THE MAYODAN METEORITE, ROCKINGHAM COUNTY, NORTH CAROLINA*

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Abstract

A new hexahedrite from North Carolina is analyzed and described. The orientation of the inclusions, the Neumann lines, and the granules of kamacite were measured and are discussed. These structures are assumed to be in effect primary and a theory is given for their origin.

Introduction

In September, 1950, Mr. James E. Beaver of High Point, N. C., submitted to the U. S. National Museum a small fragment for identification which he thought might be a meteorite. Having read in the September issue of *Science Digest* a description of a meteorite and of the interest that this Museum has in them, he asked us to investigate a sample that for years had been considered by his family to be an iron meteorite.

The sample proved to be an iron meteorite. In response to our request for permission to see the main mass, Mr. Beaver sent it for examination and supplied the historical information about its discovery. In a letter dated September 18 he wrote:

"This meteorite was discovered in 1920 near our farm in Rockingham County, N. C. Back in those days the upkeep of the roads was the responsibility of each county and it was the practice of the few neighbors to get together and repair the section of the road that passed by their property. It was while working with a few of his neighbors in repairing one of these roads that my father discovered this meteorite (embedded) in the road. They thought at first that it was just another rock, but when one of them lifted it to carry it (out of the road) they found that it was much too heavy to be an ordinary rock, so my father carried it home with him, where it remained for 30 years as an object of curiosity and conjecture. However, my father suspected that it was a meteorite, in fact we have been calling it a meteorite ever since I can remember. He sent a sample of it to an iron smelting concern and they replied that it was of no value." (Portions enclosed in parentheses were corrected in the next letter.)

The meteorite, as received, weighed 34 pounds and was an altered irregular mass with none of the original flight surfaces preserved. The loosely attached oxide scales on the surface suggested that this meteorite contained lawrencite and perhaps would be difficult to preserve. Mr. Beaver when asked to furnish the exact location of this find kindly sent a map on which the place of discovery was marked.

The nearest town to that place is Mayodan, the name selected for this

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meteorite. The latitude and longitude of the place of discovery are 36°23′ N. and 79°52′ W. respectively.

Mr. Beaver in a letter dated September 24 added the following facts that corrected the statements enclosed in parentheses which were given in his former letter:

"This meteorite was not embedded in the road itself as was my original impression, but was in the bank of the road and was uncovered when the road was being widened by men using plow, picks and shovels. The meteorite was definitely not hauled to that point from another location when the road was built or repaired, as no material was ever brought from a distant point for this purpose.

"During the 30 years since this meteorite was discovered it has been exposed to the weather part of the time, and part of the time it has been completely protected from the weather. For two or three years it was out of doors and was completely exposed to the weather and then for several years it was stored in a building where it was completely protected from the weather. During all the rest of the time it was kept in an old building with a leaky roof, and the meteorite would get wet every time it rained.

"While making this investigation, I uncovered some more information that will probably be of interest to you. About 30 years before this meteorite was discovered several people reported seeing and hearing a meteorite fall somewhere in the general locality where this meteorite was found. Some of them said they heard the sound it made while falling through the air, while others said they heard the sound and also saw the flash of light that accompanied the fall.

"Of course I do not definitely know that this was the same meteorite that was discovered, but everyone presumed it to be. From the information the date of fall would be somewhere around 1890."

The information about the possible date of this fall is given for what interest it may have, but as Mr. Beaver stated, we can not be certain this is the date of fall for this meteorite.

It is perhaps fortunate that this iron was stored as Mr. Beaver described, since storage for 30 years in a well-roofed building and consequent accumulation of corrosive iron chloride on the surface might have caused even more extensive alteration. Probably the frequent wetting removed much of the corrosive agent and thus helped to preserve the specimen.

Chemical Analysis

The pieces selected for analysis were placed in a flask, covered with dilute hydrochloric acid ($1\ HCl+2\ H_2O$) and the gas given off was passed through a solution of lead acetate. The lead sulfide was recovered, converted to lead sulfate, and the sulfur content calculated.

The acid which dissolved the sample was not heated above the minimum temperature needed to make it react with the sample. Cold acid will attack the metal at first, but soon all action practically stops. When the flask is heated by suspending it in hot water, the sample again started to dissolve. After everything that would dissolve had gone into solution in the hydrochloric acid, some rhabdite needles and a few rectangular plates remained. There also was a small amount of black particles which were non-magnetic and had a density only slightly higher than that of the acid solution. By attaching a magnet on the bottom of the flask, the metallic portion was retained in the flask while the dark non-magnetic inclusions were separated by washing with dilute acid, filtered off, dried and weighed as carbon.

The magnet was removed and the magnetic residue was dried quickly within the flask, brushed out, and weighed. It made up 0.53% of the sample and consisted of essentially two different types of crystals.

