THE SHALLOWATER METEORITE; A NEW AUBRITE

William F. Foshag[1]
U. S. National Museum, Washington, D. C.

Abstract

The Shallowater meteorite was found near Shallowater, Lubbock County, Texas. It is an aubrite made up of enstatite (En_{100}) 81%, fosterite (Fo_{100}) 5%, oligoclase ($Ab_{83}An_{17}$) 2%, iron-nickel ($Fe_{93}Ni_7$) 9%, troilite 1½%, miscellaneous 1½%. The silicates are remarkably free from iron. It is suggested that this meteoric material is the result of crystallization from a melt and that the iron-nickel and troilite are later.

Introduction

The Shallowater meteorite was brought to my attention by Mr. Harvey H. Nininger of the American Meteorite Laboratory, who obtained it from Mr. B. O. McWhorter of Lubbock, Texas, who marketed the Estacado stone many years ago. Mr. Nininger has given me the following interesting account of its discovery:

In 1933, I spent some time with Mr. McWhorter showing him various types of meteorites and urging him to keep on the lookout for specimens. We exchanged letters frequently thereafter. In 1936 during May, he was visiting with the man who then lived on the old ranch once owned by Mr. McWhorter near Shallowater, Texas. He showed Mr. Mullican a number of specimens which I had left with McWhorter for that purpose. Mullican thought at the time that he remembered seeing such a stone but said nothing. A few weeks later while working on the farm he came across the meteorite and reported it to McWhorter who in turn reported it to me. The stone was found on the S.E. quarter of Section 7, Block D 5, Lubbock County, Texas. This is about 3 miles northwest of Shallowater. Quite a thorough search has been conducted in the community but no other material has as yet shown up. The weight of the stone was 4750 grams.

The Shallowater meteorite as received was a polyhedral mass measuring 16 cm.×14 cm.×12 cm. The crust is now oxidized and badly iron stained but where it is best preserved shows a pimply surface. Where the corners or edges are broken, the coarse cleavage of the enstatite is easily evident. The color of the mass is now light chocolate brown, but this color is due to a tenuous infiltration of limonite.

The meteorite is extremely coarsely crystalline. The longest individual noted measured 4.5 cm. by .5 cm., while the largest equidimensional grain measured 2 cm. by 2.5 cm. or 5 cm.^{2} in area. Many of the grains are long lath-like individuals but with very irregular boundaries, the whole presenting a broad reticulating texture. Many of the crystals show iron oxide introduced along the cleavages during oxidation and weathering. Under the binoculars the clearer unstained grains are colorless, transparent to translucent and glassy. The enstatite, when cleaned of limonite by acids,

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becomes pure white in color. Cleavage is pronounced, giving the cut or polished surfaces a mottled silky sheen, and is conspicuous in thin section.

Occasional small inconspicuous vugs are present, showing a few rough faces of the bounding enstatite, some limonite and rarely a rounded fosterite grain, but no well defined crystals.

Unlike other aubrites and diogenites the Shallowater meteorite is not fractured or brecciated but is entirely made up of a firm, compact aggregate of enstatite individuals.

Except for the enstatite no mineral is evident except the small, irregular grains of nickel iron and troilite. Thin sections, however, reveal the presence of a little feldspar and fosterite.

Mineralogy

Enstatite. The Shallowater meteorite is essentially a monomineralic rock, consisting of enstatite, very coarsely crystalline in texture. On the broken surfaces the enstatite individuals can readily be distinguished by their prominent cleavage; on the polished faces by a prominent sheen, due to this cleavage. The crystal cross sections are, in general, coarse lath-like and the texture an irregular mosaic of these laths.

The color of the enstatite in the mass is gray-brown, but this color is induced by the minute films of secondary iron oxide introduced along the cleavage planes during oxidation and weathering. Under the binoculars the clear, unstained grains are colorless, glassy and transparent to translucent. The enstatite when cleaned of limonite by acids becomes pure white in color.

Cleavage is prominent both megascopically and microscopically. Measurement of cleavage fragments on the goniometer gave indifferent results but indicated the presence of the normal prismatic cleavage of 88° and 92°.

The optical properties of the Shallowater enstatite are given below: Biaxial, positive, $2V=54\frac{1}{2}°$.[2] Dispersion weak, $r>v$. Extinction parallel, but undulatory and other extinction anomalies common, including a hackly pattern suggestive of twinning. Plane of the optic axes is parallel

Table 1. Indices of Refraction of Enstatite, Shallowater, Meteorite

Foshag	Glass	Hess	$MgSiO_3$[3]
$\alpha=1.653$	1.647		1.651
$\beta=1.656$	1.649		
$\gamma=1.660$	1.658	1.6592	1.660

[2] Determination by Harry H. Hess.

