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The classification and complex thermal history of the enstatite chondrites

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Abstract. We have carried out instrumental neutron activation analyses of 11 enstatite chondrites and electron microprobe analyses of 17 enstatite chondrites, most of which were previously little described. We report here the third known EH5 chondrite (LEW 88180) and an unusual EL6 chondrite (LEW 87119), new data on four EL3 chondrites (ALH 85119, EET 90299, PCA 91020, and MAC 88136, which is paired with MAC 88180 and MAC 88184), the second EL5 chondrite (TIL 91714), and an unusual metal-rich and sulfide-poor EL3 chondrite (LEW 87223). The often discussed differences in mineral composition displayed by the EH and EL chondrites are not as marked after the inclusion of the new samples in the database, and the two classes apparently experienced a similar range of equilibration temperatures. However, texturally the EL chondrites appear to have experienced much higher levels of metamorphic alteration than EH chondrites of similar equilibration temperatures. Most of the petrologic type criteria are not applicable to enstatite chondrites and, unlike the ordinary chondrites, texture and mineralogy reflect different aspects of the meteorite history. We therefore propose that the existing petrologic type scheme not be used for enstatite chondrites. We suggest that while "textural type" reflects peak metamorphic temperatures, the "mineralogical type" reflects equilibration during postmetamorphic (probably regolith) processes. Unlike the ordinary chondrites and EH chondrites, EL chondrites experienced an extensive low-temperature metamorphic episode. There are now a large number of enstatite meteorite breccias and impact melts, and apparently surface processes were important in determining the present nature of the enstatite chondrites.

Introduction

The enstatite chondrites occupy a unique niche in our thinking about conditions in the early solar system. They formed in very reducing environments, with C/O higher than the cosmic value of 0.6 [*Larimer and Bartholomay,* 1979]. Thus, while they have approximately chondritic bulk composition, the enstatite chondrites generally have FeO-free enstatite, Si-bearing metal, and a host of sulfides including troilite (FeS), niningerite [(Mg,Fe)S], alabandite [(Mn,Fe)S], oldhamite (CaS), daubreelite ($FeCr_2S_4$), and chromium sulfides known as minerals A and B (approximately CrS [*Ramdohr,* 1963]). They also contain terrestrially unknown nitrides, sinoite (Si_2N_2O), osbornite (TiN), and nierite (Si_3N_4) [*Mason,* 1966; *Keil,* 1968; *Alexander et al.,* 1993; *Lee et al.,* 1995].

Like the other chondrite classes, the enstatite chondrites underwent a complex accretion history so that metal and silicates, which ceased equilibration at high-temperatures and pressures, were mixed, in various proportions, with material that ceased to equilibrate at the same pressures but lower temperature [*Sears,* 1980]. It is possible that the high temperature process was chondrule formation [*Larimer and Anders,* 1967]. It is also possible that the reduced state of enstatite chondrites reflects nebulawide variations in the precursor solids. Some authors conclude that the enstatite chondrites formed closer to the Sun than other chondrites; suggestions range from the inner fringes of the asteroid belt [*Larimer and Anders,* 1967], to 1 AU from the Sun [*Baedecker and Wasson,* 1975], to the orbit of Mercury [*Cameron,* 1978; *Sears,* 1980].

In addition to their unique state of reduction, enstatite chondrites display complex relationships with regard to petrologic type, bulk composition, and equilibration temperature. This complexity, combined with relatively small numbers of known enstatite chondrites, is reflected in the history of our attempts to classify these meteorites. Using bulk composition (Fe/Si and S/Si), *Anders* [1964] sorted several enstatite chondrites into "type I," "intermediate type," and "type II," a scheme that was adopted by *Mason* [1966] and *Keil* [1968] in their major studies of the mineralogy of 15 enstatite chondrites. When *Van Schmus and Wood* [1967] developed their chemical-petrologic scheme for classifying chondrites, they assigned the type I, intermediate type, and type II enstatite chondrites to their petrologic types 4, 5 and 6, respectively. However, bulk Fe/Si cannot be altered by closed-system metamorphism without partial melting [*Urey,* 1962], so *Baedecker and Wasson* [1975] and *Sears et al.* [1982] proposed that the enstatite chondrites consisted of two incompletely sampled isochemical series of enstatite chondrites, EH and EL chondrites. A number of EH4 chondrites were shown to be EH3 chondrites [*Prinz et al.,* 1984], and recently the first EL3 chondrites were reported, MAC 88136, MAC 88180 and MAC 88184, all of which may be paired [*Lin et al.,* 1991; *Chang et al.,* 1992]. The weathered RKP A80259 is an EL5 chondrite [*Sears et al.,* 1984; *Weeks and Sears,* 1985], although *Kallemeyn and Wasson* [1986] suggest that it may be another EH5 chondrite.

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It is thus apparent that some of the uncertainty over the origin and history of the enstatite chondrites has been the result of the small number of available meteorites and incomplete sampling of the parent body or bodies. However, like many rare and unusual classes, the enstatite chondrites are remarkably well represented in the Antarctic collection. On the basis of the preliminary descriptions by Mason in the *Antarctic Meteorite Newsletter*, it seemed to us that many of these occupied sparsely populated or unpopulated positions in *Van Schmus and Wood*'s [1967] chemical-petrologic grid. We therefore analyzed duplicate chips of 10 Antarctic enstatite chondrites (and Qingzhen) by instrumental neutron activation analysis (INAA) and their major phases by electron microprobe analysis (EMPA). Most of the samples were revealed to be members of well-known chemical-petrologic types, but we have discovered what we propose are EH5 chondrite, four new EL3 chondrites, and the second known EL5 chondrite. We discuss LEW 87223 in some detail, an anomalous enstatite chondrite that we suggest is an EL3 chondrite which has experienced heating and brecciation, and LEW 87119 that we suggest is an unusual EL6 chondrite. Not only do the present samples nearly complete the chemical-petrologic grid (we are now missing only a representative of the EL4 and EH6 chondrites) but, more important, they afford new opportunities for insight into the origin and metamorphic history of the EH and EL parent bodies.

We find that the Van Schmus and Wood petrologic classification scheme, which works well for ordinary chondrites, is not well suited to enstatite chondrites because texture and mineral chemistry indicate different thermal histories. We discuss the cause of the dichotomy between texture and mineral compositions for enstatite chondrites. We also propose that separate "mineralogical types" and "textural types" be used for enstatite chondrites instead of Van Schmus and Wood's "petrologic types."

Experiment

Optical Microscopy

The enstatite chondrites we studied are listed in Table 1, along with previous literature classifications, mainly from the preliminary survey observations of Antarctic meteorites by Mason. We examined 18 thin sections under transmitted and reflected light, noting especially the modal olivine abundances of the type 3 enstatite chondrites. We also checked for a lineation we had perceived in the texture of LEW 87119 by measuring grain sizes in two mutually perpendicular directions. Modal analysis under reflected light was performed by counting about 600 points on sections, which were typically 1.5 x 1.0 cm^2.

Instrumental Neutron Activation Analysis

Duplicate 100- to 200-mg chips were analyzed by INAA in two separate irradiations in the University of Missouri Research Reactor in Columbia. Each chip was given a 5-second irradiation and then counted for two 3-min periods to determine the nuclides with <5 min half-lives. The samples

Table 1. List of Enstatite Chondrites Studied, Brief Petrographic Descriptions and Existing Classifications

Name	Class*	Wthg†	Description‡
Qingzhen	EH3[1]	fall	abundant chondrules
ALH 84170	E3[2]	B	abundant well-defined chondrules, 2.1% olivine grains
ALH 84206	E3[2]	A/B	small abundant well-defined chondrules, lower than 1% olivine grains
EET 87746	E4[3]	C	evaporites on surface, abundant chondrules, lower than 1% olivine grains
PCA 82518	E4[4]	B	a few chondrules, small thin section
LEW 88180	E6[5]	B/C	evaporites on surface, chondrules rare, abundant metal
MAC 88136§	EL3[6,14]	A	large chondrules (some oscillatory extinction), 1% olivine grains
MAC 88180§	EL3[6,14]	C	abundant chondrules, 0.44% olivine grains
MAC 88184§	EL3[6,14]	C	abundant chondrules, 0.87% olivine grains
ALH 85119	E3[7]	B	abundant chondrules, lineation of texture, lower than 1% olivine grains
LEW 87119	E7[8]	C	only a few chondrule relics in a 0.6 x 0.6 cm^2 section, lineation of texture
RKP A80259	E5[9]	B/C	fine-grained texture, few chondrules, little metal
LEW 87223	E3[8]	C	abundant chondrules, abundant metal, many shock veins
EET 90299	E3[10]	C	abundant chondrules, lower than 1% olivine grains
PCA 91020	E3[11]	C	abundant chondrules, lower than 1% olivine grains
TIL 91714	E5[11]	C	lots of weathering veins, few chondrules
LEW 88135	E6[12]	B/C	few chondrules
LEW 88714	E6[13]	C	few chondrules

*References: 1, *Rambaldi et al.* [1983]; 2, *Mason* [1986]; 3, *Mason* [1989b]; 4, *Mason* [1984]; 5, *Mason* [1990b]; 6, *Mason* [1990a]; 7, *Mason* [1987]; 8, *Mason* [1989a]; 9, *Mason* [1982]; 10, *Mason* [1992b]; 11, *Mason* [1993]; 12, *Mason* [1991]; 13, *Mason* [1992a]; 14, *Chang et al.* [1992].

†Weathering category as defined by *Score and Lindstrom* [1990].

‡Mineral percentages are volume percentages as determined by point-counting.

§MAC 88136, MAC 88180, and MAC 88184 were paired by *Mason* [1990a].

were then given a 30-min irradiation followed by five counts ranging from 30 min to 12 hours to determine nuclides with 2.5-hour to 5.25-year half-lives. Our procedures for reducing data are those of *Weeks and Sears* [1985], except that, where necessary, manual baseline insertion was performed using interactive software [*Baedecker and Grossman,* 1989]. We also analyzed two chips of Qingzhen, three splits of Allende, and two splits of BCR-1 so that we could compare our results with literature data. Our results for Allende and BCR-1 are within error of literature values. The 1-σ uncertainties for duplicate analysis ($\sigma/\sqrt{2}$) are 5% for Na, Mg, Al, K, Sc, V, Cr, Mn, Fe, Co, Ni, Se, Sm, and Eu; 8% for Ca and La; and 11% for Ir. We did not use the unproven premise that members of chondritic groups are always isochemical as a criterion for evaluating our data and placing baselines under the peaks in our gamma ray spectra.

Electron Microprobe Analysis

We determined the compositions of the kamacite, troilite, niningerite, alabandite, and phosphides in 17 thin sections indicated in Table 1 (except Qingzhen) using the Cameca electron microprobe at the Johnson Space Center in Houston. Weathering effects were avoided, and typically the data for five to 10 grains were averaged for each meteorite. We used the following as standards: kaersitite for Ca, Ti, Fe, Si, and Mg; garnet for Mn; troilite for S; apatite for P; and NBS steel 479A for Ni and Cr. The electron microprobe accelerating voltage was 15 kV with a 1-μm beam and a beam current of 17.2 nA.

Results

Petrographic and Modal Analysis

Table 1 summarizes some of our petrologic observations on the samples, and Figure 1 illustrates the textural trends observed among enstatite chondrites. The MAC 88136 and ALH 84206 chondrites contain highly distinct chondrules located in a matrix of chondrule and mineral fragments and opaque metal and sulfides. Chondrules are still well delineated in ALH 85119 and EET 83322, but in LEW 88180 are indistinct almost to the point of complete obscuration. In fact, LEW 88180 includes several chondrules whose textures grade smoothly into the matrix. In many respects, the range of textures in the enstatite chondrites resembles that of the ordinary chondrites and is similar in both the EH and EL classes.

Figure 2 shows photos of two unusual enstatite chondrites. LEW 87223 is much coarser grained than the other enstatite chondrites we examined and contains numerous well-delineated chondrules. However, the chondrules containing