This residue was separated into two portions by handpicking. Both portions were x-rayed and found to be identical schreibersite. The portion consisting of the needles was dissolved and found to contain 33.6% Ni. This is more nickel than usually is found in schreibersite, but agrees with the nickel-poor rhabdites reported by Farrington (1915).

There were not enough of the rectangular plates to make a reliable nickel determination, but the tests made gave 25.1% Ni. This value is only useful in showing that the larger phosphide inclusions contain less nickel than the needles. This is consistent with existing information. The needles which are the last of the phosphide to separate apparently always contain more nickel.

These rectangular bodies required about 30 hours to dissolve in aqua regia. The needles dissolved much more rapidly. However they have a

TABLE 1. COMPOSITION OF THE MAYODAN, ROCKINGHAM COUNTY, N. C., METEORITE
E. P. Henderson, analyst

	1 Composition of the portion sol. in HCl	2 Composition corrected for inclusions, see text
Fe	93.42*	93.70*
Ni	5.48	5.63
Co	0.48	0.49
P	0.09−	0.17
C	0.003	0.003
S	0.003	0.003
Phosphides residue	0.53	
Total	100.006	99.996
Mol. Ratio $\frac{Fe}{Ni+Co.}$ =	16.55	16.28

* By difference.

much higher ratio of surface to mass and it may be that these two types of inclusions actually dissolved at about the same rate.

The composition of the Mayodan meteorite reported in column 1, Table 1, was determined on the portion which was soluble in dilute HCl, and does not include the composition of the insoluble phosphides. The phosphorus contents of schreibersite and rhabdite have been determined several times in these laboratories and elsewhere and average between 15 and 15.5%, hence it is possible to calculate the phosphorus content of this meteorite.

The sulfur reported was determined on a 14-gram sample. The piece selected contained no appreciable inclusions of troilite so that the sulfur content of the meteorite is somewhat but not much higher. The nickel, cobalt, and iron determinations given in column 1, Table 1, do not include the percentage of these elements from the insoluble phosphide. Column 2 has been corrected for the estimated composition of the phosphide inclusions.

Description

This meteorite is a hexahedrite. The two distinct sets of Neumann lines shown in Fig. 1 intersect at an angle slightly more than 37° as measured on the polished surface. The theoretical angle between the trace of the $1\bar{2}1$ and the $2\bar{1}1$ faces on the 001 face should be 36°52′. Thus these two sets of Neumann lines are parallel to the trace of these two trapezohedral faces. More conspicuous than the Neumann lines are the two sets of straight lines which intersect at right angles. These are the traces of the cleavage of kamacite. Hexahedrites often show a tendency to separate along these cubic planes.

The small fragment of this meteorite which Mr. Beaver first sent for examination apparently was broken from the main mass by a hammer. It had two flat surfaces which were at right angles to each other and on these surfaces a few silvery rectangular plates were noticed. These were later identified as rhabdites.

Oxides occur within some of the cleavage planes of the first two slices cut from this iron, but these are weathering products. Small beads of lawrencite developed along these cleavages when the specimen was exposed to the humid atmosphere for several days.

The dark irregular area at the center of Fig. 1 is iron oxide, the result of weathering penetrating into the meteorite. This slice was cut parallel to a relatively flat surface on the main mass, but just deep enough to pass below the lowest depression on that surface. By good fortune the slice removed happened to be parallel to the 001 direction, a cleavage plane. Thus at some time this mass may have been cleaved from another, possibly during flight through the atmosphere.

