

## EQUILIBRATION IN SILICATE (PYROXENE) VS SULFIDE (TROILITE) DURING METAMORPHISM OF ENSTATITE CHONDRITES

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**Introduction:** The enstatite chondrites (ECs) are characterized by minerals and mineral compositions indicating formation at low oxygen fugacities ( $f(O_2)$ ) compared to the much more abundant ordinary chondrites [e.g., 1-3]. Yet the ECs are similar to the ordinary chondrites in that they exhibit a metamorphic progression from unequilibrated type 3 to equilibrated type 5 and 6 textures and mineral compositions. A main feature of the textural progression consists of the change from distinct, clearly-defined boundaries of silicate chondrules to a texture where chondrule boundaries have merged with adjacent materials and are difficult to discern (in the case of relict chondrules) or completely recrystallized. The textural change from type 3 to types 5 and 6 is accompanied by a change in the distribution of mineral compositions: olivine and pyroxene compositions have wide ranges in  $Fe/(Mg+Fe)$  (=Fe#) in unequilibrated, type 3 chondrites and homogeneous Fe# in equilibrated, type 5 and 6 chondrites [1,3,4]. Thus, a key factor for distinguishing unequilibrated vs. equilibrated conditions in ordinary and enstatite chondrites is the extent of homogenization of Fe# in mafic silicates.

The sulfide mineral troilite (FeS) is common in ordinary and enstatite chondrites and occurs throughout the range in petrologic types from 3 to 6 [5]. In ECs, troilite has minor, but detectable, amounts of Ti and Cr—in their analyzed and compiled data, Weyrauch et al. [6] list mean concentrations\* of 0.2 to 0.9 wt% Ti and 0.3 to 4.1 wt% Cr in troilite from ECs (\*excluding data from four anomalous ECs). Therefore, ECs offer a chance to compare the response of a sulfide (troilite) with a silicate (low-Ca pyroxene) from the same metamorphic history. Does EC troilite exhibit the same type of homogenization in composition that is observed in pyroxene (and in olivine in ordinary chondrites)? What are the implications for metamorphic histories of enstatite chondrites?

**Methods:** X-ray elemental and back-scattered electron (BSE) maps of polished thin sections of the following ECs were collected by electron probe micro-analyzer (EPMA): Allan Hills A81189 (ALHA81189, EH3); Allan Hills 84170 (ALH 84170, EH3); Yamato 691 (Y-691, EH3); Sahara 97096 (SAH 97096, EH3); Indarch (EH4); St. Mark's (EH5); Lewis Cliff 88180 (LEW 88180, EH5); Northwest Africa 974 (NWA 974, E6); Hvittis (EL6). Elemental maps were collected using the JEOL JXA-8900 EPMA at Waseda University (WU). The elemental and BSE maps were input as layers in a graphics program. For each sample, a grid was overlain on the map layers and was used to select an even distribution of points for quantitative analyses. Quantitative analyses of low-Ca pyroxene, troilite, and in some cases olivine were collected by wavelength dispersive analysis using the WU EPMA and typical conditions of 15 kV, 20 nA and  $\sim 1\mu m$  beam diameter. Well characterized silicates, oxides and sulfides were used as standards.

**Results and Discussion:** The expected homogenization of pyroxene compositions in type 5 and 6 ECs was confirmed by our analyses. The EH3s investigated all have similar distributions of Fs-contents in pyroxene, with most analyses having  $Fs_{<0.5}$ , but with a range extending to  $Fs_{15}$  or  $Fs_{20}$ . The two EH5s and the type 6 ECs investigated have tighter clusters of pyroxene compositions closer to the enstatite ( $Fs_{00}$ ) endmember.

Compared to the pyroxene data, the troilite Cr- and Ti-contents do not appear to show the same extent of homogenization in higher petrologic types, although interpretation is difficult because of the high relative analytical uncertainties in Cr- and Ti-concentrations. The Ti-concentrations detected in troilite in ALHA81189 (mean Ti  $< 0.05$  wt %) are lower than in troilite from the other EH chondrites (mean Ti  $\sim 0.2$  to  $0.4$  wt %).

The homogenization of pyroxene compositions in ECs contrasts with the apparent heterogeneity in troilite compositions in the same set of meteorites, suggesting that although troilite and pyroxene in individual samples had essentially the same metamorphic thermal histories, they do not reflect the same equilibration. We suggest that pyroxene “locked in” equilibrium compositions near peak metamorphic temperatures, whereas at least some troilite grains were subject to continuing reaction while temperatures declined. Retrograde metamorphism affecting troilite might have occurred by ongoing diffusion over a range of temperatures or by reactions with a post-metamorphic-peak, S-rich fluid. The relatively Ti-poor composition of troilite in ALHA81189 may indicate slightly oxidizing conditions for this sample compared to other ECs [7].

**References:** [1] Weisberg M.K. et al. (2006) in Lauretta D.S. and McSween H.Y.Jr. (eds.) *MESS II*, p. 19-52. [2] Weisberg M.K. and Kimura (2012) *Chemie der Erde* 72: 101-115. [3] Van Schmus W.R. and Wood J.A. (1967) *GCA* 31: 747-765. [4] Huss G.R. et al. (1981) *GCA* 45: 33-51. [5] Brearley A.J. and Jones R.H. (1998) in Papike J.J.(ed.) *Planetary Materials, Reviews in Mineralogy* 36 Chapter 3, Chondritic meteorites p. 1-398. [6] Weyrauch M. et al. (2018) *MaPS* 53: 394-415. [7] Lusby D. et al. (1987) *Proc. LPSC* 17 (in *JGR* 92(B4)), E679-E695.