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THE WALTERS METEORITE

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The main mass of the Walters meteorite and the data relating to its fall are in the Geological Department of the United States National Museum. During a trip there Dr. Roy had studied the surface features of the main mass and examined the records of the fall. Prior to this, in conjunction with his studies on the Paragould stone (Roy and Wyant, 1955), he had worked on the interior structure and examined the minerals in thin sections of the Walters meteorite from representative specimens in possession of the Chicago Museum. He did not know then that Mr. E. P. Henderson of the United States National Museum and Miss Jewell J. Glass of the United States Geological Survey were also making a study of this meteorite and that their studies on certain of its essential features were nearing the final stage. To avoid further duplication of efforts, the results of their investigations were incorporated with those attained by Dr. Roy, and the manuscript in its present form was prepared for publication under joint authorship.

CIRCUMSTANCES OF THE FALL

The Walters meteorite fell at 3:45 P.M., July 28, 1946, about 11½ miles west of Walters, in Cotton County, southwestern Oklahoma (in northeastern corner of NW. ¼ Sec. 25, T. 2 S., R. 13 W.; Lat. 34° 22′ N., Long. 98° 31′ W.). The weight was 22.33 kilograms.

The meteorite was purchased by the United States National Museum from Mr. Frank Moore, Route 5, Walters, Oklahoma.

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[1] Deceased April 17, 1962.

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Chicago Natural History Museum has a large polished slice of the main mass. The description of the interior structure is based upon this slice and that of the surface features upon the main mass.

SHAPE, SURFACE MARKINGS, AND CRUST

The Walters stone is roughly equidimensional. It has many surface irregularities and its general form lacks the features of atmospheric shaping of a well-oriented meteorite. The irregularities indicate that parts of the meteorite had broken off shortly before it reached the earth and that there had not been time enough for the broken areas to be reshaped. They can be recognized by their angularity and partial crusting.

The apex is not well developed but it can be determined from the smooth and sloping surface immediately surrounding it. The sloping surface is interrupted by a concavity with broad, shallow pits—a feature that commonly develops on the rear side where less air is encountered. Contrariwise, the rear side of the meteorite shows certain characteristics usually found on the front side, such as the presence of an incipient apex in the form of a rounded protuberance, from which have passed currents of air radially that have given rise to smaller and deeper pits.

At one place, a little above and opposite the apex, the surface is marked by a V-shaped cleft 4 inches long and 1¼ inches deep. Its walls are coated with slaggy crust, and its edges slope inward and are rounded. All these suggest that originally the cleft was a narrow crack that has been enlarged and deepened by the passing of air currents. The cleft, in turn, is almost entirely bounded by a fissure, which has weakened the encircled area to the breaking point, and doubtless it would have broken off had the meteorite stayed in the air for a fraction of a second longer. To judge from the damage suffered, it would seem that the meteorite was subjected to considerable shock during its flight.

With the exception of a portion of the apical region, the entire surface of the meteorite is pitted, but the pits do not conform to the usual pattern, which would indicate that the mass has encountered currents of air from different directions at different times. The shape and size of the individual pits vary but little from those of other stone meteorites. Some are circular, some are oval, others are elongated. The circular ones are the shallowest and the elongated ones the deepest.

The arrangement of these pittings, the markedly irregular form of the meteorite, and the anomalous shaping it has undergone, strongly indicate that the Walters meteorite did not maintain a fixed position during its passage through the earth's atmosphere; it had turned around, in particular, from front to rear near the end of its flight.

It has been stated and mathematically shown that the apex of a meteorite is generally in line with the center of gravity of the mass. Accordingly, if the distinguishing features of the front or the apical region in a meteorite are found on more than one of its sides, it can be assumed that the meteorite has changed positions during its flight. The change is most likely to occur when a portion of the falling meteorite suddenly breaks off, incurring loss of weight of the mass and subjecting it to the resultant force of the break. These are factors that may very well affect the course of the meteorite and cause it to turn and take up a position in line with the center of gravity of the reduced mass. Under these circumstances, the degree of development of the front will depend on the altitude at which the breaking takes place and on the speed of fall of the meteorite thereafter; the higher the altitude and the lower the velocity the longer the time for more complete shaping.