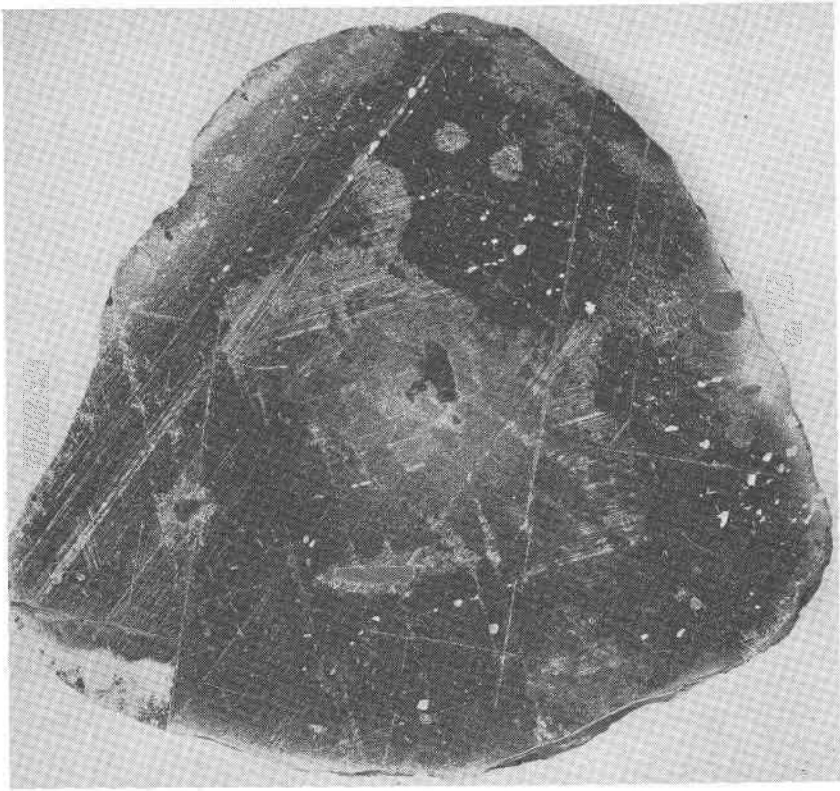

Fig. 1. Etched section of the Mayodan, N. C., meteorite. Note the orientation of the small light colored kamacite granules and their relationship with the Neumann lines, cleavage planes and phosphide inclusions. The prominent lines at right angles to each other are cleavage planes. The dark area at the center represents the penetration of alteration from the outside. The gray inclusions, lower center and upper right, are troilite. About $\frac{2}{3}$ natural size.

The specific gravity of this iron was determined on two pieces. The portion from near the surface, although it appeared to the eye to be fresh, gave a density of 7.82 which is lower than the density of a hexahedrite should be. The density measured on a piece selected from nearer the center of the mass, far below the zone of alteration, gave a density of 7.910.

The troilite has a peculiar grayish-black color because it contains carbon. Some phosphides occur around the edges of the troilite inclusions. In most meteorites the troilite and its enclosing zone of schreibersite form rounded inclusions but in this meteorite many of the troilite masses have an irregular outline because small prongs extend into the surrounding metal.

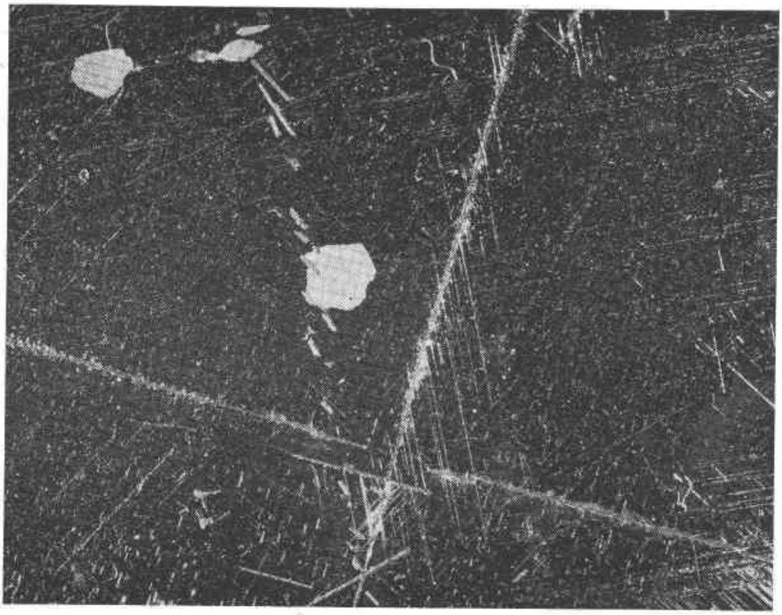

FIG. 2. An area near the lower edge of Figure 1. Rhabdite rods lie en echelon roughly parallel to each other and form rows. Occasionally rhabdites penetrate one of the kamacite granules, which sometimes are bounded by straight edges. The two lines at right angles are cleavages and lie parallel to the cube face, hence it was easy to orient the Neumann lines. ×5.

The iron surrounding many of the larger troilite inclusions (Fig. 1) appears to contain brilliant needle-like inclusions, but when these are examined more closely they are found to be Neumann lines that are more deeply etched out. Thus the brilliant lines around the troilite inclusions are not phosphide bodies but reflections from the sides of deeply etched Neumann lines.

There are two types of phosphide inclusions in the Mayodan meteorite. One type is rectangular or rod shaped (Fig. 2) and the other, not visible in Figure 1, occurs in delicate needles. These needles should be called rhabdites and perhaps the larger rectangular inclusions would be called schreibersite, but because they have a more symmetrical outline than most observed schreibersite, rhabdites seem to be a better name.

A feature of this meteorite is the alignment of the rectangular phosphide inclusions (Figs. 1–4 and 7–9). In many places these rod-like inclusions are aligned in rows. Each single inclusion seems to lie roughly parallel to the others in a given row, and at an angle to the direction the row makes across the surface.

