

Composition and origin of clasts and inclusions in the Abee enstatite chondrite breccia

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The concentrations of 25 major, minor and trace elements have been determined in four clasts, a metal-rich inclusion and two dark metal-poor inclusions from the Abee enstatite chondrite. The clasts are heterogeneous, displaying 2-fold enrichments or depletions in some elements. The data suggest that there are two generations of metal, one with low, the other with high concentrations of refractory siderophiles. The other elemental patterns can be understood in terms of variations in the abundance of major minerals. We infer that Sc and Mn are located largely in the niningerite ((Fe,Mg)S), V in the troilite (FeS) and rare earth elements in the oldhamite (CaS).

Heterogeneities among the clasts are probably primary, resulting from the accretion-agglomeration process, although shock processes in a regolithic setting remain a possibility provided that they were followed by a period of metamorphism sufficient to erase petrologic evidence.

In the dark inclusions the concentrations of the rare earths, Eu excepted, are $4 \times$ higher than mean EH levels; this infers enhanced amounts of CaS. The dark inclusions are low in siderophiles, Sc, Mn, K, Na and Al, implying low amounts of metal, niningerite and feldspar. The origin of the dark inclusions is unclear; they do not appear to be the result of a simple, single-stage process.

1. Introduction

The Abee meteorite is of special interest because it is the largest (107 kg) of a rare and unusual clan of meteorites, the enstatite chondrites. Only 2% of observed falls are members of this clan and only 23 are known. To add to its particular interest, Abee is brecciated, containing clasts of up to several centimeters in dimension (some metal-rich), and some 5-mm-sized dark "inclusions".

The enstatite meteorites are unusual because of their highly reduced mineral assemblages; Si is present in the metal, normally lithophile elements like Mn, Ti, Cr and Ca are present as sulfides and the major mafic silicate (enstatite) is almost Fe-free.

This is in sharp contrast to the other chondrite classes where 50–100% of the Fe is bound to O. This extraordinary degree of reduction poses an interesting problem for genetic models. Larimer [1,2] and Baedeker and Wasson [3] have proposed that these meteorites formed in a nebular gas of nonsolar composition, while Herndon and Suess [4] have argued that the desired degree of reduction could be achieved in a solar gas at exceptionally high temperatures and pressures. Sears [5,6] reviewed these theories and emphasized that, independent of model, enstatite chondrite materials could not have formed in a narrow temperature interval, but that high-temperature (i.e., reduced) assemblages must have been mixed with low-temperature (i.e., volatile-bearing) materials.

The enstatite chondrites have many analogies in bulk composition and petrology to the ordinary chondrites; for example their bulk siderophile/Si ratios suggest that there are two classes of enstatite

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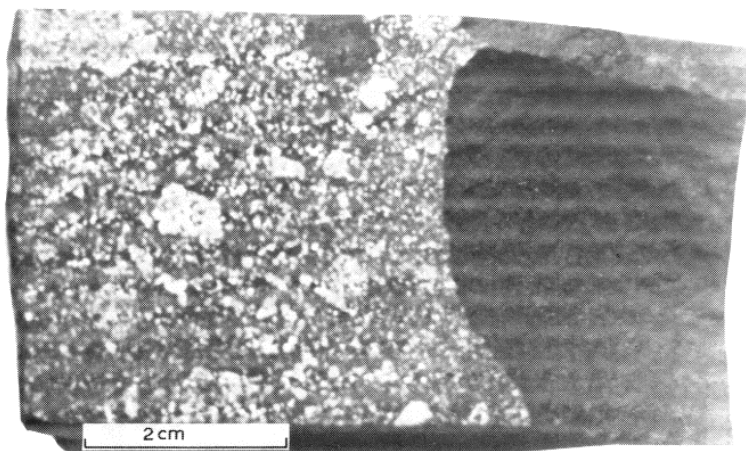


Fig. 1. Photograph of Abee sample SI 2096 showing the dark inclusion used in this study.

chondrite, the EH (high-iron) and EL (low-iron) groups [7]. A factor which has complicated their study in the past is that EH meteorites are less metamorphosed than EL chondrites; in the scheme of Van Schmus and Wood [8] EH meteorites are type 4 and 5 while EL meteorites are type 6. Even EH4 meteorites, like Abee, have suffered significant metamorphism and—as we discuss below—it is difficult to distinguish between equilibria which were established during the condensation and accretion stage from those which followed subsequent processes. The problem is increased by the possible effects from other conceivable parent body processes; in the case of Abee brecciation is a strong possibility. The present study is an attempt to explore the importance of the various processes in the history of one EH4 chondrite.

Details of the fall and an initial description of the Abee meteorite were published by Dawson et al. [9]. Its mineralogy and petrology were described in some detail by Mason [10] and Keil [11]. Baedeker and Wasson [3] and Binz et al. [12] determined and compiled elemental data. In the present paper, we report the determination of 25 major, minor and trace elements in six samples from the Abee meteorite. All but one were from the slice shown in Fig. 1 and were removed as part of a consortium study organized by K. Marti.