The crust of the Walters meteorite is black with scattering brownish stains resulting from oxidation that has occurred since its recovery. The surface of the crust, as seen under magnification, is covered with narrow, thread-like ridges, some of which are straight, some wavy, others forking. This sort of pattern, formed by fused matter flowing longitudinally and sending off branches, is a common feature of the crust of stony meteorites. Areas of contraction cracks and scoriaceous texture with characteristic pits of expanded gas bubbles have also been observed. Thickness of the crust varies; the variation was caused by the partial disruption of the meteorite during its flight, as different surfaces were exposed for different lengths of time. On uniformly exposed surfaces the average thickness is ± 0.5 mm. It is only in the fissures and certain angular pits where the fused matter has accumulated that the crust is perceptibly thicker, often massive. A noteworthy feature of this meteorite is the total absence of protruding grains of nickel-iron on the surface of the crust.

Examination of thin sections of the crust shows only one zone—the outer fused zone. The so-called absorption and impregnation zones are not present, or at least are not recognizable in the sections examined. Absence of these zones—believed to be formed by deeper penetration of heat during flight—in a meteorite so extensively veined as this one, seems unusual, especially to those who believe that veins are produced by fused matter from the surface which flowed into fissures, rather than by the penetration of heat which fused the walls of the fissures or by the injection of molten matter into the fissures. A brief discussion of this subject is given (p. 544).

Another feature observed in relation to this question of heat penetration is the existence of minute grains of at least two minerals within the crust just below its outer margin, one of which is olivine, the other probably hypersthene; the latter has not been positively identified optically. X-ray powder analyses of three samples of the crust show the presence also of plagioclase and magnetite. The existence of these silicates indicates that the surface was not completely fused to form the crust, and that some of the more refractory silicates survived the heat.

SIZE AND WEIGHT

Since the acquisition of the meteorite by the United States National Museum (USNM 1430), several slices have been cut from it for distribution and for petrographic and chemical analyses. One of these slices, as indicated elsewhere, was secured by exchange and is in the collection of Chicago Natural History Museum (CNHM Me 2422). At the present time, the approximate measurements of the main mass of the Walters meteorite are: height 9½ inches; length 10¼ inches; and width 8¼ inches. Weight of the original mass was 28.33 kilograms.

INTERIOR STRUCTURE

The stone is compact and takes a good polish. A cut and polished section reveals that the most conspicuous feature of this stone is the presence of numerous black veins. Almost as conspicuous a feature is the occurrence of countless troilite bodies. Modal analysis gives 10.4 ± 1 per cent of troilite by volume. So numerous are these two elements that they have visibly modified the original homogeneous gray color of the interior to a variegated one of black, shades of gray, and bronze—the black from the veins and the bronze from the troilite bodies. Reddish brown stains resulting from the oxidation of the nickel-iron grains have spread through much of the mass and have further modified the original color.

The veins vary in thickness from 0.01 mm. to 10 mm. or wider; the more numerous ones average 0.1 mm. Some of the widest and massive ones are localized; they appear more like swellings and knottings than veins. The course of the veins is usually straight but it may be curved or undulating. In some areas, two systems of veins cross at an angle of approximately 90°, forming rectangles; in others, the veins branch and anastomize and appear like matted hair. In the light-colored groundmass, the veins may cut through or surround rectangular or rounded areas and give the interior a brecciated appearance. In fact, the stone was brecciated earlier in its cosmic history. Whether the veins cut through or surround given areas, they merely occupy the fracture lines of a brecciated meteorite and thus emphasize the shapes and sizes of the fragments and the nature of the brecciation. This phase has been briefly elaborated (see p. 544). As in the case of the groundmass, some of the narrow veins cut across a few larger chondrules, but the general tendency is to surround them. Here again the veins occupy the fracture lines or the lines of weakness. The majority of the chondrules are fractured or distorted. Those that are intact are not firmly embedded in the groundmass and are commonly characterized by an encircling line of weakness between the two formed by the shrinkage of the chondrules during their crystallization. Veins cutting across small chondrules are rare, but a number of small chondrules are found as inclusions in the veins.

