Variable equilibration in silicates and sulfides in enstatite chondrites: Implications for metamorphic and nebular reaction histories.

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Introduction: Enstatite chondrites are thought to have formed in highly reducing environment. This inference is supported by the high Mg/(Mg+Fe) of olivine and pyroxene, presence of Si in Fe,Ni-metal, and occurrence of typically lithophile elements, such as Ca, Mg, Mn and K, in sulfide minerals in enstatite chondrites (e.g., [1]). Enstatite chondrites are divided into two main groups, EH and EL, based on high and low abundances of Fe,Ni-metal; both groups show a metamorphic sequence from type 3 to 6, similar to that observed in ordinary chondrites. Minor element variations in silicates in ordinary chondrites have revealed subtle variations in metamorphic grade and some details of element transfers during metamorphism [2]. In contrast, although a general sense for metamorphic grade in enstatite chondrites has been determined [3-6], a detailed understanding of metamorphic petrogenesis remains elusive. Yet, under the low $f(O_2)$ conditions characteristic of enstatite chondrites, metamorphic reactions are bound to differ from those in other chondrite groups [7].

In this study, we collect multiple analyses of olivine, pyroxene and troilite from a set of E chondrites to assess variations in composition and approach to equilibrium (uniform compositions) during metamorphism.

Methods: We investigated 6 polished thin sections of 3 EH3 chondrites (ALHA 81189, ALH 84170, Sahara 97096), two EH5 chondrites (St. Marks, LEW 88180), and one E6 chondrite (NWA 974). NWA 974 might not come from the EH parent body, thus should not be linked with the EH chondrites to evaluate compositional trends during metamorphism; however, it still can be used for comparison of extent of equilibration in troilite and pyroxene. Elemental maps collected by electron microprobe (JEOL JXA-8900 at Waseda University) were combined with petrographic microscope observations. Elemental X-ray maps were combined as false-color images and used as "base maps" for quantitative electron microprobe analyses of olivine (type 3 only), and pyroxene and troilite (all samples) on grid patterns. On the order of 90 to 200 analyses of each mineral were collected from each sample. Electron backscatter diffraction (EBSD) analysis data were obtained with Oxford EBSD system equipped with S-3400 SEM using HKL Channel5 software (at Waseda University). EBSD data were collected to determine sub-grain boundaries in troilite and compare grain boundaries with variations in minor element composition.

Results and discussion: All meteorites studied consist mainly of enstatite with plagioclase, kamacite, troilite, and (Mg,Mn,Fe)S. Olivine is present in ALHA81189, ALH84170, and Sahara 97096 EH3 chondrites, but not in the higher petrologic types. Daubreelite, niningerite, oldhamite are present in complex nodules with troilite and/or kamacite in the EH3 chondrites; sulfides are more dispersed in St.Marks, LEW88180, and NWA974. Textures show a distinct contrast, with the type 3 chondrites having well-defined chondrules, and the type 5 and 6 chondrites having diffuse chondrule boundaries.

Chemical compositions of pyroxene and troilite

Enstatite is the dominant phase in ECs. The average Fs content in pyroxene decreases with increasing petrologic type (Fig. 1). The range of composition becomes smaller in type 5 and 6 than EH3s, indicating equilibration during metamorphism.

Troilite in the E chondrites generally has minor but detectable concentrations of Mn, Cr and Ti, reflecting low $f(O_2)$ conditions. Systematic variations in composition of troilite are more difficult to ascertain, but in general Ti increases with petrologic type (Fig. 2). Furthermore, troilites from the type 5 and 6 chondrites do not always have more uniform compositions than in the type 3 chondrites.

Distribution of Cr and Ti

Based on preliminary detailed X-ray mapping, the ranges in composition of troilite in EH3 chondrites may be due to variations between grains of homogeneous composition (Fig.3). In contrast, troilite from St. Marks shows wide variations in composition within grains (Fig. 4). EBSD data from St. Marks show that enrichments in Cr and Ti tend to coincide with grain or sub-grain boundaries. Thus, Cr and Ti of troilite in EHs may be roughly analogous with Cr in ferrous olivine of ordinary chondrites [2]. In any case, even though E chondrite pyroxene and troilite experienced similar metamorphic thermal histories, the approach to equilibrium compositions in these mineral groups do not match. Uniformity of Fs-content in pyroxene probably represents a near-peak metamorphic temperature condition, whereas variations in minor elements in troilite reflect post-peak partial re-equilibration.

References: [1] Weisberg M.K. et al. (2009) *LPS XL*, #1886. [2] Grossman J. and Brearly. A. J. (2005) *MaPS 40*, 87-122. [3] Zhang Y. et al. (1995) *JGR, 100,* 9417-9438. [4] Hicks T. et al., (2000) *LPS XXXI*, #1491. [5] Kimura M. et al. (2005) *MaPS 40, 855-868.* [6] Bendersky C. et al., (2007) *LPS XXXVIII #2077.* [7] El Goresy A., et al. (1988) *Proc. NIPR Symp. Ant. Metorit. 1*, 65-101.

