

**PETROLOGIC – GEOCHEMICAL STUDY OF CHONDRULES IN ENSTATITE CHONDRITES.** M. K. Weisberg<sup>1,2</sup>, D. S. Ebel<sup>2</sup>, H. C. Connolly Jr.<sup>1,2</sup>, N. T. Kita<sup>3</sup> and T. Ushikubo<sup>3</sup>. <sup>1</sup>Dept. Phys. Sci., Kingsborough College, City University New York, Bklyn, NY 11235 and Dept. Earth and Environmental Sci., The Graduate Center of CUNY 365 5<sup>th</sup> Ave., NY, NY. (mweisberg@kbcc.cuny.edu). <sup>2</sup>Dept. Earth Planet. Sci., American Museum Natural History, NY, NY 10024. <sup>3</sup>Dept. Geology and Geophys., University Wisconsin-Madison, WI 53706.

**Introduction:** Enstatite (E) chondrites record extremes in the nebular conditions that resulted in formation of chondrites. Their silicate, sulfide, and metal compositions indicate highly reducing conditions [1]. Their major silicate phase is enstatite (FeO<1.0 %). They contain higher amounts of FeNi metal than O or most C chondrites, except for the metal-rich CB and CH chondrites, and their metal is Si-bearing, with more than 2 wt. % Si in the EH chondrites. Elements that are typically lithophile in most chondrites (i.e., Mg, Mn, Cr, Na, K) are both lithophile and chalcophile in the E chondrites. E chondrites contain the oxo-nitride and nitride phases sinoite (Si<sub>2</sub>N<sub>2</sub>O) [2-4] and osbornite (TiN<sub>2</sub>) [4], which are also indicators of highly reducing conditions. The Hvittis EL6 was shown to have a remarkably low intrinsic *f*O<sub>2</sub> compared to other chondrites [5]. In spite of their remarkable characteristics their chondrules have received considerably less attention than chondrules in other groups. Some properties of chondrules in E3 chondrites have been described previously [6-11]. We have begun a detailed petrologic and oxygen isotopic investigation of chondrules in the E3 chondrites. Our goals are to (1) understand the origin of these chondrules compared to chondrules in other chondrite groups, (2) provide constraints on their thermal histories in the context of chondrule formation models and, (3) place constraints on physico-chemical conditions within the disk region where they formed.

**Results: Textures and Mineral Assemblages.** We previously described chondrules in EH3 and EL3 chondrites [12,13] and reported limited oxygen isotope compositions of FeO-bearing silicates [13]. Here we review our results and report on 23 newly studied chondrules from the Yamato 691 and Sahara 97096 EH3 chondrites, which were selected for oxygen isotope study. These two meteorites were selected because they are among the most primitive of the EH3 chondrites [14]. The chondrules were selected because they contain olivine in various textural settings and/or FeO-bearing silicates. Chondrules in EH3 chondrites have a reported average diameter of 278 ± 229 μm [11]. However, one chondrule we studied in Sahara 97096 is a 4 mm barred olivine (BO). All chondrule textural types are present in E3 chondrites, but porphyritic pyroxene (PP) is most common, compared to O and C chondrites in which porphyritic olivine pyroxene (POP) and porphyritic olivine (PO) are dominant.

Prophyritic chondrules in Sahara 97096 and Y 691, as well as other EH3 chondrites, consist of low-Ca pyroxene (generally enstatite) ± olivine (absent in most chondrules) with albitic glass ± silica. Cr-bearing troilite is common and in some chondrules, nodules with assemblages of troilite, Si-bearing metal ± oldhamite (CaS) ± niningerite (Mg,Fe,Mn)S are present. Olivine in E3 chondrules, when present, occurs as poikilitic inclusions in enstatite, as large crystals (up to 200 μm size) surrounded by fine enstatite and albitic glass and silica (Fig. 1) and as rare BO.

Another interesting aspect of the E3 chondrules is the lack of dusty rims, which are commonly observed on chondrules in other groups. Dusty matrix is also extremely rare in E3 chondrites.

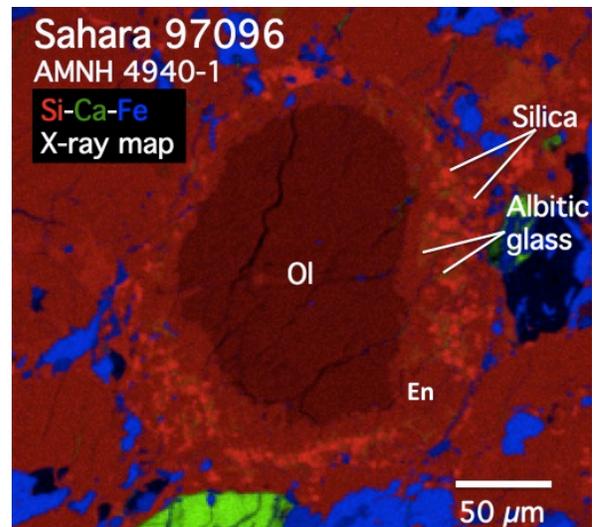


Fig. 1. Si-Ca-Fe (red-green-blue) x-ray map of C11 in Sahara 97096 (AMNH 4940-1). C11 consists of a large olivine (Ol) surrounded by fine enstatite (En), albitic glass and silica.