Many of the veins appear to be definitely related to the crust, and this suggests that they might have originated from fused surface-matter that flowed into fissures. Some of these have started as thick flows; others, which were narrow at the beginning, have gradually widened or terminated as large concentrations of black shapeless masses. These masses are generally located a short distance below the crust, but some have been observed in the deeper portion of the interior. The latter might have had a different mode of origin and existed prior to the meteorite's entrance into the earth's atmosphere.

A distinct feature which the vein material exhibits is the presence of small, rounded troilite bodies, generally along the margins of the veins. The marginal location of these bodies suggests that they have been forced out by a viscous medium that rejected these heavy insoluble grains, and they solidified along the cool borders.

Globular troilite bodies, however, are not confined to the margins of the black veins. They may occur as isolated inclusions which vary in size; the largest ones are generally oval or elliptical with their long axes parallel to the veins. More remarkably, troilite may occur as delicate threads that occupy the center of the black veins. These threads are interspersed with minute troilite globules, isolated or in clusters. Such an arrangement simulates an irregularly strung string of beads. Besides occurring in the various forms referred to here, troilite may occur as flakes and plates both in the black veins and in the lighter-colored groundmass but more abundantly in the latter, in which the spherical or oval-shaped troilite bodies are extremely rare.

The majority of the troilite bodies contain inclusions of nickel-iron (kamacite), even though the two compounds are immiscible and the crystallization temperature of the two is vastly different. The association of the two unlikes represents a eutectic between the two phases, Fe–FeS, the eutectic temperature being 988° C. at one atmosphere. It should be recalled, however, that the stone had suffered brecciation, a process which required much higher pressure to be effective. As such, the eutectic temperature was also higher than indicated under one atmosphere pressure. The kamacite plates are intergrown with the troilite bodies and have no set arrangement; they present a cuneiform appearance or graphic texture, being the result of simultaneous crystallization of the two minerals.

The production of an elaborate vein system in the groundmass of meteorites, such as in this one, presents a subject which cannot be satisfactorily dealt with from studies of a few examples. We have, therefore, restricted our studies to the Walters stone and noted what we have observed. We have been, however, substantially aided by the previous studies of the Paragould meteorite, in which the veining system is somewhat similar in distribution but more intricate.

Extensive veining implies extensive brecciation. The more severe the brecciation, the more numerous are the veins, for veins are filled-in cracks or fissures between and around fragments of brecciated meteorites. The filled-in vein matter is not matter introduced into cracks except in polymict meteorites, which are the rarest among meteorites. As a rule, veins have been formed in place by thermo-metamorphism of the substance of the meteorite. Extensive or even moderate brecciation can hardly take place either from shock or from pressure during a meteorite's flight or from the impact with the earth.

The vein system of the Walters meteorite thus arouses serious doubt that the cracks were formed by any of the methods cited above. Cracks formed in this manner are not likely to be filled to form veins by the penetration of heat into the supposedly cold interior during a few seconds of terrestrial flight of the meteorite. It is more likely that the Walters meteorite was severely brecciated earlier in its cosmic history, prior to the disruption of the parent body, and that many of these veins were produced by hot gas that penetrated into cracks and fused the constituents of the walls of the cracks. The linear alignment of the troilite bodies, formed from reaction of sulphur in the vapor and nickel-iron, suggests flowage. Apparently, the mass was heated above the melting point, and this rendered the molten material sufficiently fluid to flow. The molten matter may have been injected into the fissures during one time or another of the meteorite's metamorphic history, thus forming some of the veins. There is evidence that the vein system of the Walters meteorite was not completed in only one stage, by the penetration of hot gas into the cracks. It is also clear that some of the veins that are contiguous to the crust were formed from fused surface matter that flowed into fissures during the meteorite's terrestrial flight. The heat encountered during the flight could well have melted away some of the pre-existing vein material from the fissures that adjoined the surface of the meteorite. The opening up of these fissures would have allowed the fused surface matter to flow into them and form veins of a later generation, which would be close to the surface and due to an excess of molten matter would be generally thicker and wider. That many of these marginal veins are distinctly shorter and wider and that they abruptly thin out and connect the narrower veins of the interior lend support to this view of their origin.

