PETROLOGIC EVIDENCE OF HYDROTHERMAL ACTIVITY ON THE EL3 PARENT ASTEROID. M. K. Weisberg[1,2,3], M. E. Zolensky[4], K. T. Howard[1,2,3], M. Kimura[5,6], D. S. Ebel[2, 3], C. M. O'D. Alexander[7] and Y. Bolega[8] [1]Dept. Physical Sci., Kingsborough College CUNY, Brooklyn, NY 11235. (mweisberg@kbcc.cuny.edu) [2]Dept. Earth and Environmental Sci., CUNY Graduate Center, New York, NY 10016. [3]Dept. Earth and Planetary Sci., American Museum of Natural History, New York, NY 10024., [4]ARES, NASA Johnson Space Center, Houston, TX 77058. [5]National Institute of Polar Research, Tokyo, Japan. [6]Ibaraki University, Mito, Japan. [7]Earth and Atmospheric Sciences, [7]Carnegie Institution of Washington, 5241 Broad Branch Road, Washington, District of Columbia, 20015, [8]City College, City University of New York, New York, NY 10031.

Introduction: Hydrothermal alteration is an important process in the evolution of asteroids. It was active in the earliest stages of asteroid evolution as evidenced by the secondary minerals in the meteorite record and is thought to be active today in the asteroid belt on icy bodies such as Ceres, as suggested by imaging and surface mineralogy from the DAWN mission. The Northwest Africa (NWA) 8785 enstatite chondrite is an anomalous EL3 chondrite that shows potential evidence of extensive hydrothermal activity on the E chondrite parent asteroid [1]. The enstatite meteorites are of particular significance for the evolution of the terrestrial planets, having stable (O, Cr, Ti, Ni, Zn) isotope compositions similar to the Earth-Moon [2-4] and reduced chemistry similar to planet Mercury, as inferred from experiments [5]. NWA 8785 is the first EL3 enstatite chondrite known to be rich in fine-grained matrix and is further unusual in that the matrix is FeO-rich. All previously studied enstatite chondrites are matrix-poor and/or their matrices are composed of reduced mineral assemblages similar to their chondrules. Here we describe the matrix mineralogy of this unusual EL3 chondrite NWA 8785 and discuss its implications for the EL3 parent asteroid(s) and hydrothermal activity in meteorite parent bodies.

Methods: We used the scanning electron microscope (JEOL JSM-6390 LV/LGS SEM at Kingsborough), electron microprobe (SX 100, AMNH) and focused ion beam (FIB) sectioning and transmission electron microscope (TEM, NASA JSC) and X-ray diffraction (XRD, Kingsborough/AMNH) to study the matrix mineralogy of NWA 8785.

Results: NWA 8785 was studied in polished sections. It contains (in area %) sharply defined chondrules (45.9%), metal/sulfide-rich nodules (9.8%), mineral and lithic fragments (10.6%) and rare refractory inclusions all surrounded by a fine-grained FeO-rich matrix (33.7%); the highest matrix abundance known among E chondrites. Chondrules range in diameter up to 2mm with most 500-700µm, close to reported mean EL3 chondrule sizes [6]. All chondrule textures are present but are dominantly enstatite-rich type IB (PP and RP) varieties. Chondrule enstatite compositions are nearly FeO-free. NWA 8785 contains sharply bound metal/sulfide-rich nodules, which is a common characteristic of all EL3 chondrites. The metal contains (average wt. %) 0.9 Si, 6.1 Ni, and 0.3 Co, similar to EL3 metal. However, the nodules in NWA 8785 are unlike those in other EL3 chondrites [e.g., 7, 8]. They contain enstatite, silica, graphite and sulfides as in other EL3s, but are texturally, and in some cases mineralogically, different [9]; the intergrowths of enstatite laths characteristic of nodules in other EL3s are less common, suggesting a different origin for the NWA 8785 nodules. Alkali-rich minerals albite, djerfisherite and the rare mineral roedderite [$(Na,K)_2(Mg,Fe)_5Si_{12}O_{30}$] are present in some nodules [9].