[3] Bowen, N. L., and Schairer, J. F.: *Am. Jour. Sci.*, **29**, 199 (1935).

to the cleavage, with $Z=c$. No intergrowth of monoclinic pyroxene with the enstatite, so common in terrestrial rocks, was observed.

Indices of refraction, by the immersion method, are given in Table 1.

Inclusions are fairly abundant consisting of (1) long rod-like cavities parallel to the cleavage direction, often with included bodies of unrecognizable character, and (2) rounded or irregular inclusions, sometimes arranged in lines parallel to the cleavage direction, also with small included bodies.

The pure enstatite separated from the other constituents by a magnetic removal of the iron, and by heavy solution; and cleaned of limonite by dilute hydrochloric acid, gave upon analysis, the composition given in the table below.

Analysis of Enstatite, Shallowater Meteorite
W. F. Foshag, *Analyst*

SiO_2	59.92
Al_2O_3	None
Fe_2O_3	None
FeO	0.38
MgO	39.51
CaO	0.32
Na_2O	None
	100.13

This analysis, together with the indices of refraction indicate an enstatite of almost theoretically pure composition. Such pure enstatites are not found in terrestrial rocks but are characteristic of aubritic meteorites.

Fosterite. This mineral is not apparent to the eye but can be found sparingly in thin sections. It occurs as equant or subhedral grains sometimes with indications of crystal outline, poikilitically embedded in enstatite, from which it can be distinguished by its higher birefringence and poor cleavage. In contrast to oligoclase, which is quite irregular in shape, the fosterite is more equidimensional and quite round. In Fig. 1, characteristic grains of fosterite (F) are shown, the middle one being quite spherical in shape.

Fosterite was also found as rounded, glassy crystals in a few of the cavities of the meteorite from which they could be detached for further examination. These grains do not exceed a mustard seed in size. They are clear, glassy, rounded grains, without inclusions, somewhat flattened and with indications of crystal facets on their surfaces. They suggest the

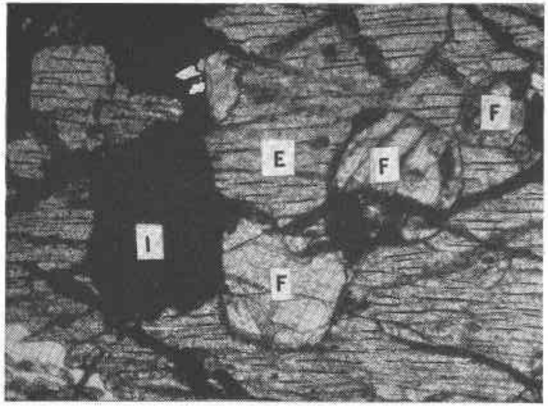

FIG. 1. Fosterite (F) and nickel-iron (I) in enstatite (E). Shallowater meteorite (×50).

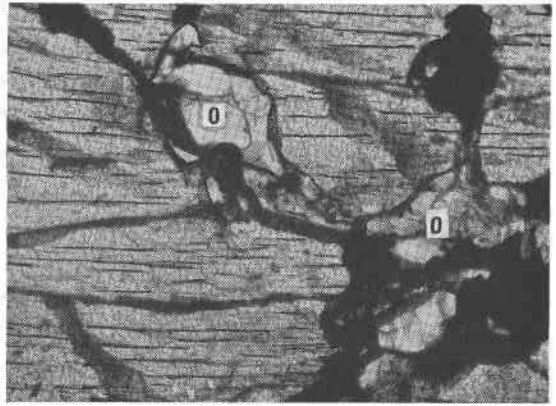

FIG. 2. Oligoclase (O) in enstatite. Shallowater meteorite (×50). The dark veins in 1 and 2 are secondary limonite stains.

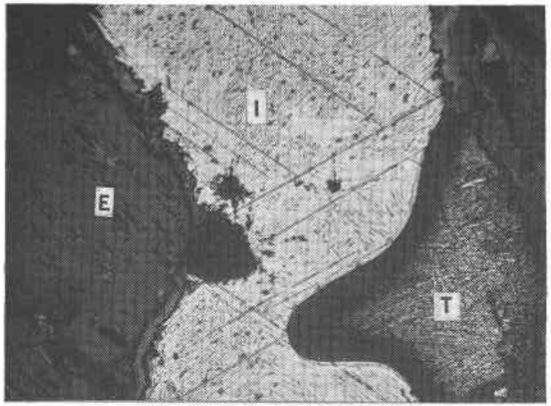

FIG. 3. Nickel-iron (I) etched with nitol, showing Neumann lines and pearlitic structure. Troilite (T) and enstatite (E). The border around the nickel-iron and the troilite is due to oxidation (×100). Shallowater meteorite.

