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ENSTATITE METEORITES

The term 'enstatite meteorites' is used to describe collectively several small groups of meteorites (see Meteorite) which differ in many respects but which have in common a high state of reduction. Thus unlike other meteorites, the iron in the enstatite meteorites is entirely in the metallic and sulfide forms, while their silicates are remarkably Fe-free (see Chondrites, ordinary and Carbonaceous chondrite). The metallic phase of enstatite meteorites even contains Si (despite the strength of the Si–O bond), and there are a great many sulfide minerals in these meteorites which also involve elements normally bound to oxygen. These are absent from other meteorites and extremely rare or unknown on Earth. The enstatite meteorites even contain nitride minerals.

Another distinctive feature of these meteorites is the low Mg/Si ratio of the silicate fraction (approximately 0.85) compared to that of other early solar system materials (the solar ratio is 1.05). As a result of this, and the low oxidation state, the dominant silicate mineral is enstatite ($MgSiO_3$).

A recent list of the known enstatite meteorite stones was published by Keil (1989). Other enstatite meteorites are the Horse Creek iron meteorite and the Mount Egerton stony iron meteorite.

Classification

While sharing these unusual compositional properties, the enstatite meteorites show great diversity in texture and composition and include many very different classes. Horse Creek and Mount Egerton were mentioned above. Of the stones, some are chondrites, having essentially solar composition and often containing chondrules (see below), while others are igneous rocks. These igneous rocks are termed 'enstatite achondrites', the term 'achondrite' arising from their conspicuous lack of chondrules, or they are termed aubrites, after an important member of the class, Aubres. Enstatite meteorites thus span the full range of stone (achondrite and chondrite), iron, and stony iron meteorites.

Enstatite chondrites

The texture of the chondrites, as well as their compositions, suggests agglomeration of their components (silicates, metal and sulfides) in the early solar system without subsequent reprocessing. However, the relative proportions of the metal, sulfide and silicates vary widely. They have been subdivided into two groups, the EH (high iron) and EL (low iron) chondrites, depending on the amount of iron and other siderophile elements in the bulk analysis. The plot of the Fe/Si ratio against the Mg/Si ratio (Figure E29) is thus a convenient way of summarizing the enstatite meteorite classes in terms of their bulk compositions (Sears *et al.*, 1982). A recent count included 21 EH chondrites, 19 EL chondrites and 13 enstatite achondrites, but this number changes frequently as new discoveries are reported.

Like the other chondrite classes, (see Carbonaceous chondrite; Chondrites, ordinary), many enstatite chondrites contain chondrules. These are approximately spherical aggregates of silicate grains encased in glass which may subsequently have crystallized.

The space between the grains is filled with silicate, sulfide and metal grains. Very little of the fine-grained matrix characteristic of the other chondrite groups is present.

Aubrites

The aubrites are igneous rocks consisting of coarse-grained enstatite with small amounts of other silicates and trace amounts of metal and iron sulfide. This mineralogy is reflected in their bulk compositions; not only are their Mg/Si ratios lower than that of the Sun, but they are also highly depleted in siderophile and chalcophile elements (e.g. Fe/Si; Figure E29).

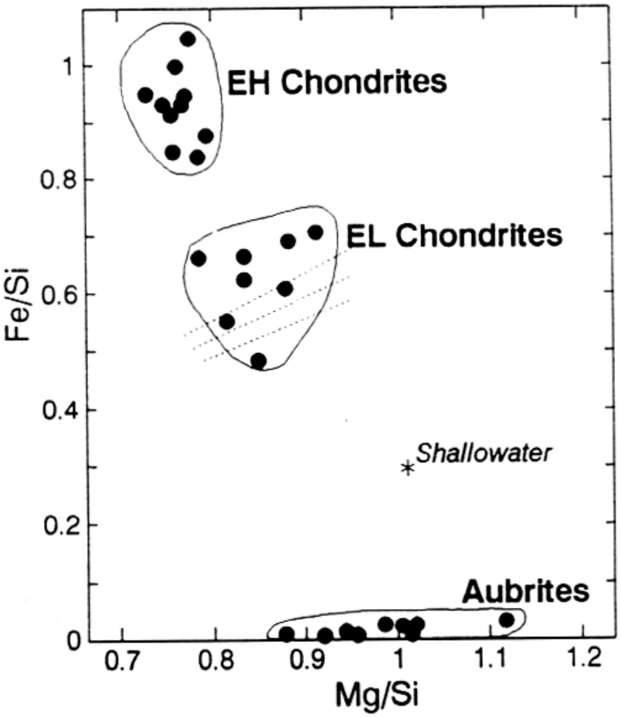

Figure E29 Plot of Fe/Si against Mg/Si for the bulk compositions of enstatite meteorites. These data enable the EH, EL and aubrite classes of enstatite meteorites to be resolved. Plotting in the field between the EL chondrites and the aubrites is the unusual metal-rich Shallowater aubrite. The broken lines refer to meteorites whose Si content is unknown, so their exact placement on the plot is unclear.