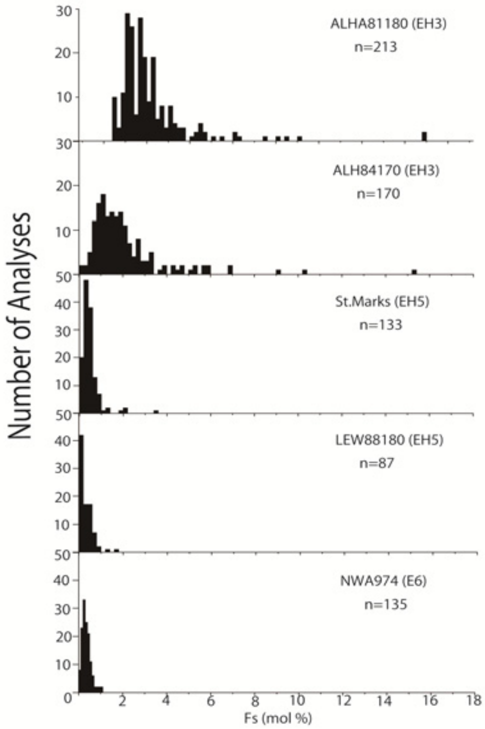

Fig.1. Histogram of Fs content in pyroxene in enstatite chondrites. NWA 974 may be part of a different metamorphic sequence .

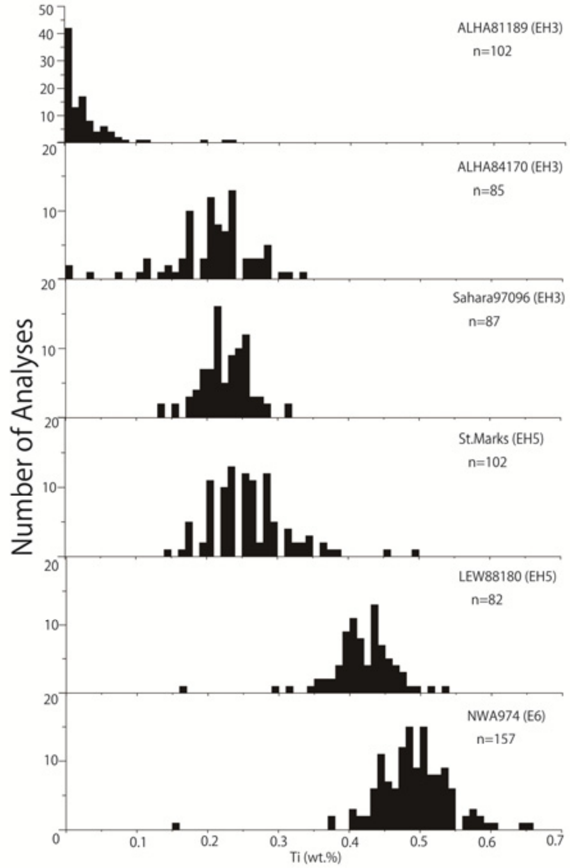

Fig.2. Histogram of Ti content in troilite in enstatite chondrites. NWA 974 may be part of a different metamorphic sequence.

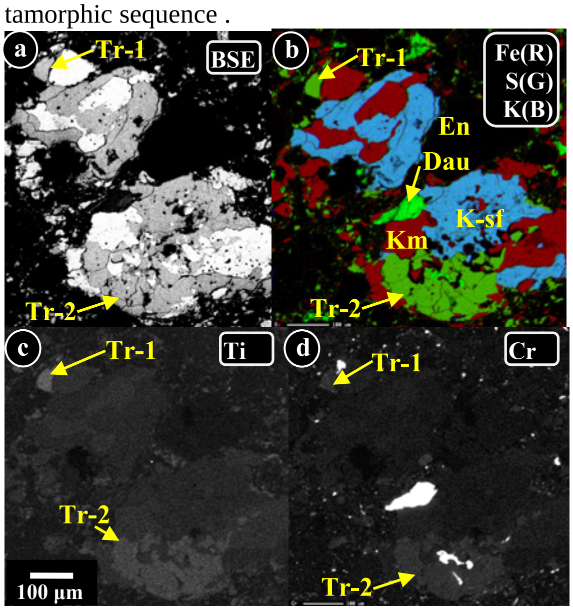

Fig. 3. BSE images of troilite #1 in ALH84170 and combined elemental map of the same area (R;Fe, G; S, B; K). (c) The Ti content of troilite is variable (Tr-1 and Tr-2). Tr; troilite, En; enstatite, Km; kamacite, K-sf; K-sulfide, Dau; daubreelite.

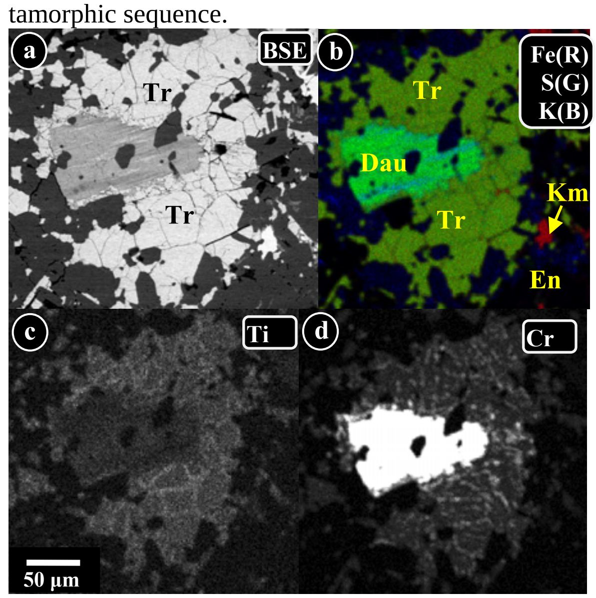

Fig. 4. BSE image of troilite #3 in St.Marks and combined elemental map of the same area (R;Fe, G; S, B; K). (c,d) Concentration of Cr and Ti along the cracks and grain boundaries are observed.