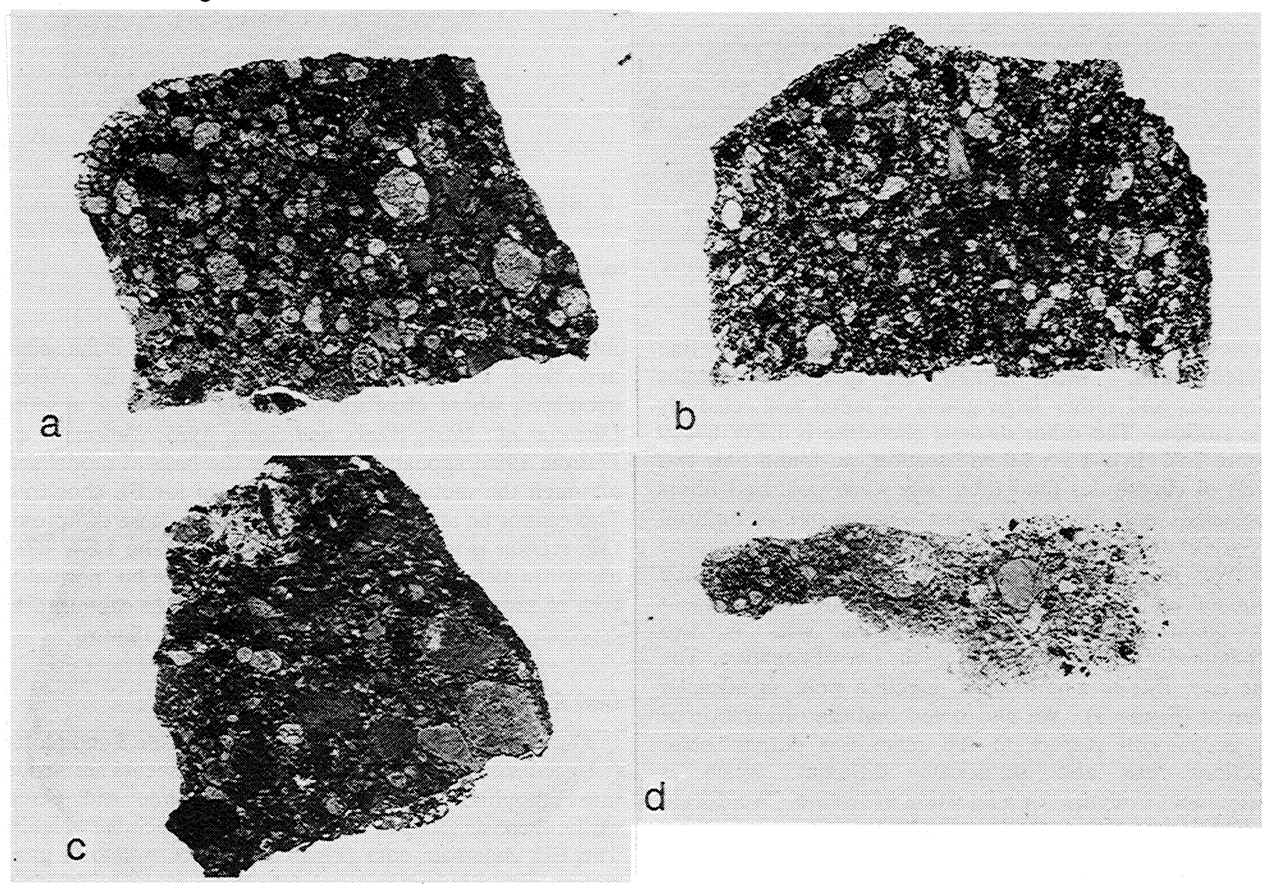

Figure 1. Photomicrographs of EH chondrites (series on the right) and EL chondrites (series on the left). Chondrules and other components are very well delineated in textural types 3 and 4, but difficult to impossible to distinguish in textural type 6. In textural type 5 chondrites the chondrules are readily recognized, but their outlines are not sharp because extensive intergrowth with the matrix has occurred. Textural types 3 and 4 are very similar in their appearance under the microscope, but may be distinguished on the basis of olivine content, since type 3 contains a few percent olivine, which is absent in type 4. The meteorites are as follows: (a) MAC 88136, EL3; (b) ALH 84206, EH3; (c) ALH 85119, EL3; (d) EET 83322, EH4; (e) RKP A80259, EL5; (f) St. Sauveur, EH5; (g) ALH 81021, EL6; (h) LEW 88180, EH5. All photographs were taken with plane transmitted light and a 15-mm field of view.

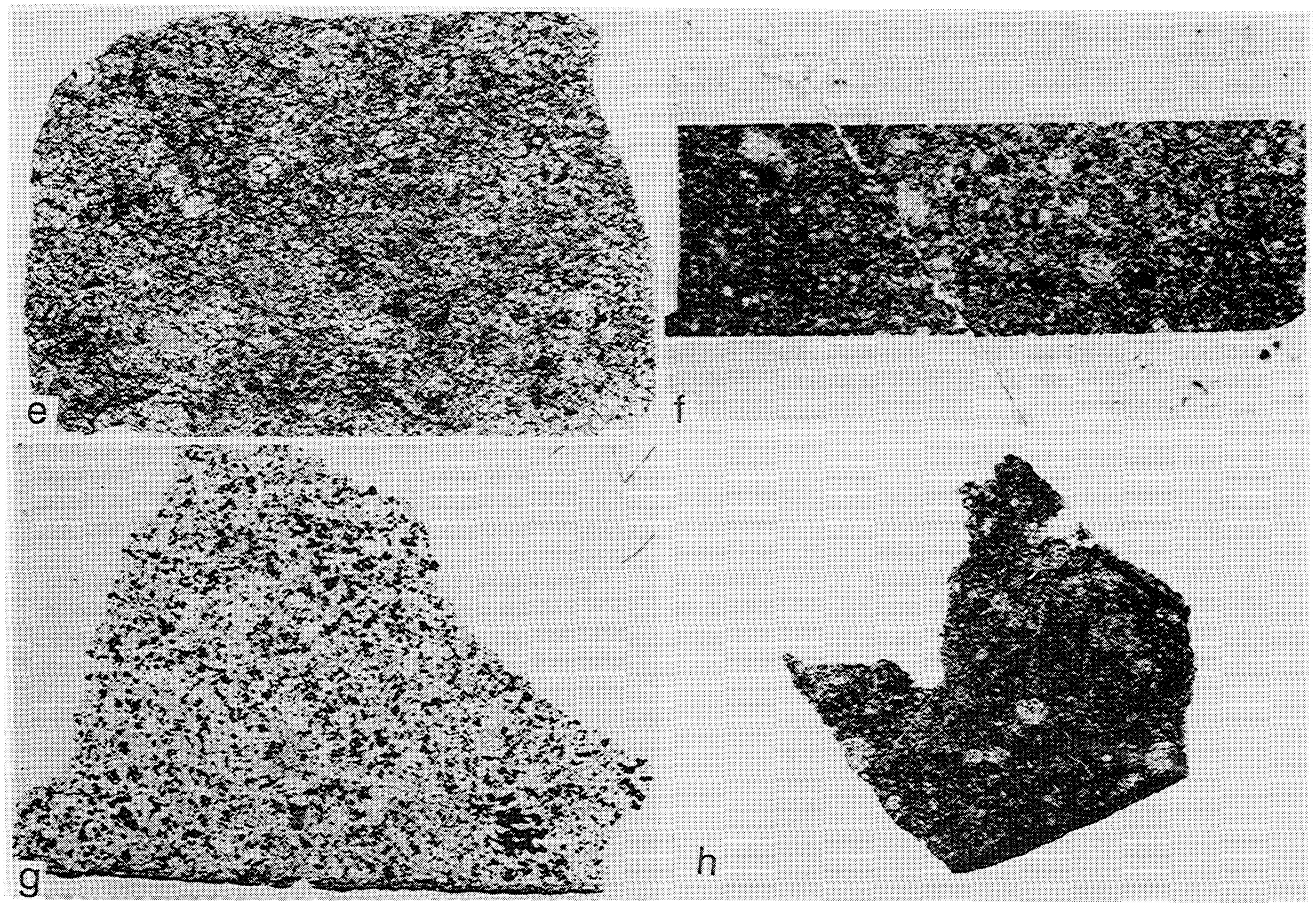

Figure 1. (continued)

silicates are darkened by the presence of ubiquitous very fine grained metal. Most notably, the meteorite contains ubiquitous and rather large grains of metal and relatively little sulfide. The other unusual chondrite is LEW 87119 (Figure 2b). In a 1.5 x 1.0 cm^2 section, we found only two relicts of chondrules (and then only when polarized filters were used), and the texture is an unusual one of uniform fine-grains of silicate, metal, and sulfide. Three independent observers in our group saw lineation in the texture when examined under the microscope, and in order to document this quantatively, we measured grain sizes in two perpendicular directions, one along the line of lineation. The grain size distributions in each direction were significantly different (Figure 3). We also noted that the orientation of the grains with respect to the same two perpendicular directions was also statistically different, which is independent evidence for a lineation of texture. We discuss the significance of textural lineation below.

Our modal analyses, compared with those of *Keil* [1968], are listed in Table 2. Our results agree well with the previous data, which were obtained on much larger sections with a greater number of points. In general, EH chondrites have a metal/silicate weight ratio greater than ~0.35, while EL chondrites are generally below this value. Several samples for which we do not yet have INAA data but which appear to be EL chondrites on the basis of their metal/silicate ratio are LEW 88714, LEW 88135, EET 90299, and PCA 91020. The EET 90299 and PCA 91020 chondrites are especially interesting, since this classification would make it the second and third known EL3 chondrite. The RKP A80259 chondrite, whose classification as EL5 or EH5 is disputed [*Sears et al.*, 1984; *Weeks and Sears,* 1985; *Kallemeyn and Wasson,* 1986] appears to be EL on the basis of modal data, although the metal content is low even for EL chondrites. This cannot be attributed to weathering because our present thin section is relatively little weathered. The LEW 87119 chondrite also has very low metal abundance but normal-to-high abundance of troilite. The LEW 87223 chondrite has especially high metal and very low troilite abundance.

Bulk Compositions

Our complete INAA data are listed in Table 3 and plotted (CI-normalized) in Figure 4, where the elements are divided into lithophile, siderophile and chalcophile and plotted within these divisions in order of increasing nebular volatility. The EH chondrite data (Figure 4a) agree well with group means, with siderophiles, and lithophiles agreeing especially well [*Kallemeyn and Wasson,* 1986]. There is some scatter among the chalcophile elements, but they are also about the group mean value.

We found considerably more scatter in our data for EL chondrites than for our data for EH chondrites. This is probably a result of greater metal-silicate heterogeneity in our EL chondrite samples, and the explanations for this might be (1) the average mass of our EL samples (114 mg) is

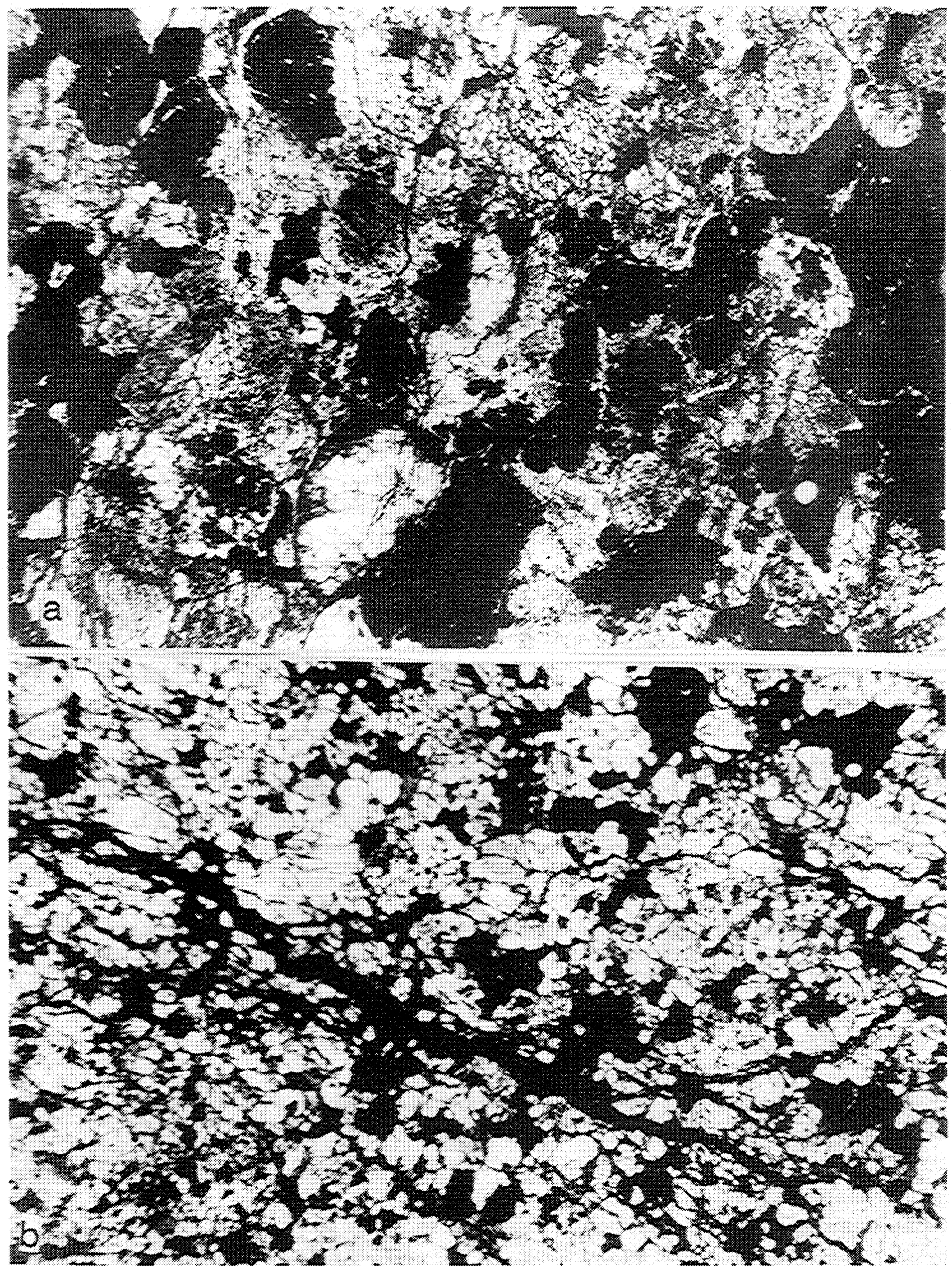

Figure 2. Photomicrographs of two unusual enstatite chondrites studied in the present work. (a) LEW 87223 is unusually coarse grained (grain sizes are typically 500 μm, compared to 200 μm), and the metal occurs as large (700 μm) ovoid masses rather than small irregular intergrown grains normally observed. The meteorite is compositionally also very unusual, containing siderophile elements 15% higher than usual, and most chalcophile elements are highly depleted. We suggest that LEW 87223 is an EL3 chondrite whose composition has been altered by heating and brecciation. (b) The LEW 87119 enstatite chondrite shows alignment of grains in the direction of top left to bottom right. A vein of weathering material follows the textural lineation. We suggest that LEW 87119 is an EL6 chondrite and that perhaps the lineation is the result of an intense shock event. Both images taken with plane transmitted light and 5-mm field of view.

smaller than that of our EH samples (169 mg); (2) the proportion of the heterogeneous type 3 chondrites in the enstatite chondrites we analyzed is higher for EL chondrites than for our EH chondrites; (3) since the literature data [*Kallemeyn and Wasson*, 1986], for many elements, also show a greater spread for EL chondrites than EH (even though the former are of a higher petrologic type and, therefore, expected to be compositionally more homogeneous), greater metal-silicate heterogeneity might be a property intrinsic to the EL parent body. Fortunately, the scatter is not sufficient to confuse classification, especially since trends within geochemically similar elements are insensitive to this problem.