**Mineral Compositions.** Enstatite with near-endmember composition (Fs<sub><1</sub>) is the most common phase in most E3 chondrules. Minor elements MnO and Cr<sub>2</sub>O<sub>3</sub> range from below detection (bd) up to 0.6 and 0.8 wt. %, respectively. More Fe-rich compositions (up to Fs<sub>34</sub>) are also found in some chondrules, with up to 0.9 MnO and 1.8 wt. % Cr<sub>2</sub>O<sub>3</sub>. Fe-rich pyroxene grains generally contain tiny (<1 μm) inclusions of FeNi metal and/or Fe-sulfide. Some show areas of low-Fe enstatite associated with the metal blebs suggesting reduction of Fe from the Fe-rich grains. In a previous study [12] we used cathodoluminescence (CL) to identify three types

of pyroxene in E3 chondrules. These include (1) pure (minor element-poor) enstatite (blue CL), (2) minor element-bearing enstatite (red CL) and (3) Fe-rich pyroxene (no CL). Some chondrules contain disequilibrium assemblages of all three types of pyroxene. Olivine ranges from near pure forsterite ( $Fa_{-1}$ ) up to  $Fa_{11}$ , with MnO from bd to 0.5 and  $Cr_2O_3$  from bd to 0.7. Mesostasis compositions are albitic with (wt. %) up to ~ 68  $SiO_2$ , 18  $Al_2O_3$ , 9  $Na_2O$  and 5  $CaO$ . Precise values are difficult to obtain for mesostasis compositions due to the presence of microcrystals in the mesostasis and loss of Na during electron probe analysis.

**Discussion and Conclusions:** (1) Chondrules in E3 chondrites have petrologic and isotopic characteristics that differ markedly from the common type I and type II chondrules in other chondrite groups. On the oxygen 3-isotope diagram individual chondrules from EH3 chondrites form a distinct cluster, not overlapping chondrules from O or C chondrites and scatter about a best-fit line of slope-0.7 [15]. Thus, EH3 chondrules represent a distinct oxygen reservoir with the range of chondrules forming a slope consistent with gas–solid mixing and not mass-dependent fractionation.

(2) Some chondrules in E3 chondrites may contain relict grains and are mixtures of grains that experienced low degrees of melting. Some chondrules contain large (possibly relict) olivine surrounded by fine enstatite and others are disequilibrium mixtures of FeO-rich pyroxene, olivine and enstatite. Fe-rich pyroxene and olivine in Y 691 have been interpreted to be relict grains that survived the chondrule-melting event [16]. The relict grains may be from a previous generation of chondrules indicating recycling (and remelting) of materials as suggested for O and C chondrules [17]. It has been argued that some of the compositionally pure enstatite grains with minor element compositions below detection are also ‘relict’ grains that did not crystallize from the chondrule melt [12].

(3) The origin and relationship between the FeO-bearing grains and the pure enstatite and forsterite in E3 chondrules is unclear. The FeO-rich and FeO-poor olivine and pyroxene in chondrules from the Sahara 97159 EH3 chondrite were shown to have similar oxygen isotopic compositions [13], suggesting that both the FeO-rich and highly reduced FeO-poor silicates in the EH3 chondrules formed from the same oxygen reservoir, but the oxygen fugacity varied widely. Another interpretation is that the FeO-poor enstatite evolved from grains similar to the FeO-rich pyroxene through reduction during or following chondrule formation. More extensive oxygen isotope analyses are currently underway on a larger population of chondrules, in order to better understand the relationship between the minerals in the chondrules from E3 chon-

drites, and test a possible relationship between the FeO-rich and FeO-poor silicates and relationships of FeO-rich silicates to other chondrite groups.

(4) The chondrules in E3 chondrites record a complex history and appear to be records of reducing nebular conditions. Their reduced compositions may be due to reaction with a nebular gas having an enhanced C/O ratio. Sulfidation reactions may also account for the mineral assemblages observed in some EH3 chondrules [e.g., 18]. Solid-vapor reaction of pyroxene with an  $H_2S$ -rich vapor can result in sulfidation of Mg to form MgS and silica. Sulfidation of Fe from Fe-bearing pyroxene can yield FeS, silica and enstatite. It is also possible that the chondrule precursor assemblage included reducing agents such as C or S.

(5) The lack of dusty rims around E3 chondrules may have important implications about the (low) dust/gas ratio and/or the composition of the dust in the nebular region in which they formed.

Thus, the chondrules in E3 chondrites represent a distinct (local) nebular environment and/or chondrule precursors compared to chondrules in other chondrite groups. However, like O and C chondrules, chondrules in E chondrites are complex mixtures of mineral grains that show evidence of relict grains and recycling and remelting. Some chondrules have had a complex history that may include solid-vapor reduction and/or sulfidation reactions and are records of an extremely reducing environment. Oxygen isotope data is currently being collected to better constrain the history of these remarkable chondrules.

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