr$_2$S$_4$ single crystal [7] was used as a standard for S, Cr and Fe measurements. Single-crystal electron backscatter diffraction (EBSD) analyses at a sub-micrometer scale using methods described in [8-9] were performed using an HKL EBSD system on the Zeiss 1550VP SEM at Caltech. The EBSD system was calibrated using a single-crystal silicon standard. The structure was determined and cell constants were obtained by matching the experimental EBSD patterns with structures of synthetic MnCr$_2$S$_4$ and daubréelite.

Results: Joegoldsteinite occurs as two subhedral inclusions, 13 μm and 15 μm in diameter, in Social Circle thick section TK 724 (Fig. 1). Physical properties were not measured because of the small grain size; however, they are likely to be close to those of daubréelite. Optical properties of joegoldsteinite were assessed in reflected light and compared to daubréelite grains that are adjacent to metallic Fe-Ni in the Aliskerovo and NWA 4704 IIIE iron meteorites. Both minerals have similar reflectivity and color. EPMA data indicate that the empirical formula (based on 7 atoms) is (Mn$_{0.82}$Fe$_{0.23}$)Cr$_{1.99}$S$_{3.95}$; the general formula is (Mn,Fe)Cr$_2$S$_4$ and the end-member formula is MnCr$_2$S$_4$. The calculated density, based on the empirical formula, is 3.71 g cm^{-3}. The EBSD patterns match the cubic space group Fd3m spinel-type structure (a = 10.11, V = 1033.4 Å3, Z = 8) and give a best fit using the MnCr$_2$S$_4$ structure from [10] (Fig. 2), with a mean angular deviation of 0.40° to 0.45°. Some tiny grains of joegoldsteinite associated with troilite (FeS) and niningerite ((Mg,Fe)S) were also observed in the Indarch EH4 enstatite chondrite (Fig. 3), but the grains are too small for accurate quantitative analysis by EPMA.

Other Mn- and Cr-bearing sulfides in meteorites: The only known phases with detectable Mn in IVA irons besides joegoldsteinite are daubréelite (~0.2-0.8 wt.% Mn) in Maria da Fé (this study) and orthopyroxene (~0.5-0.6 wt.% MnO) and clinopyroxene (~0.5 wt.% MnO) in Steinbach and São João Nepomuceno [4]. Social Circle contains a few Cr-rich phases in addition to joegoldsteinite; these include daubréelite (FeCr$_2$S$_4$), chromite (FeCr$_2$O$_4$), and possibly, brezinaite (Cr$_3$S$_4$) [3]. Additional Cr-rich phases reported in magmatic iron meteorites (but not in the IVA group) include carlsbergite (CrN) in several IIIAB samples and kosmochlor (NaCrSi$_2$O$_6$) in a few IIA

samples [4]. Mn-bearing sulfides in enstatite chondrites (and related impact-melt rocks and impact-melt breccias) include daubréelite (with 0.7-4.0 wt.% Mn), troilite (FeS: 0.02-0.39 wt.% Mn), oldhamite (CaS: 0.18-1.3 wt.% Mn), niningerite ((Mg,Fe)S: 6.1-12.9 wt.% Mn), keilite ((Fe,Mg)S: 3.4-23.7 wt.% Mn), rudashevskyite ((Fe,Zn)S: 1.6-3.6 wt.% Mn), buseckite ((Fe,Zn,Mn)S, ~10 wt.% Mn), browneite (MnS, ~62 wt.% Mn) and pentlandite ($(Fe,Ni)_9S_8$: 0.66-1.1 wt.% Mn) [11-16]

Shock effects?: The presence of Neumann lines in Social Circle kamacite indicates that the sample was shocked to at least 10 kb after cooling [3]. A later shock event caused widespread heating of the meteorite: (a) kamacite throughout the mass recrystallized, partially obliterating the Neumann lines (and forming "parallel ghost-lines"), (b) taenite and plessite fields partly decomposed and underwent minor spheroidization, and (c) troilite-metal eutectic shock melts formed [3]. We speculate that impact melting of the sulfide assemblages increased the Mn concentration in portions of the S-rich melts, facilitating the crystallization of joegoldsteinite.