The present data differ from earlier measurements in that we do not observe the somewhat surprising fractionations of rare earth elements observed in the EL chondrites by

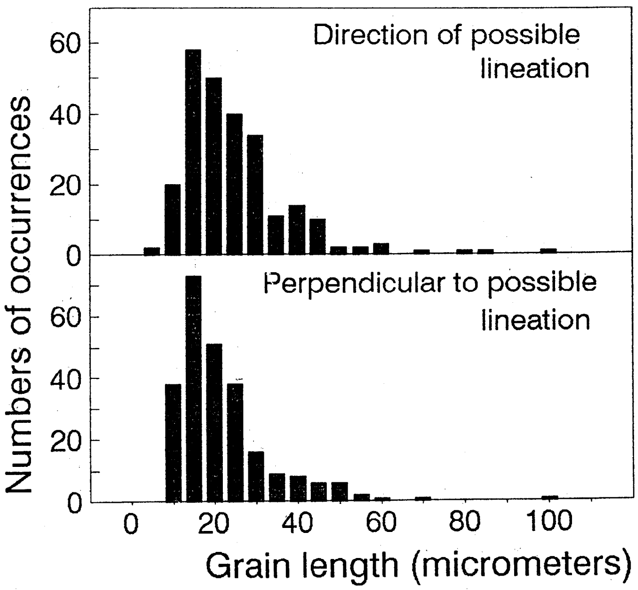

Figure 3. Grain size distributions in the apparent direction of lineation in LEW 87119 and perpendicular to the apparent direction of lineation. According to the t-test, the two distributions are different at the 95% level of confidence.

Kallemeyn and Wasson [1986]. The rare earth element abundances for the present EL chondrites show flat abundance patterns relative to Sc, Ca, V, and Mg, with no indication of a 15% depletion in La relative to the other refractories and then a steady rise to Yb as reported by previous workers [*Kallemeyn and Wasson,* 1986].

Data for LEW 87223 are plotted in Figure 4c. Data for the two chips analyzed in separate irradiations agree very well. Unlike any other sample we analyzed, Ir, Ni, and Co are 30% above mean EH group average; Fe and Au are close to EH average; the chalcophiles (except Cr) are much below the EH and EL averages; and Al, Sc, Ca, V, and Mg are intermediate between EH and EL values.

Mineral Compositions

The compositions of metal, sulfide, phosphide, and troilite phases in the present samples (Table 4) are plotted in Figure 5, with data from *Keil* [1968] and others (see below, Table 7). Mineral compositions reflect both the bulk composition of the meteorite (and therefore class) and the petrologic type. It seems likely, and is normally assumed, that chemical class reflects preaccretionary processes and petrographic type reflects parent-body processes. The first step is to examine the extent to which these two processes can be separated and to look for separate trends related to petrologic type for the EL and EH classes.

Metal compositions are shown in Figure 5a. Both the EH and EL chondrites contain metal in which Si and Ni generally increase with petrologic type. While the metal in EH chondrites generally contains >20 mg/g Si, the metal in EL chondrites generally contains <20 mg/g Si. In EL chondrite metal, with increasing petrologic type, Ni increases from 40 to 100 mg/g, and Si increases from <5 to nearly 20 mg/g. In EH chondrite metal, Ni increases from 20 to 100 mg/g, and Si increases from 20 to near 40 mg/g. The metal in RKP A80259 plots on the EH/EL border, while the unusual LEW 87223 plots close to the Ilafegh 009 impact melt [*Bischoff et al.,* 1992; *McCoy et al.,* 1992] near the boundary between EL3 and EL6 chondrites (with <10 mg/g Si in the metal). The Happy Canyon EL6 impact melt contains no Si in its metal [*Olsen et al.,* 1977].

Phosphide compositions also permit resolution of the EH and EL classes, since in general, EL chondrite phosphides contain > 200 mg/g Ni, while EH chondrite phosphides generally contain <200 mg/g Ni (Figure 5b). Both EH and EL chondrite phosphides contain decreasing abundances of Ni with increasing petrologic type: 400 to 200 mg/g for EL and 200 to just less than 100 mg/g for EH chondrites. Phosphides are absent from the most metamorphosed enstatite chondrite (LEW 87119). The LEW 87223 meteorite and Ilafegh 009 impact melt plot fairly close to each other in the EH4,5 region; Ilafegh 009 also plots close to the EL6 field.

The monosulfides of EH and EL chondrites are compositionally distinct. The EH chondrites contain niningerite (modal MgS>MnS), while EL chondrites contain alabandite (modal MnS>MgS). In both cases, the FeS content of (Mn,Mg)S increases with petrologic type, as expected from *Skinner and Luce's* [1971] data for the Fe-Mn-Mg-Ca-S system (Fig. 5c). Ilafegh 009 plots in the EL6 group again, but LEW 87223 contains higher FeS than the EL6 chondrites but similar MgS. RKP A80259 plots in the EH5 field, while LEW87119 plots far removed from the EL6 chondrites. Those plots are closer to the EH5 chondrites. Our thin sections of EET 90299 and PCA 91020 were highly weathered, and we could not obtain data for these samples.

Troilite compositions are shown in Figure 5d as a plot of Ti against Cr. The EH and EL chondrite troilites overlap in their Cr contents but, to a reasonable approximation, EL chondrites contain >5 mg/g Ti, while EH chondrites contain <5 mg/g Ti. In both the EH and EL chondrites, Ti and, especially Cr, in FeS increase with petrologic type. The LEW 87223 plot of Cr and Ti is at much higher values of Cr and Ti and in the general region of the plot occupied by other unusual enstatite meteorites Happy Canyon, Mount Egerton, and Shallowater [*Watters and Prinz,* 1979, 1980].

Discussion

Compositional Classification of Enstatite Chondrites: ALH 85119, LEW 87119, LEW 88180, RKP A80259 and TIL 91714

The EH and EL chondrites are defined in terms of bulk composition [*Sears et al.,* 1982]. Siderophile elements are nearly 30% higher in EH chondrites than in the EL chondrites, so that mass balance dictates that the lithophile elements are about 30% lower. The EH chondrites contain significantly higher chalcophile elements than the EL chondrites, but the relative abundance depends on the volatility of the element. Multielement plots of INAA data (Figure 4) provide the best means of compositional classification because they are less sensitive to errors in an individual element. The classifications used for the remainder of this paper will be classifications determined from the bulk compositions in the manner described by *Sears et al.* [1982].

The bulk compositional trends can be summarized on plots of element ratios in a manner often used in the past. Fe/Si and Mg/Si were originally used for enstatite chondrite classification [*Anders,* 1964; *Mason,* 1966], but since Si cannot be determined by INAA, we have plotted the Fe/Mg ratio for the present samples in Figure 6. The Fe/Mg ratio for EH chondrites is >0.95, while for the EL chondrites the Fe/Mg is

Table 2. Present Classification and Modal Analysis of the Enstatite Chondrites (wt %) in the Present Study

Meteorite	PTS	Class*	Points	Sil†	Kam	Troil	Other‡	Kam/Sil
EH chondrites								
ALH 84170	15	EH3	727	61.4	29.6	7.1	1.8	0.48
ALH 84206	10	EH3	592	64.0	19.8	14.0	2.1	0.31
EET 87746	21	EH4	344	60.9	26.4	9.2	3.5	0.43
PCA 82518	14	EH4	466	64.0	22.8	12.3	0.9	0.36
LEW 88180	13	EH5	713	56.7	29.4	11.6	2.4	0.52
Mean				*61.4*	*25.6*	*10.8*	*2.1*	*0.42*
EH mean§				65.1±5.5	22.2±2.7	7.7±1.9	5.6±3.5	
EL chondrites								
ALH 85119	11	EL3	748	64.0	20.8	10.9	4.8	0.33
EET 90299	6	EL3	323	68.8	13.5	14.0	3.7	0.20
MAC 88184	21	EL3	317	65.3	24.3	6.8	3.6	0.37
MAC 88180	14	EL3	598	67.9	23.4	6.0	2.5	0.34
MAC 88136	34	EL3	670	66.7	22.8	9.7	0.8	0.34
PCA 91020	16	EL3	699	64.4	24.9	7.8	2.8	0.39
TIL 91714	7	EL5	1126	65.5	13.7	13.0	8.1	0.21
RKP A80259¶	26	EL5	1046	72.2	14.0	12.0	1.9	0.19
			1555	*51.0*	*10.0*	*10.0*	*29.0*	*0.20*
LEW 88135	11	EL6	820	67.0	15.5	9.6	7.9	0.23
LEW 88714	9	EL6	395	71.3	15.3	9.2	4.2	0.21
LEW 87119	11	EL6	654	78.9	6.4	11.3	3.3	0.08
LEW 87223@	18	E3 an	1006	66.0	29.0	3.8	1.2	0.44
Mean				*68.4*	*17.7*	*10.0*	*4.0*	*0.26*
EL mean+				69.6±4.8	21.8±5.5	6.1±2.0	2.5±1.5	

*Class assignments and textural types are based on the present work.

†*Keil*'s [1968] "silicates" were estimated by difference, while for the present work, silicate phases were counted. It was assumed that they were all enstatite.

‡Minerals included in this category are graphite, schreibersite, oldhamite, alabandite, niningerite, daubreelite, sinoite, and weathering products.

§Mean of the values for Indarch, Adhi-Kot, Abee, St. Marks, and Saint Sauveur quoted by *Keil* [1968]. The uncertainties are 1 σ.

¶The values in italics are from *Sears et al.* [1984].

@Not included in the mean; "an" means anomalous.

+Mean of the values for Daniel's Kuil, Hvittis, Jajh deh Kot Lalu, Khairpur, Pillistfer, and Ufana quoted by *Keil* [1968]. The uncertainties are 1 σ.

<0.90, but within each class there is an indication of Fe/Mg increasing with petrologic type for both enstatite chondrite classes. The major difficulty in applying this plot to classification is that metal-silicate heterogeneity in the samples creates scatter on the Fe/Si axis. This is less of a problem for bulk compositions determined by XRF and wet-chemical analysis because these techniques typically require 10-gram samples, a mass comparable to the recovered masses for many of the present samples. Calculation by modal and mineral composition analysis is subject to considerably greater uncertainties than INAA bulk compositional analysis.

Of greater classification value than the Fe/Si versus Mg/Si plot is the plot of Ni/Ir versus Al/V (Figure 7). This plot utilizes the well-known refractory element fractionation displayed by enstatite chondrites. By normalizing a volatile siderophile to a refractory siderophile, and a volatile lithophile to a refractory lithophile, the plot is insensitive to metal-silicate heterogeneity. A Ni/Ir ratio of about 2.65×10^4 resolves the EH and EL (EH chondrites being above this value, EL chondrites below), while an Al/V ratio of 1.6×10^2 also resolves the two classes (EH chondrites have ratios below and EL chondrites have ratios above this value) [*Kallemeyn and Wasson*, 1986; *Wasson and Kallemeyn*, 1988].

Since mineral abundances and sometimes compositions may reflect bulk composition, mineralogical data can also be used to determine class (Table 2, Figure 7). Thus the metal in the EL chondrites has lower Si in its metal (<20 mg/g) than EH chondrites (>20 mg/g), and the dominant monosulfide in EH chondrites is niningerite, while in EL chondrites it is alabandite. As noted elsewhere, the metal/silicate ratio can also be used to determine compositional class.

We will now discuss certain meteorites which are of particular interest.

Allan Hills 85119. The bulk composition of ALH 85119 corresponds to an EL classification, as do mineral

Table 3. Instrumental Neutron Activation Analysis Results for the Present Enstatite Chondrites and Allende and BCR-1