Four of our samples are from different clasts in the meteorite and two are dark inclusions. *

2. Samples and techniques

Samples of four clasts were examined under the binocular microscope and, except for 2,1,2 (which was too small) broken into two fragments for duplicate analysis. Each sample from the consortium slab is identified by three digits, in the present case 1,1,3; 2,2,4; 2,1,2; 3,3,2 and 9,13,1. For the sake of simplicity, we will usually use only the first two digits which identify the source clast. Clast 2,1 was described as metal-rich, and our examination confirmed this. Additionally, a sample which, at low power, looked like pure metal was taken from sample 3,3,2 for separate analysis. We also analyzed two dark inclusions, one from the same slab as the above clasts (9,13,1) and one from a Smithsonian sample of Abee (SI 2096) at Caltech (Fig. 1). Samples were prepared in a clean room. Matrix was removed, where necessary, with a screw-driven pincer.

* For the purpose of this paper we distinguish between “inclusions” and “clasts”. The clasts have all the characteristics of enstatite chondrite material. The inclusions are grossly fractionated.

TABLE 1

Concentration of 25 elements in separated clasts from the Abee meteorite. Masses are in mg, units are g/g except Na, Mg, Al, Ca, Cr, Mn, Fe, Ni (mg/g) and Cd, Sb, Sm, Os, Ir and Au (ng/g)

	Mass	Na	Mg	Al	K	Ca	Sc	V	Cr	Mn	Fe	Co
Clasts												
1,1,3	304	9.30	100	9.5	1080	8.2	11.7	26	3.52	5.30	294	830
	316	9.17	96	9.2	840	8.1	11.7	24	3.37	5.20	290	840
Mean		9.24	98	9.4	960	8.2	11.7	25	3.44	5.25	292	830
2,1,2	258	5.02	56	6.0	590	5.2	1.8	32	1.66	0.58	575	2070
2,2,4	303	8.84	100	9.7	920	9.3	11.3	33	3.65	5.06	310	890
	204	8.59	101	9.7	940	8.6	11.3	33	3.62	5.00	310	910
Mean		8.72	101	9.7	930	9.0	11.3	33	3.64	5.03	310	900
3,3,2	255	9.22	72	9.0	1020	12.4	3.4	73	3.57	1.18	380	1140
	247	9.61	77	9.1	860	12.7	3.5	77	3.58	1.25	341	990
Mean		9.42	75	9.1	940	12.6	3.5	75	3.58	1.22	361	1060
Dark inclusions												
9,13,1		6.03	145	6.8	640	34.8	6.2	116	47	1.19	185	310
SI 2096		4.12	131	5.7	370	37.4	9.3	208	7035	2.16	209	243
Mean EH		7.3	109	8.0	860	8.6	6.2	57	3.5	2.3	310	900

^a Concentrations of Eu, Tb, Yb and Lu in ng/g listed in this order in dark inclusions and mean EH are: 9,13,1: 100, 159, 575, 95; SI 2096: 145, 229, 955, 176; mean EH: 56.5, 33, 155, 25.2

^b These are the values used in plotting Figs. 2–5, see text for qualifying remarks.

Our neutral activation procedure requires three sets of measurements:

(1) A two-minute irradiation in the U.C.L.A. reactor (neutron flux $2 \times 10^{12} \text{ cm}^{-2} \text{ s}^{-1}$) yields data on Mg, Al, V and Mn.

(2) A three-hour U.C.L.A. irradiation followed by five counts over a period of several weeks yield data on 15–20 additional elements.

(3) A 25-hour irradiation in the University of Missouri reactor (neutron flux $2 \times 10^{14} \text{ cm}^{-2} \text{ s}^{-1}$) followed by a 3-hour irradiation after return to U.C.L.A. (to reactivate short-lived nuclides) is followed by a radiochemical separation procedure [13] and gamma counting to yield data on 6 additional elements and redundant data on 4 INAA elements.

The precision was determined by six analyses of homogenized Allende standard power and standard rocks. For Mg, Al, Si, V, Cr, Fe, Co, Ni, Ga, Se, La, Ir and Au the 95% confidence levels on the mean of two replicates are ± 4 –7%, for Na, K, Ca, Mn, As, Br, Ru, Sm, Eu and Os ± 8 –14%, for Zn,

Cd, Yb and Lu $\pm 17\%$, for Ge $\pm 23\%$ and Sb $\pm 21\%$. In the two dark inclusions we were also able to determine Tb, for which analyses of U.S.G.S. standard rock BCR-1 indicate 95% confidence limits of $\pm 15\%$.

