The Woodbine meteorite, with notes on silicates in iron meteorites

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Summary. The Woodbine meteorite, ploughed up in Illinois in 1953, is a fine octahedrite with numerous inclusions of silicate minerals. The minerals present include kamacite, taenite, troilite, schreibersite, orthopyroxene (Fs_6), diopside, olivine (Fa_4), plagioclase (An_9), and graphite. The chemical analysis is: Fe 73·06, Ni 9·08, Co 0·15, P 0·47, C 0·21, FeS 1·65, SiO_2 8·55, TiO_2 0·02, Al_2O_3 0·53, Cr_2O_3 0·03, FeO 0·49, MnO 0·03, MgO 5·19, CaO 0·34, Na_2O 0·29, K_2O 0·02, sum 100·11. Woodbine is compared with other meteorites of similar composition. The silicate material has chondritic composition, and is quite different from the silicate material of the mesosiderites, with which some of these meteorites have been classed.

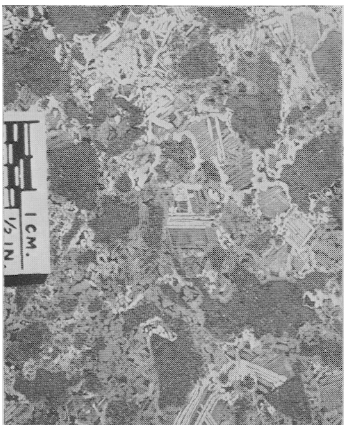
THE Woodbine meteorite was ploughed up on Mr. Henry Albrecht's farm, one mile west of Woodbine, Illinois, in the spring of 1953. The circumstances of the find, and a brief description of the meteorite, have been given by Read (1963). The meteorite when found weighed 48·2 kg, and was acquired by the U.S. National Museum. It is a rare type, an iron with silicate inclusions, and on that account was selected for detailed investigation.

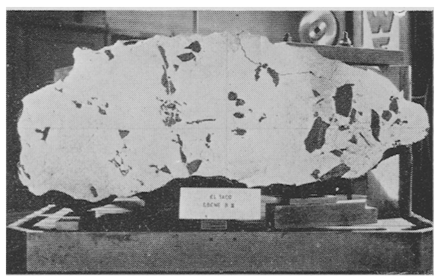
Mineralogical composition and structure

The macroscopic structure is well shown by a photograph of a polished and etched slice (fig. 1). Angular aggregates of silicate minerals, associated with troilite, are scattered throughout the matrix of nickel-iron. The nickel-iron does not have uniform crystallographic orientation, but consists of a large number of distinct grains each with its own Widmanstätten structure; the kamacite bands are about ½ mm wide, and the metal can thus be classed as a fine octahedrite. The silicate minerals are granular and allotriomorphic, the average grain size being about 0·2 mm.

The metallic minerals are nickel-iron (kamacite and taenite), troilite, and schreibersite. The principal silicate mineral is orthopyroxene, with lesser amounts of olivine, plagioclase, and clinopyroxene. Graphite is associated with the silicates. Rare grains of a phosphate (probably apatite or merrillite) were detected during microprobe analysis. Notes on the silicates follow.

Orthopyroxene. The refractive indices are α 1·661, γ 1·670, indicating a content of 6 mole % of the $FeSiO_3$ component, according to the determinative curve of Kuno (1954). The low iron content shows that this pyroxene can be described as an enstatite.





FIGS. 1 and 2: FIG. 1 (left). Polished and etched slice of the Woodbine meteorite, showing patches of silicate and troilite (dark grey) in the nickel-iron matrix. FIG. 2 (right). Cut and polished surface of the 'El Taco' specimen of the Campo del Cielo meteorite, showing angular aggregates of silicate minerals (black) in the nickel-iron matrix; the long dimension of the specimen is 44 in.

Olivine. The refractive indices are α 1·640, γ 1·678, indicating a content of 4 mole % of the Fe_2SiO_4 component, according to the determinative curve of Poldervaart (1950). This is a low-iron forsterite.

Clinopyroxene. In an acid-insoluble silicate fraction the accessory clinopyroxene can be distinguished by its prominent green colour. It is a chrome diopside with α 1·671, γ 1·700; these indices indicate about 3 % Fe in Ca+Mg+Fe, according to the determinative curves of Hess (1949).

Plagioclase. The refractive indices are α 1·532, γ 1·540, indicating a composition of An_9.

Because of the irregular distribution of the silicates, it is difficult to obtain a representative sample for density determination. Two thin slices were measured by weighing in air and in carbon tetrachloride and gave densities of 5·96 and 6·34; the mean value, 6·2, is probably a reasonable figure, and is consistent with the quantitative mineralogical composition.

