PRIMITIVE FINE-GRAINED MATRIX IN THE UNEQUILIBRATED ENSTATITE CHONDRITES.

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Introduction: Enstatite chondrites (EC) have important implications for constraining conditions in the early solar system and for understanding the evolution of the Earth and other inner planets. They are among the most reduced solar system materials as reflected in their mineral compositions and assemblages [e.g., 1,2]. They are the only chondrites with oxygen as well as Cr, Ti, Ni and Zn stable isotope compositions similar to the earth and moon [3-5] and most are completely dry, lacking any evidence of hydrous alteration; the only exception are EC clasts in the Kaidun breccia which have hydrous minerals. Thus, ECs likely formed within the snow line and are good candidates to be building blocks of the inner planets [6].

Chondrite matrix is an important, distinct component of primitive (unequilibrated) chondrites. It is, in general, a mixture of materials that range from being highly primitive to highly altered. It is the component of chondrites that harbors refractory olivine, primitive amorphous materials, organic matter and interstellar grains. However, the origin of matrix and its constituents, the relationship of matrix to chondrules and refractory-rich inclusions, the relationship of matrix from one chondrite group to that of another and the relationship of chondrite matrix to other fine-grained solar system materials, e.g., comet dust, interplanetary dust particles and micrometeorites, are all poorly understood. Here we focus on the matrix in E3 chondrites.

Matrix material has been studied in some E3 chondrites [7-10]. The matrix in Y 691 consists of "fine-grained silicate and opaque minerals filling the interstices among fragments and chondrules" [7]. ALH 81189 matrix was described as consisting of chondrule and mineral fragments and a fine component referred to as "nebular fines" [10]. Additionally, pre-solar grains have been identified in the matrix in Y 691, ALH 81189 and Sahara 97072 EH3 chondrites [9,11]. Interestingly, highly reduced forsterite and enstatite grains recently found in Wild-2 samples returned by the Stardust mission are compositionally similar to grains from EH3 matrices [12]. Our goals are to provide a more detailed characterization the fine-grained matrix in E3 chondrites, understand its origin and relationship to chondrules, decipher the relationship between EH and EL chondrites and compare E3 matrix to matrices in C and O chondrites as well as other fine-grained solar system materials. Is E3 matrix the dust remaining from chondrule formation or a product of parent body processing or both?

Results: We studied matrix in 3 primitive EH3 (ALH 81189, Sahara 97096, Y 691) and 2 EL3 (MAC 88136, QUE 93351) chondrites using a combination of scanning electron microscope (SEM) and focused ion beam (FIB)/transmission electron microscope (TEM). We define matrix as the fine grained material interstitial to the chondrules and other fragments and focused on the materials ≤ 5 µm in size . In general, matrix makes up a minor component of EH3 and EL3. Matrix in EH3 chondrites reportedly constitutes 4.9 vol% of the Y 691, 11.7 % of the ALH 81189 and 14 % of the Qingzhen EH3 chondrites [8,10]. We found that matrix makes up $\leq$5% of the E3 chondrites we studied except for in ALH 81189. We have not yet studied Qinzhen. ALH 81189 has an unusually large amount of matrix, consistent with previous findings [10], and in some cases occupies wide areas between chondrules (Fig. 1) and filling in embayments on the outer edges of chondrules. The high abundance of matrix and relatively low degrees of weathering in ALH 81189, made it a prime target for characterizing EH3 matrix and for FIB/TEM analysis. Matrix in the two EL3's is less abundant than in the EH3 chondrites. In MAC 88136, for example, the chondrules are tightly packed with little to no fine grained component between them.

Matrix in ALH 81189 contains rounded silicates (silica, olivine, enstatite and albitic plagioclase) that are uniformly ~1-3 µm in size (Fig. 1). These grains are mixed with sulfides (mostly Cr-bearing troilite, oldhamite and daubreelite), shreibersite, lesser amounts of FeNi metal, lithic fragments (presumably broken chondrules), all surrounded by a fine-grained component (<< 1 µm in size). FeNi is silicon-bearing, similar to that in the chondrules. However, the matrix appears to contain a higher abundance of silica than in the chondrules. Silica grains (1-3 µm in size) constitute ~7 % of the matrix areas studied. Additionally, SEM reveals that the matrix silica contains tiny (sub-micron) inclusions of FeS and Al- and Mg-bearing silicates, presumably a feldspathic material and enstatite. TEM examination of ALH 81189 matrix reveals that some matrix silica is amorphous (glass), containing acicular crystals of plagioclase, small grains of enstatite and in some case patches of a crystalline silica phase (Fig. 2). SEM examination shows that matrix in the Y 691 and

Sahara 97096 EH3 chondrites contains a similar mineral assemblage to that in ALH 81189. However, the fine-grained component is slightly coarser consisting of enstatite, 1-2µm in size, with <1µm silica, sulfide and metal and appears to be porous (Fig. 1). Matrix in the two EL3 chondrites is dominated by irregular-shaped to angular enstatite and albitic plagioclase (1-2 µm in size) Silica abundance is lower and albitic plagioclase higher than in EH3 matrix.

