The compositional classification of chondrites: II The enstatite chondrite groups

Derek W. Sears*, Gregory W. Kallemeyn† and John T. Wasson*†

Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024 USA

Abstract—We present new data from a neutron activation analysis of four enstatite chondrites including the taxonomically important St. Sauveur, and discuss the classification of enstatite chondrites. The enstatite chondrites can be divided into two compositionally distinct sets; in one set abundances of nonrefractory siderophiles and moderately volatile chalcophiles and alkalis are 1.5–2.0× higher than in the other. A well-resolved compositional hiatus separates these two sets. The differences in composition are as great as those between the groups of ordinary chondrites, and therefore it appears best to treat these sets as separate groups. By analogy with the symbols used for ordinary chondrites we propose to designate the high-Fe, high siderophile group EH and the low-Fe, low-siderophile group EL. Known members of the EH group belong to petrologic types 4 and 5, whereas all EL members are petrologic type 6. Within the EH group no correlation is observed between petrologic type and abundance of non-refractory siderophiles or moderately volatiles or alkalis.

Two physical properties show only modest overlap between the EH and EL groups. Cosmic-ray ages for EH chondrites are 0.5–7 Ma, while those for EL chondrites are 4–18 Ma. Relative to Bjurböle, I-Xe formation intervals are −1.3 ± 0.6 Ma for EH chondrites and 2.9 ± 0.5 Ma for EL chondrites. The weight of the chemical and physical evidence indicates that the EH and EL groups formed separate bodies at similar distances from the Sun.

The available evidence for Shallowater and Happy Canyon, two strongly recrystallized silicate-rich meteorites containing >40 mg/g Fe-Ni, indicates that the former is an enstatite-clan chondrite altered by loss of sulfide- and plagioclase-rich melts, whereas the latter is intermediate in composition between EL chondrites and the chondritic silicates in the Pine River IAB-anomalous meteorite.

INTRODUCTION

PRIOR (1916, 1920) noted the unique bulk and mineralogical compositions of a set of chondrites and named them enstatite chondrites after their dominant silicate mineral. Yavnel (1963) and Anders (1964) showed that, in contrast to ordinary chondrites, the enstatite chondrites comprise an extremely heterogeneous class, with total Fe varying over a factor of two and S by nearly a factor of three. Significantly, the Fe and S concentrations correlated inversely with the degree of metamorphism, a point later emphasized by Mason (1966) and Keil (1968). Anders therefore proposed subdivision of the class into types I (high Fe and S, little recrystallization) and II (low Fe and S, highly recrystallized). The compositional hiatus between these "types" were observed by Baedecker and Wasson (1975) to extend to many other elements and they questioned whether the two kinds of material originated in the same parent body. Meteorites assigned to a group should show properties consistent with origin on a single body, and our present reinvestigation of the enstatite chondrites was instigated in order to reevaluate this question.

Two meteorites that feature strongly in our discussion below are St. Sauveur, which Anders assigned to type I, and St. Marks, which Anders placed in type II. Henceforth we will sometimes refer to this pair as the saints. Because St. Marks was much less

recrystallized than the others in type II, Anders later suggested that it might be considered transitional. Mineral abundance and mineral chemistry led Keil (1968) to opine that St. Sauveur should also be considered intermediate. On the basis of bulk chemical data Baedecker and Wasson (1975) assigned the saints to their high-Fe "subgroup" (= type I), although there were virtually no modern data on St. Sauveur.

The Van Schmus-Wood (1967) classification scheme is based on a two-dimensional grid on which one dimension is group and the other is petrologic type. Petrologic type numbers reflect changes which could have been brought about by metamorphism. Most such changes involve petrography or mineral chemistry, but the contents of highly volatile substances, such as C, H_2O, In and the rare gases, also tend to vary with petrologic type. Van Schmus and Wood included all enstatite chondrites in the E group and replaced Anders' enstatite chondrite types I and II with petrologic type numbers. Type I became type 4, type II became type 6 and the saints became type 5. The fractionation of Fe, S and related elements between types I and II were submerged in this scheme. In Table 1 the known enstatite chondrites are listed together with their classifications given by Anders-Keil, Van Schmus-Wood (as modified by Baedecker and Wasson) and the later sections of this paper.

In this paper we reexamine the question of whether the enstatite chondrites form a compositional continuum or two discrete compositional populations,

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* Also Department of Chemistry.
† Also Department of Earth and Space Sciences, NSF Grant EAR 78-03336.

Table 1.   Classification of enstatite chon-
drites into groups and petrologic types.
Falls are in heavy type.

	Anders -Keil	Van Schmus -Wood*	This work
EH			
Abee	I	E4	EH4
Adhi-Kot	I	E4	EH4
Bethune	-	E4,5	EH4,5
Indarch	I	E4	EH4
Kota-Kota	I	E4	EH4
Parsa[+]	-	E4,5	EH4,5
South Oman	-	E4,5	EH4,5
St. Marks	int	E5	EH5
St. Sauveur	int	-	EH5
Yamato Y69001	-	E4,5	EH4,5
EL			
Atlanta	II	E6	EL6
Blithfield	II	E6	EL6
Daniel's Kuil	II	E6	EL6
Hvittis	II	E6	EL6
Jajh deh Kot Lalu	II	E6	EL6
Khairpur	II	E6	EL6
North West Forrest	-	E6	EL6
Pillistfer	II	E6	EL6
Ufana	II	E6	EL6
Yilmia	-	E6	EL6

*As updated by Baedecker and Wasson (1975).
+Though a fall, Parsa is terrestrially altered.

and report new neutron activation data on four en-
statite chondrites (including St. Sauveur) that have
an important bearing on this question.

NEW COMPOSITIONAL DATA ON ENSTATITE CHONDRITES

Samples of the Indarch, Parsa, Pillistfer and St. Sauveur
meteorites were analyzed by radiochemical and instrumen-
tal neutron activation analysis (RNAA and INAA). The
procedures were the same as those used by Sundberg and
Boynton (1977) and Kallemeyn and Wasson (1981), and
need not be repeated here. Table 2 gives the results of our
analyses and the precision estimated from replicate analyses
of standard Allende meteorite powder and the USGS stan-
dard rocks. The Parsa data were obtained somewhat earlier
than the others and, because of this and the weathered state
of the meteorite, precision limits are ~50% greater.