The direction of both the Neumann lines and the rows of these phosphide inclusions was determined by assuming the two right angle cleavages (Figs. 1–2), are parallel to 100 and 010. The rows of phosphide inclusions are essentially parallel to $1\bar{2}1$ and $2\bar{1}1$ directions. The Neumann lines in these two plates closely parallel the $2\bar{1}1$ and $1\bar{2}1$ directions. The measurements of the Neumann lines from these plates are not in perfect agreement with the theoretical directions of $2\bar{1}1$ and $1\bar{2}1$ lines, because the plane of the section is not exactly parallel to the 001 face and the sample was slightly inclined to the axis of the camera when the picture was made. Yet the agreement in the direction of these Neumann lines and the orientation of the rows of inclusions so closely parallel the trace of the $1\bar{2}1$ and $2\bar{1}1$ faces on the 001 face that it can be assumed they are aligned along those directions.

The rectangular phosphide bodies which remained as a residue when the sample was dissolved in dilute hydrochloric acid, vary in size (Figs. 1–3 and 7). Many of the particles shown in Figure 6 may be fragments of the longer ones which were broken in the process of separating them from the matrix. The dimensions of the fragments of inclusions determined from Figure 6, range between 0.2 and 0.3 mm. in width and the maximum length is 1 mm. However an average of 10 measurements made on the polished surface gave 3.6 mm. as the average length of these phosphides. The maximum length was 7 mm.

Many of the schreibersite bodies show minute holes, usually about midway of the width of the inclusion. Such minute holes, or islands of kamacite in phosphide inclusions, have been observed in other hexahedrites (see Fort Duncan, Plate 56, in The Metallography of Meteoric Iron by S. H. Perry, U. S. Natl. Museum Bull. 184 (1944)).

Another feature of this meteorite is the small light-colored areas shown in Figure 1, which resemble inclusions. These are kamacite. Their long direction lies parallel to a set of Neumann lines. In other words the kamacite granules and the Neumann lines are aligned parallel to the trapezohedral directions. These small and irregular granules occur rather closely spaced along these directions. Their longest dimensions range between 3 and 4 mm. and their shorter dimensions are about half of that distance.

Commonly these kamacite inclusions consist of 2 or 3 granules. Generally there are some differences in the orientation of these granules but the difference between the group and the groundmass is more conspicuous. No taenite occurs between these granules or around them, a significant point discussed elsewhere in this paper by Dr. H. H. Uhlig. These granules interrupt Neumann lines. A few needle-like rhabdites extend from the groundmass into the granule without a break in the rhabdite. Because of this we suggest the granule formed after the rhabdite was in place. Whatever produced these granules did not exert enough force to break a rhabdite needle.

Some small phosphides are uniformly oriented within these kama-

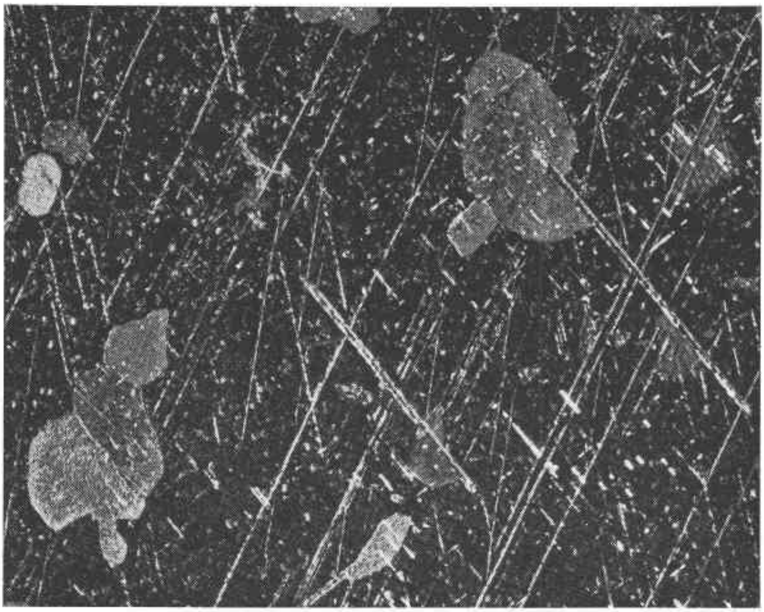

FIG. 3. The groundmass is kamacite containing kamacite granules many of which are aggregates of smaller granules. These apparently crystallized due to some mechanical working but the secondary crystallization did not disturb the orientation of the included rod-like phosphide bodies because they have about the same orientation as the rods in the groundmass. ×9.

cite granules (Fig. 3). Commonly these granules have a flat side which parallels a Neumann line or a rhabdite inclusion. Since the kamacite inclusions in the groundmass are distributed along a direction of one of the trapezohedral faces and the Neumann lines are always so aligned the kamacite granules and the Neumann lines must be related. Any explanation for one must account for the other.