Discussion: Fine-grained (≤5 µm) matrix in the E3 chondrites is a primitive, distinct component that is not derived from broken chondrules. Like other EC components it has reduced mineral assemblages and differs markedly from matrix in O or C chondrites. It contains silica and/or enstatite as major components, whereas in most C and O chondrites, olivine is the dominant matrix silicate. Additionally, matrix in many C and O chondrites contains FeO-bearing silicates and shows evidence of secondary alteration, which is not the case for matrix in E3 chondrites, consistent with the dry environment in which the ECs formed. The amorphous (glassy) silica component of ALH 81189 matrix attests to this being among the most primitive EH3 chondrites and suggests that some matrix grains experienced melting and/or irradiation damage. The rounded, glassy silica grains containing tiny sulfide and silicate inclusions are suggestive of GEMS (rounded globules of glass with embedded metal and sulfides), interpreted to result from nebular radiation damage [13]. However, pure silica GEMS have not been reported previously and further work is underway to test the origin of the silica.

EL3 matrix appears to differ from that in EH3 and may be the result of different formation and/or accretion histories for the EC groups. In MAC 88136 chondrules appear more compact with less fine-grained material between them and chondrules deform each other. A hot accretion scenario for EL3s may account for these features. The matrix preserved in E3 chondrites is a distinct, primitive material (dust and debris) from the EC region of the solar system, closely related to, but different from other EC components.

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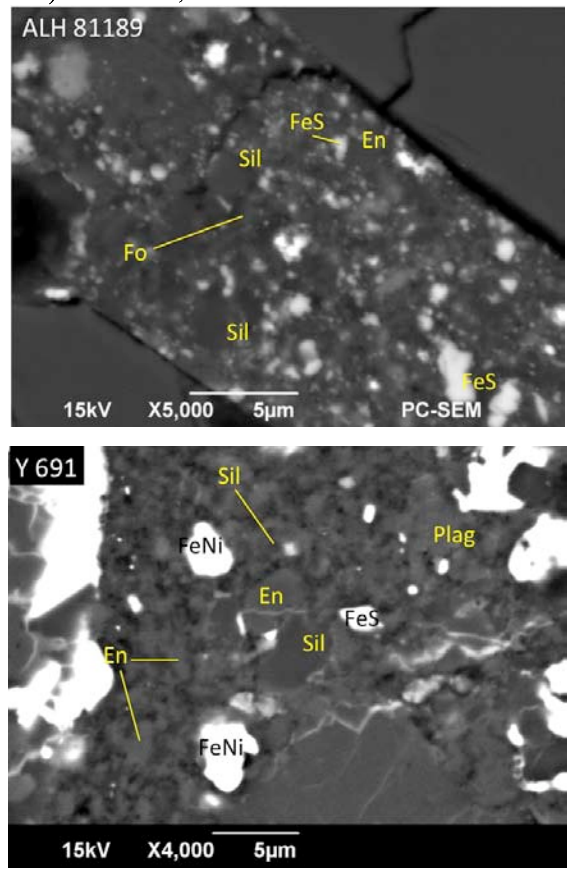

Fig. 1 Backscattered electron images of matrix in the ALH 81189 (top) and Y 691 (bottom) EH3s. Both consist of 1-3 µm silica (Sil), Enstatite (En), forsterite (Fo), plagioclase (Plag), FeNi and FeS grains surrounded by a finer-grained (sub-micron) mixture of similar minerals.

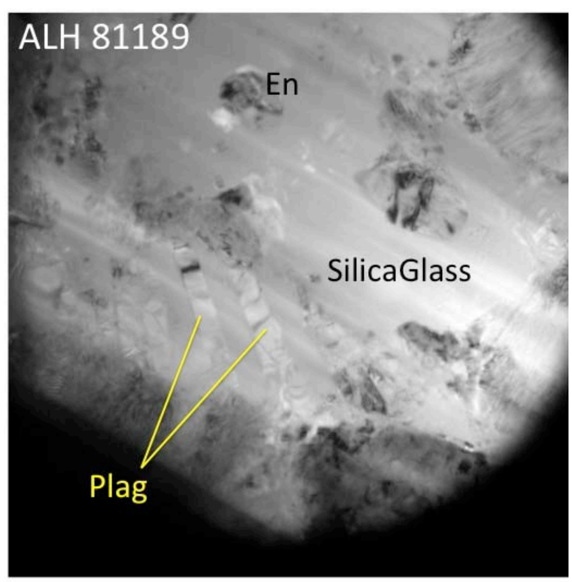

Fig. 2. TEM bright field image of a matrix area from ALH 81189 showing silica glass with included crystals of plagioclase (Plag) and enstatite (En). Field of view is 0.8 μm.