Accuracy is best assessed by comparing our data with
previous results. Ours are the only data for Parsa, but Bae-
decker and Wasson (1975) compiled literature data for the
others. Literature data are numerous for Indarch and Pil-
listfer, but for St. Sauveur exist only for Se, Fe, Mg, Cd
and Zn. Of 37 instances where direct comparisons are pos-
sible, in 10 (involving Mg, Al, Cr, Mn, Fe, and K) the
agreement is particularly good, and the data usually com-
parable within precision limits (±5%). In all but 8 of the
remaining instances, our data are within ~10% of the lit-
erature values.

Those cases where the results differ by more than 10%
probably reflect either low analytical precision or moderate
sample inhomogeneity. The serious discrepancies are: our
Indarch In value that is only 17% of the value of Baedecker
and Wasson (1975); Se and Cd values in Pillistfer that are
76% and 13% of literature values; and Zn values in all three
meteorites that are 27%, 71% and 45% of the mean Pil-
listfer, Indarch and St. Sauveur literature values. It is per-
haps significant that the elements for which agreement is
poorest are volatile elements that show very large ranges.
This suggests that some or all of the discrepancies result
from the inhomogeneous distribution of these elements
within the meteorites. Our data on separate splits from
Abee (Sears *et al.*, 1981) support this interpretation. On

the other hand, these are elements which are prone to con-
tamination, and the fact that our values are systematically
lower than the older data suggests that our data are the
more trustworthy. Because the range of ~2 orders of mag-
nitude is much greater than the scatter for individual me-
teorites, all data remain useful for interpretation. We at-
tribute the fact that our new data for Na, V, Mn, Fe, Co
and Ni are 10-15% lower than Baedecker and Wasson's
(1975) previous results to small systematic errors in our
earlier work.

There appear to be no literature data with which to com-
pare our data for Ru, Sb and La, although the Baedecker
and Wasson (1975) Sb value for Indarch agrees well with
our new value for St. Sauveur.

BULK COMPOSITIONAL EVIDENCE FOR TWO GROUPS

As discussed in the Introduction, and clearly evi-
dent in Fig. 1, there seems to be no difficulty in sep-
arating enstatite chondrites from the other meteorite
classes. They are unique in their bulk chemistry, par-
ticularly in their Mg/Si, O/Si and refractory/Si ra-
tios, and consequently also in their mineralogy. To-
gether with the aubrites they are the most reduced
class of meteorites; they contain Si in the metal and
their silicates are almost Fe-free. Numerous elements
exist as sulfides that in other chondrite classes are
oxides. Among all chondrites they also have the
smallest Mg/Si and refractory/Si ratios.

The chief compositional question we wish to in-
vestigate is whether there are distinct and well-re-
solved groups of enstatite chondrites as opposed to
an uninterrupted continuum. The tendency to seg-
regate into two compositional clusters is already ap-
parent in Fig. 1, where Abee, Indarch and St. Marks
lie in a field that is well separated from that of Pil-
listfer, Hvittis and Atlanta.

Table 2. New INAA and RNAA data on four E chondrites.

Sample≠	Sample Wt. mg	Na mg/g	Mg mg/g	Al mg/g	K μg/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	Zn μg/g	Ga μg/g	Ge* μg/g	As μg/g	Se μg/g	Ru* ng/g	Cd* ng/g	In* ng/g	Sb ng/g	La ng/g	Sm ng/g	Ir ng/g	Au ng/g
Indarch	355	6.8	105	7.74	892	8.9	5.4	52	2.97	2.23	269	775	15.1	280	15.8	42	3.2	25.0	901	847	13	231	252	112	518	308
Parsa	409	6.7	108	7.85	850	7.3	6.3	52	3.10	1.92	277	822	16.9	246	16.1	37	3.8#	30#	1380	610	59	235#	280	122	495	307
	263	6.6	105	8.4	709	8.2	5.6	53	2.92	1.98	275	830	17.5	255	19.7	37	3.2	22	687	570	64	200	220	141	526	310
mean		6.6	107	8.13	780	7.7	6.0	53	3.01	1.96	276	826	17.2	251	17.9	37	3.4	25	–	590	62	212	250	132	511	309
Pillistfer	256	5.6	137	10.0	686	9.5	7.3	54	2.46	1.39	270	890	16.0	26	13.0	33	3.4	10.2	1520	22	5	115	106	133	695	352
	316	5.1	133	10.2	600	9.2	6.1	55	2.65	1.69	233	756	13.3	20	12.0	38	3.0	11.8	1056	15	26	101	94	117	594	250
mean	288	5.4	135	10.1	643	9.4	6.7	55	2.56	1.54	252	823	14.7	23	12.5	36	3.2	11.0	1288	19	–	108	100	125	645	301
St. Sauveur	334	6.9	101	7.56	869	7.5	4.1	74	3.87	1.56	310	854	17.4	250	17.0	36	3.6	32.5	–	550	–	230	275	134	543	352
	228	7.8	111	8.66	891	10.7	6.1	64	3.61	2.65	279	762	16.4	290	16.7	–	3.3	31.2	–	–	–	232	296	160	526	312
mean		7.4	106	8.11	880	9.1	5.1	69	3.74	2.11	295	808	16.9	270	16.9	36	3.4	31.9	–	–	–	231	286	147	535	332
Precision⊕		2.2	1.8	1.6	2.8	3.9	0.9	1.7	1.1	3.0	0.6	0.8	1.9	4.3	1.4	6.5	3.2	1.0	2.5	4.1	–	6.1	1.4	2.7	1.9	1.8

#Highly uncertain values given 1/2 wt.
*By RNAA.
⊕Standard Deviation of six replicate measurements on Allende standard powder split 3, position 18.
≠Sources and catalog numbers are as follows: Indarch, E. Olsen, Chicago Natural History Museum (ME 1403); Parsa, N. Bhandari, Physical Research Lab., Navrangpura, Ahmedabad, India; Pillistfer, G. Kurat, Naturhistorisches Museum, Wien (H 3962); St. Sauveur, Museum National d'Histoire Naturelle, Paris.
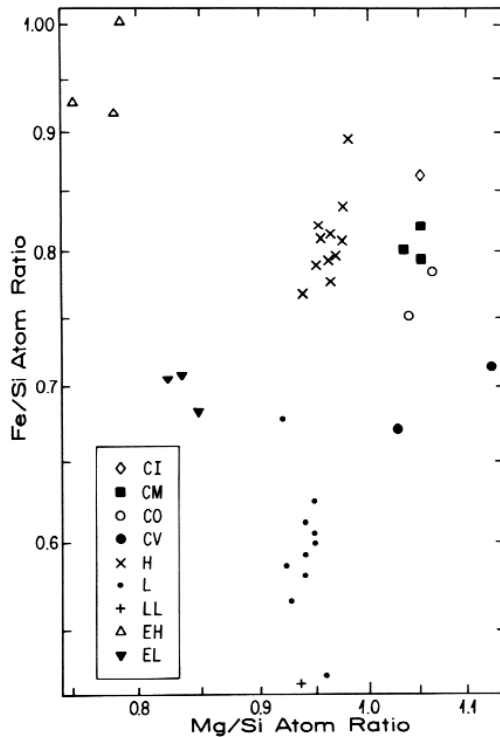
FIG. 1. Fe/Si against Mg/Si (atom ratios) for chondritic meteorites. This diagram demonstrates the good separation of enstatite chondrites from other groups and suggests the existence of two groups of enstatite chondrites (EH and EL). (Data from von Michaelis et al., 1969).