The close relationship between these features suggests that both are primary structures. It seems more logical to consider the Neumann lines as primary structures than to assign their origin to a shock which occurred during the flight of the meteor. Before attempting an explanation of the granules or Neumann lines, the composition of this iron should be considered in reference to the nickel-iron diagram, Fig. 10.

Observed Relations in the Light of the Iron-Nickel Diagram

The cut through the Mayodan iron by good fortune paralleled the 001 direction, so it provided an excellent opportunity to observe many relationships about the features in hexahedrites. The points considered were the sulfides, phosphide inclusions, Neumann lines and the separately oriented granules of kamacite within the groundmass of the hexahedrite. All of these except the troilite, and carbon occurring within the troilite, seem to have formed at a time when they were controlled by the lattice structure of the kamacite. The troilite separates from the melt in particles that coalesced into round masses which solidified before the beginning of the gamma-alpha transformation and therefore are older than any structure in the meteorite.

No sizable inclusions of schreibersite were found, and the limited amount of phosphide which is present may be close to the limit of the solubility of schreibersite in meteoritic iron of this composition. As the temperature is lowered, more and more phosphide separates. The larger rods, which we regard as the first generation of phosphide, contain less nickel than the small needles. These minute needles separate at lower temperatures, hence had more time to become enriched in nickel. Since rhabdites are orientated in hexahedrites as well as in the kamacite in octahedrites, we infer that these phosphides, if given a chance, will take a position parallel to one of the trapezohedral directions.

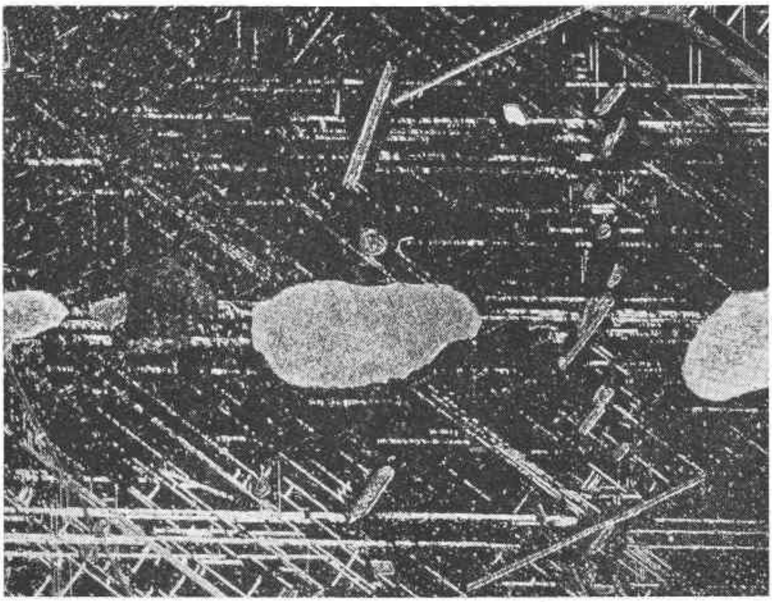

FIG. 4. The kamacite granules, Neumann lines and the vertical row of phosphide inclusions, at the right, are parallel to one of the directions of the trapezohedron. The rather indistinct diagonal line extending from below left center towards the bottom, is a cubic cleavage. The sizable granules across the center are not perfectly parallel, but deviate by a few degrees from paralleling a trapezohedron face; rather than regard them as aligned along some complex form they are assumed to parallel the trapezohedron. ×8.