Possibly the most unusual feature of NWA 8785 is the high abundance of an FeO-rich, fine-grained (sub-micrometer) matrix, which is littered with mineral (enstatite, Na-rich plagioclase, FeS and FeNi) and lithic (chondrule) fragments ranging from sub-micrometer up to 50µm in size. FIB sectioning/TEM study of one matrix area reveals that the fine-grained portion is dominated by a mixture of magnetite and non-crystalline material (Fig. 1). The non-crystalline material contains SiO_2, MgO, CaO, FeO, S and Ni. This contrasts sharply with the clastic matrices in other E3s that are composed of silica and enstatite as major components, with metal, sulfides and enstatite having reduced compositions that are compatible with associated chondrules [10, 11]. Additionally, one matrix area in NWA 8785 contains a 30µm spinel-rich inclusion, consisting of $MgAl_2O_4$ spinel surrounded by sodalite (Fig. 1). Sodalite is a common alteration product of refractory inclusions in C chondrites. (Identification as sodalite is based on EDS spectra. Marialite, a scapolite mineral that forms in silica-saturated environments, is also a possibility.) We powdered a chip of NWA 8785 and separated the powder into magnetic and non-magnetic portions. XRD analysis of the magnetic fraction confirms the presence of magnetite. XRD of the powders also reveals hump like features at low angles, consistent with the presence of a non-crystalline material.

Discussion: *High abundance of FeO-rich matrix.* NWA 8785 is the first identified matrix-rich EL3 and the first EL3 known to have mineral assemblages that suggest extensive hydrothermal alteration, aside from E chondrite clasts in the Kaidun breccia [12, 13]. The high matrix abundance of NWA 8785 is more like that in some C and R chondrites. The FeO-rich composition of the NWA 8785 matrix and presence of magnetite is

in sharp contrast to most other E chondrites in which the matrices are composed of reduced mineral assemblages with compositions similar to their chondrules and fragments [10, 11]. Thus, NWA 8785 is anomalous compared to other EL3s or any other E chondrites and the matrix composition and presence of non-crystalline material are more like in C chondrites.

Magnetite. The presence of magnetite coexisting with the highly reduced mineral assemblages in an E chondrite is perplexing. Magnetite is present in most C and R chondrites and is generally interpreted to be a product of parent body alteration. It is also present in some of the least thermally altered O chondrites, such as Semarkona [14]. Its presence, apparently throughout the matrix in NWA 8785, suggests extensive, presumably post-accretion, hydrothermal alteration. However, a pre-alteration, primary origin of the magnetite cannot be ruled out. Although terrestrial weathering is also a concern, we note that magnetite is not a typical weathering product of NWA meteorites. Additionally, the intimate association of magnetite with non-crystalline material suggests the magnetite is not terrestrial.

Roedderite. The occurrence of the rare mineral roedderite in metal-rich nodules [9] and fragments in the matrix of NWA 8785 may be the result of alkali-rich fluids generated during hydrothermal activity. Roedderite is a rare mineral in meteorites and terrestrial rocks. One of the few terrestrial occurrences of roedderite is in volcanic ejecta from the Eifel volcanic region in Germany and it is interpreted to have precipitated from a highly alkaline, Mg-rich, Al-poor vapor formed during contact metamorphism [15]. Based on its textural occurrence, roedderite in the Qingzhen EH3 was interpreted to be a precipitate from an alkali-rich fluid phase during parent body alteration [16].

Other secondary minerals. Sodalite (possibly marialite) associated with a spinel-rich inclusion (Fig. 1) is also a likely product of secondary alteration. Additional micrometer-scale evidence of hydrothermal reactions has been previously identified in E chondrites. For example, breakdown of minerals such as djerfisherite and the presence of hydrated minerals have been described in Qingzhen and other EH3 chondrites [17, 18]. These observations suggest hydrothermal activity to various degrees on portions of the EL3 parent body or may indicate multiple parent bodies for EL3 chondrites. Thus, at least some E chondrites may have accreted with ice and portions of the enstatite chondrite parent asteroid were likely ice-rich.