3. Results

Our INAA and RNAA data are shown in Table 1, along with sample weights and the mean concentrations of EH meteorites from Sears et al. [7]. We show plots of these data, Mg-normalized, as a ratio to Mg-normalized values for mean EH chondrites in Figs. 2–5. The elements are divided into geochemical classes and, within each subdivision, are arranged in order of decreasing nebula condensation temperature. Many normally lithophile elements are chalcophile in enstatite chondrites; therefore chalcophile and lithophile elements have not been separated. We will discuss the clasts and then the dark inclusions.

TABLE 2

Instrumental neutron activation analysis and electron microprobe data for a metal grain removed from Abee clast 3,3,2

	mg/g		μg/g
Si ^a	32	Ga	64.6
P ^a	54	As	12.7
Cr	2.83	Sb	0.74
Fe	893	W	0.45
Co	3.08	Re	0.38
Ni	68.8	Ir	0.95
Cu	0.45	Au	1.40

^a Determined by electron microprobe.

data is the low Os and Ir values; while siderophiles generally show a four-fold enhancement in clast 2,1, Os and Ir show only a two-fold enhancement. Os and Ir are also low in clast 3,3 compared to the other siderophiles, but their relative depletion is only about 10%. The metal-rich inclusion removed from clast 3,3 is also depleted in refractory siderophiles.

3.2. "Metal" inclusion from clast 3,3

Data for the metallic inclusion are shown in Table 2. Fig. 3 shows siderophile/Ni normalized to mean EH. Nickel, Co, Au and Ga are close to EH values, whereas Fe, As and Sb are at $\sim 0.8 \times$ mean EH; the latter are presumably also present in nonmetallic phases. As in the metal-rich clast 2,1, Ir shows a two-fold depletion.

Osmium and Ir are usually regarded as strongly siderophile elements, yet they are sometimes fractionated relative to the common siderophiles such as Ni and Co. Thus Chou et al. [16] found that the proportion of total Ir in the non-magnetic portion of H chondrites was greater than for Ni and they suggested that some of the Ir was in refractory metal that was physically trapped in silicates. Rambaldi [17] observed that his finest sieve fraction of metal separated from ordinary chondrites was Ir-rich, and suggested that tiny ($\sim 10 \mu\text{m}$), refractory metal grains observed inside chondrules were responsible. In contrast, Rambaldi and Cendales [42] analyzed magnetic separates from

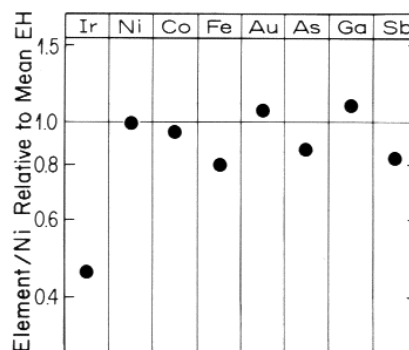


Fig. 3. Data on 8 elements in a sample of apparently pure metal from clast 3,3,2. Abundances are normalized to Ni and mean EH chondrites. Like clast 2,2,1, this grain shows a 2-fold depletion in Ir. Iron, As and Sb are low, perhaps due to their presence in other probably sulfide phases.

Abee and were unable to find any Ir depletion in the metal, or any grain-size dependence in its composition, thus the two metal components seem to show similar size dependences.

We suggest that the metallic inclusion formed by shock, and that the metal mobilized during shock events is generally Ir poor. During nebula condensation Ir-rich metal was probably either trapped in silicates or served as condensation nuclei for Fe-Ni grains. Much of the metal mobilized during shock is probably from the Ir-poor exterior of Fe-Ni grains adjacent to FeS, which condenses from the nebula by reaction with and deposition on the surface of metal grains.

3.3. Lithophile and chalcophile elements in the clasts

The scatter shown by these elements indicates considerable sample inhomogeneity, and, in contrast to siderophiles, a fairly complex mineralogical siting (Fig. 4). Clasts 1,1 and 2,2 again have very similar abundance patterns. Aluminum, Sc, Mg, Cr, Na and K are relatively close to the mean EH values ($1.0\text{--}1.4 \times$ mean EH). In contrast, Sc and Mn are enhanced by a factor of over two, and V is a factor of two low. In these two clasts there is also a small depletion in the rare earths, Sm and La ($\sim 0.7 \times$ mean EH).

