PRIMARY AND SECONDARY DIVERSITY AMONG ENSTATITE CHONDRITES AND IMPLICATIONS FOR THEIR PARENT BODIES. M. K. Weisberg[1,2,3], M. Kimura[4], M. E. Zolensky[5], M. L. Gray[1,3], D. S. Ebel[1,3], [1]Dept. Earth and Environmental Sci., CUNY Graduate Center, New York, NY 10016. (mgray1@gradcenter.cuny.edu) [2]Dept. Physical Sci., Kingsborough College CUNY, Brooklyn, NY 11235. [3]Dept. Earth and Planetary Sci., American Museum of Natural History, New York, NY 10024. [4]National Institute of Polar Research, Tokyo, 190-8518 Japan. [5]ARES, NASA Johnson Space Center, Houston, TX 77058.

Introduction: The enstatite chondrites (ECs) are noteworthy in having stable isotopic compositions similar to Earth and Moon [1-3], suggesting they were present in Earth's feeding zone during terrestrial planet formation. To better understand these primitive meteorites, we have been studying their primary and secondary mineralogies and documenting the diversity among the EC groups. Since Keil's landmark paper [4] at least two major groups of ECs have been identified, now known as EH and EL. Lack of EC breccias containing both EH and EL implies at least two separate parent bodies. The ECs are a relatively small meteorite class making up less than 1% of all known meteorites with less than 20 unequlibrated (type 3) individuals known. However, with new samples returned from Antarctica, hot deserts and occasional non-desert meteorites, the diversity of E chondrites has seemed to grow, with potential new groups emerging [e.g., 5]. Based on sulfide compositions, division of EH and EL each into subgroups "a" and "b" has also been proposed and a minimum of four parent bodies for the ECs has been suggested [6]. ECs such as NWA 8785 have secondary minerals not present in other ECs, potentially representing yet another EC parent body [7]. Here we explore the petrologic diversity of EH and EL and anomalous ECs to evaluate their origins, alteration histories and parent bodies.

Primary (pre-accretionary) diversity in the ECs The ECs have unusual, reduced and/or sulfidized mineral assemblages and compositions unlike any other primitive meteorite group [4,8]. Their major silicate phase is near-pure endmember enstatite (FeO<1.0wt%). They contain higher amounts of FeNi alloy than ordinary or carbonaceous chondrites, except for the unusual CH and CB chondrites, and their metal is Si-bearing with more than 2 wt% Si in EH metal. Elements that are typically lithophile in most other chondrites (i.e., Mg, Mn, Cr, Na, K) are chalcophile in ECs. The ECs contain oxynitride and nitride phases sinoite (Si_2N_2O) and osbornite (TiN) [9-11], also indicators of highly reducing conditions.

The recognized EC groups, EH and EL, have mineralogical differences. EH has higher Si contents in the metal than in ELs. Also, EH contain niningerite (Mg,Fe)S whereas EL lack niningerite but instead contain alabandite (Mn,Fe)S. Along with these, there are other differences such as metal abundances and average chondrule sizes [8,12]. Recently variations in sulfide compositions were shown and used to suggest division of ECs into four subgroups [6].

Abundance of matrix is another characteristic of ECs that varies considerably. Matrix abundance in most EL3s is <5 vol.%. According to [13], clastic matrix constitutes 4.9 vol.% of Yamato 691 and 11.7 vol.% of the ALH 81189 EH3 chondrites. In the EL3 NWA 8785, matrix makes up >30% [7].

Secondary alteration diversity in the ECs*:* Micrometer-scale evidence of hydrothermal reactions has been identified in enstatite chondrites. These include breakdown of minerals such as djerfisherite and the presence of hydrated sulfides in Qingzhen and other EH3 chondrites [14]. The breakdown reaction of djerfersifsherite (referred to as the "Qingzhen Reaction") in both the Qingzhen and Yamato 691 EH3s suggests mobilization of volatile components to form secondary phases [15]. Secondary sphalerite [(Zn,Fe)S], idaite (Cu_5FeS_6), bornite (Cu_5FeS_6), hydrated phases (termed Phase A and B) and a hydrated chromium sulfide mineral have also been found in Qingzhen [16]. These observations suggest hydrothermal activity to various degrees either prior to accretion or in local portions of an EH3 parent body.