Sample	Class*	Wt., mg	Na, mg/g	Mg, mg/g	Al, mg/g	K, mg/g	Ca, mg/g	Sc, μg/g	V, μg/g	Cr, mg/g	Mn, mg/g	Fe, mg/g	Co, μg/g	Ni, mg/g	Ga, μg/g	As, μg/g	Se, μg/g	Ir, ng/g	Au, ng/g	La, μg/g	Sm, μg/g	Eu, μg/g	Yb, μg/g
Qingzhen	EH3	130	7.70	120	8.8	--	10.0	5.7	57	2.80	1.80	282	888	17.4	--	3.3	21	649	344	0.24	0.13	0.067	--
		165	7.40	109	7.7	--	8.9	5.2	51	2.70	1.67	253	793	17.8	--	3.1	22	577	309	0.23	0.12	--	--
ALH 84206	EH3	182	5.20	120	8.6	0.79	7.4	5.7	61	3.03	1.97	276	894	17.5	17	3.5	10	630	339	0.19	0.11	0.048	170
ALH 84170	EH3	198	4.70	113	8.4	0.75	10.0	5.0	52	2.74	1.71	246	748	15.4	14	2.7	20	514	304	0.21	--	0.045	140
EET 87746	EH4	189	5.55	112	8.5	1.2	9.3	5.8	58	3.22	2.22	288	838	17.3	16	3.4	26	592	340	0.24	0.13	0.056	160
		133	6.40	99	7.3	--	8.5	5.7	48	3.01	2.53	267	818	18.8	7.1	3.3	23	568	337	0.22	0.13	0.058	--
LEW 88180	EH5	187	6.75	104	7.7	1.0	7.9	5.7	54	3.09	2.41	274	818	17.4	14	3.3	22	568	335	0.20	--	0.045	170
EH mean		*169*	*6.24*	*111*	*8.1*	*0.94*	*8.9*	*5.5*	*54*	*2.94*	*2.01*	*269*	*828*	*17.4*	*13.6*	*3.2*	*21*	*585*	*330*	*0.22*	*0.12*	*0.053*	*160*
MAC 88184	EL3	145	5.00	122	9.3	0.42	13.0	6.1	64	3.14	2.10	181	522	11.3	8.7	1.6	19	428	189	0.28	0.19	0.059	210
		113	4.80	115	8.9	--	12.0	6.9	61	3.46	2.43	225	653	13.1	--	2.1	20	515	220	0.32	0.16	--	--
MAC 88180	EL3	115	5.20	133	9.8	0.46	--	5.5	54	2.42	1.50	173	457	10.9	7.0	1.8	15	447	174	0.19	0.15	0.044	170
MAC 88136	EL3	110	6.10	141	9.6	0.68	12.0	7.1	58	2.95	1.97	215	617	12.7	10	2.2	17	539	235	0.32	0.19	0.073	200
ALH 85119	EL3	69.3	5.80	105	8.9	0.73	12.0	5.3	45	2.29	1.70	164	497	10.5	9.9	2.5	16	385	175	0.24	0.17	0.064	180
LEW 87119	EL6	133	6.95	113	11.0	0.98	7.4	6.6	62	2.79	1.20	208	648	14.2	15	2.8	13	601	274	0.24	0.11	0.051	--
EL mean		*114*	*5.64*	*122*	*9.6*	*0.65*	*11.3*	*6.3*	*57*	*2.84*	*1.82*	*194*	*566*	*12.1*	*10.1*	*2.2*	*17*	*486*	*211*	*0.27*	*0.16*	*0.058*	*190*
LEW 87223	E3 an	93.5	2.60	119	9.9	0.48	9.5	6.0	58	2.42	0.84	301	984	20.4	6.5	2.3	7.3	837	248	0.24	0.15	0.073	180
		154	2.60	113	9.3	--	9.7	6.3	57	2.77	0.82	314	1054	21.5	--	2.7	10	914	279	0.24	0.14	0.078	--
Allende		172	3.30	128	12	--	16	11	75	3.96	1.40	247	719	14.0	--	--	14.0	675	189	0.48	0.25	0.14	--
		194	3.51	134	13	--	17	11	76	3.78	1.50	255	684	14.0	--	--	15.0	732	204	0.46	0.25	0.13	--
		127	3.40	133	13	0.29	15	11	79	3.96	1.30	255	739	14.2	6.0	--	11.6	827	213	0.53	0.34	0.13	--
Allende mean			*3.40*	*132*	*13*	*0.29*	*16*	*11*	*77*	*3.90*	*1.40*	*252*	*714*	*14.1*	*6.0*	--	*13.5*	*745*	*205*	*0.49*	*0.28*	*0.13*	--
Allende Lit†.			*3.41*	*148*	*17.3*	*0.27*	*19.1*	*11*	*115*	*3.68*	*1.47*	*233*	*629*	*14*	*6.3-*	--	*8.0*	*791*	*163*	*0.475*	*0.28*	*0.116*	--
BCR-1		182	20.9	--	70	16.8	--	32	419	0.018	--	99	43	--	--	--	--	--	--	29	4.7	2.2	--
		135	20.6	--	74	13.9	--	29	439	0.018	1.3	95	38	--	--	--	--	--	--	24	5.0	2.2	--
BCR-1 mean			*20.8*		*72*	*15.3*	--	*31*	*429*	*0.018*	*1.3*	*97*	*41*	--	--	--	--	--	--	*27*	*4.9*	*2.2*	--
BCR-1 Lit†.			*24.3*	--	*72.0*	*14.1*	--	*33.0*	*399*	*0.018*	*1.4*	*94*	*38*	--	--	--	--	--	--	*26*	*6.6*	*1.94*	--

*Classifications as in Table 2. The 1-σ uncertainties for duplicate analysis ($\sigma/\sqrt{2}$) are 5% for Na, Mg, Al, K, Sc, V, Cr, Mn, Fe, Co, Ni, Se, Sm, and Eu; <8% for Ca and La; and 11% for Ir.
†See Weeks and Sears [1985]. "Lit" means literature.

compositions which are usually in the EL3 range. This meteorite contains numerous sharply defined chondrules and small amounts of olivine (<1%). If, as *Mason* [1987] suggests, the meteorite should be regarded as type 4, then ALH 85119 would be the first known EL4 chondrite. However, below we argue that it should be considered an EL3 chondrite.

Lewis Cliff 87119. The bulk composition of LEW 87119 is in the EL range (Figures 4, 6, 7). Mineral compositions are also generally near the EL trajectories (Figure 5), but (with the exception of FeS) the EL and EH trends converge at the high metamorphism ends, so mineral compositions are not particularly definitive. For FeS, LEW 87119 plots between the EH and EL trajectories where data tend to scatter. Chondrules are extremely rare and intergrown with the matrix, moreso than for the type 6 enstatite chondrites. The lineation displayed by LEW 87119 might also indicate particularly intense metamorphism. *Mason* [1992a] paired LEW 88135 and LEW 88714 with LEW 87119. However, it seems to us that chondrules are more numerous and better delineated in these two meteorites than in LEW 87119, and they do not display any indication of lineation in their fabric. We therefore doubt that LEW 88135 and 88714 are paired with LEW 87119.

Lewis Cliff 88180. The bulk composition of LEW 88180 corresponds to EH classification, and mineral chemistry is also in the EH range, although at the metamorphosed end of the range. *Mason* [1990b] described the meteorite as a type 6 chondrite, which would make LEW 88180 the first known EH6 chondrite. However, the present criteria (discussed below) suggest that it is better considered the third known EH5 chondrite.

Reckling Peak A80259. The classification of RKP A80259 has proved contentious [*Sears et al.,* 1984; *Weeks and Sears,* 1985; *Kallemeyn and Wasson,* 1986]. The INAA data of *Weeks and Sears* [1985] suggest an EL classification, while that of *Kallemeyn and Wasson* [1986] were somewhat tentatively interpreted as indicating a highly weathered EH chondrite. Metal abundance and composition are also consistent with EL classification. Low metal content, relative to EH chondrites, does not appear to be the result of weathering, since unlike the earlier thin section of *Sears et al.* [1984], our present section did not contain unusual amounts of weathering products. Neither is there any evidence in the

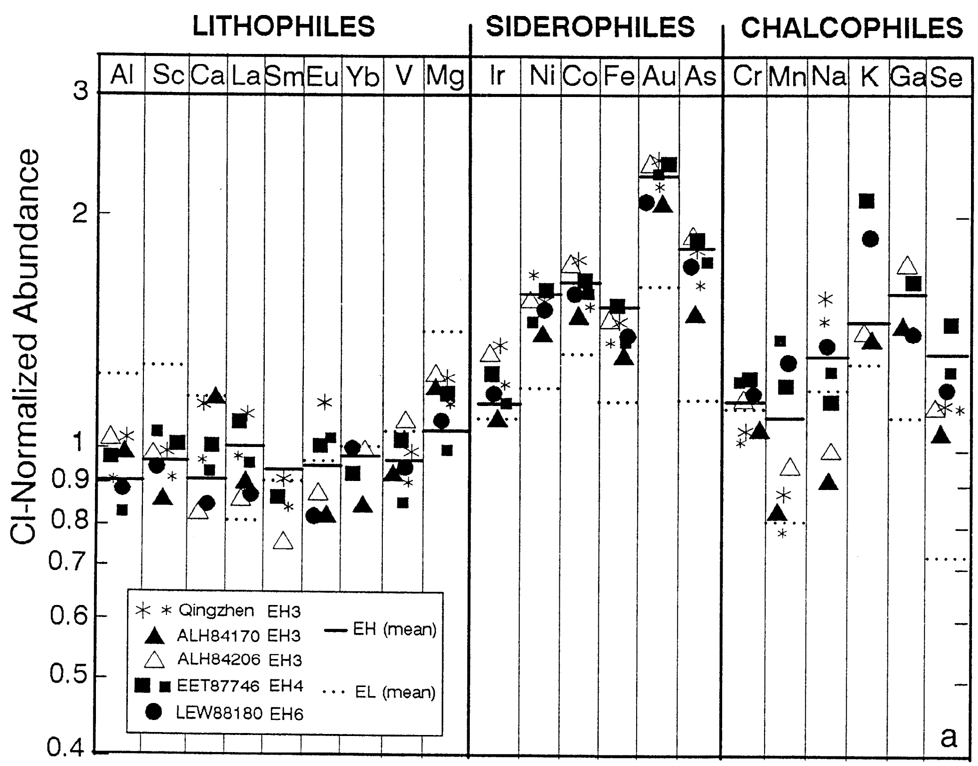

Figure 4. The CI-normalized abundances of EH and EL chondrites as determined in the present study by neutron activation analysis. Group mean values for EH chondrites (i.e., EH3,4 and 5) and EL chondrites (entirely EL6) are from *Kallemeyn and Wasson* [1986], and H mean from *Wasson and Kallemeyn* [1988]. Two symbols for one meteorite indicate that duplicate chips were analyzed and these are shown to illustrate the similarity of the two chips (Table 3). (a) Elemental abundances for the present EH chondrites cluster fairly well around the EH group mean published by *Kallemeyn and Wasson* [1986]. (b) Elemental abundances for the present EL chondrites scatter, presumably because of the sample heterogeneity of these unequilibrated meteorites, but are clearly consistent with their classification as EL chondrites. We do not confirm the somewhat surprising fractionations of rare earth elements observed in the EL group mean of *Kallemeyn and Wasson* [1986]; the rare earth elements show flat abundance patterns relative to Sc, Ca, V, and Mg. (c) Elemental abundances for the unusual E3 chondrite LEW 87223. This meteorite is enriched in metal (and depleted in silicates by an amount dictated by mass-balance) and highly depleted in chalcophile elements. The data suggest that this is an EL chondrite with 15% more metal than most EL chondrites, and sulfides (troilite excepted) are almost completely absent. It is unlikely that this reflects sample heterogeneity because such extreme effects are not observed in any of the other type 3 enstatite chondrites and there is excellent agreement between duplicate chips.

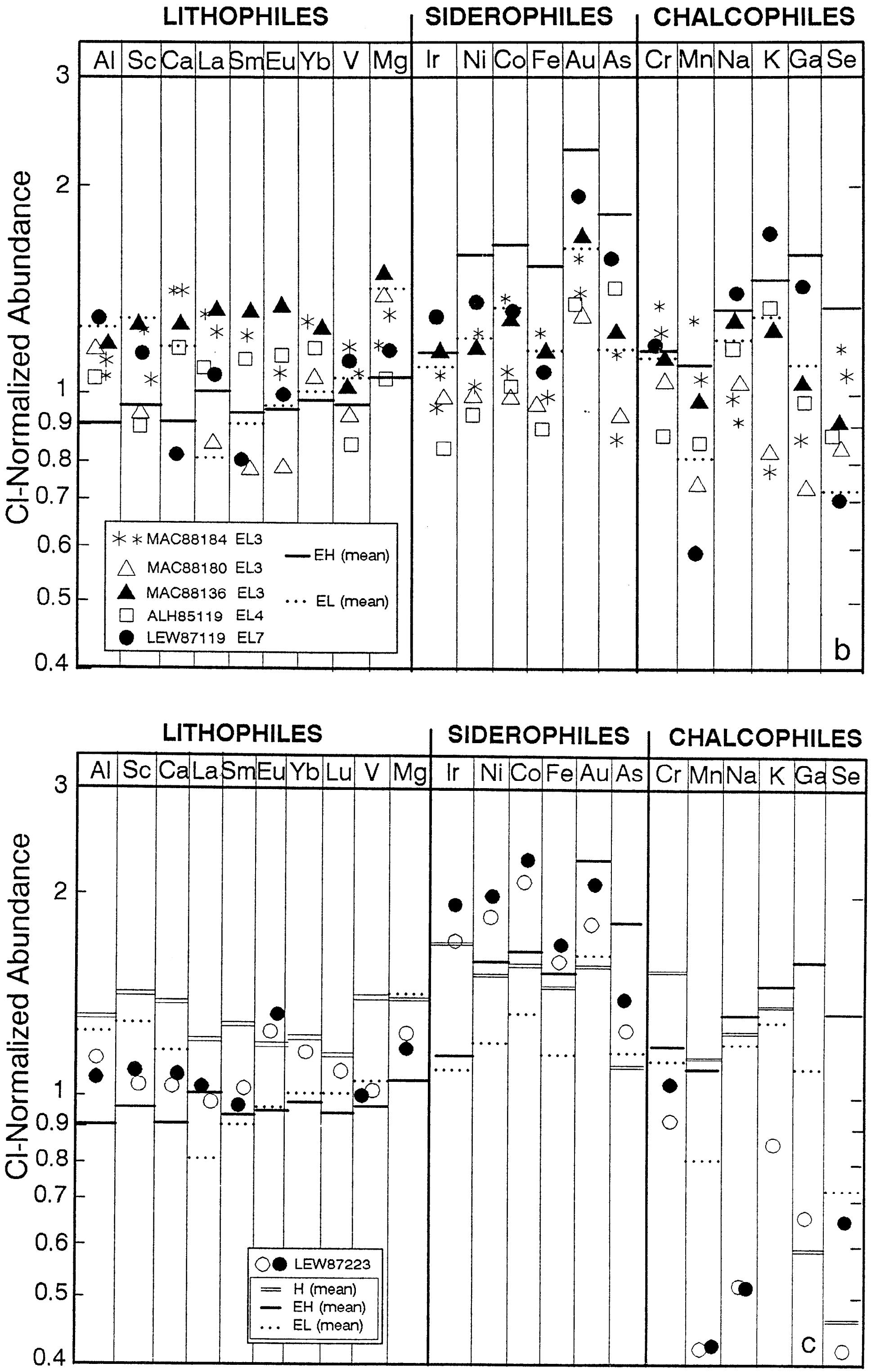

Figure 4. (continued)

INAA data (ours or Kallemeyn and Wasson's) for large amounts of weathering. Chondrule size distributions are also suggestive of EL classification (J. N. Grossman, personal communication 1994). However, the Fe/Mg ratio is intermediate to EH and EL values, which might reflect metal-silicate heterogeneity, but the Ni/Ir and Al/V ratios for the bulk sample are in the EH range, and the composition of the cubic sulfides and troilite are consistent with EH classification. We were inclined to suggest an intermediate EH/EL classification for RKP A80259 until we recently obtained cathodoluminescence (CL) data, which provide very strong evidence for the EL classification [*Zhang et al.,* 1994a]. We are therefore confident in the initial assessment that RKP A80259 is an EL5 chondrite [*Weeks and Sears,* 1985].