NWA 8785 greatly widens the range of known E chondrite materials and secondary processes on the E chondrite parent asteroid.

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References: [1] Weisberg M. K. et al. (2019) *Meteorit. Planet. Sci., 54*, 6340. [2] Javoy M. (1995) *Geophys. Res. Lett., 22,* 2219-2222 [3] Warren P. (2011) *Earth Planet. Sci. Lett., 311*, 93-100. [4] Paniello R. C. (2012) *Nature, 490,* 376-379. [5] Burbine T. H. et al. (2002) *Meteorit. Planet. Sci., 37*, 1233-1244. [6] Friedrich J.M. et al. (2015) *Chemie der Erde, 75*, 419-443. [7] Van Niekirk D. & Keil K. (2011) *Meteor. Planet. Sci., 46*, 1487–1494. [8] Weisberg et al. (1997) *LPSC 28th*, 1523-1524. [9] Rindlisbacher M. A. et al. (2020) *LPSC 51st,* this volume. [10] Rubin A.E. et al. (2009) *Meteorit. Planet. Sci., 44*, 589-601. [11] Weisberg M. K. et al. (2014) *LPSC 45th*, #1551. [12] Zolensky M. E. & Ivanov A. (2004) *Chemie der Erde, 63,* 185-246. [13] Higashi K. et al. (2019) *LPSC 50th*, #2344. [14] Hutchison R. et al. (1987) *Geochim. Cosmochim. Acta, 51*, 1875-1882. [15] Hentschel G., et al. (1980) *Contrib. Mineral. Petrol., 73, 127-130* [16] Rambaldi E. R. et al. (1986) *Meteoritics, 21*, 141-149. [17] El Goresy A. (1985) *Meteoritics, 20*, 639. [18] Lin Y. & El Goresy A. (2002) *Meteorit. Planet. Sci., 37*, 577-599.

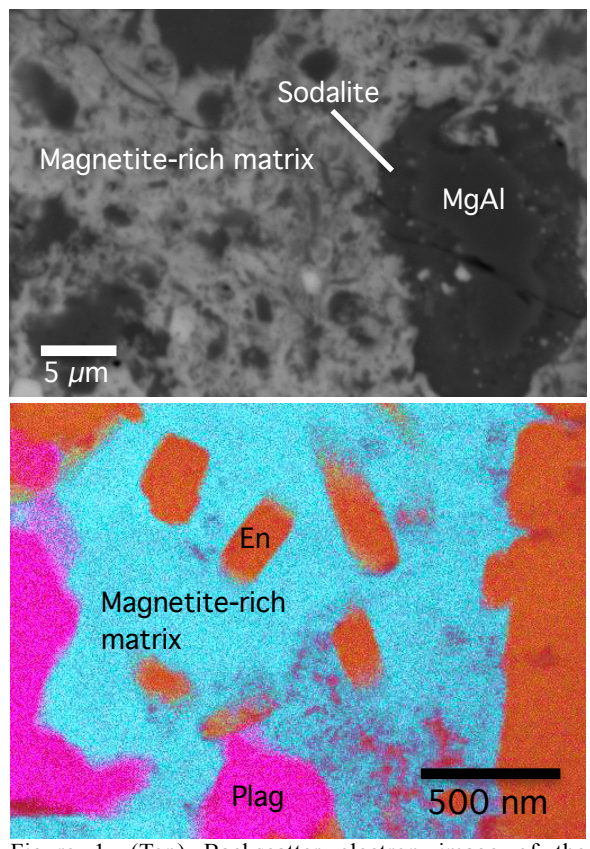

Figure 1. (Top) Backscatter electron image of the magnetite-rich matrix and a MgAl spinel-rich inclusion with a sodalite rim. (Bottom) Colorized transmission electron image of the magnetite-rich matrix (blue) and enclosed enstatite (red) and albitic plagioclase (pink) mineral fragments.