Chemical compositional data for many elements are summarized in Fig. 2. These are largely from the compilation of Baedecker and Wasson (1975), augmented and revised to include new data. Data are plotted as abundances relative to Si (neither Mg nor Si are truly satisfactory normalizing elements because appreciable fractions are present as sulfides and metal, respectively) normalized to CI abundances. Elements are divided roughly according to their cosmochemical affinities and within each division appear in order of decreasing condensation temperature. As noted by Baedecker and Wasson and Binz et al. (1974), siderophiles, chalcophiles, phosphorus and the alkalis show similar patterns. All siderophiles except the refractories Ir, Os, and Re, separate the enstatite chondrites into two groups (Fig. 2). In this respect these elements resemble Fe/Si and lead to the Anders-Keil high-Fe type (group) I and low-Fe type (group) II. Siderophile/Si ratios of Fe, Co and Ni in the high-Fe group are greater than those in the low-Fe group by factors of ~1.5 with the low-Fe group abundances near CI values. Gold and As are also higher by a factor of 1.5 in the high-Fe group and the low-Fe values are ~1.3× CI values. The more volatile siderophiles Ga and Ge are ~2× higher in the high-Fe than in the low-Fe groups. Siderophile abundance ratios tend to decrease with

increasing elemental volatility; similar trends are observed in other chondrite groups (see Wai and Wasson, 1977).

Sulfur, P and Cu also yield good separations between the high-Fe and low-Fe clusters (Fig. 2). The high/low abundance ratio is ~2 for these elements. Similar enrichments occur in the remaining chalcophiles, Se, Sb and Mn, and the alkalis, Na and K, but the scatter is somewhat larger and the resolution of the cluster not so marked. This scatter may in part reflect a difficulty in obtaining representative samples. Abundances in the high-Fe group are generally ~1.5× CI and the low-iron group are usually ~0.6–0.9× CI; again, volatile-element abundance ratios decrease with increasing volatility.

The location of the saints on these plots is important because of their intermediate status in the Anders-Keil scheme. In their siderophile contents these meteorites clearly belong with the high-Fe group. This is also true of the chalcophiles and of P, Na and K, except that the St. Marks K value is intermediate between the high- and low-iron groups.

The refractory siderophile elements (Os, Re and Ir) in enstatite chondrites differ from the other siderophiles; abundance ratios for Re and Ir in EH are probably only ~1.25× higher than those in EL chondrites (Fig. 2). This smaller enhancement combined
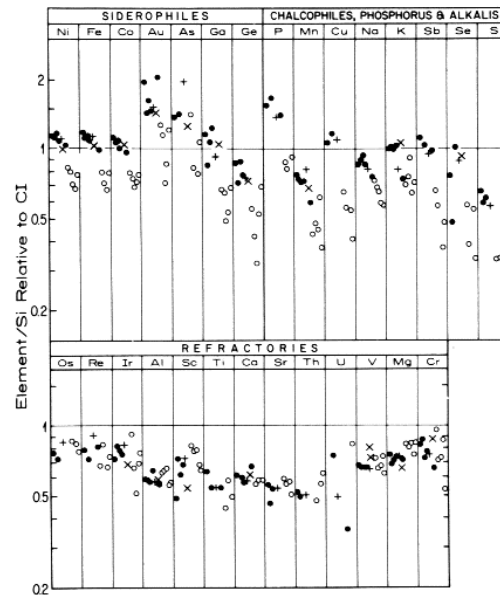

FIG. 2. Abundance of Si-normalized elements in enstatite chondrites relative to Si-normalized CI chondrites. Within each geochemical division, elements are ranked according to decreasing nebular condensation temperature. Filled symbols, EH chondrites; open symbols, EL chondrites; vertical crosses, St. Marks; and diagonal crosses, St. Sauveur. Within groups the meteorites are plotted in alphabetical order, left-to-right. (Data from the sources given in Baedecker and Wasson, 1975, and from Rambaldi and Cendales, 1980, Ikrumuddin et al., 1976, Shima and Shima, 1975, and the present work).

with degrees of scatter comparable to those of other siderophiles obscure a possible hiatus, but the saints plot together with the other EH chondrites.

Similar small differences between EH and EL can sometimes be made out in the refractory lithophiles. Scandium and, particularly, Mg tend to have higher values in EL than EH. In general the scatter is too great to show systematic trends. This is another respect in which EH and EL chondrites resemble L and H chondrites; lithophile abundances are also similar in the latter, and difficult to resolve because of experimental scatter. However, superior data reveal a difference in Mg/Si (Ahrens *et al.*, 1968).

The highly volatile elements tell a very different story (Fig. 3). Instead of showing EH values 1.5–3.0× higher than those in EL, the difference may be anything from a factor of 5 to nearly 100. Furthermore, except for Bi these elements place St. Sauveur firmly among the EH chondrites; St. Marks plots either between the EH and EL range (Ag and In) or with the EL chondrites (Cl, Rb, Cs, Zn, Cd, Bi and Tl). Thus St. Marks and St. Sauveur could be designated "compositionally intermediate" on the basis of highly volatile abundances.

Such large variations in highly volatile element content are familiar. Ordinary chondrites show up to 1000-fold variations in their abundances of In, Tl, Bi and Pb, and there is a strong relationship between highly volatile element content and petrologic type. Volatile abundances in St. Marks (and less often, St. Sauveur) are lower than those in other enstatite chondrites having similar siderophile abundances. This is typical of the behavior of parameters which may be affected by metamorphic equilibration. We therefore believe that abundances of highly volatile elements cannot be used to classify these meteorites, but that the abundances are related directly or indirectly to changes associated with metamorphism, and are useful for inferring petrologic type.

