

# STUDIES OF SEVEN SIDERITES

BY

EDWARD P. HENDERSON AND STUART H. PERRY

No. 3388.—From the Proceedings of the United States National Museum  
Vol. 107, pp. 339-403, 6 figs., 22 pls.

✓ Grant, NM



Goose Lake, CA  
Cincinnati, OH  
Pittsburgh, PA  
Breece, N.M.  
✓ Tombigbee, AL  
Soroti, Uganda  
Keen Mt, VA

SMITHSONIAN INSTITUTION  
UNITED STATES NATIONAL MUSEUM  
WASHINGTON, D. C.

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## STUART H. PERRY

Stuart Hoffman Perry died on February 15, 1957, in Tucson, Ariz. He was the publisher of the Adrian Telegram and vice president of the Monroe Evening News, both well known Michigan newspapers. From April 1940 he was an associate in mineralogy at the U. S. National Museum.

Perry was born October 13, 1874, in Pontiac, Mich., and while very young showed an interest in science. At 15 he presented a paper on rhizopods before the American Microscopical Society. In 1894 he graduated from the University of Michigan, where he studied chemistry, geology, and zoology. Two years later he graduated from the University of Michigan Law School, and for nearly five years practiced law in Detroit. In 1901 he entered newspaper work. After a few years of publishing various papers in Michigan he purchased an interest in the Adrian Telegram, and a few years later an interest in the Monroe Evening News.

Fossils were one of Perry's early scientific pursuits, but when someone showed him a meteorite and asked some questions about it his reply was that he did not know but that he would look into that subject. From that moment on, Perry's scientific interests were essentially directed towards the study of meteorites. He was both a keen student of meteorites and a vigorous collector of them. However, the unique thing about his collecting was that almost as soon as he became the owner of a meteorite he was concerned with giving the specimen to a collection where it would help others in the study of meteorites.

In 1944 the U. S. National Museum published Bulletin 184, Perry's "Metallography of Meteoritic Iron." Shortly thereafter Perry compiled and privately published five albums of photomicrographs on meteorites, the background of the study on which Bulletin 184 was based. Because of the excessive costs of this publication, the album series was limited to six sets. Later the album series was expanded to nine volumes, in which the studies on 166 meteorites were reported and 2,308 photomicrographs presented.

In 1946 the National Academy of Science awarded Perry the J. Lawrence Smith gold medal for his investigations on meteorites. Through the years that Perry was studying and collecting meteorites he generously shared his knowledge and specimens with others. Although he presented specimens to many institutions and privately assisted others in their studies of meteorites, he was sincerely interested in the growth of the national collection of meteorites and presented what he considered to be his important specimens to the U. S. National Museum. During his life Perry donated 192 different meteorites to the national collections.



STUART HOFFMAN PERRY  
1874-1957

(Photo by Fabian Bachrach)

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STUDIES OF SEVEN SIDERITES

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Introduction

These seven descriptions are some of the investigations the authors made between 1940 and 1956. Some of these observations formed the background study to U. S. National Museum Bulletin 184, by S. H. Perry, published in 1944. After that volume was published, a limited number of albums of photomicrographs on iron meteorites with interpretations were also privately published by S. H. Perry and given a limited distribution. These nine volumes are now available in the following institutions: American Museum of Natural History; Chicago Museum of Natural History; Mineralogical Museum, Harvard University; U. S. National Museum; Mineralogical Museum, University of Michigan; and British Museum (Natural History).

During these studies our findings sometimes differed from the data that others had published on the same meteorites, and we suggested that a reexamination should be made. The divergences were found in the descriptions of specimens, chemical analyses, the assignment of types and the identifications of conspicuous minerals.

Some of these findings confirm data published by others and some correct errors in earlier descriptions. Two of the studies are descriptions of undescribed irons.

The undescribed meteorites are the Goose Lake, California, and the Keen Mountain, Virginia, irons. The former was found in 1938, and although it had been pictured in several publications, its unique surface features were not described properly. The Keen Mountain iron was found in 1950 and is not as well known. The main masses of both meteorites are in the U. S. National Museum.