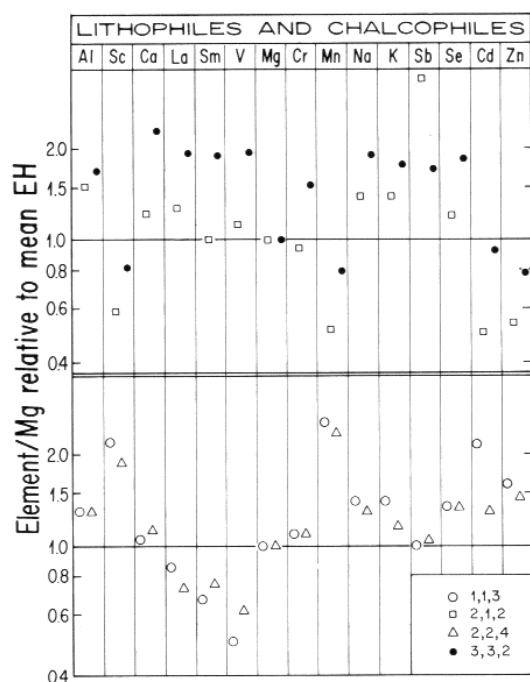


Fig. 4. Abundances of 15 lithophile and chalcophile elements in four clasts from the Abee consortium slice. Data are normalized to Mg and mean EH chondrites. The low Mg relative to most other elements in 3,3,2 reflects low MgSiO_3 ; this aside, clasts 2,2,1 and 3,3,2 have almost identical patterns with 2-fold depletions in Sc, Mn, Cd and Zn. Clasts 1,1,3 and 2,2,4 also have very similar patterns to each other, with Sc and Mn 2-fold higher, V 2-fold lower and the two rare earths 25% lower. On the basis of these and literature data the following trace element-mineral associations are suspected; niningerite (Sc and Mn), troilite (V), oldhamite (Sm and La).

Clasts 2,1 and 3,3 have very different patterns from the other two clasts. In clast 3,3 all but three elements (Sc, Mn and Mg) including the siderophiles are $\sim 2\times$ enriched. Since Mg was used for normalization, it seems probable that Mg is ~ 2 -fold depleted and most elements are present in EH proportions. Except for the Mg depletion, the two clasts then have very similar patterns; both are lower in Sc and Mn than Mg by an additional factor of ~ 1.5 . Apparently there is a Mn- and Sc-rich phase that is low in abundance in 2,1 and 3,3 but enriched in 1,1 and 2,2 whereas

one or more V- and REE-rich phases are two-fold low in 1,1 and 2,2. The situation for Mg is discussed below.

Electron microprobe studies of EH chondrites indicate that the Mn content of niningerite ((Mg,Fe)S) is 44 mg/g, and planimetric measurements indicate that there is 112 mg/g of this mineral in Abee [11], thus 96% of the Mn in Abee is present in the niningerite. The amount of niningerite determined by planimetry of the clasts is consistent with the Mn variations we see; 1,1 and 2,2 both contain 132 mg/g while 2,1 and 3,3 contain 15 and 37 mg/g, respectively [14]. Is it plausible that niningerite is also the site for a major fraction of the Sc?

Allen and Mason [15] examined four mineral fractions (metal, FeS, orthopyroxene and feldspar) from the Khairpur (EL6) chondrite. (Because it belongs to a different group, the results will not be precisely applicable to Abee, but the oxidation state and bulk composition are very similar; the main difference is that Khairpur has a bulk S content much smaller than Abee's (28 mg/g compared with 61 mg/g), and ferroan alabandite replaces the niningerite of Abee.) They found $\sim 45\%$ of the total Sc was in the FeS fraction, the remainder primarily in the orthopyroxene. Allen and Mason's FeS fraction probably included several sulfide minerals since six have been reported in EH chondrites; ZnS, FeS, CaS, niningerite ((Fe,Mg)S), djerfisherite ($\text{K}_3(\text{Na,Cu})(\text{Fe,Ni})_{12}\text{S}_{14}$) and daubreelite (FeCr_2S_4). Of these, the last two have never been reported in Abee and ZnS is present in only trace amounts. On the basis of crystallography (Table 3), one would not expect ScS to form a solid solution with FeS, and the ionic radius of Sc seems to favor solid solution with (Fe,Mg)S rather than CaS. Although the Khairpur data suggests orthopyroxene as a feasible site, the lack of a strong correlation between Mg and Sc rules this out as the dominant Sc phase. However, we cannot dismiss the possibility that perhaps $\sim 20\%$ of the Sc resides in the pyroxene.

The low V observed in clasts 1,1 and 2,2 implies that a V-rich mineral is underabundant in these clasts. Allen and Mason's [15] data for the mineral separates from Khairpur indicate that V con-

TABLE 3

Crystallography of inorganic monosulfides and ionic radius of relevant cation

Sulfide	Crystallography	Ionic radius (pm) [39]
MnS	cubic (NaCl) type	66
CaS	cubic (NaCl) type	99
MgS	cubic (NaCl) type	65
ScS	cubic (NaCl) type	81
RES	cubic (NaCl) type	90–110
FeS	hexagonal (NiAs) type	78
VS	hexagonal (NiAs) type	64
ZnS	hexagonal (wurtzite) type	60
CdS	hexagonal (wurtzite) type	78