Except for Shallowater, the aubrites are all breccias. Some are fragmental breccias, composed of angular pieces, while a few are regolith breccias (see Breccia). Regolith breccias consist of rock fragments embedded in a soil-like matrix which is rich in inert gases. The elemental and isotopic patterns of the gases show that they were deposited by the solar wind. The process occurred while the meteorites were part of a regolith similar to that on the lunar surface (Keil, 1989). This suggests a near-surface location on the parent body for the aubrites.

Mineralogy

In addition to enstatite, metal and troilite (FeS), the enstatite chondrites contain minor amounts of graphite, schreibersite ($(Fe,Ni)_3P$), sphalerite (ZnS), oldhamite (CaS), daubreelite ($FeCr_2S_4$), various crystallographic forms of SiO_2 and the silicates, plagioclase and olivine. There are several mineralogical differences between EL and EH chondrites, some reflecting differences in bulk composition while the others reflect differences in metamorphism on the parent body. Thus in general, only the EH chondrites contain djerfisherite (a complex potassium sulfide containing Na, Cu, Fe and Ni) and niningerite (MgS, with some dissolved FeS), while the EL chondrites contain sinoite (Si_2N_2O) and alabandite (MnS with some FeS). The EH chondrites also contain greater quantities of metal and sulfide than the EL chondrites, and the plagioclase in EH chondrites is albite ($NaAlSi_3O_8$) while in EL chondrites it is oligoclase (a solid solution of albite and 15 mol% anorthite, $CaAl_2Si_2O_8$; Keil, 1968). The composition of the unusual metal found in enstatite meteorites and of the so-called 'cubic sulfides' (FeS–MgS–MnS) is summarized in graphical form in Figure E30.