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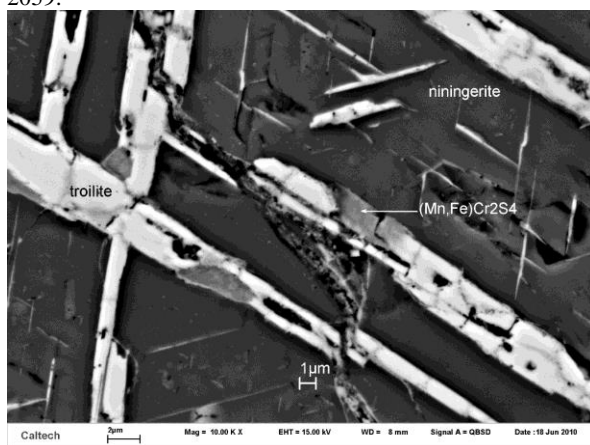

Fig. 1. BSE images showing two joegoldsteinite grains in Social Circle thick section UCLA TK 724.
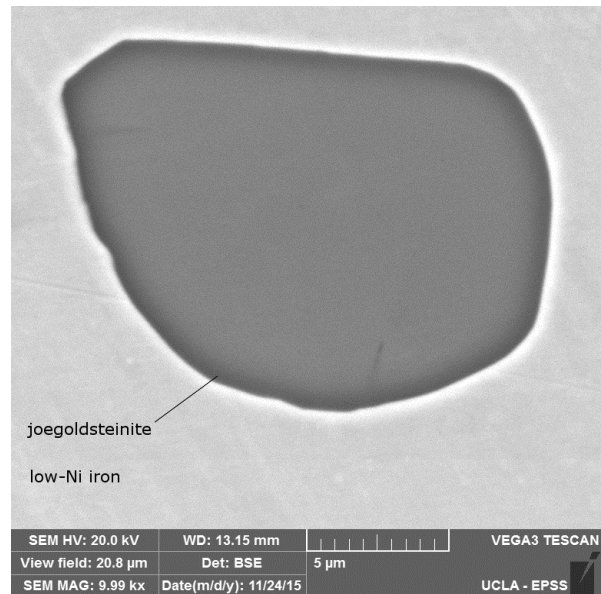

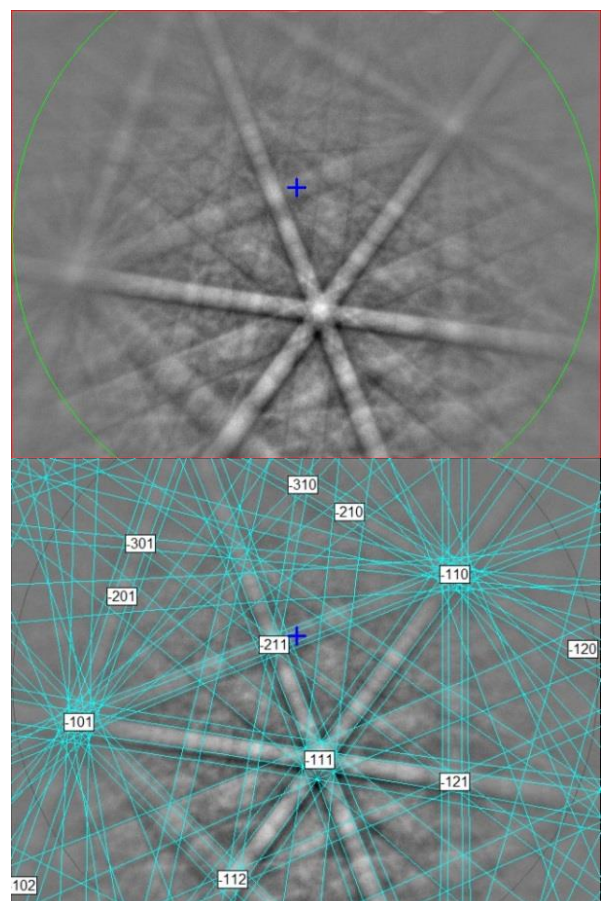Fig. 3. BSE image of a $(Mn,Fe)Cr_2S_4$ phase in Indarch.

Fig. 2. (up) EBSD patterns of the joegoldsteinite crystals in Figure 1, and (down) the patterns indexed with the Fd3m $MnCr_2S_4$ structure.