Most of the elements so far discussed sort the enstatite chondrites into two compositional clusters separated by a hiatus, and those which do not are volatile and thus subject to alteration in a way related to metamorphism. Only the nonrefractory siderophile and moderately volatile lithophiles yield separate groups, refractory and highly volatile lithophiles are rarely definitive. We conclude that the two compositionally resolved sets should be reclassified into separate groups, since they differ as much from each other as do the individual groups of ordinary chondrites.

The three ordinary chondrite groups were originally distinguished on the basis of differences in bulk Fe/Si ratios and bulk metal contents, and were consequently termed H, L and LL (high-Fe; low-Fe; low-Fe, low-metal) in the Urey-Craig (1953) classification as modified by Keil and Fredriksson (1964). Following this precedent, we propose to call the two enstatite chondrite groups the EH and EL chondrites. St. Marks and St. Sauveur are normal members of
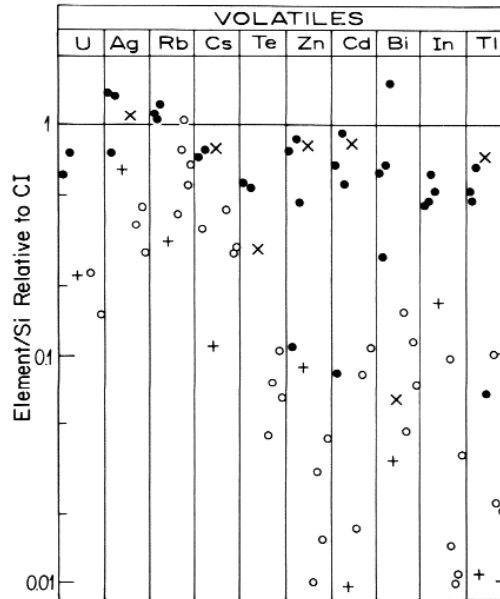

FIG. 3. Volatile elements in enstatite chondrites, Si-normalized and expressed relative to CI chondrites, in order of increasing nebular volatility. The symbols and meteorite order are the same as in Fig. 2 (See caption to Fig. 2 for sources of data).

the EH class, differing only in their contents of volatile elements. These two groups may collectively be referred to as the enstatite clan of chondrites, just as the H, L and LL chondrites are collectively termed the ordinary clan of chondrites.

We prefer to replace the Anders-Keil I, II and intermediate classes with group and type designations to make the classification consistent with the two dimensional scheme of Van Schmus and Wood. The group aspect of EI and EII we describe as EH and EL and we note that there are no intermediate members in terms of the best classificational parameters. The petrologic aspect of EI, E-intermediate and EII is described adequately with Van Schmus-Wood types 4, 5 and 6, as discussed in a later section.

By way of summary, Fig. 4 consists of histograms of concentrations of typical siderophile, chalcophile, alkali, refractory siderophile and refractory lithophile elements. These demonstrate the bimodal distribution of Fe and S with broad hiatus between the peaks. Sodium, and to a lesser extent, Al, marginally resolve the groups, while Ir does not resolve them.

OXYGEN ISOTOPES

The relevance of oxygen isotope ratios to the classification of meteorites was stressed by Clayton *et al.* (1976). These authors discovered that many chondrite groups occupy separate fields on a $\delta^{17}O$ *vs.* $\delta^{18}O$ plot and noted that groups falling near one another on this diagram also showed compositional evidence of a close relationship. The enstatite chondrites oc-

Fe (mg/g)
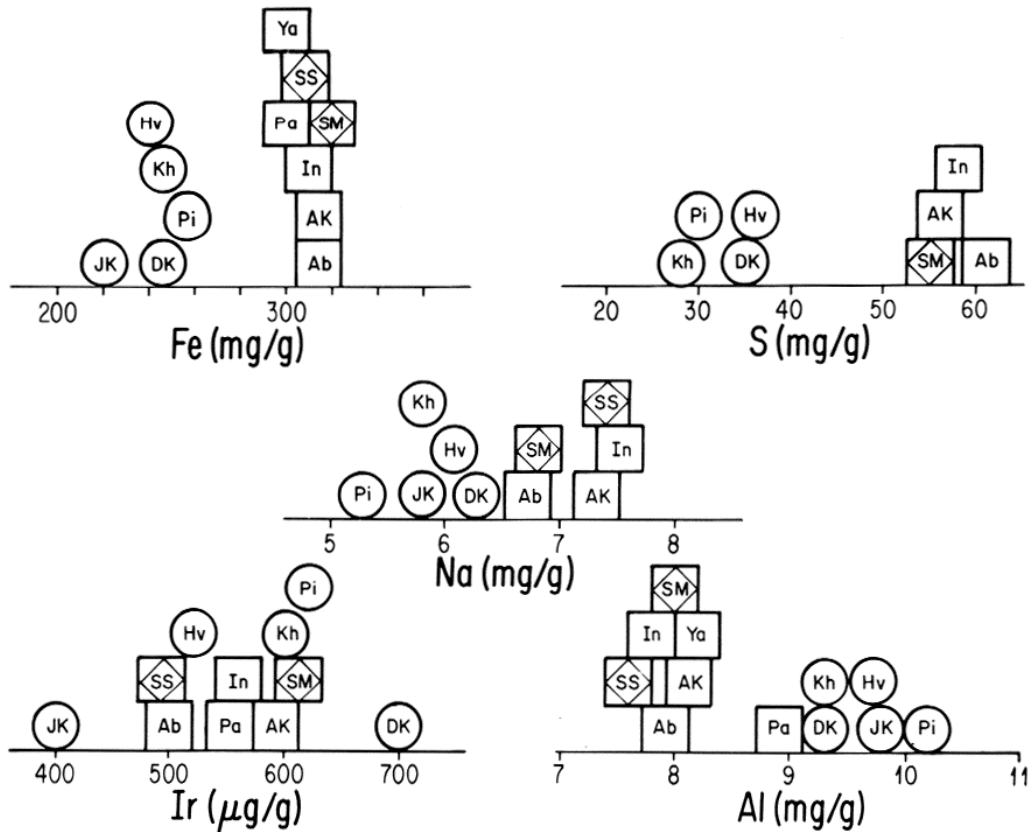
S (mg/g)

Na (mg/g)

Ir (μg/g)

Al (mg/g)