Chemical composition

The chemical analysis is given in table I, together with the quantitative mineralogical composition derived therefrom. Since the nickel-iron is soluble in dilute hydrochloric acid whereas the schreibersite is not, it

TABLE I. Chemical and mineralogical composition of the Woodbine meteorite

Chemical Analysis		Mode	
Fe	73·06	Nickel-iron	79·6
Ni	9·08	Orthopyroxene	7·6
Co	0·15	Olivine	4·2
P	0·47	Plagioclase	2·6
C	0·21	Diopside	1·1
FeS	1·65	Schreibersite	3·0
SiO_2	8·55	Troilite	1·7
TiO_2	0·02	Graphite	0·2
Al_2O_3	0·53		100·0
Cr_2O_3	0·03		
FeO	0·49		
MnO	0·03		
MgO	5·19		
CaO	0·34		
Na_2O	0·29		
K_2O	0·02		
	100·11		

was possible to determine the composition of these two components separately. The composition of the nickel-iron is Fe 89·60, Ni 10·22, Co 0·18, consistent with the fine octahedrite structure. The composition of the schreibersite is Fe 53·62, Ni 30·83, Co 0·25, P 15·30.

The silicates comprise 15·5 % of the meteorite. Their overall chemical and mineralogical composition is comparable with that of the ordinary chondrites. The Si/Mg ratio (atomic) is 1·09, within the range of that for the common (bronzite and hypersthene) chondrites, and the mineral assemblage—orthopyroxene, olivine, diopside, and sodic plagioclase—is similar. However, the iron content of the olivine and orthopyroxene is considerably lower than that for these minerals in the bronzite chondrites. In the latter the FeO/(FeO+MgO) molecular percentage ranges from 15 to 20, whereas in Woodbine this figure is 5. However, it is significant that these silicates in Woodbine contain appreciable amounts of ferrous iron, in contrast to the enstatite chondrites, in which the pyroxene is essentially iron-free. Thus the silicate material in Woodbine resembles chondritic material (and may have been derived therefrom), but shows a state of reduction intermediate between the bronzite chondrites and the enstatite chondrites.

Discussion

In order to relate the Woodbine meteorite to others of the same or similar type, a search was made of the literature and through several meteorite collections for comparable material. The results of this search

TABLE II. Silicates in iron meteorites*

Meteorite	Ni in metal	Class	Olivine	Enstatite	Diopside†	Plagioclase
Campo del Cielo	6·7	Ogg	Fa_5	Fs_6	Fe_3	An_{10}
Colomera	7·16	Og	none	Fs_7	Fe_5	An_7
Copiapo	7·42‡	Og	Fa_5	Fs_6	Fe_2	An_{10}
Enon			Fa_6	Fs_9	Fe_4	An_{10}
Four Corners	9·7	Of	Fa_4	Fs_5	Fe_3	An_9
Kendall County	5·2	H	Fa_1	Fs_1	Fe_1	An_9
Kodaikanal	7·96‡	Of	none	Fs_{14}	Fe_7	An_0
Linwood	5·98	Ogg	Fa_4	Fs_6	Fe_3	An_{12}
Netchaevo§	9·8	Om	Fa_{13}	Fs_{12}	Fe_5	An_8
Odessa	7·2	Og	Fa_3	Fs_5	Fe_3	An
Persimmon Creek	13·60‡	Of	Fa_5	Fs_5	Fe_3	An_8
Pine River	7·18‡	Ogg	Fa_4	Fs_5	Fe_2	An_{19}
Pitts	11·4	Of	Fa_5	Fs_8	Fe_4	An_7
Toluca	8·6	Om	Fa_5	Fs_6	Fe_2	An_{10}
Udei Station	9·4		Fa_5	Fs_6	Fe_5	An_{16}
Weekeroo	6·9	Og	none	Fs_6	Fe_5	An_{15}
Woodbine	10·22	Of	Fa_4	Fs_8	Fe_3	An_9

* Compositional data on the silicate minerals are derived from refractive index measurements by the author, except for Kodaikanal (Olsen and Mueller, 1964), Odessa (Marshall and Keil, 1965), and Weekeroo (Wasserburg, Burnett, and Frondel, 1965). Park, Bunch, and Massalski (1966) have reported on silicate material from another specimen of Campo del Cielo, with similar results to those reported here.

† Fe_x is x atoms of Fe in Ca+Mg+Fe = 100.

‡ J. Nelen, unpublished analysis.

§ Netchaevo was heated in a forge after its discovery, which may have altered the original composition of its silicate minerals.

are summarized in table II. It appears that at least three different types of silicate occurrence in iron meteorites can be distinguished: Irregular patches of silicates in Campo del Cielo, Copiapo, Enon, Four Corners, Netchaevo, Pine River, Pitts, Udei Station, and Woodbine. Silicates as minor constituents of troilite or graphite nodules or both in Kendall County, Linwood, Odessa, Persimmon Creek, and Toluca. Rounded and drop-like silicate inclusions in Colomera, Kodaikanal, and Weekeroo. This classification is rather subjective, especially as between the first two groups. The silicates in Woodbine are always associated with troilite, but as irregular aggregates rather than the rounded nodules characteristic of the second group. The listing in table II is not exhaustive, and other silicate-bearing irons will undoubtedly be discovered. It should be emphasized that the discovery of silicates in iron meteorites is often a matter of chance, depending upon the specific cross-section intersected by the cut or cuts. For example, silicates were first discovered in the Campo del Cielo meteorite in 1963, although specimens of this meteorite have been examined over the past century and a half. In the specimen described by Park, Bunch, and Massalski (1966), the silicates occurred in small amount in a troilite nodule. Recently, however, the large 'El Taco' specimen, weighing about 2 tons, was cut in half, revealing a considerable number of angular masses of silicate (fig. 2).