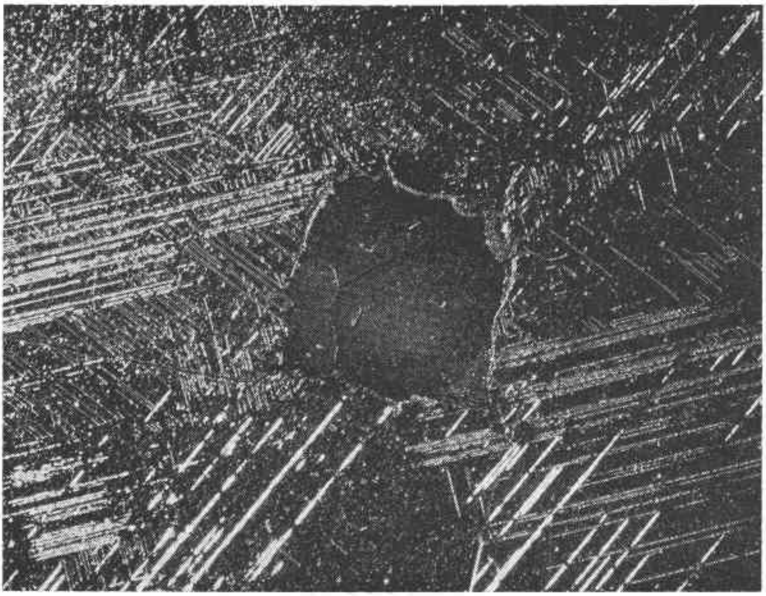

FIG. 5. The troilite and the smaller amount of phosphide that surrounds the FeS are not oriented, but all the other inclusions in this iron are. We believe the FeS separated from the iron-nickel alloy at relatively high temperatures and remained in the same relative position ever since. Many of the troilites are darkened by carbon. The phosphide around some of the troilite inclusions extend as prongs into the groundmass which gives an unusual outline to some of these bodies. ×8.

As the iron cooled along its composition line (Fig. 10), a normal hexahedrite would have formed because this line enters the single phase area at approximately 450° C. However something further must have happened before the metal was cooled to room temperature. This event, in our opinion, took place before either the Neumann lines or the granules of kamacite were formed.

Probably many theories could be proposed to explain the origin of the granules of kamacite, but two new possibilities are offered in the hope of stimulating others to discuss this important point.

Cooling took place along a composition line of 5.6% Ni which corresponds to the Mayodan meteorite. On the Owen and Liu (1949) diagram (Fig. 10) this line enters the mixed phase at about 760° C. Here the kamacite will contain slightly more than 2% Ni while the taenite will carry about 6%. As the temperature drops the Ni content of the kamacite separating increases until at 450° C. it contains about 5.6% Ni.

Assuming that the metal cooled slowly—a logical assumption if it was part of a large mass—there is ample time for one continuous kamacite crystal to form. Yet if the smaller quantities of mixed phases, which are

FIG. 6. Most of the rhabdites have holes midway of their width. The large pieces average between 0.2 and 0.3 mm. wide; the longest one shown is 1 mm., but longer ones can be seen in Figure 4. Although many of the smaller pieces may be fragments, made during the process of recovery, the analytical data show there is a difference in the nickel content of the coarse and fine material. ×8.

essentially kamacite, had separated at various places throughout the metal, and if the temperature was sustained between 400 and 450° C. for a long time, these incipient quantities of mixed phases could migrate and coalesce into small areas within the groundmass. However, since each area was essentially kamacite at the time of its formation, it would ultimately appear as kamacite if the cooling rate was accelerated.

An accelerated cooling rate or anything which will reduce the molecular mobility would freeze these areas into their position before they could be assimilated by the groundmass. The very limited amount of taenite which could be present should lie at the boundary of the granules where it could be most readily assimilated when the temperature went lower than 450° C. because the composition line then enters the single phase area.

The above interpretation is based on the temperatures above 450° C. and rigidly following the iron-nickel diagram in Fig. 10. However in the earlier diagram of Owen & Sully (3) the kamacite at 400° C. contained the same percentage of nickel as shown in Fig. 10, only the line AB bent slightly to the left below 400° C. so that at 300° C. kamacite contained 5.5% Ni. The recent diagram indicates no such curve to the left; unless that curve is there or the line AB is moved to the left, the Owen and Liu diagram fails to explain the structures in iron meteorites.

If those granules of kamacite, Figure 1, formed between temperatures of 760–450° C. and if Figure 10 faithfully tells what takes place, there should be decreasing amounts of taenite formed around the granules as the temperature is lowered. The quantity of taenite decreases because, as the diagram shows, the nickel content of the taenite increases rapidly as the temperature is lowered.

Thus, taenite should not occur around kamacite islands in a hexahedrite because at 450° C. such an alloy as the Mayodan iron enters into the kamacite area. As the Mayodan iron has no taenite around these kamacite granules, it indicates either that Owen and Sully erred in indicating the kamacite boundary curved towards the left or that this meteorite has yet to reach equilibrium.

The Owen and Liu diagram fails to explain the composition and structures found in iron meteorites because the kamacite at 400° C. or lower would contain between 6 and 7.5% Ni and no hexahedrite with such a nickel percentage has been found although about 60 hexahedrites are