concentrates very strongly in the sulfide fraction; their V concentration in this fraction was apparently too high to measure ($\geq 10 \times$ bulk). A priori, the most reasonable site for V in enstatite chondrites is daubreelite (FeCr_2S_4). The ionic radii of V and Cr are similar (64 and 55 pm, respectively) and in ordinary chondrites V is located in chromite (FeCr_2O_4) [18], which replaces daubreelite. Surprisingly, V does not appear to be associated with daubreelite in Abee. First, neither Keil [11] nor Rubin and Keil [14] report daubreelite in Abee, despite other minerals being reported when present in amounts ≤ 1 mg/g. Second, Cr does not show the large depletion observed for V in clasts 1,1 or 2,2 or the enrichment shown by V in the dark inclusions described below. The ionic radii of V and Fe, and the crystallography of their monosulfides, suggest that FeS is a plausible host phase. The planimetric data are probably consistent with this; 2,1 and 2,2 have only 54 mg/g FeS, 1,1 has 65 mg/g while clast 3,3 contains 129 mg/g (the last figure is misleadingly high because of the low Mg in this clast).

Associated with the V depletion in clasts 1,1 and 2,2 is a small ($\sim 20\%$) rare earth element (REE) depletion. Allen and Mason [15] did not determine rare earths in their mineral fractions, but REE were measured by Shima and Honda [41] in selective dissolution experiments on Abee. Their first solvent was a weak acid (pH 5) that removed CaS, the second was EDTA, and the third was

bromine-water that dissolved FeS. Subsequent solvents dissolved the silicates and phosphides. Little or no REE were found in the acid leach (CaS) fraction, about 75% of the REE was in the EDTA fraction and 25% in the FeS fraction. In ordinary chondrites EDTA dissolved calcium phosphates, but in Abee it is not clear what minerals were involved. However, these data do preclude the major silicates pyroxene and plagioclase being the host for REE other than a small (12%) fraction of the Eu. They also demonstrate that phosphides are not a significant REE reservoir. This seemingly leaves only the sulfides as serious possibilities; in particular FeS, niningerite and CaS.

FeS seems an unlikely site for REE on chemical and crystallographic grounds (Table 3). If the REE were concentrated to any extent in niningerite, we would expect them to correlate with the highly variable Mn, which they do not. The most reasonable host phase for the REE seems to be the oldhamite. REE have covalent radii resembling that of Ca and their monosulfides have the same crystallography. But then why were the REE not concentrated in Shima and Honda's weak acid solution? It seems likely that the CaS dissolved in the acid, but that the rare earths precipitated nearly quantitatively as sulfides or hydroxides which remained with the meteoritic solids and appeared in the next two dissolutions. It is also significant that the actinides (U and Th), which have cubic (halite) monosulfides and, in their trivalent state, have ionic radii resembling that of Ca are also concentrated in the oldhamite [19,20].

3.4. Volatile chalcophile elements (Zn, Cd and Se) in the clasts

These three elements are chalcophile in all chondrite groups. They show considerable variation in their observed abundance in enstatite chondrites, hence it is difficult to assign mean EH values; we have fairly arbitrarily chosen values of 450 $\mu\text{g/g}$ Zn, 800 ng/g Cd and 26 $\mu\text{g/g}$ Se. Since we are primarily interested in relative abundances, this should introduce no problems.

Zn and Cd are not located in niningerite, or they would be as enriched as Mn in 1,1 and 2,2. This is also unlikely on crystallographic grounds.

Rather they are probably in phases that are only occasionally associated with niningerite. Sphalerite (ZnS) has been reported as a trace mineral in EH chondrites and is the most probable main host for one or both of Cd and Zn.

Selenium does not correlate with any chalcophile cation suggesting that it does not strongly prefer a particular sulfide. Unlike the elements so far discussed, Se substitutes as an anion and therefore is probably distributed fairly uniformly among the sulfide minerals. Similarly, Sb does not correlate strongly with Mn or V although it is frequently assumed to be chalcophile. In these data, Sb seems to show siderophile behavior in that it is high ($\sim 3 \times$ mean EH) in metal-rich clast 2.1. Note however, this enrichment is not quite so high as the other siderophiles ($\sim 4 \times$ mean EH) suggesting that at least some Sb is non-siderophile.

3.5. Dark inclusions

Our data for the two dark inclusions from Abee are listed in Table 1 and are shown in Fig. 5, Mg-normalized and ordered according to cos-

mochemical behavior. The two inclusions are chemically very similar to each other. Siderophile elements are generally about $0.25 \times$ mean EH in both inclusions, reflecting their low metal abundances. A. Rubin (personal communication) found a still lower metal content by planimetric determinations of one dark inclusion (SI 2096 contained 21 mg/g compared with a normal value for Abee of ~ 300 mg/g). In both inclusions, the abundance of Fe is higher than that of other siderophiles, probably because Fe is also present as sulfides.