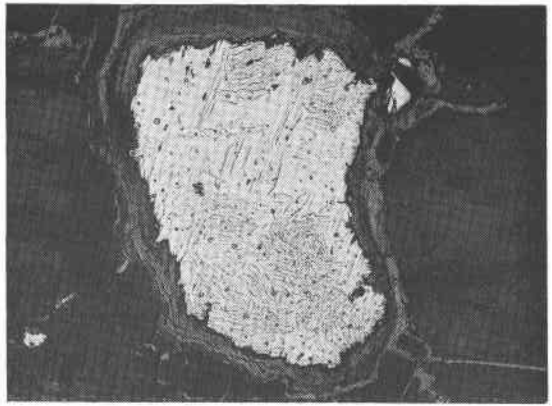

FIG. 4. Nickel-iron in enstatite, showing pearlitic structure. The border about the nickel-iron is due to oxidation (×100). Shallowater meteorite.

olivine grains described and figured by G. Rose[4] and N. V. Kokscharov.[5] The optical properties of these grains are as follows:

Biaxial, positive, with a large optical angle (2V nearly 90°). $\alpha=1.635$, $\beta=1.650$, $\gamma=1.670$. These grains have two prominent parallel facets and α(X) is normal to this face. From the optical orientation of fosterite this face is identified as the brachypinacoid (*b*).

The indices of refraction of pure fosterite are, according to Bowen and Schairer:[6] $\alpha=1.6359$, $\beta=1.6507$, $\gamma=1.6688$. The fosterite of the Shallowater meteorite is, then, pure magnesium silicate.

Oligoclase. Feldspar is not evident to the naked eye but is observable in thin sections under the microscope and was found sparingly in the insoluble portion, from which it was separated by heavy solution. The material so recovered is in clear and glassy fragments, very rarely showing crystal form. A single small crystal showed the forms: *a*(100), *b*(010), *c*(001) and $x(\bar{1}01)$, with $c\wedge x$, measured under the microscope, of 52°.

The indices of refraction of this feldspar indicate little or no variation in its chemical composition. $\alpha=1.537$, $\beta=1.541$, $\gamma=1.545$. This corresponds to oligoclase of the composition $Ab_{83}An_{17}$.

Under the microscope the oligoclase is seen as small irregular grains embedded within the enstatite crystals (O in Fig. 2) or associated with rounded fosterite grains. It is clear and glassy and rarely shows inclusions. In the crystal mentioned above, long rodlike cavities or rows of small irregular cavities formed lines parallel to the face $x(\bar{1}01)$ and to the base *c*(001). Occasional grains show a faint, very fine polysynthetic twinning. An unusual feature is that oligoclase grains within the same general area often come to extinction simultaneously, even though they are quite widely separated. Usually all the oligoclase grains enclosed in a single enstatite individual extinguish together.

Tridymite or cristobalite was sought for in the heavy solution fraction but was not found.

Nickel-iron. The nickel-iron forms irregular masses, which, in rare cases reach 3 mm. in maximum diameter. The iron masses often show deep semicircular embayments, where they are in contact with rounded rods of enstatite. There are occasional cavities in the meteorite, into which protrude such rounded grains of enstatite. These cavities resemble in size and shape the iron masses, and they have the appearance of cavities that have escaped a filling of iron. Irregular grains of iron occasionally are found embedded in the enstatite.

[4] Rose, G.: *Abhandl. Königl. Acad. Wiss., Berlin*, 73–75, 1864 (for 1863).
[5] Kokscharov, N. V.: *Mem. Acad. Imp. Sci. St. Petersburg*, 7th ser., **15**, 1–40 (1870).
[6] Bowen, N. L., and Schairer, J. F.: *Am. Jour. Sci.*, **29**, 196 (1935).

The nickel-iron and troilite grains are usually distinct but occasionally the two minerals (Fig. 3) show an area of troilite in association with iron.

Since the nickel-iron is sparsely distributed in the meteorite, a small sample sufficient only for a nickel determination was separated and cleaned for analysis. Nickel was determined by dimethylglyoxime from a solution in which the iron was retained in solution by tartaric acid. This method has proven to be the best for simple nickel determinations. The results of this determination gave 6.70 per cent nickel, insoluble (enstatite) 1.91 per cent. On the basis of a silicate free sample the nickel content would be 6.83 per cent. This conforms well with Prior's[7] theory that low-iron silicates are associated with low nickel irons, in this case iron free enstatite and fosterite with nickel-iron almost the composition of kamacite.

The structure of the nickel-iron shows, upon etching with 10% nitol, two sets of figures; one, straight lines, similar to and perhaps identical with Neumann lines (Fig. 3); and a second pattern resembles that of pearlite (Figs. 3 and 4). The straight etch lines I would interpret as the cleavage lines of α-iron (kamacite) but for the second pattern, I offer no explanation.