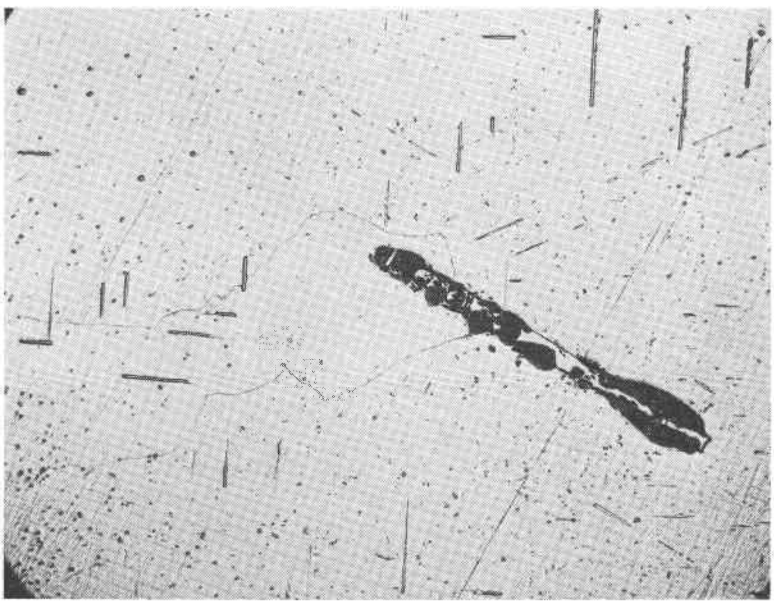

FIG. 7. The big inclusion is rhabdite, perhaps large enough to be called schreibersite, the dark spots are due to chipping in the preparation of the surface. If the plane of the picture is parallel to 001, the small rhabdites at right angles to each other lie along the cube face and the large phosphide body and the other rhabdites are parallel to trapezohedral faces. ×40.

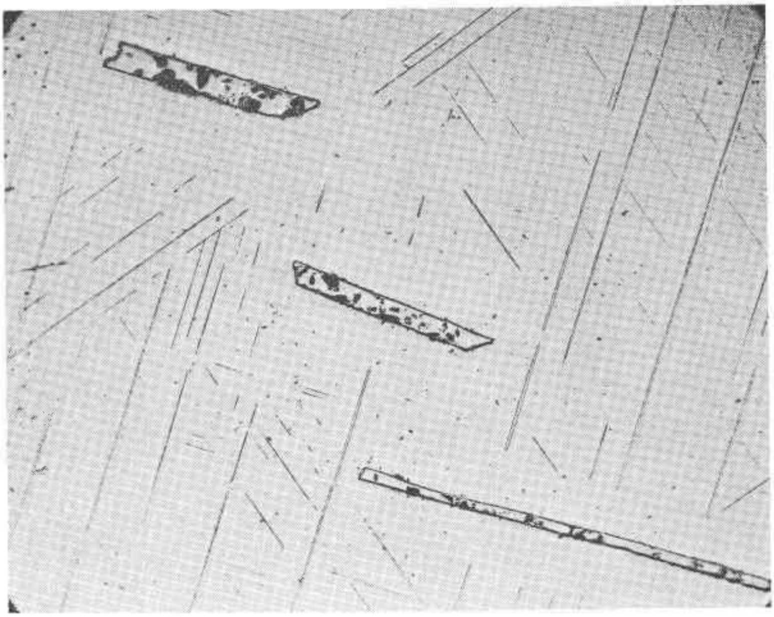

FIG. 8. The large inclusions are phosphide, dark spots due to chipping. There are 4 sets of Neumann lines in the kamacite, but as usual they terminate a short distance from the phosphide bodies. ×40.

known. Meteorites with nickel between 6 and 7.5 are usually coarse octahedrites.

Through informal communications regarding this point, Dr. Uhlig reports that he regards Owen and Liu's work as representing the conditions of normal pressure and since meteorites fail to agree with their diagram, it is likely they formed under different conditions,—most likely higher pressures.

It has been repeatedly proved that Neumann lines in artificial irons are a product of shock or sudden stress and these lines may have been produced in meteorites by the stress of extreme air pressure, by disruption in the air, or possibly in some cases by the impact of the meteorite on a hard surface. Furthermore it seems reasonable to assume that if a planet-like body with a cooling core of iron, should disrupt or explode, the fragments would be subjected to such shock and stress as to develop Neumann lines. In such a case the lines might fairly be termed a primary structure.

On that theory, it seems necessary to relate the kamacite granules and the Neumann lines in the Mayodan iron and to conclude that they were produced simultaneously. Dr. Uhlig has offered the following explanation, which has merit because all the steps take place at moderate tem-