FIG. 4. Concentrations of five representative elements in EH (squares) and EL (circles) chondrites. Iron, S and Na have discretely different values in EH and EL chondrites. St. Marks and St. Sauveur, the two meteorites considered intermediate in the Anders-Keil Scheme, clearly plot with the EH chondrites. Iridium does not resolve the groups, whereas Al does albeit without a hiatus between EH and EL. Abbreviations as follows: Ab, Abee; Ak, Adhi-Kot; Be, Bethune; In, Indarch; KK, Kota-Kota; Pa, Parsa; SO, South Oman; SM, St. Marks; SS, St. Sauveur; Ya, Yamato Y69001; At, Atlanta; Bl, Blithfield; DK, Daniel's Kuil; HV, Hvittis; JK, Jajh deh Kot Lalu; Kh, Khairpur; Pi, Pillistfer; Uf, Ufana; Yi, Yilmia.

cupy a region well removed from the other chondrite classes, in keeping with their unique chemistry and mineralogy, and, in fact, lie on the terrestrial fractionation line. Clayton *et al.* measured the O isotope ratios in only three enstatite chondrites; the two EH4 chondrites have $\delta^{17}O$ somewhat higher than that of the EL6 chondrite, but the difference does not appear to exceed experimental uncertainty. More data are required before it can be determined whether O isotopes can be used to distinguish the EH and EL groups.

MINERALOGY AND PETROLOGY

Anders (1964), Mason (1966) and Keil (1968) observed that the petrology of the enstatite chondrites was consistent with them having suffered various degrees of metamorphism and that the extent of metamorphism varied with the Fe/Si ratio of the meteorite: EH chondrites have abundant chondrules with sharp outlines, while EL chondrites have no

chondrules but their silicates are coarse-grained, as if metamorphism has obliterated chondrule outlines. In terms of their chondrule petrology and the coarseness of their silicates, St. Marks and St. Sauveur are intermediate between the least and most metamorphosed enstatite chondrites. Thus Van Schmus and Wood (1967) assigned petrologic type 5 to St. Marks and St. Sauveur, type 4 to the remaining EH chondrites and 6 to EL chondrites. To fully describe an enstatite chondrite we need to use a term like EH4, EL6 or EH5. At present we do not know of any EL4, EL5 and EH6 meteorites. This may be a very significant point, but in most cases one should not drop the 6 from EL6 or the 4 from EH4 simply because at the moment the type number appears to offer redundant information.

Keil (1968) noted that mineral crystallography and chemistry could be used to distinguish different degrees of metamorphism among enstatite chondrites. His data and others are summarized in Fig. 5. Meteorites that have suffered the highest degree
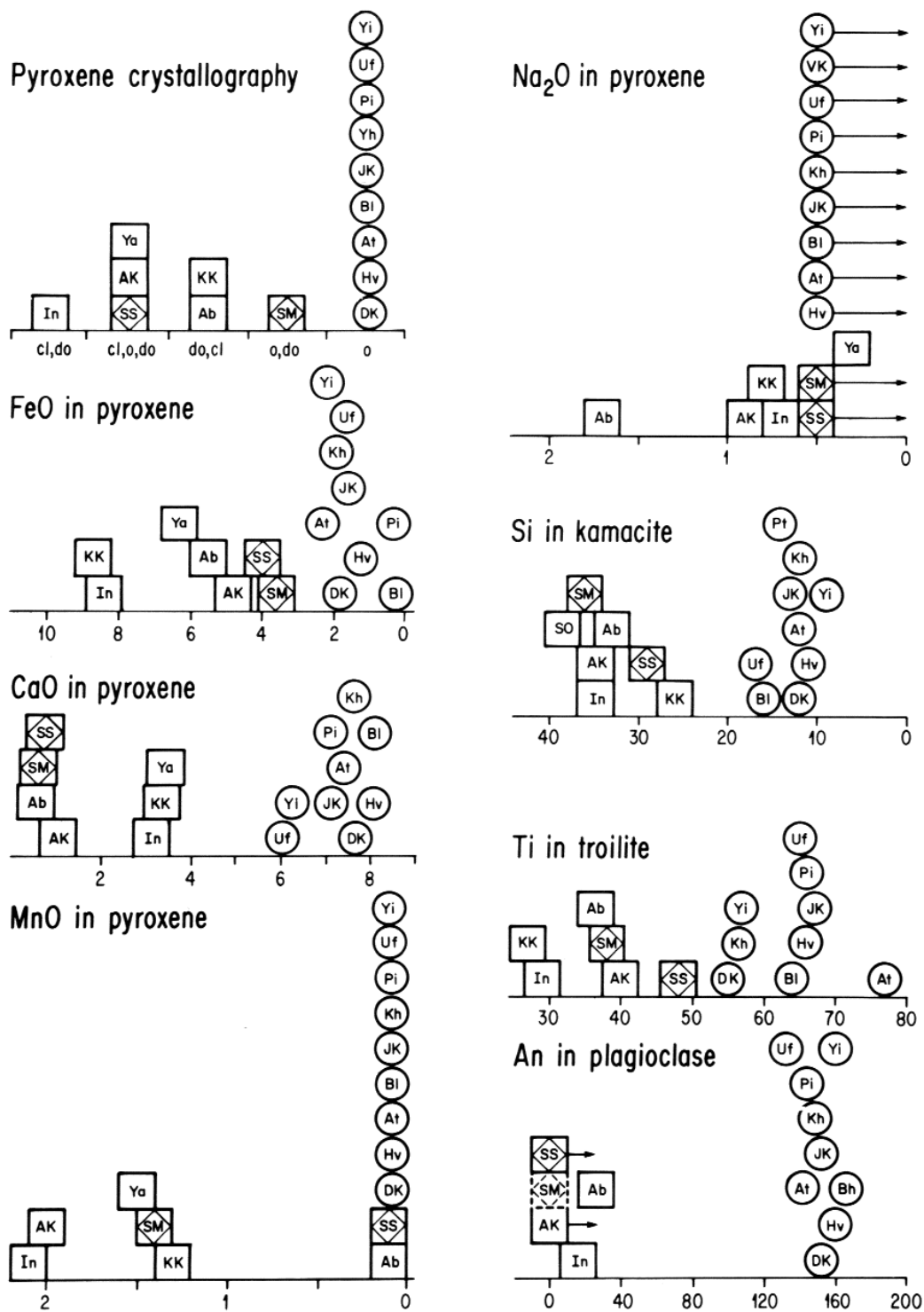
FIG. 5. Petrologic data for enstatite chondrites, summarized in histogram form; circles represent EL chondrites and squares represent EH chondrites. See Fig. 5 caption for abbreviations of names. Units are mg/g. Most parameters indicate that EL are petrologic type 6 and EH chondrites are generally type 4. St. Sauveur and St. Marks often show intermediate phase compositions and are considered type 5. (Data from Keil, 1968; Rubin and Keil, 1980, and unpublished; Okada, 1975; Buseck and Holdsworth, 1972; Reed, 1968, and G. W. Kallemeyn, unpublished).