An unexpected feature of these dark inclusions is their high abundance of REE. It was possible to determine six REE by INAA in these inclusions, whereas only two were readily measurable in the other clasts. In both inclusions, all but Eu are much higher than mean EH values; $5 \times$ mean EH in 2096 and $3 \times$ mean EH in 9,13,1. The dark inclusions are also enriched in V ($\sim 1.5 \times$ mean EH). If our above assignments of elements to phases are correct, the inclusions are very rich in oldhamite and troilite, but the proportion of oldhamite to troilite is higher in the inclusions

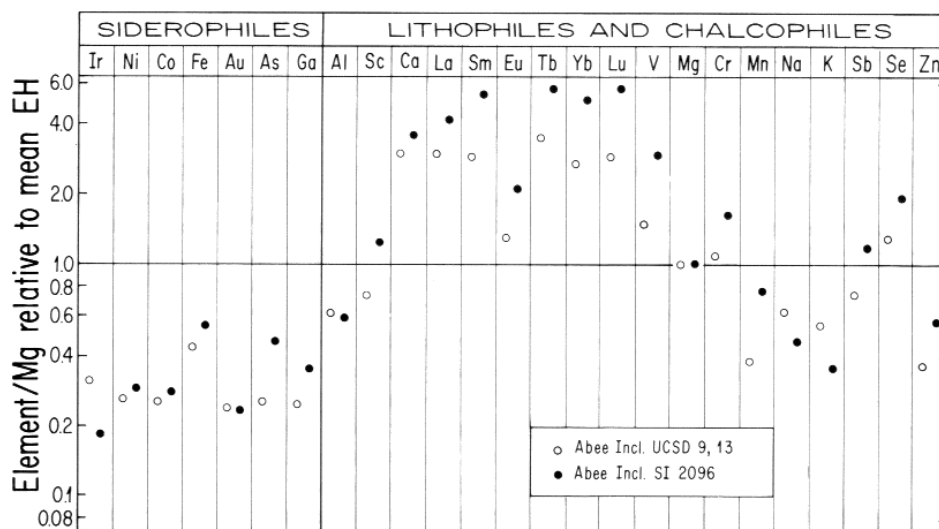


Fig. 5. Abundance pattern of 24 elements in two dark inclusions from the Abee meteorite. Data are Mg and mean EH normalized. The low siderophiles reflect low metal content, the low Sc and Mn reflect low niningerite ((Fe,Mg)S), the low Al, Na, K and the negative Eu anomaly reflect low feldspar contents. The high rare earth and Ca abundances are interpreted to indicate high CaS and the high V to reflect high troilite contents in the inclusions.

than the clasts; the REE/V ratio is ~ 3 compared with ~ 1.0 – 1.3 for the REE/V ratio in the clasts. Scandium and Mn are lower than REE abundances in both inclusions, which probably reflects low niningerite contents. Scandium is less depleted than Mn, presumably because some Sc is present in orthopyroxene. Since Ca is evenly distributed between niningerite and oldhamite, and niningerite is low, the high Ca abundance ($3 \times$ mean EH) also indicates a considerable enrichment of CaS.

The REE, V, Sc and Mn abundances are about a factor of two higher in SI 2096 than in 9,13, which presumably reflects a higher abundance of oldhamite, troilite and niningerite in the former. The alternative explanation, that SI 2096 is ~ 2 -fold depleted in enstatite relative to 9,13,1 is ruled out because abundances of the feldspathic elements (Al, Na and K) and siderophiles are generally very similar in the two inclusions. We emphasize, though, that despite these differences, the elemental abundance patterns displayed by the inclusions are quite similar.

The Eu depletion in the dark inclusions is probably due to the location of some of the Eu in the plagioclase or pyroxene. Shima and Honda [41] found that 12% of the Eu in Abee was in the HF-soluble fraction (i.e. pyroxene and plagioclase—less than a few % of other REE were in this fraction). Plagioclase is the more likely site, since Al, Na and K are 0.2 – $0.6 \times$ mean EH in these inclusions (less than a few percent of the Ca is in plagioclase, thus low plagioclase does not affect total Ca).

The two dark inclusions are compositionally very different from mean EH, and their similarity to each other suggests that they represent a definite entity, rather than random samples of a continuous population that includes the clasts. They are also very different from any known class of meteorite or any reasonable interpolation between known meteorite classes.

4. Origin of the chemical heterogeneity among the clasts

The heterogeneous nature of clasts is surely related to the brecciated texture of Abee, but the

reason is not immediately clear. The St. Mesmin LL chondrite is also brecciated, yet except for those that have been melted, its clasts are closely similar in composition on a 200-mg scale [21]. What made Abee more heterogeneous?

There are probably five stages in the history of the Abee meteorite when the trace elements could have been redistributed. In reverse chronological order these are: (1) mobilization associated with recent shock events; (2) metamorphism that post-dates brecciation; (3) the brecciation process itself including concurrent metamorphism and regolith activity; (4) metamorphism that predated brecciation; (5) condensation and agglomeration in the nebula.