Reference has been made to the vein system of the Paragould stone as being more intricate than the present one. By this, it is meant that Paragould has passed through one or more additional cycles of thermo-metamorphism; that is, it has undergone further crushing, melting, and consolidation, after its major metamorphic features were developed. This is strongly indicated by the small angular fragments of black material that are enclosed in the gray matrix. Some of these fragments are isolated, and there are no visible connecting veins or passageways through which the black material might have been injected. The presence of black chondrules enclosed in fused and unfused groundmass, of olivine and enstatite chondrules within a black matrix, and of chondrules with fused matter at center, may be considered as further evidence of an additional cycle of metamorphic alterations suffered by the Paragould stone.

The stone is chondritic, as may be inferred from the reference already made to chondrules which have been cut across or surrounded by veins. Of the number of thin sections examined, few show well-defined chondrules. The majority of them are either deformed or broken. Some are so badly crushed that they can hardly be distinguished from the groundmass. The total effect of the deformation, fragmentation, and crushing lends to the meteorite the appearance of a howardite. Well-defined chondrules are generally very small in size and are composed of aggregates of olivine grains. No entire larger olivine chondrules of any type have been observed. They are chiefly represented by fragments composed either of olivine bars, or of a mixture of olivine and hypersthene lamellae, or merely of crystalline aggregates of these two minerals. Scattered grains of glass and feldspar in some of these chondrules and in the groundmass are of common occurrence. The hypersthene chondrules are generally fibrous and are characterized by multiple centers of crystallization. Eccentrically radiating hypersthene chondrules were looked for but none was found, nor did we find a single well-defined glass chondrule. In a meteorite so highly metamorphosed, the absence of glass chondrules seems unusual, although glass is one of the common constituents of this meteorite. Feldspar, both fragmental and twinned, has been detected, especially in the groundmass of many of the sections examined.

CHEMICAL AND MINERALOGICAL COMPOSITION

The analytical investigations on this meteorite were made to establish the composition of the light- and dark-colored portions and to find how uniform they were. Two samples were prepared from the light and dark areas for chemical analyses. The material was dissolved in dilute hydrochloric acid and divided into two portions, the acid soluble material and the insoluble residue.

When the acid attacks the powdered sample the olivine is rapidly decomposed and some silica separates out. When this silica encloses some of the unattacked powder it seriously interferes with the com-

Analysis of the Acid Soluble Portion

	Light-Colored		Dark Veins	
	1	2	1	2
Insoluble	43.15	41.85	33.51	39.10
SiO_2 (soluble)	18.71	19.42	21.71	19.59
MgO	18.40	18.85	19.32	17.52
FeO	11.81	12.69	17.31	15.46
Al_2O_3	0.47	0.32	1.01	0.58
Fe_2O_3	0.66	0.01	1.98	3.42
P_2O_5	n.d.	.....	0.25	n.d.
CaO	0.25	0.31	0.68	0.47
Fe	3.65	n.d.	2.39	2.34
S	2.09	n.d.	1.37	1.33
Ni	.....	.....	0.57	n.d.
Co	.....	.....	0.017	n.d.
Ratio $\frac{SiO_2}{MgO}$	1.01	1.03	1.12	1.11

Analysis of the Insoluble Material

	Light-Colored	Dark Veins
SiO_2	56.14	55.90
Al_2O_3	5.23	4.23
Fe_2O_3	1.39	1.11
P_2O_5	n.d.	.....
FeO	7.91	7.10
CaO	3.60	3.50
MgO	19.32	20.92
FeO	0.52	0.35

plete digestion of the sample in the acid. Also, an appreciable proportion of the silica which should belong to the olivine contaminates the insoluble material.

For the above reasons one rarely gets satisfactory checks to the determinations even when the sample analyzed came from the same tube. In these analyses, the insoluble residue was filtered off and treated with sodium carbonate to dissolve the silica from the olivine; then the residue was again treated with hydrochloric acid.

The treatment of the sample with sodium carbonate possibly may not have contaminated the insoluble residue for an analysis of the alkali metals, but since this was not positively known it seemed best to omit alkali determinations.

SPECIFIC GRAVITY

Before the material was treated with acid a series of density measurements was made on the selected areas. The density of the lighter-colored portion was 3.52, 3.53, 3.52 and 3.54, while that of the darker areas was 3.58, 3.56, 3.56. Thus in all cases the material filling the veins is slightly heavier than the lighter-colored matrix.