of thermal metamorphism contain well crystallized orthopyroxene. In the least metamorphosed cases, most pyroxene is clinopyroxene. Intermediate between these two extremes the proportions vary and some of the orthopyroxene is disordered. In Fig. 5 we have plotted a histogram intended to show the location of each meteorite on the sequence: cl, do; cl, o, do; do, cl; o, do; o, where cl, do, and o mean clinopyroxene, disordered orthopyroxene and orthopyroxene, respectively. Within each division, pyroxene crystallographies are listed in order of decreasing abundance. On such a scale, St. Sauveur falls amongst the type 4 chondrites and St. Marks is intermediate between the type 4 and type 6 chondrites.

Pyroxene composition varies with petrologic type; MnO, Na$_2$O and FeO are lowest in type 6 and CaO is highest. In Fig. 5 we also show in histogram form, how mineral chemistry of pyroxene, metal, FeS and plagioclase responds to metamorphism. Again these data are based primarily on Keil's work although we have added data for South Oman, Yilmia and Yamato 69001 from Reed (1968), Buseck and Holdsworth (1972) and Okada (1975), respectively, and we have substituted our own datum for FeO in Pillistfer enstatite (0.032 wt %) and a more recent determination by Rubin and Keil (1980) for the Ti in the troilite of Abee. In all parameters except the Na$_2$O in pyroxene, the EH chondrites differ from the EL chondrites, reflecting the fact that all the EL chondrites are type 6 while most of the EH chondrites are type 4. Okada (1975) reported no plagioclase and an abundance of glass in Yamato 69001; this intriguing information suggests type 3 character. St. Sauveur and St. Marks fall in the type 4 range in some parameters (CaO in pyroxene, Si in kamacite, An in plagioclase) while pyroxene MnO content of St. Sauveur is in the type 6 range. Other parameters suggest that the saints are intermediate (FeO in pyroxene, Ti in troilite). A few of the EH4 meteorites have low (<0.5 wt %) Na$_2$O in pyroxene, but this parameter seems to be too sensitive to metamorphism to serve as a measure of the petrologic type as defined; further research is needed to determine whether the range among EH4 chondrites is indicative of a fine structure within this type. The pyroxene MnO in Abee is lower than that in other type 4 meteorites, consistent with Rubin and Keil's (1980) observation that it has type 5 characteristics.

The Si contents of the metal clearly distinguish EH chondrites ($\gtrsim$25 mg/g) from EL chondrites ($\lesssim$16 mg/g). The two groups are also resolved in terms of the Ti in their troilite, $\gtrsim$55 mg/g in EL, $\lesssim$48 mg/g in EH. Most parameters fail to distinguish EH5 from EH4 chondrites. These are resolved on the pyroxene-FeO diagram, on which St. Sauveur and St. Marks are intermediate between EH4 and EL6. Baedecker and Wasson noted (1975) that equilibration of EH-chondrite materials should decrease both their pyroxene FeO contents and their kamacite Si content. Two EH chondrites are exceptions to the

prediction regarding the kamacite-Si contents: St. Marks, which at 36 mg/g seems 8–10 mg/g too high, and Kota-Kota, which at 26 mg/g seems 4–8 mg/g too low. Further studies of these chondrites are indicated, especially of the fine matrix kamacite grains that most rapidly approach equilibrium.

Of course, it need not be surprising that different mineral systems lead us to different type assignments; each mineral system records a different maximum temperature (or a different cooling rate) because of kinetic and thermodynamic considerations specific to the system.

Mineral abundances also vary between EH and EL chondrites. Sometimes this is a trivial consequence of changes in bulk composition (*e.g.*, metal content) and these can safely be used for classification purposes. However, *in many instances it is unclear whether they are related to bulk composition or metamorphic equilibration and it is probably safer not to use them for classification.* Examples of the latter are the observations that ferroan alabandite and sinoite are only present in EL6 chondrites and niningerite is only present in EH4 and EH5 chondrites. In general, the mineral chemistry seems governed more by metamorphic equilibration than bulk composition; if an EL4 is ever found, for example, the Si content of its kamacite may fall in the EH range.

PHYSICAL PROPERTIES

Many properties of meteorites are more informative when the group is considered as a whole than when individual meteorites are considered. Examples are the K-Ar age and cosmic-ray exposure ages; a significant proportion of several meteorite classes have similar ages, and this is evidence that they originated in the same parent body. With the recognition of two enstatite chondrite groups, new insights into the meaning of such group properties should materialize. Note, however, that we do not propose that these properties are appropriate for classification purposes.

Cosmic-ray exposure ages

Fig. 6 shows that ^{3}He cosmic-ray ages are very similar to ^{21}Ne ages for all enstatite chondrites except Yamato 69001 and Indarch, for which the ^{3}He age is appreciably lower than the ^{21}Ne age; presumably this results from a greater degree of diffusive loss of the lighter He. The two enstatite groups are nearly resolved; EH ages are 0.5–7 Ma, EL ages 4–18 Ma, although more data, particularly for EL chondrites, are needed to confirm this. Although the EH and EL chondrites do not tend to cluster in exposure age, their tendency towards different ranges of values possibly indicates important differences in the break-up and orbital history of their parent bodies. On this subject, it is interesting to note that Skinner and Luce (1971) suggest that EH chondrites, unlike EL chon-

drites, cooled very rapidly, possibly following a shock event. However, their interpretation is based on an unproven assumption that the sulfides were at equilibrium at high temperatures ($\gtrsim 800°C$).

Formation ages

Gas-retention ages for enstatite chondrites have been calculated from the compilation of inert gases by Schultz and Kruse (1976 and unpublished supplements) and other data given in the caption in Fig. 7. Only four meteorites give K-Ar and U, Th-He ages that are concordant within the ±15% uncertainty in the techniques; three at ~4.0 Ga and one at ~1 Ga. The others have U, Th-He ages lower than their K-Ar ages. Such discordant behavior is well-known for other meteorite classes and occurs because partial outgassing removes more He than Ar. Apparently, concordant meteorites either avoided outgassing (ages $\gtrsim$ 4.0 Ga) or were outgassed completely at the time indicated by the concordancy.