Evidence for late shock in Abee is meagre; there are no cross-cutting veins and none of the metallographic, X-ray diffraction or gas-loss evidence frequently discussed in connection with blackened ordinary chondrites [22–24]. Any shock events must have occurred early and have been followed by a period of metamorphism sufficient to erase most of the petrologic evidence. Local variations in metal content are also present in the EL6 chondrite Khairpur [45], which may also be the result of the redistribution of a low-temperature, shock-induced melt. Shock events would redistribute elements by mobilizing metal and sulfides and by generating impact melts. The temperature of the liquidus in the FeS-MgS-Fe system is poorly known. If the melting point of niningerite is near that of MgS then it could not be fractionated from CaS by melting processes without melting and differentiating the whole meteorite (Chase et al. [27] estimate the 1-atm melting points of CaS and MgS to be ~ 2673 K and ~ 2273 K, respectively).

Any post-brecciation metamorphism experienced by Abee resulted in low-temperatures (< 500 K), because Sugiura and Strangeway [25] find randomly oriented magnetic vectors in several clasts. The intense metamorphism suffered by Abee was therefore clearly concurrent or predated brecciation. In any event, regolithic processes such as comminution in the regolith and metamorphism that accompanied regolithic activity would mainly homogenize bulk composition and are thus unlikely sources for the heterogeneity of Abee. Argu-

ments based on analogies yield a confused picture, presumably because there are several ways of producing metal inhomogeneities in meteorites. The presence of local variations in the metal content of Khairpur, which is not a breccia, seems to argue against brecciation-produced heterogeneity. On the other hand, mesosiderite clasts often have metal contents that differ from clast to clast but that are relatively uniform within each clast (see Wasson [28, fig. XIV-3]). Mesosiderite silicates were extruded metal free and the finely divided metal which is present was mixed during regolithic processes. Thus regolithic processes did apparently produce heterogeneous clasts in this case. In the present case, it is important that the metal heterogeneities are accompanied by complex variations in the abundance of several major sulfides which are not readily understood in terms of simple shock-melting models.

It is clear that nebula processes are capable of causing variations in the total siderophile and sulfur contents of enstatite chondrites since only nebula processes could produce meteorites classes which contain chondrules and roughly solar proportions of sulfides, silicates and metal [3,6,29] and it is variations in these materials that distinguish EH from EL meteorites. It is plausible, therefore, that much of the heterogeneity observed in Abee was of nebular origin.

5. Origin of the dark inclusions

The major properties of the dark inclusions may be summarized as follows:

(1) In the hand specimen they appear irregular in shape, and range from millimeter to centimeter dimensions. They are softer than the host material, so they appear slightly depressed on a polished surface, and their high sulfide abundance gives them a characteristic yellow tinge. They seem to occur only in the matrix of the breccia; no large (> a few millimeters) irregular inclusions of this kind occur in the clasts.

(2) They are metal-poor, although some metal is still present. This metal is variable in composition, and, unlike any elsewhere in the meteorite, is particularly Ni-rich (~ 140 mg/g Ni) [14].

(3) The inclusions are sulfide-rich. Probably related to this is the observation that they are also REE-rich, with CaS the probable REE carrier.

(4) The REE display a negative Eu anomaly and Na, Al and K contents are low suggesting a low abundance of feldspar.

(5) Mn is depleted, suggesting a low (Mg,Fe)S abundance in the inclusions.

The dark inclusions are not chondrules because the Ni abundance of chondrule metal is indistinguishable from metal outside chondrules (~ 70 mg/g) and remarkably homogeneous. Chondrules are almost always sulfide-poor, are not enriched in REE and, in Abee, are always porphyritic or radiating pyroxene.

There are problems with explaining the observed sulfide distribution by melting processes. Dark inclusion 5,1*, for example, contains 9.4% CaS and 39% FeS (Keil's [11] figures for the bulk meteorite are 0.19% and 5.8%, respectively) yet CaS has probably the highest and FeS the lowest melting point of the minerals in Abee.

The siderophile elements and certain lithophile elements (Al, Sc, Mn, Na, K and Zn) have abundances in the dark inclusions which could fit into the EH-EL-aubrite sequence. However, in their most distinctive feature, their REE enrichment, and in their high Ca, V, Sb and Se values, the dark inclusions do not resemble the other classes or any reasonable interpolation between them or extrapolation from them. Thus they are not a new class of enstatite chondrite. Alternatively, the dark inclusions could be the result of an unusual combination of condensation and agglomeration, perhaps limited to a narrow temperature interval. For example, Ganapathy and Larimer [26] suggest that a 6- μ g graphite grain from Abee, which was found to be volatile-rich, formed at very low temperatures in the nebula.

This is a difficult hypothesis to test, since it requires details of the condensation sequence applicable to the enstatite chondrites. Although the sequences calculated by Larimer and Bartholomay [2] and Lattimer and Grossman [30] assume a two-fold enrichment in carbon and predict large

* Preliminary INAA data for this inclusion indicate that it too has a considerable (~ 5 \times) enrichment in REE [46].