Thiel Mountains 91714. *Mason* [1993] described TIL 91714 as an E5 chondrite, and the Si in the metal (0.6-0.8 wt

Table 4. Composition of Selected Phases in the Present Enstatite Chondrites (wt %)

	ALH 84170 EH3	ALH 84206 EH3	EET 87746 EH4	PCA 82518 EH4	LEW 88180 EH5	MAC 88136 EL3	MAC 88180 EL3	MAC 88184 EL3	ALH 85119 EL3	EET 90299 EL3	PCA 91020 EL3	TIL 91714 EL5	RKP A80259 EL5	LEW 87119 EL6	LEW 88714 EL6	LEW 88135 EL6	LEW 87223 E3 an
									Kamacite								
Fe	92.8	95.7	93.3	93.9	88.4	93.4	92.3	92.4	93.6	92.9	91.9	92.6	91.1	89.2	90.2	89.6	92.9
Ni	2.9	2.3	5.8	4.3	9.0	5.0	5.2	5.7	5.6	6.6	7.5	6.0	7.0	8.8	7.1	7.3	6.2
Si	2.2	1.9	2.0	2.9	2.6	0.5	0.3	0.5	0.5	0.4	0.5	0.9	1.8	1.5	1.5	1.1	0.5
									Schreibersite								
Fe	68.5	68.7	70.4	67.2	77.0	38.7	49.0	41.6	42.6	53.8	58.1	53.6	--	--	74.2	71.3	74.3
Ni	17.8	16.2	18.0	18.1	7.4	44.4	34.8	40.6	41.5	32.1	28.3	33.2	--	--	12.9	15.6	10.4
P	14.2	15.4	10.7	14.8	16.1	17.0	16.8	15.4	16.1	14.2	14.3	13.1	--	--	12.7	13.1	15.6
									Mg-Mn-Fe Sulfide								
Fe	11.9	11.8	20.6	--	39.5	8.8	10.6	9.4	8.7	--	--	15.9	33.7	32.9	33.3	--	27.8
Mg	27.1	26.1	26.3	--	10.6	1.7	1.5	0.8	3.0	--	--	2.7	9.4	8.2	9.1	--	2.0
Mn	11.7	14.6	5.6	--	5.3	50.4	50.6	51.0	48.9	--	--	43.4	12.8	15.5	14.5	--	28.8
S	48.9	47.5	47.9	--	44.1	38.7	37.2	36.8	39.6	--	--	38.3	43.7	42.9	43.1	--	39.0
									Troilite								
Ti	--	0.23	0.17	0.4	0.4	0.4	0.4	0.4	0.36	--	--	0.59	0.35	0.6	0.67	0.25	1.2
Cr	--	0.59	1.19	0.3	2.59	0.5	0.5	0.4	0.28	--	--	1.21	2.63	2.9	3.86	2.93	7.8
Fe	--	62.6	58.2	58.2	61.2	59.6	61.2	62.2	60.4	--	--	61.8	59.2	57.0	57.6	61.0	51.5
S	--	38.5	38.8	38.6	33.9	39.2	38.3	37.1	38.1	--	--	36.4	37.7	37.5	38.6	36.1	40.0

Classifications from Table 2.

%) indicates that this is an EL chondrite. The compositions of the kamacite, phosphide, cubic sulfide, and troilite (Figure 5), and the CL properties of this meteorite [*Zhang et al.,* 1994a], confirm its EL classification. This meteorite is therefore the second known EL5 chondrite [*Zhang et al.,* 1994a].

Metamorphic Trends in Enstatite Chondrites: Textures

Van Schmus and Wood's [1967] petrologic types are poorly applicable to enstatite chondrites for two reasons. (1) Many of the parameters they proposed are not relevant to the enstatite chondrites (olivine heterogeneity, feldspar abundance, matrix properties, Ni content of the FeS, carbon and water abundance), nor do they show metamorphically related depletions in the highly volatile elements. (2) Unlike the ordinary chondrites, the mineral compositional properties suggest different thermal histories from those suggested by textures. (These difficulties might partially explain the large variety of petrologic type assignments some enstatites chondrite have received [see *Keil,* 1989]). The EL chondrites, especially have sometimes completely lost their chondritic texture, suggesting high levels of metamorphism, while their mineral phases imply low equilibration temperatures. More will be learned by treating texture and mineral composition as independent variables and defining separate "textural" and "mineralogical" types.

By "texture", we mean physical properties which reflect peak metamorphic temperatures rather than those which reflect closure temperatures for particular systems. Such properties include extent of chondrule integration, mesostasis devitrification, and presence of unstable phases like olivine, etc. Our proposals for textural types 3-6 are summarized in Table 5, are essentially those described by *Van Schmus and Wood* [1967], although we stress that only textural properties are involved. Chondrules and other components are very well delineated in textural types 3 and 4, readily recognized in type 5 although outlines are not sharp because of extensive intergrowth with the matrix has occurred, and very difficult to distinguish in textural type 6. Enstatite chondrites essentially devoid of chondrules are defined as type 7.

Textural types 3 and 4 are very similar in their appearance under the microscope, but may be distinguished, since type 3 contains a few percent olivine while it is absent in type 4. Unlike ordinary chondrites, no quantitative methods are available to distinguish type 3 and 4 chondrites. The nearest equivalent to the >5% standard deviation rule is the observation of *Lusby et al.* [1987] that, for the four type 3 EH chondrites they examined, $\geq$4% by number of the pyroxene grains contained >3 wt % FeO, while two chondrites of higher petrologic type contained enstatite with dusty cores where reduction during metamorphism had caused the formation of submicrometer Fe grains.

Metamorphic Trends in Enstatite Chondrites: Mineral Compositions

On the basis of Figure 5, we have defined four "mineralogical" types, α-δ, so that chondrites may be succinctly described in terms of the equilibration temperatures. The fields are summarized in Table 5. The major mineralogical changes occurring during metamorphism may be summarized as follows.

1. The Si content of EH chondrite metal increases from 20 to 40 mg/g, and the Ni content increases from ~20 to 100 mg/g. The Si content of EL chondrite metal increases from ~3 to ~20 mg/g, while the Ni content increases from ~40 to ~100 mg/g (Figure 5a).

2. The Ni content of the schreibersite in EH chondrites

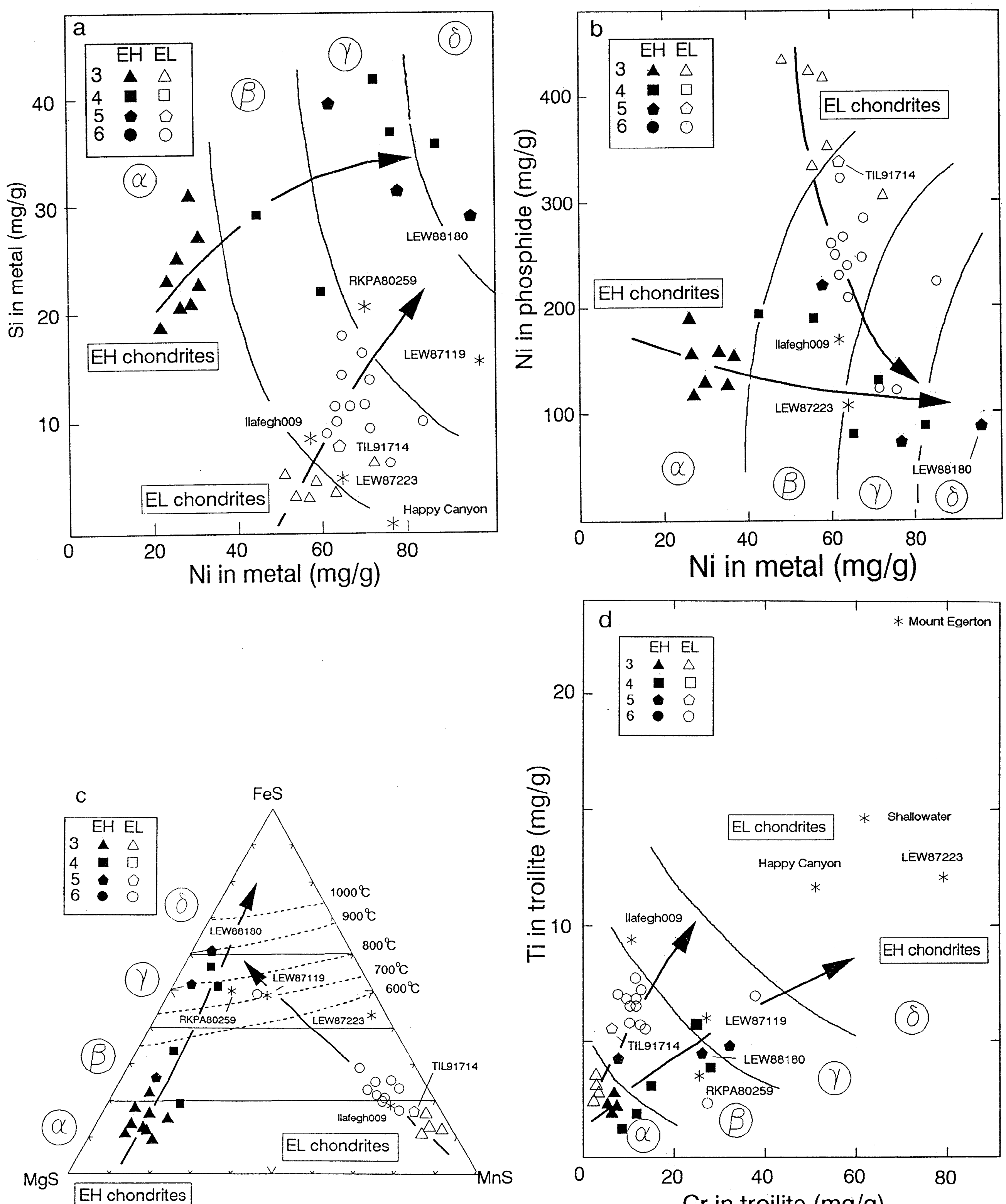

Figure 5. Compositions of metal, troilite, shreibersite, niningerite, and alabandite in enstatite chondrites. (a) Si in kamacite versus Ni in kamacite. (b) Ni in phosphide versus Ni in kamacite. (c) Ternary diagram for the Fe, Mn, and Mg sulfides (mole %). The isotherms are from *Skinner and Luce* [1971]. (d) Ti in troilite versus Cr in troilite. The arrows indicate the paths followed by each chondrite class during metamorphic equilibration. The compositional ranges have been divided into four "mineralogic types" (α-δ) for the purposes of descriptive classification. The ranges are essentially arbitrary but were chosen so as to yield approximately equal divisions and preserve *Van Schmus and Wood*'s [1967] petrologic type assignments. The petrologic types, which are well suited to ordinary chondrites, assume that texture and mineral composition can both be used to infer a unique metamorphic history, but this is not the case for the enstatite chondrites, and the two parameters must be used separately. Data from the sources listed in Table 7.

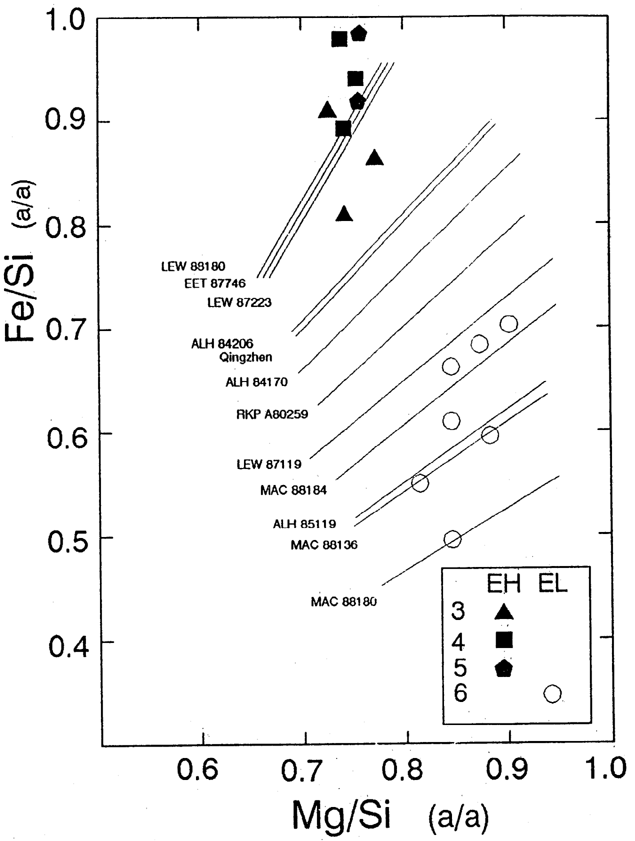

Figure 6. Plot of Fe/Si versus Mg/Si (atom ratios) for enstatite chondrites. Literature data [*Weeks and Sears,* 1985] are indicated as points, while the present data, for which Si is not available, are plotted as lines of given Fe/Mg. Enstatite chondrites were orginally classified according to Fe/Si and Mg/Si [*Anders,* 1964; *Mason,* 1966], and the present chondrites may be sorted into EH and EL classes on this basis, although metal-silicate heterogeneity add scatter to the Fe/Si data. The EH chondrites may be distiguished from the EL chondrites, since the former have an Fe/Mg ratio greater than 0.95, while the EL chondrites have an Fe/Mg ratio less than 0.90.

decreases from ~200 mg/g to ~80 mg/g and from about 400 to ~200 mg/g for EL chondrites schreibersite (Figure 5b). The inverse correlation between the Ni in the schreibersite and the Ni content of the metal would suggest that Ni is diffusing from the phosphide to the metal with increasing metamorphic temperature, or that Fe is migrating from the metal to the phosphide.