Vivianite. A very few of the small cavities of the meteorite are filled with a compact dark gray-blue mineral of a semi wax-like consistency. Under the microscope this mineral is very fine grained, sometimes rather shredded. The large shreds show a strong pleochroism in deep blue and pale olive and have a mean index of refraction of less than 1.655. Chemical tests show the presence of iron and phosphorus. The mineral is probably vivianite. It appears to be a secondary product due to the weathering of some original phosphide or phosphate mineral.

Mineral Composition

A characteristic sample of the meteorite of almost ten grams was crushed and digested in nitric acid. In the insoluble residue, separated silica was redissolved by digestion with sodium carbonate. The soluble portion was analyzed with the following results:

Analysis of the Shallowater Meteorite

Soluble portion

SiO_2	2.90 per cent
Al_2O_3	0.25
MgO	2.74
CaO	0.21
Na_2O	0.21
K_2O	0.04
Cr_2O_3	0.05

[7] Prior, G. T.: *Min. Mag.*, **18**, no. 83, 26–44 (1916).

Fe[1]	9.05
Ni	0.60
S	0.45
P[2]	0.19
	16.69 per cent

[1] Includes also Fe as oxides in limonite, chromite, vivianite, etc.
[2] Probably as P_2O_5 in vivianite, etc.

No determination was made of the amount of oligoclase present in the meteorite but it was estimated at about 2 per cent.

The mineralogical composition of the Shallowater meteorite can be given as follows:

Mineralogical Composition of the Shallowater Meteorite

Enstatite (En_{100})	81 per cent
Fosterite (Fo_{100})	5
Oligoclase ($Ab_{83}An_{17}$)	2
Iron-nickel ($Fe_{93}Ni_7$)	9
Troilite	1½
Miscellaneous	1½
	100 per cent

Origin

The silicate portion of the Shallowater meteorite, like the terrestrial enstatolites and other similar pyroxenites, is difficult to interpret in the light of the equilibrium relations found in the system $MgO-SiO_2$ as worked out by N. L. Bowen and Olaf Anderson[8] and the system $MgO-FeO-SiO_2$ as worked out by N. L. Bowen and J. F. Schairer.[9] Clinoenstatite is the stable form at high temperatures; its inversion to enstatite takes place at 1140°. From the data furnished by these equilibrium studies it is not to be expected that an orthorhombic enstatite of the nature of the Shallowater meteorite should form directly by crystallization of its melt, or magma, without the intervention of the monoclinic form. For terrestrial enstatolites, Bowen and Schairer have been led to conclude that these rocks are the result of local accumulations of crystals of one kind from a magma of complex constitution.

Yet the extraordinarily coarse crystallinity of the enstatite, the total lack of any evidence of its derivation from a pre-existing form, and the reticulated fabric of the crystals, as well as the relation of the fosterite to the enstatite, suggest that this meteorite may, indeed, be a direct crystallization from a magma. The evidence of orthorhombic pyroxenes in

[8] Bowen, N. L., and Anderson, Olaf: *Am. Jour. Sci.*, **37,** 487–500 (1914).
[9] Bowen, N. L., and Schairer, J. F.: *Am. Jour. Sci.*, **29,** 151–217 (1935).

the chondrules of chondritic meteoric stones, too, should not be overlooked. There is perhaps some mechanism that has as yet escaped attention by which orthorhombic pyroxenes can result directly from melts.

The origin of the nickel-iron involves further difficulties in interpreting the origin of this rock. The association of iron-nickel and the iron-rich sulfide, troilite (FeS) with iron free silicates that normally contain iron, is an extraordinarily anomalous one. Two explanations suggest themselves: (1) that the system during crystallization was deficient in oxygen to the extent that, while sufficient to satisfy the magnesium, none was available for even a trace of the iron; or (2) that the iron and the troilite were introduced after the crystallization of the magnesium silicates. The first calls for an extraordinarily fine balance in the oxygen supply and since this condition is not peculiar to the Shallowater meteorite, but exists in other aubrites as well, it appears quite beyond the laws of chance that such a condition could exist in a number of distinct cases.

On the other hand there are suggestions that the nickel-iron and the the troilite were later introductions. The stone contains a number of small cavities, of much the size and shape of both the iron and troilite masses, and, although they were very carefully examined, no indications could be detected that they had ever been filled. This problem of the relation of nickel-iron to silicates in stony meteorites is one that deserves considerable attention.

The writer wishes to thank Mr. Stuart H. Perry of Adrian, Michigan, for the 2 excellent photomicrographs of the nickel-iron.