The investigations on the Cincinnati, Pittsburgh, Breece, Tombigbee, and Soroti meteorites are restudies of described specimens.

Appreciation is expressed to all who have helped in various ways in this study. The investigation of these meteorites began many years ago and presented a variety of problems that were discussed with many workers. We may have failed to give credit to all the contributors to this work, but we hope this is not the case.

Among the many who have made important contributions and whom we wish to thank for their assistance are Prof. H. H. Uhlig of Massachusetts Institute of Technology; Dr. Walter Curvello of Museum National, Rio de Janeiro, Brazil, who was a visitor in the U. S. National Museum when some of these investigations were in progress; Dr. Frederick H. Pough, formerly of the American Museum of Natural History; R. O. Roberts of Uganda for providing samples of the Soroti meteorite; Dr. Clifford Frondel of Harvard College and Dr. Carl Dunbar of Yale University for the loan of samples of the Pittsburgh meteorite; Dr. Gunard Kullerud of the Carnegie Institute Geophysical Laboratory; and Dr. George Ellinger of U. S. National Bureau of Standards.

### The Goose Lake, California, Meteorite

#### PLATES 1-9

While deer hunting west of Goose Lake, Modoc County, Calif. (lat.  $41^{\circ}58'$  N., long.  $120^{\circ}32'$  W.), on Oct. 13, 1938, Clarence Schmidt, Joseph Secco, and Ira Ivers discovered a large, irregular, rounded object that proved to be the fourth largest iron meteorite thus far reported from this country. The U. S. National Museum acquired this specimen through the cooperation of Clarence Schmidt, acting as agent for the finders, and the U. S. Forest Service, on whose land the specimen was found.

The details of discovery and removal of the specimen to San Francisco, Calif., have already been published (Leonard, 1939a, 1939b, 1940, 1950; Linsley, 1939a, 1939b). The specimen was displayed during the 1939 and 1940 seasons of the International Exposition at

Treasure Island, Calif.; when the Exposition closed, the sample was shipped to the U. S. National Museum.

Any description of the Goose Lake iron that neglected to discuss the cavities would be incomplete. The description of this meteorite and its cavities is not controversial, but our discussion of the origin and significance of the cavities definitely is controversial. Although we are not qualified to work in the sciences needed to explain the origin of these cavities, we have made this study available to many persons working in other sciences and have stimulated considerable thinking about cavities in meteorites. Our opinions about the origin of these cavities are not in accord with the thinking of F. L. Whipple and R. N. Thomas, whose comments have been given mainly by informal communications.

At the Boston meetings of the American Association for the Advancement of Science in 1953, Thomas discussed some of our theories and raised some challenging points. His objections are not entirely convincing, but on the other hand we are not completely satisfied with our own theories concerning the origin of cavities in the Goose Lake iron. We hope that this paper will stimulate more discussion on this important feature of meteorites.

After the Boston meetings the authors discussed the problem with J. M. Kendall, U. S. Naval Ordnance Laboratory, Silver Spring, Md., and with C. H. McLellan and William J. O'Sullivan from Langley Aeronautical Laboratory, Langley Field, Va. Actually, the topics in this study have been so widely discussed with others that it is becoming difficult properly to credit the suggestions. We are grateful for the interest others have taken.

### Description

The Goose Lake meteorite measures 46 x 29 x 20 inches and weighs 2,573 pounds. Its surface, although comparatively fresh, is covered with a thin, firm layer of brown iron oxide, but in many places flight markings are still preserved. The appearance of this iron would seem to indicate that it fell a few years before its discovery but long enough ago for the black crust of a freshly fallen iron to rust.

The thin films of deformed metal that occur on the surface of the iron range in thickness from one-sixteenth to three-sixteenths of an inch. These, we believe, are flow structures and represent the last physical change to take place on the iron during its flight. The deformed metal shows that a strong lateral force was exerted on the surface during its fall. After studying these zones of deformed metal, we found similar structures on other meteorites. The side of the iron

which has the best development of these features was, we suspect, the forward face during the last moments of high-velocity flight.