NWA 8785 is an anomalous EL3 with a high abundance of a magnetite-rich, sub-micrometer matrix. The matrix magnetite is associated with amorphous silicate [7]. Additionally, metal-rich nodules in NWA 8785 contain alkali-rich minerals albite, djerfisherite ($K_6(Fe, Cu, Ni)_{25}S_{26}Cl$) and the rare alkali-rich mineral roedderite [$(Na,K)_2(Mg,Fe)_5Si_{12}O_{30}$] [17], suggesting mobilization of alkali elements.

LEW 87223 is an anomalous EL3 containing objects that show varying degrees of Na-enrichment [18]. Albitic plagioclase (plag) occurs on chondrule edges and along fine Na-rich veins within chondrule interiors. Some Al-rich chondrules in LEW 87223 contain both albitic and anorthitic plag occurring together. For example, one chondrule in LEW 87223 contains two feldspars: anorthitic (An_{90}, Ab_9) and albitic (An_{22}, Ab_{71}) plagioclase. Vein-like intrusions of the albitic plag into the anorthitic plag are observed. The anorthitic plag is a primary phase and the albitic plag is secondary, from their occurrences.

Noteworthy too, are E chondrite clasts in the Kaidun breccia, which have hydrous minerals [19]. However, in this case, the alteration may have taken place on the Kaidun (C chondrite) parent body.

Another secondary process that has modified the EC asteroid(s) is impact. EL3s, in particular, have been interpreted to be breccias containing regions of impact melt [20]. They contain chondrule-like metal-rich nodules that have been interpreted to be products of impact melting formed by mobilization and injection of metal into pores in the EL3 regolith [21] or clasts that resulted from collision of early differentiated bodies [22], although they are also interpreted to be primary, chondrule-like melts formed in the early Solar System [23] or aggregates of condensates [24]. PCA 91020 is an EL3 in which the chondrules and metal-rich nodules are elongated and exhibit a preferred orientation, likely due to impact-induced deformation [25]. Impact events may have also supplied the heat that initiated the hydrothermal activity and volatile metasomatism on EC parent bodies.

Discussion: ECs show a wide range of diversity in both their primary and secondary petrologic features. Although nominally dry, ECs show various degree of rock-water interactions, from micrometer scale hydration products in some ECs to the rare case of magnetite distributed throughout the matrix of NWA 8785 [7,16]. Metasomatism by Na was also a prominent process, as evident in one anomalous EL3 [17]. Thus, it is likely that hydrothermal fluids were active to some degree during the early history of ECs and their parent bodies. It has been inferred that ice accreted with matrix-rich C chondrites and was responsible for hydrated minerals in the matrices of these chondrites. The relationship between anomalously high matrix abundance (>30%) in NWA 8785 and presence of secondary magnetite, interpreted to be hydrothermal, suggests that NWA 8785 accreted with an icy matrix component, although hydrated silicates have not been found. If the ECs formed inside of the nebular snow line, ices may have migrated inward and accreted with some EC material. This was possibly an early event during initial parent body accretion or during a late-stage redistribution of icy materials due to migration of Jupiter [26]. In either case, EC parent bodies may have had heterogenous distributions of ices, or the ECs represent more than 2 parent bodies, i.e., EH and EL, with ECs like the magnetite-bearing NWA 8785 representing a separate, relatively ice-rich body and LEW 87223 possibly yet another parent body. Alternatively, the minor, micro-scale, heterogeneously distributed secondary minerals observed in some ECs formed due to chondrule-forming shock waves in icy nebular regions which produced conditions of rapid mineral hydration [27].

It has been inferred that impact melt is a common phenomenon in EH6 chondrites, and that collisional heating was the primary process responsible for EH metamorphism [28]. This, along with evidence of impact melt and chondrule deformation in some EL3 chondrites suggests that impact was particularly prominent as a heat source for EC parent bodies [29] and thus, impacts may also be related to the generation of hydrothermal fluids and metasomatism that resulted in the secondary minerals observed in many ECs.

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