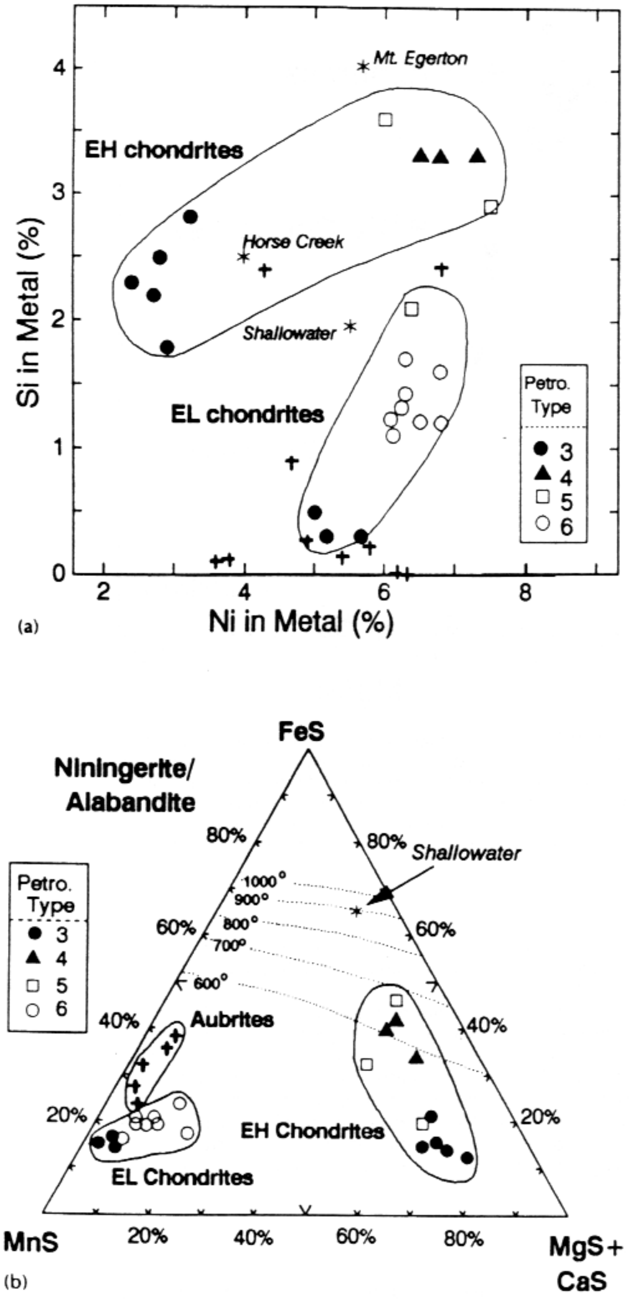

Figure E30 The compositions of metal and sulfide in enstatite meteorites are among their most characteristic properties. (a) The metal is noted for its Si content which is here compared with Ni. The EH and EL chondrites plot in discrete fields within which the Ni and Si in the metal increase with petrographic type. The aubrites (plus symbols) plot near or in the EL field, Mount Egerton and Horse Creek plot with the EH chondrites while Shallowater is intermediate. (b) The curved lines on this FeS–MnS–MgS/CaS triangular plot refer to experimentally determined values observed at the indicated temperatures (Skinner and Luce 1971). The EH chondrites and the Shallowater aubrite contain niningerite (Mg-rich solid solution) and the equilibration temperatures decrease along the series Shallowater, EH4, 5 and EH3. The EL chondrites and the other aubrites contain an Fe-rich alabandite (MnS-rich solid solution) with very low equilibration temperatures. The equilibrium curves below 600°C are unknown, but equilibration temperatures for EL3 appear to be lower than those for EL6 chondrites.

Aubrites consist predominantly of enstatite with lesser amounts of sulfide and metal, small amounts of plagioclase, olivine and diopside, and trace amounts of the sulfides discussed above and phosphides (Watters and Prinz, 1979). They resemble the EL chondrites more closely than the EH chondrites in several respects, for example the composition of their metal grains and cubic sulfides (Figure E30). Osbornite (TiN) has been observed in several aubrites.

Metamorphism

Petrographic types

Like most chondrites, the EH and EL chondrites have experienced elevated temperatures which caused various solid state changes ('metamorphism') on their parent bodies. The petrographic types of Van Schmus and Wood (1967) divide the chondrites into types 1 to 6 according to metamorphism, where the higher value refers to greater levels of metamorphic alteration. Types 1 and 2 are reserved for aqueously altered carbonaceous chondrites, so that enstatite chondrites cover types 3 to 6. The type is usually written alongside the class, e.g. EH5 or EL3. During metamorphism, mineral grains became compositionally homogeneous; the chondrule glass characteristic of the low types is absent. The enstatite has been converted from the monoclinic to the orthorhombic crystal structure; and textures were obliterated to the extent that it is very difficult to detect chondrules in type 6 enstatite chondrites. At the present time EH chondrites of types 3–5 are known while EL chondrites of type 3 and 6 are known. This is changing almost daily as new meteorites are being recovered, especially in the Antarctic.

Metamorphic temperatures

The temperatures experienced by the enstatite chondrites can be estimated from equilibria between the various sulfide minerals, and between the phosphides and metal (Zhang, Benoit and Sears, 1992). An example of the method, and an important feature of the results, is illustrated in Figure E30b. Inserted on Figure E30b are five isotherms showing the equilibrium compositions at these temperatures. Similar isotherms could have been drawn on Figure E30a. Type 4 and two type 5 EH chondrites appear to have equilibrated at around 600°C, one of the EH5 and the EH3 chondrites seem to have equilibrated well below 600°C, while for Shallowater the value is 900°C. In contrast, all the EL chondrites plot well below the 600°C value, even though some are type 6 and the aubrites are igneous. The simplest interpretation is that the meteorites lying well below the 600°C isotherm have either experienced (1) very little metamorphism (which is apparently the case for the type 3 chondrites), or (2) they cooled very slowly following metamorphism and were able to continue to react down to temperatures << 600°C. This suggests a very different physical history for the EH and EL chondrites (Skinner and Luce 1971; Zhang, Benoit and Sears, 1992). In contrast, equilibration temperatures involving the silicates and oldhamite are around 1000°C, suggesting that these systems were unaffected by metamorphism at low temperatures and may preserve a record of pre-accretionary (nebular) processes.