3. Niningerite in EH chondrites (with about 10 mol % MnS) increases in FeS from about 10 to ~60 mol %, while EL chondrite alabandite (with 10 mol % MgS) increases in FeS from ~10 to ~50 mol % (Figure 5c).

4. The troilite in EH chondrites increases from ~5 to ~40 mg/g Cr and from ~3 to ~8 mg/g Ti during metamorphism. While EL chondrite troilite shows an increase in Cr from below detection to ~40 mg/g, the Ti increases from ~7 to ~10 mg/g.

As discussed in many papers, the reactions which seem to be occurring in enstatite chondrites during metamorphism are of the kind

$$FeSiO_3 + 3C \dashrightarrow Fe_{metal} + Si_{metal} + 3CO$$
$$Ni_3P_{schreib} + 3Fe_{metal} \dashrightarrow Fe_3P_{schreib} + 3Ni_{metal}$$
$$Fe_{metal} + H_2S \dashrightarrow FeS_{cubic\ sulfide} + H_2$$

so that one might expect the Si and Ni content of the metal, and the FeS content of the cubic sulfides to increase with temperature while the Ni in the phosphide decreased [*Skinner and Luce,* 1971; *Larimer and Buseck,* 1974; *Doan and Goldstein,* 1979; *Sears,* 1980; *Petaev and Khodakovsky,* 1986; *Fogel et al.,* 1989]. *Peteav and Khodakovsky* [1986] discussed the formation of daubreelite from reaction between CrS and FeS, during metamorphism but did not discuss the related question of the concentration of Cr (and Ti) in FeS. Petrological observations do not provide much evidence for particular reactions. Most or all of these phases are in physical contact, and grain boundary diffusion between intervening silicates has been shown to be possible for the Rennazzo CR chondrite and we assume would also occur for enstatite chondrites [*Wood,* 1967]. We are not aware of any compositional profiles which might provide further help in understanding these processes. The Mg/Mn of the alabandite increases along the series ELα --> ELδ --> LEW 87119, which might also suggest that Mn is migrating out of the sulfide and into another phase. However, it is not clear into which phase it is migrating, since pyroxene also loses Mn during metamorphism [e.g., *Keil,* 1968]. The very complex mass balance considerations have not been discussed at any length in the literature.

There are a great many other mineralogical processes which appear to be the result of metamorphism on the parent body. These include the breakdown of djerfisherite ($K_3CuFe_{12}S_{14}$) to produce FeS and other sulfides, the decrease in the Ca/Na ratio of the plagioclase/glass, the replacement of graphite spherulites with octahedral lamellae of graphite in kamacite [*El Goresy et al.,* 1988], and the formation of sinoite [*Petaev and Khodakovsky,* 1986; *Fogel et al.,* 1989].

Metamorphic Trends in Enstatite Chondrites: Bulk Compositions

In the ordinary chondrite classes, carbon and the volatile elements show negative correlations with petrologic type. Except possibly for carbon, this appears not to be the case for the enstatite chondrites (Figure 8). In fact, the inert gas abundances (which decrease with petrologic type in the ordinary chondrites) show positive correlations with petrologic type in EH chondrites, with the slope decreasing with isotopic mass (Figure 8) [*Schultz and Kruse,* 1989]. This suggests greater loss from the lower petrologic types, suggesting perhaps that the loss was governed by textural considerations. Carbon may be showing a negative correlation, but the data are meager, and St. Sauveur is discordant (Figure 9) [*Moore and Lewis,* 1966]. The highly volatile trace elements, also, show no evidence for a decrease in abundance with petrologic type, reflecting simply the lower siderophile and chalcophile element abundance of the EL class relative to the EH class (Figure 10) [*Binz et al.,* 1974].

There are too few data for the EL chondrites to explore evidence for metamorphism-related differences in the bulk properties of EL chondrites. There are certainly large variations in several properties which might be metamorphism-related; silicon in the metal and bulk carbon for instance (Figures 5a and 8), but there is no correlation between these parameters, suggesting that the scatter is caused by sample heterogeneity and analytical uncertainty. There are also very large variations in TL sensitivity among the EL6 chondrites, which will be discussed elsewhere [*Zhang et al.,* 1994b].

The oxygen isotopic compositions of both EH and EL chondrites are on the terrestrial fractionation line [*Clayton et al.,* 1984], and differences in oxygen isotopic composition of EH and EL chondrites are small. Among EH chondrites,

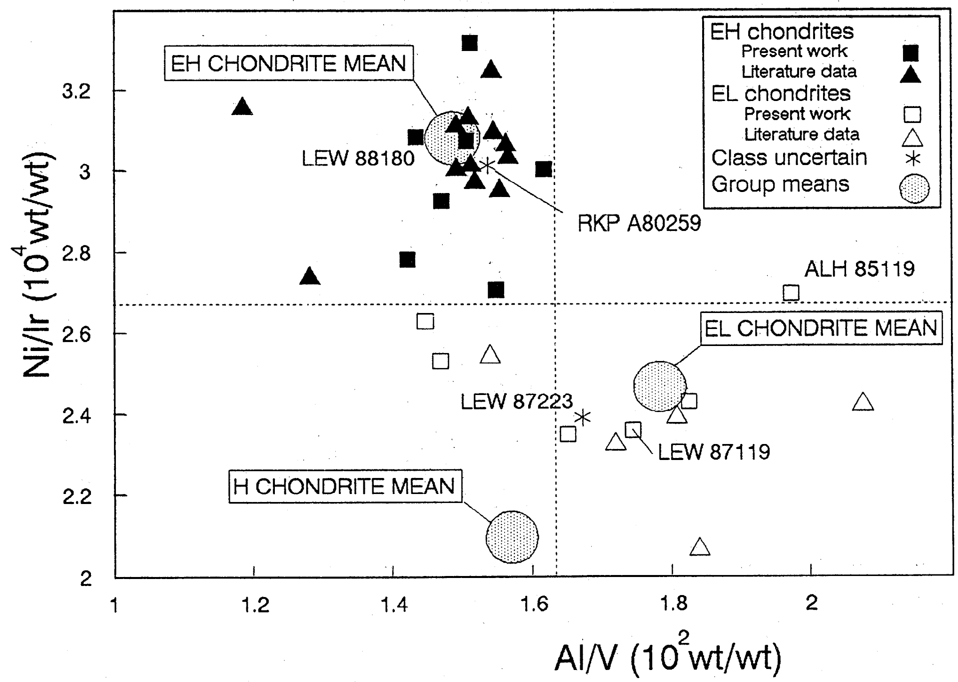

Figure 7. Plot of Ni/Ir versus Al/V (atom ratios) for enstatite chondrites. These ratios utilize the refractory element fractionation to distinguish EH from EL chondrites. By plotting a siderophile element ratio against a lithophile element ratio, the plot is insensitive to metal-silicate heterogeneity in the samples. "Class uncertain" refers to meteorites whose classification has proved controversial or which have sufficiently unusual compositions that their classification is not straightforward. See the text for details. The literature data and the EH and EL group means are from *Kallemeyn and Wasson* [1986], while H group mean is taken from *Anders and Grevesse* [1989].

EH3 have lower ^{18}O and ^{17}O than the EH4,5 chondrites, which is the opposite trend to that observed in ordinary chondrites. The EL6 chondrites have a narrow range in the ^{18}O and ^{17}O composition, and the values are close to those of EH5 chondrites.

We think that it is highly significant that none of the compositional trends in highly volatile elements observed for the ordinary chondrites [*Larimer and Anders*, 1967; *Dodd*, 1969; *Wasson*, 1972] are present in the enstatite chondrites. At the very least this is another indication of the very different thermal history of the enstatite and ordinary chondrites. The decreasing abundance of volatile elements with petrologic type for the other chondrite classes has been variously attributed to loss of volatiles during metamorphism [*Dodd*, 1969; *Wasson*, 1972] and simultaneous accretion and condensation [*Larimer and Anders*, 1967]. We suggest that since these elements do not show a decrease in abundance with petrologic type in the enstatite chondrites, that the loss of volatiles did not occur during metamorphism, a conclusion which is consistent with the laboratory heating experiments of *Biswas et al.* [1980].

Mineralogical and Textural Types

The mineralogical types we obtain for the known enstatite chondrites, using the present and literature data, are listed in Table 6, and the complete classifications (class, textural type, and mineralogical type) are listed in Table 7.

Lewis Cliff 87119 and Lewis Cliff 87223: Two Enstatite Chondrites with Evidence for High-Temperature Histories

These two enstatite chondrites both appear to have experienced a high-temperature event in their history, but the details are very different. We suggest that Lewis Cliff 87223, which is paired with five other samples (Table 6), is an anomalous EL3 chondrite that suffered considerable alteration by brecciation and heating, and that LEW 87119 is an EL6δ chondrite [*Zhang et al.*, 1993b].

Lewis Cliff 87119. Chondrules are very rare in LEW 87119 and extremely poorly delineated. Its texture shows lineation, and its mineral chemistry suggests equilibration at high temperature. The Ni content of the metal is especially high, the cubic sulfides have high FeS contents, and the FeS is high in Cr and Ti. In this latter respect, it resembles other enstatite meteorites such as Happy Canyon (achondritic texture and EL composition), the Mount Egerton stony-iron, the unusual metal-rich Shallowater aubrite, and the Ilafegh 009 impact melt [*Olsen et al.*, 1977; *Keil et al.*, 1989; *Keil*, 1989; *McCall*, 1965; *Watters and Prinz*, 1980; *McCoy et al.*, 1992; *Bischoff et al.*, 1992] all of which have igneous histories or some evidence for partial melting. The Shaw and Yamato-74160 ordinary chondrites have both been described as textural type 7 chondrites because they have experienced temperatures higher than those of textural type 6 chondrites [*Rambaldi and Larimer*, 1977; *Takeda et al.*, 1984]. However, they also show petrographic evidence of partial or complete melting, and *Taylor et al.* [1979] argued that Shaw is an impact melt. There are several enstatite chondrites with achondritic textures that are thought to be impact melts [*McCoy et al.*, 1992].

However, we doubt that LEW 87119 is an impact melt. Unlike Ilafegh 009, Shaw and LEW 74160, LEW 87119 shows no petrographic evidence for partial melting and, while rare and poorly defined, it does still contain chondrules. With the exception of its cubic sulfide compositions, which resemble those of EH5 and EH6 chondrites but with higher MnS content, the mineral compositions plot at the metamorphosed end of the EL range. We suggest that unlike

Table 5. Textural and Mineralogical Types in Enstatite Chondrites

	Textural Types				
	3	4	5	6	7
Dominant pyroxene structure	monoclinic	monoclinic	orthorhombic	orthorhombic	orthorhombic
Pyroxene composition (FeO%)	≥4% of grains with >3 wt% FeO	<1%	<1%	<1%	<1%
Olivine, %	<2	<1	little or none	little or none	little or none
Chondrule glass	few	few	absent	absent	absent
Chondrule feldspar	absent	absent	little or none	little or none	little or none
Chondrule delineation	clear, sharp	clear, sharp	Readily recognized	Well-intergrown	Extremely difficult to recognize
Chondrule density, no./cm^2	>40	>40	<40	<10	<5

	Mineralogical Types*			
	α	β	γ	δ
EH chondrites				
Si in metal, mg/g	20-28	28-45	>45	>45
Ni in metal, mg/g	<40	40-60	60-80	>80
Ni in phosphide, mg/g	200-140	120-140	120-100	<100
FeS in niningerite, mol %	<20	20-40	40-60	>60
Cr in troilite, mg/g	<10	10-23	23-43	>43
Ti in troilite, mg/g	<3	3-5	5-15	>15
EL chondrites				
Si in metal, mg/g	<7	7-16	>16	>16
Ni in metal, mg/g	<60	60-72	>72	>72
Ni in phosphide, mg/g	>300	200-300	100-200	<100
FeS in alabandite, mol %	<20	20-40	40-60	>60
Cr in troilite, mg/g	<5	5-15	15-25	>25
Ti in troilite, mg/g	<4	4-7	7-10	>10

*Since the compositional fields are not rectangular, these ranges are approximate. See Figure 5.

most EL chondrites that are EL6β, LEW 87119 is an EL6δ chondrite. Blithfield is also an EL chondrite with an especially high-temperature history. This meteorite is metal-poor and sulfide-rich [*Keil,* 1968], contains Fe,Ni-FeS eutectic intergrowths [*Rubin,* 1984], and shows opaque mineral structures indicating higher levels of metamorphism than those experienced by typical type 6 enstatite chondrites [*Easton,* 1983]. Its mineral compositions are very similar to those of the EL chondrites, which are mineralogical type β, so we suggest that it should be described as EL6β.