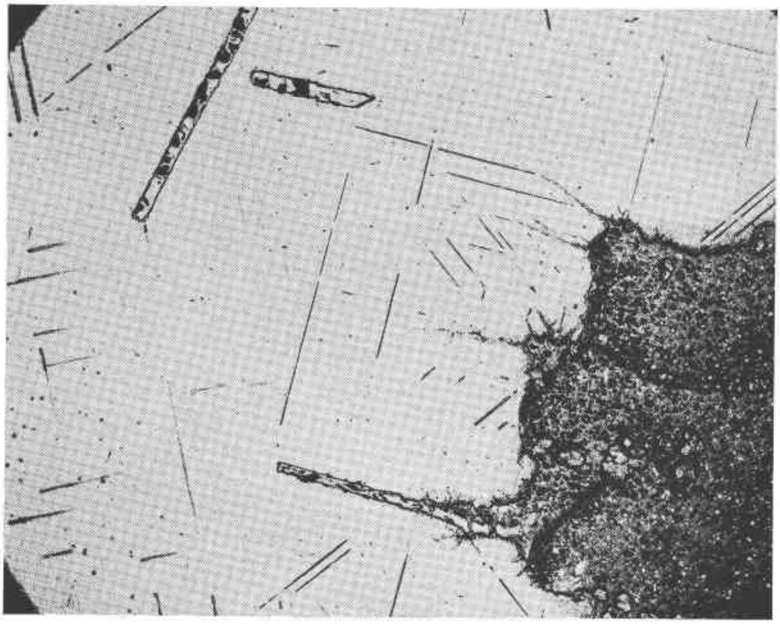

FIG. 9. The troilite at lower right is darkened by carbon, lacks a sharp border, and occasionally phosphide rods extend as prongs from the edges of the FeS. Four sets of Neumann lines are shown in the kamacite. ×40.

peratures and are those which would have occurred if the mass came from a planet-like body which fragmented.

The temperature of the metal was probably below 450° C. when an explosion separated the mass into smaller fragments and produced numerous Neumann bands. These Neumann bands are mechanical twins and therefore produce a certain amount of what the metallurgist calls "cold working." Cold working an alloy produces nuclei for new crystals ot grow and these have a different orientation from the background material. Since mechanical twinning occurs along the 211 planes, the cold-work nuclei also occur along these planes, because under terrific stress or impact these apparently are the only planes that take part in mechanical deformation. Therefore until the alloy cools to room temperature, these nuclei grow and would consist of kamacite of identical composition with the background but with a different orientation. There would be no taenite in these granules if this mechanism is correct, and in fact none is observed.

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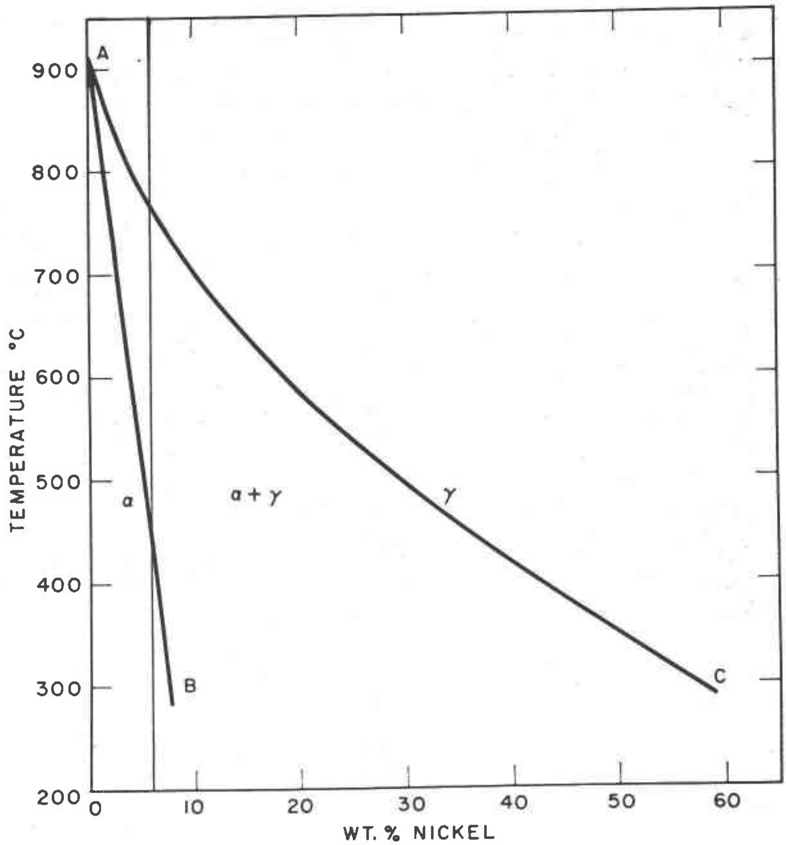

FIG. 10. Phase diagram for iron-nickel alloys at one atmosphere. (Owen and Liu, 1949.)

whom some of these plates showing the included minerals were sent; E. John Long, a science writer who prepared the popular magazine article on meteorites which, when read by James E. Beaver, prompted him to communicate with the Museum. Drs. H. H. Uhlig of Massachusetts Institute of Technology for his suggestions and to Walter Curvello, Museu Nacional, Rio de Janeiro, Brazil, who was visiting this laboratory during this investigation and took an active interest in discussing the results.

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