Type 3 enstatite chondrites

Enstatite chondrites of type 3 have been recognized only recently. Several EH3 chondrites are known (Prinz *et al.*, 1984) but only three fragments of a single EL3 chondrite are known (Lin *et al.*, 1991; Chang, Benoit and Sears, 1992) although there are clasts of EL3 material in the unusual Kaidun meteorite (Ivanov and Ivanov 1989). Type 3 enstatite chondrites contain heterogeneous minerals, including enstatite, which is sometimes unusually FeO-rich for the class, and abundant well-defined, glassy chondrules. Unlike the higher petrographic types, they also contain significant amounts of olivine (Mg_2SiO_4 containing small amounts of Fe_2SiO_4). There are also detailed differences in the composition of the metal and sulfides between type 3 and the higher types (Figure 30a,b), reflecting their different equilibration temperatures. Type 3 enstatite chondrites are enriched in volatile elements relative to the higher types and there is experimental evidence that this is because metamorphic heating caused volatile element loss (Biswas *et al.*, 1980).

Unusual enstatite meteorites

Happy Canyon is an EL6 chondrite with an igneous texture (Olsen *et al.*, 1977). It is probably an impact melt (Keil, 1989). Shallowater is an unusual aubrite, rich in metal (3.3 vol%) and is unbrecciated. Keil *et al.* (1989) recently suggested that it has experienced a multistage cooling history on a separate parent body from the other enstatite meteorites.

The Horse Creek iron meteorite contains 2.5% Si, similar to the metal in EH chondrites, and there are lamellae of the Fe–Ni–Si phosphide, perryite (Buchwald, 1975). The metallic phase in the Mount Egerton stony iron meteorite resembles that of Horse Creek while its silicate portion resembles the aubrites (McCall, 1965). The silicates in the Tucson iron meteorite contain Fe-free olivine and pyroxene, and the metal phase contains Si, so an affinity towards the enstatite chondrites can be inferred (Nehru *et al.*, 1982). However, the abundance of olivine and different oxygen isotope patterns (see below) suggest that the link is weak.

There have been numerous reports of clasts resembling enstatite meteorite materials in other groups of meteorites, such as in the unusual Allan Hills A85085 and Kaidun carbonaceous chondrites and the Bencubbin stony iron meteorite. Allan Hills, Kaidun and Bencubbin are sometimes regarded as CR chondrites, so there may be a link between the enstatite meteorites and the CR chondrites.

History and origin

It is widely assumed that, like the other chondrite classes, the enstatite chondrites are aggregations of nebular materials including chondrules, metal and dust. However, their unusual compositions and their highly reduced state are a major challenge to the simple chemical models which work so well for the other chondrite classes. The observed mineral phases suggest a non-solar C/O ratio, but it is unclear how this was produced.

The enstatite meteorites have formation ages of about 4.5 Ga (Minster, Ricard and Allegre, 1979), comparable with the Earth, Moon and Sun, and they formed over a small interval of time, ~ 50 Ma, soon after the end of nucleosynthesis. There is some evidence that the EL chondrites formed about 4 Ma after the EH chondrites (Kennedy *et al.*, 1988) (see Chronology: meteorite).

Since the aubrites have igneous textures it has often been suggested that they were formed by a melting process acting on material resembling the EL6 chondrites (e.g. Fogel, Hess and Rutherford, 1988). This has been challenged on several grounds, most notably the Ti content of the FeS (which is much higher than can readily be explained by conversion of enstatite chondrites to aubrites) and the phase composition of the aubrites (Brett and Keil, 1986), but also the lack of instances where aubrite and enstatite chondrite material coexist in the same breccia, although the matter is still unresolved. Several authors have also discussed the possibility that the bulk composition of the aubrites was determined by primary (i.e. nebular) processes prior to the igneous phase of their history (Sears, 1980).

Most authors accept that the enstatite meteorites spent most of their solar system history in the asteroid belt, and several small rare asteroids have spectral reflectivity similar to that of the enstatite meteorites (Zellner *et al.*, 1977) (see Asteroid). However, others have discussed an origin for the enstatite meteorites much closer to the sun (Wasson and Wetherill, 1979; Sears, 1980). Oxygen isotope data for the aubrites, EH chondrites and EL chondrites distinguish them from the other meteorite classes and suggest not only a genetic link between the three classes of enstatite meteorite but also a possible link with the Earth and Moon (Clayton *et al.*, 1984).

The abundance of cosmic ray-produced isotopes indicates that the enstatite chondrites were fragmented to meter-sized objects 0.5–200 Ma ago, aubrites having been exposed to cosmic rays for longer than enstatite chondrites (Wasson and Wai, 1970) (see Cosmic ray exposure age).

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Cross references

Achondrite meteorites
Carbonaceous chondrite
Chondrites, ordinary
Cosmic ray exposure ages
Iron
Meteorite