The cavities in this iron are a most conspicuous feature. Many of them are large, others are narrow but deep, and many have rims that curl inward. At one place a series of cavities makes a tunnel through the meteorite.

The irregular shape of the Goose Lake meteorite suggests that it probably did not hold a fixed position very long during its fall. Thus, if the cavities were made during its passage through our atmosphere, they formed in a fraction of the time the iron was in the atmosphere. The highest temperature and the major changes in shape occur on the front side of a meteorite, but it seems to us illogical to suppose that each of the cavities was made in the brief interval during which a fixed point was in front.

F. C. Leonard (1939a) and E. G. Linsley (1939a) each published a picture of the meteorite *in situ*, but as these pictures seem to be different, it is difficult to believe that both actually show the meteorite *in situ*. The side of the meteorite which was in front at the end of the flight may not be the side next to the ground, because the iron probably rolled after it struck.

#### Metallography and Chemical Composition

A large piece from the edge of the Goose Lake meteorite (pl. 2) was cut into slices, each about three-eighths of an inch thick. In these polished and etched sections it was possible to observe the distribution of the inclusions.

Schreibersite occurs in small elongated bodies, each surrounded by swathing kamacite. Troilite is less abundant and occurs in rounded inclusions, the largest measuring 1.75 cm. in diameter. Since many consecutive slices were available for examination, we are rather confident that no large troilites or long tubelike inclusions are present. A little schreibersite occurs between the troilite and the matrix, but this is a normal association.

The thin, dark oxide veins shown in plate 7 are essentially parallel to kamacite lamellae. The slice shown came from the edge of the meteorite, where the mass of metal is comparatively thin and where the metal was under the greatest strain during the fall. The strain exceeded the bond between the kamacite lamellae or between the kamacite and taenite, which explains why the oxide veins parallel the structures. Presumably the fractures were filled when the surface of the meteorite was extremely hot, because only then would the metal flow freely enough to enter the tiny cracks. The volume of injected metal is so small in comparison with the mass of the meteorite enclos-



ing these veins that no appreciable amount of heat was carried into the meteorite in this manner.

The plessite shown in plates 8 and 9 is unusual. The spheroidized inclusions suggest that it was heated long enough to form this structure and then cooled quickly. Such cooling is inconceivable while the mass was a part of some planetlike body. This structure could be developed by heat generated at the surface during the iron's flight; the only question is: Would there have been enough time?

The widths of the kamacite bands in the Goose Lake meteorite are within the range of those in the coarse octahedrite group, but the symmetrical pattern and uniform width of the lamellae make this iron resemble a medium octahedrite.

The average width of a series of kamacite lamellae in one slice is 1.61 mm.; in another slice, 1.51 mm. A few of these bands measured 5 cm. long, but the average is near 3 cm. The taenite is abundant, most of it darkened by reason of imperfect transformation and containing needles of kamacite. The plessite fields are numerous and varied in character.

In table 1 the composition of the Goose Lake meteorite is compared with that of seven other similar irons from widely scattered localities. Since the chemical analyses are nearly alike, these specimens should be compared with respect to other features. The Mbosi, Drum Mountains, and Goose Lake irons are large, each weighing over 1,000 pounds, but the other five meteorites are comparatively small. Unfortunately we have not seen all these meteorites, and the information concerning surface features was obtained from published descriptions. We have certain reservations regarding the data in the literature relating to the surface of meteorites, because the outside of these objects has not received much critical attention.

TABLE 1.—*The composition of the Goose Lake and other similar meteorites.*

	<i>Goose Lake, California</i>	<i>Aggie Creek, Alaska</i>	<i>Drum Mts., Utah</i>	<i>Mbosi, Tanganyika</i>	<i>Baque-dano, Chile</i>	<i>Karee Kloof, South Africa</i>	<i>Lanton, Missouri</i>	<i>Moorumbunna, Australia</i>
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Fe	90.80	90.89	90.70	90.45	90.90	90.79	90.40	89.53
Ni	8.39	8.54	8.59	8.69	8.82	8.27	8.33	8.82
Co	0.42	0.67	0.58	0.66	0.15	0.68	0.61	0.56
P	0.12	0.18	trace	0.11	0.24	0.24	0.18	0.29
S	0.00	0.00	0.00	0.01	0.05	0.00	—	0.02
Cu	n. d.	—	—	trace	0.03	0.03	—	0.07
Insol.	0.03	0.03	0.01	0.03	0.01	0.03	0.005	0.30
Fe	10.91	10.42	10.47	10.23	10.68	10.76	10.64	10.08
Ni+Co								
Width of kamacite band in mm.	1.5	1-2	1	0.75	1.5-2.5	1-2	less than 1	0.5-1.5