TABLE 4

Data and results concerning the condensation of La and Sc in a cosmic gas and in a reducing nebula

Species condensing	Relevant reaction ^a	Sources of thermodynamic data ^b	50% condensation temperature		Comments
			10 ⁻³ atm	10 ⁻⁴ atm	
<i>Cosmic gas</i> ^c					
CaTiO ₃	Ca + TiO – 2 H ₂ O = CaTiO ₃ (s) + 2 H ₂	33, 34, 43	1658	1575	assumes ideal solution between LaO _{1.5} and CaTiO ₃
Sc	2 ScO + H ₂ O = Sc ₂ O ₃ (s) + H ₂	34, 35, 36, 43	1673	1603	
La	LaO + $\frac{1}{2}$ H ₂ O = LaO _{1.5} (ss) + $\frac{1}{2}$ H ₂	34, 35, 43	1598	1522	
<i>Reducing gas</i> ^c					
CaS	Ca + SiS + C(s) = CaS(s) + SiC(s)	27, 34, 43	1377	1292	assumes ideal solution between LaS and CaS
Sc	2 Sc + 3 CO = Sc ₂ O ₃ (s) + 3 C(s)	34, 36, 43	1427	1350	
La	ScS(g) = ScS(s)	27, 34, 36, 37, 43	1295 ^f	1225 ^f	
	LaO + SiS + 2 C = LaS(ss) + SiC(s) + CO	27, 33, 35, 43	1390 ^g	1304 ^g	

^a Gaseous reactants unless otherwise indicated by subscript.^b Data from Tunge et al. [37], Wagman et al. [38] and Kelley [39] were used to estimate the abundance of Sc₂(g), Sc(g), ScO(g), ScS(g), ScF(g), ScCl(g), La₂(g), La(g), LaS(g), LaF(g), LaCl(g).^c Elemental abundances (relative to Si equals 10⁶) as follows: H, 2.66 × 10¹⁰; O, 1.84 × 10⁷; C, 1.11 × 10⁷; S, 5 × 10⁵; Ca, 6.25 × 10⁴; Ti, 2400; Sc, 31; La, 0.37.^e Elemental abundances as for cosmic except C, 2.22 × 10⁷.^f Assumes Sc₂O₃(s) does not form.^g The values given are for the condensation of CaS, since La is fully present in CaS when it condenses.

amounts of unobserved phases such as SiC, they yield many phases observed in enstatite chondrites (Si-bearing metal, CaS and TiN) and provide an approximate guide as to the condensation sequence at the enstatite chondrite location *.

* The results described in papers 2 and 30 are in good agreement, except for a difference over the condensation of Ti as TiC or TiN which is probably a consequence of the different working pressures assumed. The model has serious deficiencies—it predicts a condensate which is predominantly graphite, that SiC is 10 times as abundant as CaS and that AlN is comparable in abundance to CaS, whereas graphite has only been found as a trace mineral and the others are absent. However, in that it does predict many of the reduced phases that are observed in enstatite chondrites we consider it a reasonable first-order approximation. The amount of graphite depends on the C/O assumed, being negligible if C/O = 1 and abundant as C/O becomes much larger than 1.

Instead of oxides and silicates being the initial condensates, as in a cosmic gas, AlN, SiC, CaS and TiN and probably (FeNi)₃P condense ahead of Al₂O₃. Phosphides were not included in references 2 and 30, but they are high-temperature condensates in a cosmic gas [31], and should be included. Thus a high-temperature condensate may be expected to be enriched in CaS and depleted in metal and silicates.

It also seems that REE would be enriched in such a condensate. Table 4 shows the results of some new calculations of the condensation behavior of La. We found that LaO(g) was the dominant stable gas phase for La, although LaS(g) and La(g) were also important, and that LaS(s) condensed soon after CaS(s). If LaS forms an approximately ideal solution with CaS, then it would condense

along with CaS. Using the thermodynamic data of Gschneider and Kippenhan [32], and assuming ideality, solid solution of LaC_2 in TiC and LaN in TiN were found to be unimportant.

The major difficulty with a high-temperature nebular origin for the dark inclusions concerns the FeS. Even in a highly reducing gas, FeS condenses well below 1000 K and its abundance in the inclusions is inconsistent with a high-temperature origin. The depletion of Sc in the dark inclusions offers additional evidence against this model. Our thermodynamic calculations indicate that the dominant gas phase for Sc is Sc(g), although ScO(g) and ScS(g) are also important, and that Sc condensed as Sc_2O_3 at higher temperatures than CaS (Table 4), and should be as abundant as the REE in high-temperature condensates.

In conclusion, we believe that the composition of the dark inclusions suggests that they are the result of a complex, multi-stage process. If the high CaS is the result of the isolation of a high-temperature condensate or if it is a residual solid from a melting event, a subsequent process is required to add FeS.

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