Within each group, and even between the groups, there is a notable similarity of mineral associations. The principal silicate is an orthopyroxene close to enstatite in composition. Olivine of forsteritic composition is also present (except in the third group). Plagioclase (albite or oligoclase) and accessory clinopyroxene close to diopside in composition are present in minor amounts. This appears to be a near-equilibrium assemblage, an equilibrium presumably determined by the slow cooling of the host nickel-iron.

The composition of these silicate inclusions resembles that of the chondritic meteorites. The assemblage orthopyroxene–olivine–sodic-plagioclase–diopside is typical of the common chondrites. The sodic nature of the plagioclase is especially characteristic, and serves to set these silicate-bearing irons off from the mesosiderites, with which some of them have been classed. However, the iron content of the orthopyroxene and the olivine is notably lower than in the common chondrites, indicating a higher degree of reduction. In view of the presence of graphite in these silicate inclusions, it is perhaps significant that reduction has not gone as far as to produce completely iron-free pyroxene, as in the enstatite chondrites and enstatite achondrites.

There is some indication that Prior's rules, established for the chondrites, are valid for these meteorites also. Although the silicate minerals do not vary greatly in composition from one of these meteorites to another, in Kendall County, with the lowest nickel content (5·2 %), the olivine and pyroxene are practically iron-free. The highest iron content in the silicates is in Netchaëvo, with 9·8 % Ni; however, this meteorite has been heated in a forge, which may have altered the original composition of the silicates.

The distinction between irons with silicate inclusions and the mesosiderites deserves further consideration. Neither group has been adequately defined in the past, although Prior (1920) provided a useful description of the mesosiderites as hypersthene–anorthite stony-irons. The significant feature of the mesosiderites, as Prior observed, is the association of orthopyroxene with 20–30 mole % $FeSiO_3$ and calcic plagioclase; silicate inclusions in irons, in contrast, have pyroxene near pure $MgSiO_3$ and sodic plagioclase. In the mesosiderites the amount of the silicates is usually greater than the amount of the nickel-iron, whereas in the irons with silicate inclusions the silicates are a minor constituent. On the basis of Prior's definition, the mesosiderites known at the present time are the following: Barea, Bondoc, Budulan, Chinguetti, Clover Springs, Crab Orchard, Dalgaranga, Dyarrl Island, Estherville, Hainholz, Łowicz, Mincy, Morristown, Mount Padbury, Patwar, Pinnaroo, Simondium, Vaca Muerta, and Veramin.

Two meteorites, Bencubbin and Weatherford, have been classed as mesosiderites, but do not belong with the above meteorites. Bencubbin is an iron meteorite containing a variety of silicate inclusions (Simpson and Murray, 1932; Lovering, 1962); clinoenstatite is the commonest constituent of these inclusions, and some of them are fragments of typical chondrites, an association that appears to be unique. Weatherford consists largely of silicates with isolated slugs of nickel-iron, and the principal silicate is clinoenstatite. Neither of these meteorites can be readily accommodated in either the mesosiderites or the irons with silicate inclusions, as these are defined here.

The origin of the silicate-bearing iron meteorites poses a number of problems, in particular the source of the silicates and their manner of incorporation within the metal. Many of these meteorites have been described as 'brecciated octahedrites', and this apparent brecciation is well shown in fig. 1. Metallic areas with well-developed Widmanstätten structure are usually separated from the irregular patches of silicate by borders of granular metal, giving a chaotic appearance. However, on a microscopic scale there is little evidence of mechanical deformation; the silicate minerals are well crystallized and comparatively coarse-grained. If the brecciation took place at a comparatively high temperature (but below the melting-point of troilite and silicate) then recrystallization during slow cooling could erase much of the evidence of mechanical deformation. A very significant feature of these meteorites is the uniformity of composition of the silicate minerals and their close relation to chondritic material. This suggests that chondritic material was incorporated in the nickel-iron and completely recrystallized during the slow cooling that resulted in the Widmanstätten structure. A possible mechanism would be the injection of molten nickel-iron into a mass of chondritic silicates. Alternatively, a mass of chondritic material could have been partly melted in a weak gravitational field (a small asteroid ?), resulting in incomplete separation of metal and silicate. Possibly these meteorites represent a border zone between a metallic core and a silicate mantle in one or more such asteroids.

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