Lewis Cliff 87223. The LEW 87223 EL chondrite contains abundant well delineated chondrules and small amounts of olivine that are typical of type 3 enstatite chondrites. However, its structure, mineral proportions and bulk composition are unlike EL3 enstatite chondrites [*Zhang et al.,* 1993a; *Grossman et al.,* 1993; *Weisberg et al.,* 1994]. The chondrules appear to be mechanically and thermally altered and blackened, the olivine shows shock effects, and the metal and sulfide occur as equant chondrule-sized grains. It is a breccia, and our thin section contains a plagioclase-rich xenolith. In some respects, the sulfide compositions resemble those of Shallowater and Mount Egerton (Figure 5). The oldhamite in LEW 87220 and 87234, which are paired with LEW87223, contain rare earth element patterns characteristic of EL3 chondrites [*Grossman et al.,* 1993]. No trace of solar gases is found in this meteorite (R. Wieler,

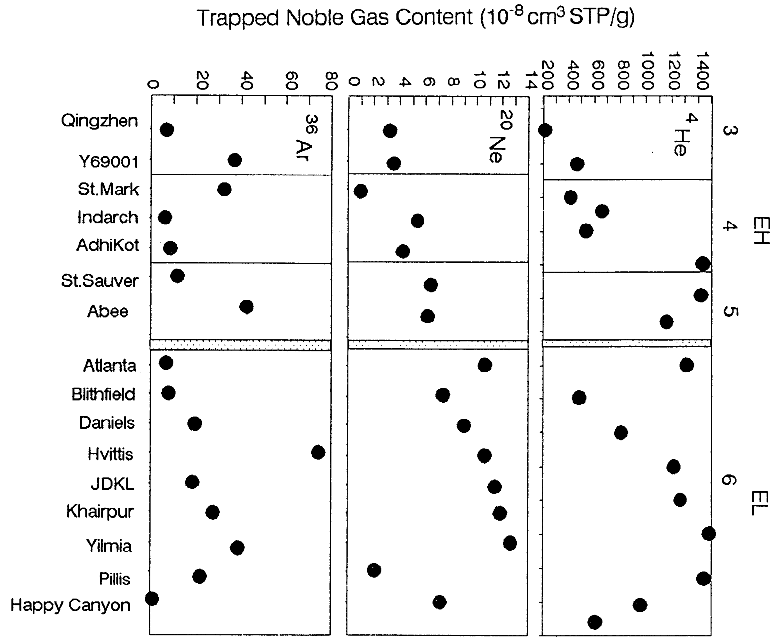

Figure 8. Trapped noble gases ^{4}He, ^{20}Ne, ^{36}Ar in enstatite chondrite falls.

personal communication, 1994); the exposure age (^{21}Ne) is ~7 Ma, which is in center of the EL range (EH ages are 0.5-7 Ma; EL are 4-18 Ma) [*Sears et al.*, 1982].

The composition of LEW 87223 can be described as an EL chondrite to which an additional ~15% of metal (with EL chondrite metal composition) has been added (Table 2), and the minor sulfides have been depleted. Since most of the chalcophile elements are fairly volatile, it is possible that the depletion of minor sulfides is due to their removal by volatilization during a shock heating and brecciation event. The bulk FeO content of the blackened chondrules is in the H chondrite range, which led *Grossman et al.* [1993] to suggest that LEW 87223 is a new primitive type of material intermediate between the H and enstatite chondrites. *Grossman et al.* [1993] suggested that the silicates in LEW 87223 had undergone reduction by shock processes, while *Weisberg et al.* [1994] argued that the reduction occured by solid-state processes in the nebula. However, there appears to have been considerable redistribution of elements, including Fe, during heating and brecciation, and it is also likely that Fe entered the chondrules during this process. We doubt that LEW 87223 is primary nebular material with intermediate H-E status. The meteorite has oxygen isotope properties characteristic of enstatite chondrites [*Grossman et al.*, 1993] and elemental compositions unlike those of H chondrites (Figure 4). For example, since the Al/V versus Ir/Ni plot is insensitive to metal-silicate mixing, the meteorite

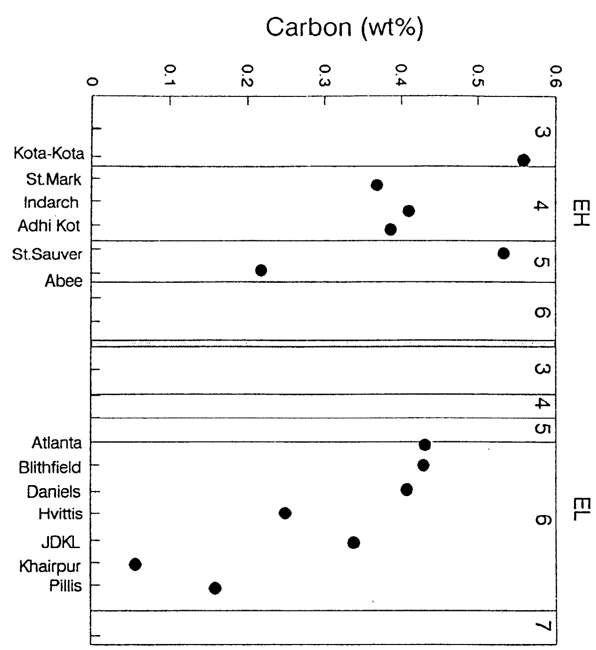

Figure 9. Carbon content in enstatite chondrite falls.

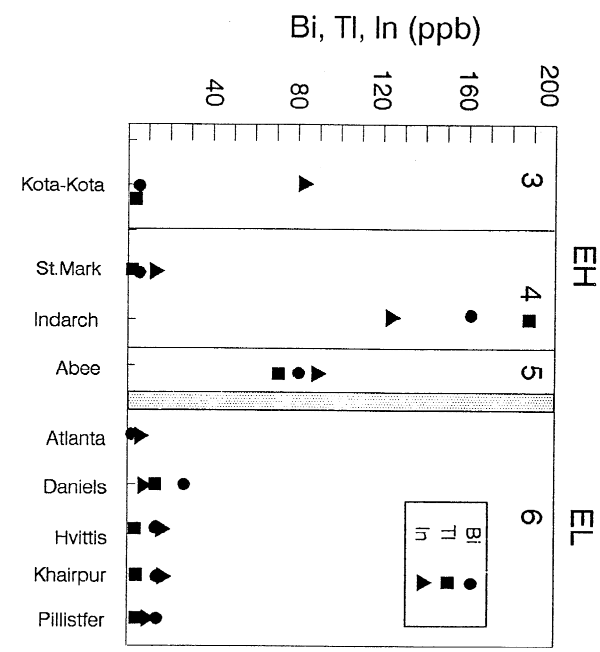

Figure 10. Abundances of In, Tl, and Bi in enstatite chondrites.

Table 6. Assignment of the Known Enstatite Chondrites (or Paired Fragments) to Mineralogical Types

Meteorite	Mineralogical Type				Suggested
	1	2	3	4	Mineralogical Type
Abee	δ	γ, δ	γ	γ	γ
Adhi-Kot	γ	γ	γ	β	γ
ALHA 77156	α		α	α	α
ALH 81189	α		α		α
ALH 84170	α	α	α		α
ALH 84206	α	α	α	α	α
ALH 85119	α	α	α	α	α
Atlanta	β	β	β	β	β
Blithfield	β, γ	β	β	β	β
Daniel's Kuil	β	β	β	β	β
Eagle	β, γ	γ		β	β, γ
EET 87746	β	α, β	α, β	α	α, β
EET 90299	α	α	α	α	α
Happy Canyon	α, β			δ	An
Hvittis	β	β	β	β	β
Ilafegh 009	β	α, β	β	β, γ	β
Indarch	γ	γ	β	β	β, γ
Jajh deh Kot Lalu	β	β	α	β	β
Khairpur	β	β	β	β	β
Kota-Kota	α	α	α, β	α, β	α
LEW 87119	γ		γ	γ	γ
LEW 87223	α, β	γ	γ		An
LEW 88135	β	γ		β	β, γ
LEW 88180	δ	δ	γ, δ	β, γ	δ
LEW 88714	β	γ	γ	γ	γ
MAC 88136	α	α	α	α	α
MAC 88180	α	α	α	α	α
MAC 88184	α	α	α	α	α
Parsa	α	α	α	α	α
PCA 82518	β	α, β		α	α, β
PCA 91020	β	β			β
Pilistfer	β	β	β	β	β
Qingzhen	α	α	α, β		α
RKP A80259	γ		γ	β	γ
St.Marks	γ	β	β	β	β
St.Sauveur	γ	γ	γ	β, γ	γ
TIL 91714	β	β	β	β	β
Ufana	β	β	β	β	β
Y 691	α	α	α		α
Y 74370		α	α		α
Yilmia	β	β	β	β	β

Assignments to mineralogical types made on the basis of 1, the Ni and Si content of the metal; 2, the Ni content of the schreibersite and metal; 3, the composition of alabandite-niningerite (cubic monosulfides); and 4, the Cr and Ti content of the troilite, using the fields indicated in Figures 5a-5d. See Table 7 for explanations of abbreviations, notes on pairing, and sources of data. "An" means anomalous.

is clearly placed in the EL class. The simplest way of explaining the bulk composition of LEW 87223 is that it is an EL3 chondrite which has gained metal and lost sulfides. This has also caused considerable mineral heterogeneity, so that we cannot assign a mineralogical type. We term it an EL3(An) chondrite. Texturally, LEW 87223 could be a regolith breccia (K. Keil, personal communication, 1993), even though it is not enriched in solar gases (R. Weiler, personal communication, 1993).

Type 3 (or Unequilibrated) Enstatite Chondrites

Although the term "type 3 chondrites" was introduced fairly recently [*Prinz et al.*, 1984], it has been known for some time that certain enstatite chondrites were "primitive," had well-delineated chondrules, and contained olivine [*Binns*, 1967]. Most have olivine contents lower than 1% by volume, but occasionally volumes as high as 3% are observed. Type 3 ordinary chondrites display a very wide range of metamorphism, and here we want to discuss the extent to which this is true of enstatite chondrites.

Texturally, the EH3 and EL3 chondrites are very similar, but in terms of their bulk and mineral compositions, they are quite different. The fact that their mineral compositions converge with increasing metamorphism (FeS excepted) suggests that most of their primary mineral compositions were determined by nebular processes. In particular, the differences are in O and S fugacity rather than bulk composition. *El Goresy et al.* [1988] argued that there were significant variations in $P(O_2)$ (and, thus, $P(S_2)$) in the formation location of the EH chondrites, and we suggest that the major cause of the mineralogical differences between the EL and EH classes is $P(O_2)$. The consequences of variations in the $P(O_2)$ and $P(S_2)$ have been discussed many times [*Larimer and Bartholomay*, 1979; *Sears*, 1980; *Lodders and Fegley*, 1993]. If the extent of reduction was caused by the intensity of heating during chondrule formation, then chondrules in EH chondrites should be petrographically distinct from chondrules in the EL chondrites, but it is not clear that this is the case. The EL3 chondrites have higher TL sensitivity and show a broader range than the EH3 chondrites, which we also attribute to differences in $P(O_2)$ during metamorphism [*Zhang et al.*, 1994b].

The EH chondrites represent a fairly straightforward series as far as mineral compositions and equilibration temperatures are concerned. Using the MnS content of the niningerite, *El Goresy et al.* [1988] suggested the following series of increasing equilibration:

Y-691, Indarch, Y-74370, Qingzhen, Kota-Kota, St. Marks, and Abee

(Y-691 and Indarch were thought to be in separate subgroups on the basis of different Mg/Mn, but we do not observe these subgroups in the present data. We suspect a typographic error in El Goresy et al.'s paper resulted in Abee being listed with Y-691, because Abee has very high FeS and is highly metamorphosed.) Metal, schreibersite, niningerite and FeS compositions in Figure 5 yield the following series: ALH 84206, 3α; Y-691, 3α; Parsa, 3α; Qingzhen, 3α; Kota-Kota, 3α; Indarch, 4α,β; St. Marks, 4β; Adhi Kot, 4γ; St. Sauveur, 5γ; Abee, 4γ; LEW 88180, 6δ, where the petrologic and mineralogical types are indicated after each meteorite. This ranking agrees reasonably well with the ranking of *El Goresy et al.* [1988]. Apparently, there is some fine structure within the type 3 chondrites. Assuming we have a complete spectrum of type 3 chondrites, dividing them into 10 subdivisions in the manner of type 3 ordinary chondrites [*Sears et al.*, 1991a] would probably result in ALH 84206, Y-691 and Parsa being considered mineralogical types 3.0-3.3, Qingzhen mineralogical type ~3.5 and Kota-Kota mineralogical type ~3.8. There are too few known EL3 chondrites to display for fine-structure.

Origin and Thermal History of Enstatite Chondrites: Four Thermal Regimes

Less is known about the thermal history of the enstatite chondrites than other classes because the metal, with its low Ni content, does not display the Ni diffusion profiles which are usually extremely informative. Every chondrite class has a unique thermal history. For example, most H chondrites are type 5, while most L and LL chondrites are type 6 [*Van Schmus and Wood,* 1967]. The CO3 chondrites have experienced comparable changes in response to metamorphism but at lower temperatures than the type 3 ordinary chondrites [*Sears et al.,* 1991b]. Within the type 3 ordinary chondrites, the dominant type increases along the series LL-L-H [*Sears et al.,* 1991a]. However, these are fairly subtle differences in thermal history displayed by the EL chondrites when compared to the other chondrites. We hope our definition of mineralogical types will help clarify the reasons for these differences.