MINERALOGICAL COMPOSITION

The following are the non-opaque minerals identified optically. In order of abundance:

Olivine (*Chrysolite*).—Olivine is the predominant mineral. It forms a large part of the coarse-grained groundmass and occurs in chondrules as swarms of small grains with random orientation, or as bars and lamellae having the same orientation.

Much of the olivine has become stained through the oxidation of the iron. The mineral grains are brown or reddish, and some are blackish and opaque; only a few grains have clear, pale, grayish-yellow color.

Optical properties: The mineral is negative. The optic axial angle is large, (–) 2V=85°–88°; dispersion distinct, $r > v$. The indices of refraction are: $\alpha=1.680$, $\beta=1.701$, $\gamma=1.720$, B.=0.040.

Hypersthene (*Bronzite*) (En_{83}).—Like the olivine with which it is often intergrown, the hypersthene is stained reddish brown, but it can be cleaned easily by acid. It occurs as rounded grains and as fibers; in chondrules it is prismatic to fibrous.

Optical properties: The optic axial angle is large, (–) 2V=80°. Faint traces of lamellae twinning. The indices of refraction are $\alpha=1.675$, $\beta=1.682$, $\gamma=1.686$.

Apatite (*Manganapatite*).—A relatively abundant mineral found in clear, usually colorless grains throughout the groundmass corresponds to manganapatite. Grains isolated and tested reacted for phosphoric acid and manganese.

Optical properties: Uniaxial negative. $\epsilon=1.652$, $\omega=1.657$, B.=0.005.

An apatite mineral which has similar properties was described as chlorapatite by Larsen and Shannon (Amer. Jour. Sci., **209**, p. 250, 1925). The indices of refraction of this mineral, however, are higher than those for that chlorapatite.

Merrillite.—It occurs in less abundance than manganapatite.

Optical properties: Uniaxial negative. $\epsilon=1.620$, $\omega=1.623$.

Anorthite(?).—A high temperature feldspar.

Optical properties: Biaxial negative. (–) 2V=40–55° (var.). Shows pseudohexagonal twinning, and, very rarely, traces of lamellar twin-

SPECTROGRAPHIC ANALYSIS[1] OF METEORITE FRACTIONS FROM WALTERS STONE

	MnO	NiO	CuO	Cr_2O_3	CoO	TiO_2	V_2O_5	SrO	CaO	MoO_3	ZrO_2	Fe_2O_3	MgO
Olivine	0.55	0.1	.002	0.3	0.01	0.1	0.007	...	1.0	...	...	xo.	xo.
Pyroxene	.20	.2	.003	.4	.02	.1	.01	...	...	...	.003	xo.	xo.
Apatite	.25	.1	.002	.4	.01	.1	.02	.0008	...	...	.002	xo.	xo.
Metal (magnetic)	.25	1.0	.005	...	.08	.1	.004	...	.3	.002	...	xo.	xo.

Phosphorus was not found at 0.5% or above, based upon visual comparison with standards.

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[1] Courtesy of Dr. A. T. Myers, Section of Geochemistry and Petrology, United States Geological Survey.

ning. Inclusions of high-index minerals are common. Indices: $\alpha=1.533$, $\beta=1.538$, $\gamma=1.540$. B.=0.007.

Glass.—One of the common constituents of this meteorite. It is distributed throughout the groundmass, in the veins, and in the chondrules. Some is clear and colorless, but much of it is stained and clouded with inclusions.

Optically the clear transparent material is isotropic with $n=1.505$.

Percentage determinations of the constituent minerals other than the order of their abundance have not been made.

X-ray diffraction pattern shows the presence of the following minerals: taenite, kamacite, olivine, hypersthene or bronzite, plagioclase of undeterminable composition, and troilite.

It will be seen that the results of X-ray studies conform closely with those obtained by other methods. The mineralogical composition itself is also much the same as that of certain other chondrites. The meteorite, however, possesses certain features which may be said to be distinctive. One of these is the presence of the numerous troilite bodies, many of which are intimately mixed with kamacite; the other is the abundance and extent and the nature of the distribution of the black veins. Apparently, both of these features were developed in consequence of the heat produced during brecciation and metamorphism, to which the Walters meteorite was, doubtless, subjected early in its cosmic history.

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