The Aggie Creek, Alaska, iron (Henderson, 1949) weighed 43 kilograms but was described without seeing the main mass. The meteorite was recovered from placer gravels 12 feet deep; thus it was wet during most of the time it was in the gravels. The weathered surface of the piece that was available for study was free from corrosion pits.

Some of the cavities in the Drum Mountains, Utah, iron (Henderson and Perry, 1948a) may have existed before the meteorite entered our atmosphere. However, one cavity was nearly filled with iron rust when the meteorite arrived at the United States National Museum. The character of the iron oxide on the surface makes it possible to determine the orientation of the specimen in the field, and in this way we knew that the rust-filled cavity was inverted. Although it could not hold water, the moisture that condensed on its walls was trapped and thus evaporation was retarded. The oxide scales that almost filled the hole were so firmly embedded that they had to be chipped out even after the rough handling this 1,164-pound iron received between its fall and its arrival in the Museum. As it was shipped in an open crate, the freight handlers could see that it was almost indestructible, and it is unlikely that they handled it with care.

The Mbosi, Tanganyika, Africa, iron, according to Grantham and Oates (1931), "was buried two to three feet in a red loamy quartz rubble which was covered by a few inches of soil. The lie of the mass very similar to the hill. Scattered through the rubble, several feet from the mass, are scraps up to an inch and a half thick of black nickeliferous iron oxide. These, no doubt, are fragments of scales detached from the mass during its travel down hill."

Evidently corrosion removed considerable material, and the altered surface may have little or no resemblance to the preflight surface. Corrosion may have gone below the zone of cavities, as it did on the under side of the Canyon Diablo iron. The illustrations of the Mbosi iron show two or more depressions, but these could be the result of corrosion.

The 22-kilogram iron from Baquedano, Chile (Palache and Gonyer, 1932), was covered with pits. Its pitted surface was said to be "the effect of sand blasting." The authors stated that a portion of the surface was corroded, but the published illustrations showed no cavities similar to those in the Goose Lake meteorite.

The Karee Kloof, Cape Province, South Africa, meteorite (Prior, 1923) weighed 92 kilograms and showed "thumbmarks." The dimensions of one cavernous depression is given as 20 x 15 x 7½ centimeters. From a 7.1-gram sample Prior recovered some insoluble residue which had "the optical characters of quartz . . . ortho-

rhombic pyroxene . . . and some of feldspar having refraction slightly less than that of nitrobenzol (1.55) and showing in one case twin-striations with a low angle of extinction."

The finding of silicates in a meteorite exhibiting cavities could be a very significant observation for us. Unfortunately, one cannot be certain that Prior's sample was uncontaminated. It might help to explain the origin of cavities if silicates occurred in the irons that contain cavities, but we have no clear evidence that they do. If there were silicates, they should appear in the polished sections and not in the nonmagnetic portion of the insoluble residue. Usually some of the abrasive used during the preparation of the sample gets embedded in the softer minerals or cracks and then is recovered in the insoluble residue; we therefore discard the traces of nonmagnetic material that appear there.

The Lanton, Missouri, iron (Cullison and Muilenburg, 1934), weighing 13.7 kilograms, was in four pieces, all of them badly weathered. No cavities were mentioned, and apparently all the flight surfaces were corroded.

The Moorumbunna, Australia, iron (Edwards and Mawson, 1946) was said to have a pitted surface: "the entire surface is pitted, apparently the result of corrosion which must have continued over a long period of time. Pitting reaches a maximum depth of five centimeters below the main surface level; this indicates that the fall is by no means a recent occurrence."