All of the meteorites with concordant ages are EH chondrites, whilst all but one of the meteorites with discordant ages are EL chondrites. The one EH meteorite with discordant ages is St. Marks. So although there seems to be little difference between EH and EL meteorites in terms of their distribution of gas retention ages, differences in degree of gas loss may be significant.

Gopalan and Wetherill (1970) studied the Rb-Sr systematics. Eight enstatite (4 EL, 4 EL) chondrites plotted on the same whole-rock isochron, which (us-
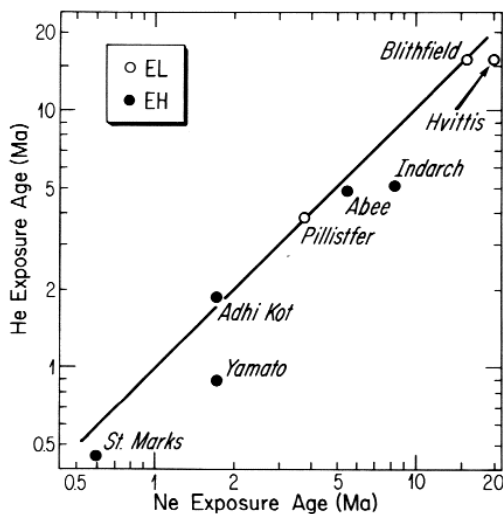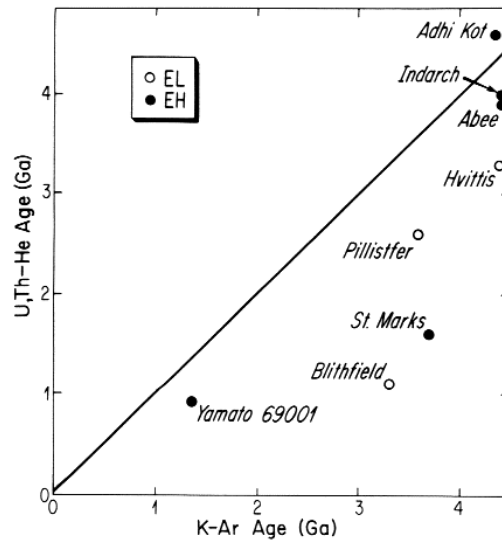

FIG. 7. Comparison of gas-retention ages calculated by the U, Th-He and K-Ar methods. EL chondrites have discordant ages due to preferential loss of lighter He, while, except for St. Marks, EH chondrites have concordant ages. Inert gas data were taken from Schultz and Kruse (1976) and unpublished supplements. The following data were used for the age calculations: $\lambda_{40} = 5.3 \times 10^{-11}$ a^{-1}, K concentrations as given in the Baedecker and Wasson (1975) compilation, 745 mg/g (EL) or 890 mg/g (EH) where none given; U = 11 ng/g, $^{238}U/^{235}U = 140$, $^{232}Th/^{238}Th = 3.7$, cosmogenic $^4He/^3He = 5.2$, $\lambda_{238} = 1.525 \times 10^{-11}$ a^{-1}, $\lambda_{235} = 9.848 \times 10^{-10}$ a^{-1}, $\lambda_{232} = 4.984 \times 10^{-11}$ a^{-1}.

ing a ^{87}Rb decay constant of 1.42×10^{-11} a^{-1}), corresponds to an age of 4.45 ± 0.13 Ga and is identical to the internal isochron age of Indarch, 4.47 ± 0.15 Ga. This study thus yielded no evidence of systematic age differences between EH and EL chondrites. Detailed Rb-Sr systematics for four EH chondrites (St. Marks, St. Sauveur, Indarch, Abee) have also been examined by Minster et al. (1979). Their whole-rock isochron gave an age of 4.516 ± 0.029 Ga, in good agreement with Gopalan and Wetherill (1970), but internal isochrons for three of them (the fourth, Abee, did not yield an internal isochron) were 60–200 Ma lower, suggesting shock events 60–200 Ma after formation.

I-Xe formation intervals

Kennedy (1981) investigated the I-Xe formation intervals of enstatite chondrites and observed that EH chondrites formed about 1.3 ± 0.6 Ma before the Bjurböle standard, while EL chondrites formed about 2.9 ± 0.5 Ma after Bjurböle. The lone exception is St. Marks, which has an apparent formation interval similar to that of the EL chondrites. However, St. Marks has an initial $^{129}Xe/^{130}Xe$ ratio that is much higher than those found in EL chondrites. A model formation interval for St. Marks based on the slope of a line drawn between the mean Xe isotopic ratios

FIG. 6. Comparison of the cosmic-ray exposure ages of enstatite chondrites as calculated from their contents of cosmogenic ^{3}He and ^{21}Ne. Ages of EL chondrites tend to be higher than those of EH chondrites. (Inert gas data from the compilation of Schultz and Kruse, 1976, and unpublished supplements; the production rates used were: 2.0 $\times 10^{-8}$ STP cm^{-3} g^{-1} (Ma)$^{-1}$ for ^{3}He, He = 5.2 ^{3}He, and 0.377 $\times 10^{-8}$ STP cm^{-3} g^{-1} (Ma)$^{-1}$ for ^{21}Ne).

in gas expelled at high temperatures and the ratios in Xe from average carbonaceous chondrites (AVCC) yields a formation interval identical to those of other EH chondrites, suggesting that the peculiar St. Marks isochron resulted from internal redistribution during a shock event ~4 Ma after initial formation. The low discordant U, Th-He and K-Ar ages also suggests this meteorite has suffered major gas-loss, but at different times. Thus, with a minor caveat regarding St. Marks, the I-Xe systematics are consistent with the chemical evidence that the formation conditions of the EH and EL chondrites were distinctive.

HAPPY CANYON AND SHALLOWATER

Happy Canyon and Shallowater are meteoritic finds potentially related to the enstatite clan chondrites.

Happy Canyon is chemically and mineralogy similar to the enstatite chondrites but has lower S and is more coarsely crystalline. The S content and crystallinity led Olsen et al. (1977) to suggest that Happy Canyon had an igneous origin and was better considered an achondrite. We disagree with this conclusion because the meteorite has important chondritic properties; 100 mg/g Fe-Ni metal, a "chondritic" amount of albitic plagioclase and an essentially EL bulk composition. The abundance of metal and the chondritic abundance and composition of plagioclase precludes igneous formation.