There are essentially three methods, broadly defined, for estimating the palaeotemperatures of enstatite chondrites. They are (1) enstatite-metal-CaS compositions, (2) texture, and (3) metal-sulfide textures and compositions. These three methods yield very different results, and this implies three discrete "regimes" in which the present properties of the meteorites were fixed. To these must be added recent events, such as those which reset certain chronometers, and must have also involved a thermal pulse [*Torigoye and Shima,* 1993] and the events which started cosmic ray exposure. We will refer to these as the four "thermal regimes." In trying to account for these regimes, we are able to sketch, in very

Table 7. Class and Petrographic/Mineralogic Types for Enstatite Chondrites

Meteorite*	Complete Classification†	References‡ Class	Texture Type	Mineralogical Type
Abee	EH4γ	1	2	3
Adhi-Kot	EH4γ	1	2	3
ALH 77156[a]	EH3α	1	4	5
ALH 81189[b]	EH3α	6	6	6
ALH 84170	EH3α	7	8	7
ALH 84206	EH3α	7	8	7
ALH 85119	EL3α	7	9	7
Atlanta	EL6β	1	2	3
Blithfield	EL6β	1	2,35	3
Daniel's Kuil	EL6β	1	2	3
Eagle	EL6β,γ	10	11	11
EET 87746	EH4α,β	7	12	7
EET 90299	EL3α	7	13	7
Happy Canyon	EL an	14	10	14
Hvittis	EL6β	1	2	3
Ilafegh 009	EL β	15,16	15,16	15,16
Indarch	EH4β,γ	1	2	3
Jajh deh Kot Lalu	EL6β	1	2	3
Khairpur	EL6β	1	2	3
Kota-Kota	EH3α	1	2	3
LEW 87119	EL6γ	7	17	7
LEW 87223[c]	E3 An	7	17	7
LEW 88135	EL6β,γ	7	18	7
LEW 88180	EH5δ	7	19	7
LEW 88714	EL6γ	7	20	7
MAC 88136[d]	EL3α	7,21	22	7,21
Parsa	EH3α	1	23,4	23,4
PCA 82518[e]	EH4α,β	7	24	7
PCA 91020	EL3β	7	25	7
Pilistfer	EL6β	1	2	3
Qingzhen	EH3α	26	27	27,28
RKP A80259	EL5γ	29,30	31	7
St.Marks	EH5β	1	2	3
St.Sauveur	EH5γ	1	2	3
TIL 91714	EL5β	7	25	7
Ufana	EL6β	1	3	3
Y 691	EH3α	1	32	32
Y 74370	EH3α	33	33	33
Yilmia	EL6β	1	34	34

*Abbreviations for meteorite names: ALH, Allan Hills; EET, Elephant Moraine; LEW, Lewis Cliff; MAC, MacAlpine Range; PCA, Pecora Escarpment; RKP, Reckling Peak; TIL, Thiel Mountains; Y, Yamato. Notes: a, paired with ALHA 77295 [*McKinley et al.*, 1984]; b, the following EH chondrites from Allan Hills are possibly paired with ALH 81189: ALH 82132, 84200, 84206, 84188, 84220, 84235, 84250, 84254, 85159 [*Mason,* 1984; 1986; 1987; 1988;]. Note that some authors consider that ALH 82132 does not belong to this pairing group [*Grossman,* 1994]; c, the following E3 chondrites from Lewis Cliff are possibly paired with LEW 87223: LEW 87057, 87220, 87234, 87237, 87285 [*Mason,* 1992b]; d, the following EL3 chondrites from MacAlpine Hills are possibly paired with MAC 88136: MAC 88180 and 88184 [*Mason,* 1990a]; e, the following EH3 chondrites from Pecora Escarpment are possibly paired with PCA 82518: PCA 91085, 91114, 91119, 91125, 91127, 91129, 91238, 91254, 91258, 91298, 91300, 91303, 91383, 91398, 91444, 91451, 91461, 91475, 91477, 91481 [*Mason,* 1993].

†"Complete classification" refers collectively to class (EH, EL), textural type (3-7), and mineralogical type (α-δ); In cases where we have assigned a class in the absence of a mineralogical type, classification is based on the Si in the metal, EH chondrites containing >20 mg/g. The Si data were taken from the reference used for the petrologic type.

‡References: 1, *Sears et al.* [1982]; 2, *Van Schmus and Wood* [1967]; 3, *Keil* [1968]; 4, *Prinz et al.* [1984]; 5, *McKinley et al.* [1984]; 6, *Prinz et al.* (1985); 7, present work; 8, *Mason* [1986]; 9, *Mason* [1987]; 10, *Keil* [1989]; 11, *Olsen et al.* [1988]; 12, *Mason* [1989b]; 13, *Mason* [1992b];14, *Olsen et al.* [1977]; 15, *McCoy et al.*[1992]; 16, *Bischoff et al.* [1992]; 17, *Mason* [1989a]; 18, *Mason* [1991]; 19, *Mason* [1990b]; 20, *Mason* [1992a]; 21, *Lin et al.* [1991]; 22, *Mason* [1990a]; 23, *Nehru et al.* [1984]; 24, *Mason* [1984]; 25, *Mason* [1993]; 26, *Sheng et al.* [1982]; 27, Wang and Xie [1981]; 28, *Rambaldi et al.* [1983]; 29, *Sears et al.* [1984]; 30, *Kallemeyn and Wasson* [1986]; 31, *Mason* [1982]; 32, *El Goresy et al.* [1988]; 33, *Nagahara and El Goresy* [1984]; 34, *Buseck and Holdsworth* [1972]; 35, *Rubin* [1984].

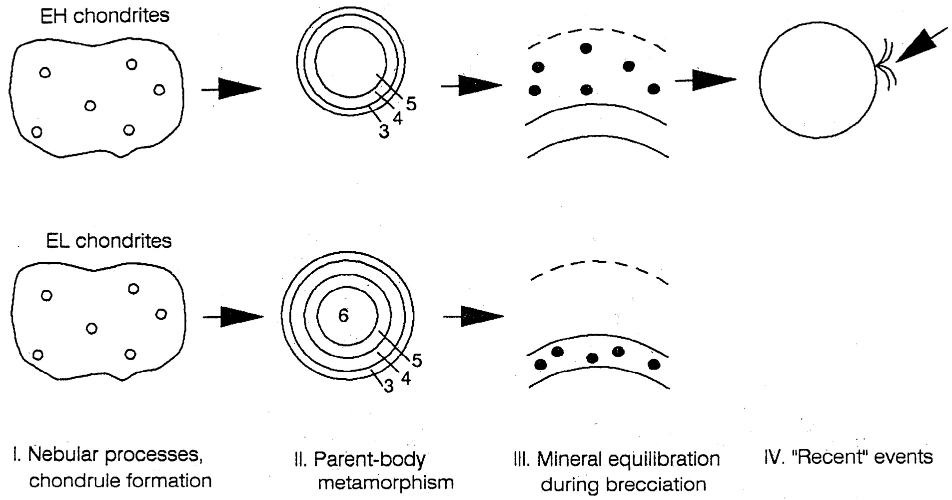

Figure 11. Schematic diagram illustrating the different histories of the EH and EL chondrites as suggested in this paper. The thermal histories are divided into four "regimes." The first refers to high-temperature equilibration recorded by the CaS-$FeSiO_3$-metal system which is independent of textural type. This might be "nebula" (i.e., pre-accretionary) processes such as chondrule formation. The second refers to textural type and is parent body metamorphism, probably in parent bodies heated by internal radioactivities. The third refers to the low-temperature equilibria and rapid cooling rates indicated by the sulfide and phosphide systems. We suggest that this is brecciation. The fourth refers to relatively recent events which caused a resetting of the Rb-Sr system. The conditions for regime II and III differed for the EH and EL chondrites, and to date, only two EH chondrites show evidence for regime IV.

broad terms, histories for the EH and EL chondrites (Figure 11).

Regime I. Regime I is reflected in the high-temperature equilibration of enstatite-metal-CaS composition. Temperatures of 800-1000°C are calculated for this equilibrium using the best methods currently available [*Fogel et al.,* 1989; *Zhang et al.,* 1992], and these are independent of textural type. In fact, there might be a slight decrease in temperature with increasing petrologic type in EH chondrites. Since EH and EL type 3 chondrites share these high equilibration temperatures for this system, the equilibrium must predate parent body metamorphism. It was either a nebular process, in which solids equilibrated with nebular gases, or it was the chondrule formation process in which solids and liquids interacted with nebular gases or gases produced by the evaporation of chondrules. Several authors have attributed the high Si contents of the metal [*Larimer and Bartholomay,* 1979; *Sears,* 1980] and the high rare earth element content of the CaS [*Lodders and Fegley,* 1993] to nebular processes, but presumably chondrule formation would be similar thermodynamically.

Regime II. Regime II refers to the episode where the textures were established. This episode was probably parent body metamorphism. The current view is that either the chondrites come from layers in an internally heated body with onion-skin structure [*Larimer and Anders,* 1970], or that a number of smaller objects were heated by different amounts of ^{26}Al and then assembled as a rubble pile [*Scott and Rajan,* 1981]. If the different ^{129}Xe levels of the EH and EL chondrites indicate that the EL chondrites formed 4.0 m.y. after the EH chondrites [*Kennedy et al.,* 1988], then EH chondrites should be the more metamorphosed group, but this is not so. We suspect that metamorphism occurred inside concentrically zoned parent bodies and that the EL body was larger (in order to produce the preponderance of type 6 EL chondrites), but the matter is very speculative.

Regime III. *Urey* [1959] was probably the first to observe that the unusual metal structures in Abee resembled those of quenched steel, an observation extended by *Herndon and Rudee* [1978]. They pointed out that the structure (caused by the exsolution of cohenite) could be reproduced by cooling from 700°C to room temperature in a few hours. This is a stringent constraint because faster cooling produces martensite or bainite, while slower cooling produces graphite. *Skinner and Luce* [1971] also pointed out that the relatively high equilibration temperatures of the cubic sulfides they examined in EH chondrites (600-900°C, mineralogical type γ) implied rapid cooling and, as a result of a series of quench experiments, suggested cooling rates of 6°C/h. *Skinner and Luce* [1971] suggested that the EH chondrite parent body suffered a catastrophic break up that resulted in rapid cooling, but we doubt that this is true because there is no petrographic or isotopic evidence for such a violent break up. The EL6 chondrites studied by *Skinner and Luce* [1971] equilibrated at $<<600$°C but cooled more slowly than 6°C/hr. From the composition-dimension plots for schreibersite, *Rubin* [1984] determined a cooling rate of 10^3-10^4°C/Ma for the EL6 chondrite Blithfield, which is 10^2-10^3 times faster than metamorphic cooling rates but $\sim 10^8$ times slower than chondrule cooling rates.

We suggest that while the textural types for the enstatite chondrites were fixed on the parent body during metamorphism, mineral compositions reflect conditions during brecciation. The most noteworthy feature of the thermal history of the EL chondrites is that, while equilibration temperatures can be very low, the petrographic evidence shows high levels of metamorphism. Thus, the mineralogical and petrologic types for EL chondrites often differ considerably. This is usually interpreted as the textures recording peak metamorphic temperatures while the mineral compositions reflect closure temperatures. Many of the enstatite chondrites are breccias (e.g., Abee, Adhi Kot, Parsa, Eagle, Hvittis, Atlanta and Blithfield) [*Rubin*, 1984; *Olsen et al.*, 1988; *Keil*, 1989], and magnetic properties indicate that the brecciation experienced by Abee postdated metamorphism [*Suguira and Strangway*, 1983]. Allan Hills 77156 is a regolith breccia [*Wieler et al.*, 1985].

Cooling rates on the order of 6°C/h experienced by EH chondrites are at the lower end of the range observed for chondrules (10 - ~2000°C/h), which cooled radiatively in free space [*Hewins*, 1988]. In contrast, the 10^3-10^4°C/Ma cooling rates for EL chondrites are consistent with burial 3-10 km in a solid parent body or <0.5 km in a regolith [*Rubin*, 1984], while normal ordinary chondrite metamorphic cooling rates of 1-100°C/Ma are consistent with burial depths of a few hundred kilometers [*Wood*, 1979]. *Keil* [1989] presents arguments based on present-day sizes of E-chondrite-like asteroids to argue for small E chondrite parent bodies. Several authors have also noted the ubiquity of enstatite chondrite impact melts [*McCoy et al.*, 1992; *Bischoff et al.*, 1992].

Regime IV. Regime IV refers to any thermal events which have occurred since the formation and final cooling of the parent object. The recent disturbances experienced by Qingzhen and Y-691 [*Torigoye and Shima*, 1993] are examples of such processes, as is the decomposition of djerfisherite described by *El Goresy et al.* [1988].

These regimes are summarized in Figure 11. Chondrule formation and primary aggregation occurred in a similar fashion for the two enstatite chondrite groups, and metamorphism on a parent body was probably fairly similar for the two classes, although a greater proportion of the ELs seem to have experienced higher levels of metamorphism. The rapid cooling rates for sulfides and metal-phosphides of both classes, especially the EH class, suggest subsequent heating in a regolithlike environment, with the EL chondrites being blanketed and suffering a protracted low-temperature annealing history. Regime IV was important for both classes, and the enstatite chondrites appear to have suffered a variety of surficial recent events, like resetting of the K-Ar system, impact melting, brecciation.

Conclusion

1. We report bulk composition for 11 enstatite chondrites and mineral compositions for 17 enstatite chondrites and discuss the classification of these meteorites.

2. Lewis Cliff 87223 has unusual bulk and mineral composition consistent with the gain of metal and loss of minor sulfide minerals from an EL3 chondrite. Its mineral composition and petrography are consistent with the meteorite having experienced a high-temperature event associated with brecciation and mixing. We do not agree with the conclusion of *Grossman et al.* [1993] that it is a new class of chondrite intermediate in properties between E and H chondrites, nor do we like *Weisberg et al.*'s [1994] conclusion that the metal was produced by in situ solid-state reduction of silicates in the nebula.

3. Lewis Cliff 87119 is an EL chondrite, which has experienced metamorphic temperatures in excess of normal type 6 EL chondrites, like Blithfield, and unlike other EL6 chondrites its metal and sulfides indicate high equilibration temperatures. We suggest that it is an EL6δ chondrite.

4. In addition to LEW 87223 discussed above, MAC 88136 (and MAC 88180 and MAC 88184 with which it is paired), ALH 85119, EET 90299, and PCA 91020 are EL3 chondrites. Only the EL4 and EH6 positions in the chemical-petrologic grid of *Van Schmus and Wood* [1967] now has no known representatives. The EL3 chondrites confirm the existence of two independent metamorphic series.

5. Lewis Cliff 88180 is the third EH5 chondrite.

6. With the discovery of EL3 and EH5 chondrites, the ranges in mineral composition displayed by EL and EH chondrites are similar. This is despite considerable differences in texture. It is, therefore, helpful to classify the enstatite chondrites in terms of both a petrographic type, which describes textural changes caused by metamorphism, and mineralogical type, which reflects mineral equilibration temperatures. Table 7 shows our complete classifications, where available, for the known enstatite chondrites.

7. There are important differences between the EL and EH chondrites: mineralogical type tends to correlate with petrographic type for the EH chondrites but not the EL chondrites. Mineralogical type reflects closure temperatures and, therefore, cooling rate, while the texture reflects peak metamorphic temperatures. We argue that the mineralogical type reflects reequilibration during regolith or other postmetamorphic processes and that these were different in intensity for the EH and EL chondrites.

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