#### Terminal Velocity

Many stony meteorites break up or explode after entering our atmosphere. Two or more pieces may fall simultaneously some distance apart and both be covered with fusion crust. When such pieces fit together, there can be no question that they came from the same object. The meteorites that separate into pieces probably do so when the velocity is high, as indicated by the fact that the fractured surfaces are covered with a fused crust. If the pieces fit together, we know that little material was lost from either portion. Stony meteorites are not as tough as the irons, and it is therefore easy to understand their breaking apart, but on the other hand some irons do the same thing. There are no statistics about the breaking of meteorites into pieces that will fit together again, but indications are that there may be nearly as many irons that do this as there are stones.

The Maldyak, Siberia, iron (Zavaritzkit and Kvasha, 1952) was split almost in half, and the illustrations show that one part apparently suffered more ablation than the other. An equally good example of the breaking up of an iron meteorite is the Boguslavka, Siberia,

specimen which fell Oct. 18, 1916 (Zavaritzkit and Kvasha, 1952). The Maldyak iron is an octahedrite; the Boguslavka iron a hexahedrite. It is much easier to explain the Boguslavka meteorite separating into fragments than the Maldyak iron, because hexahedrites have a cubical cleavage while the octahedrites have no cleavage.

Figure 1,*a*, taken from Zavaritzkit and Kvasha (1952), shows that the place of separation for these two pieces of the Boguslavka iron is at right angles to the base. The right side of the upper portion of the left piece is essentially parallel to the fracture separating the two pieces. Since these faces appear to be straight, flat, and normal to each other, possibly they are cubical cleavages.

Figure 1,*b*, was taken from Akulov and Brukhatov (1941) and is slightly different. The figure shows the reverse side of the Boguslavka iron, and the bottom of the front face of the smaller portion is unlike the view Zavaritzkit and Kvasha used. However, the right side of the smaller piece is essentially parallel with the adjacent side of the larger portion, again indicating cleavage. Neglecting the minor

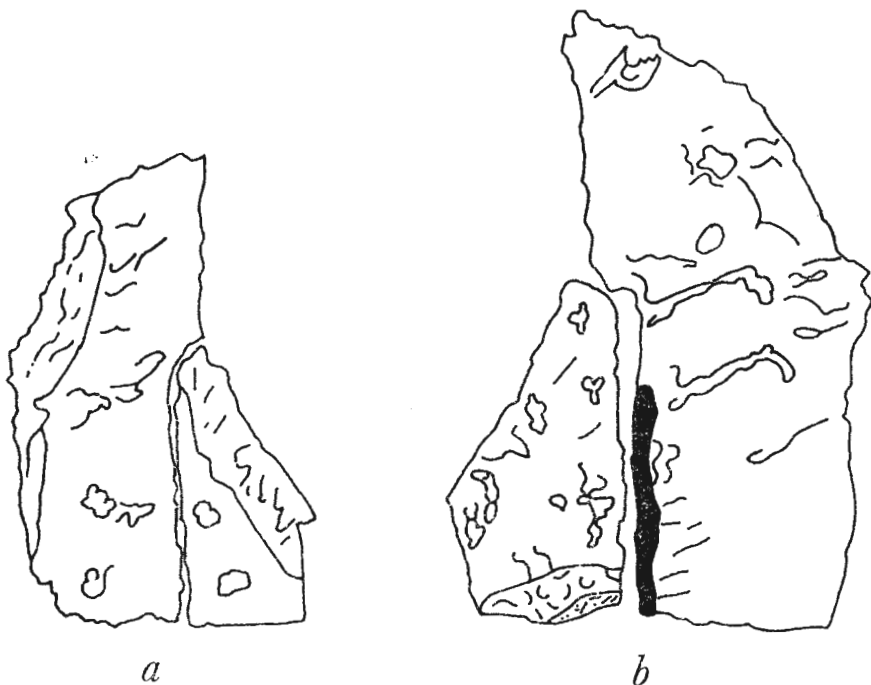


FIGURE 1.—Sketches of the Boguslavka meteorite, which possibly broke along its cubical cleavage directions. *a*, From Zavaritzkit and Kvasha (1952); *b*, from Akulov and Brukhatov (1941).

differences in the two views, it seems that this iron separated along cleavage directions during its high-velocity flight.