The S content of Happy Canyon is about 6× less than EL levels, and this may indicate that a eutectic melt having a high FeS/Fe-Ni ratio formed and a large fraction migrated out of the system. Since this melt (possibly including small amounts of other sulfides such as CaS) can form at temperatures 100 K lower than any silicate melt that could be derived from the meteorite, it seems probable that it was the only melt that formed, and that the remaining materials have preserved the composition of the chondrite precursor. We suggest that it is best to emphasize the chondrite precursor. We suggest that it best to emphasize the chondritic affinities of Happy Canyon by listing it as a chondritic material. The important genetic feature is the chondritic composition that has been preserved with only minor alteration, not the recrystallized texture reflecting processing at high temperature.

We doubt, however, that Happy Canyon is a member of the enstatite chondrite clan, since it is slightly more oxidized. Olsen et al. (1977) report that its enstatite is Fs 0.47, whereas the highest value reported in EL chondrites is about Fs 0.2, and true values for EL chondrites are lower if care is taken to avoid the fluorescence of Fe in finely dispersed Fe-Ni or FeS. The Fs content, and therefore the degree of oxidation, of Happy Canyon is roughly midway between EL chondrites and the chondritic materials in Pine River, an anomalous member of the group IAB irons-with-silicate-inclusions. Happy Canyon should therefore be considered as an anomalous chondrite and not an enstatite chondrite.

Like Happy Canyon, Shallowater is more coarsely crystalline and has lower S abundances than the enstatite chondrites. It has metal contents more closely resembling EL chondrites than aubrites (151 mg/g Fe, 91 mg/g Ni). It differs from Happy Canyon, however, in having lower abundances of Na, K and Al than EL chondrites (Shallowater: 1.8 mg/g Na, 91 mg/g K, 2.0 mg/g Al, E. Rambaldi, pers. com.; typical EL: 60 mg/g Na, 740 mg/g K, 94 mg/g Al), so it seems likely that Shallowater was produced by a partial melting process in which a low-melting plagioclase and FeS-rich melt was lost. The Si content of the metal is 10 mg/g according to Wasson and Wai (1970), and 20 mg/g according to Watters and Prinz (1979). The lower value is

in the EL range, but the higher value is intermediate between EL and EH. As noted by Baedecker and Wasson (1975), the Si in the metal is expected to decrease during any high temperature event due to reaction of metallic Si with FeO. This suggests that the Shallowater parent material was nearer EH than EL composition. Shallowater's I-Xe formation interval discussed above is in the range observed for EH chondrites. On the whole, these data suggest that Shallowater is a member of the enstatite clan chondrites, and more closely related to the EH than EL.

As discussed in numerous past papers, the aubrites, the Mount Egerton stony-iron and the Horse Creek iron are also closely related to the enstatite clan chondrites, either by nebula, igneous or metaigneous processes.

TWO PARENT BODIES: PRO AND CON

Probably the major implications of assigning the enstatite chondrites to high-Fe (EH) and low-Fe (EL) groups, concern the question of whether they formed in a single parent body. We will briefly review the question and discuss future investigations that could lead to its resolution. We assume that it is established that igneous processes could not produce EL chondrites from an EH-like precursor and that the nebular processes responsible for EH and EL compositions could have produced other materials with intermediate compositions.

The only evidence favoring a single parent body is that all EL chondrites are petrologic type 6, and all EH chondrites are petrologic types 4 and 5. Why should degree of metamorphic recrystallization correlate with bulk chemical parameters such as the Fe/Si ratio? There seems little doubt that the enstatite chondrites would have been separated into high-Fe and low-Fe groups long ago if the former included type 6 members and the latter type 4 members.

The EH and EL differences between composition require agglomeration (to planetesimals) at different times or places. If the planetesimals formed at different distances from the Sun, then there would seem to be no reason for the sequential accretion of planetesimals as a function of composition: the accretion of EH or EL or other materials from the continuum of E compositions would have depended on random dynamical processes, and any of these classes of materials could have been incorporated into any level in the parent's body, and if metamorphism resulted from internal heating, petrologic types should be distributed randomly among the compositional groups. Metamorphism of EL chondrites must have occurred after agglomeration, since chondrule outlines have largely been destroyed; a high-temperature stage occurring while the grains were dispersed in the solar nebula would not appreciably affect chondrule outlines.

If the EH and EL materials formed sequentially at the same distance from the Sun, but the mean time between formation of compositionally distinct planetesimals was appreciably less than the time required for parent body accretion, the same conclusion holds; the different compositional materials should be randomly distributed throughout the parent body.

Only in the implausible case in which (a) all classes of enstatite chondrites formed at the same distance from the Sun, and (b) the collection of planetesimals to parent bodies was more rapid than the settling of dust to the median plane and the formation of planetesimals, would it be possible to form a radially zoned enstatite chondrite parent body of the sort envisioned by Larimer and Anders (1967), Wasson and Wai (1970) and Sears (1980). We consider such a model improbable. It should be emphasized though, that placing the EH and EL chondrites in different parent bodies does not alter the feasibility of most aspects of the models developed by these authors to interpret chemical fractionations.

It seems relatively straightforward to understand how the EH chondrites could be predominantly type 4 and the ELs be all type 6, if the EH and EL chondrites came from different parent bodies. Perhaps the EL body was larger, and a larger fraction was metamorphosed by an internal heat source. Equally plausible, considering the low volumes ($<10^{-2}$ km^3) of material in Earth-crossing orbits required to explain the EH or EL groups, is that the distributions of petrologic types in our samples of these groups are not representative of those in the original parent bodies.

The point of the above discussion is to show that there are difficulties with assigning all enstatite chondrites to a single parent body, difficulties serious enough to make this possibility appear unlikely, yet it seems relatively straightforward to understand these meteorites on the basis of two parent bodies. Unless future studies show that many trends are continuous throughout the two groups (*e.g.*, that siderophile abundance trends *within each group* correlate with metamorphism so as to produce a continuous trend connecting EH and EL) it will continue to be preferable to assign these groups to different parent bodies.

FORMATION LOCATIONS

The evidence (primarily, the extremely low degree of oxidation) indicating that enstatite chondrites formed nearer the Sun than other groups was reviewed by Baedecker and Wasson (1975), Wasson (1977) and Sears (1980), and will not be repeated here. A new development that supports this assignment is the discovery by Crabb (1980) that elemental ratio in the primordial gas in enstatite-clan chondrites is less fractionated than that in other chondrites. Independently, Wetherill (1981) suggested that a similar fractionation observed in the atmosphere of Venus might be expected in primitive materials that formed near the Sun.

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