Meteoritic iron can be easily deformed by a light tap of a hammer. Since the Goose Lake iron was found on solid rock, has flight markings, and lacks impact scars, either its terminal velocity was low or something cushioned its fall. J. J. Cornish,<sup>2</sup> after a brief inspection of the specimen, stated that possibly considerable aerodynamic lift was given the meteorite during its fall because of its physical form. He said: "The large cavity [see pl. 1], which makes an opening to the tunnel through this iron, probably would give this body considerable spin during its fall. This spin could generate enough lift to reduce the velocity of fall." Independently, Cornish selected the same side of this iron that we did as the forward face during the fall.

The area in which the iron fell is covered during the winter months with deep snow which would break the impact with the ground. But if it fell on a layer of snow, how can we account for the depression that Leonard (1940) reported? Leonard mentioned an elliptical ridge measuring 24 feet east and west and 20 feet north and south and said the meteorite was located in a saucerlike depression approximately 5 feet in diameter. He apparently assumed that this was the place where the iron struck the earth.

Linsley (1939b) doubts that the saucerlike depression is significant and says, "there was only the slight depression in which it rested which appeared to be due in part to wind erosion as the air currents eddied about it."

Although one can only speculate about the terminal velocity of the Goose Lake iron, we are certain that it had a spectacular fall. The varied cavities must have produced some weird sounds as the air rushed past these openings. It is unfortunate that the iron landed in a sparsely settled area, because if it had come to earth in a more thickly populated region the terrified citizenry would surely have recorded the date and hour of the fall of this screaming meteorite.

### Cavities

Cavities occur in many iron meteorities, but it need not be assumed that all cavities have the same origin. Some definitely are the result of terrestrial corrosion, but we are convinced that the cavities in the Goose Lake iron did not originate in that way. As we became more familiar with these features and discussed them with others, we came to feel that their significance was not appreciated and that the old explanations for cavities were unsatisfactory. Their physical features, significance, and some theories of their origin, as well as the origin

<sup>2</sup> Of the Engineering and Industrial Research Station, State College, Miss. Personal communications.

of the wide, shallow depressions known as "thumbmarks," are discussed in the sections that follow.

It is difficult to describe, measure, or photograph a cavity so that a reader can obtain a comprehensive conception of it, which may partially explain why these features have been neglected in descriptions of meteorites. The measurements recorded for these cavities are approximate values but are sufficiently accurate to give an idea of their size. We have determined the volume of a few cavities.

The cavities in some meteorites are bowl-shaped, but when a cavity is two to four times as deep as it is wide, it resembles rather a drill hole. However, cavities have one almost universal characteristic: The width of the opening at the surface is less than the diameter of the cavity measured down in the hole.

A rim of deformed metal overhangs and bends into many cavities on the Goose Lake iron. If the fingers are rubbed over the rim inward toward the cavity, the surface feels smooth, but when the direction is reversed the rim feels jagged. We believe the rim of overhanging metal was produced by thermal action on the surface of the meteorite after the cavity was there.

The largest cavity in this iron, shown in plate 1, has an irregular opening measuring approximately 10 by 12 inches. Within it there are 8 smaller cavities with openings measuring 0.5 to 2.0 inches in width and 0.5 to 1.0 inch in depth. An interesting feature of this large cavity is an opening in its base approximately 2 by 4 inches that leads into an oval cavity entirely within the meteorite. The oval cavity is approximately 7 inches long and 4 inches wide and has an opening on the rear face of the meteorite. The side wall of this cavity at one place is only about an inch below the surface. This place can be located in plate 1 between the middle of the long rule and the lower part of the opening to the large cavity directly above.

The oval chamber makes a tunnel through the meteorite. But since concealed cavities have not been found in any of the sections cut through iron meteorites, we do not believe that this oval chamber was a concealed cavity. The lip around the larger cavity (pl. 1) turns inward as does the lip around the opening from the bottom of the large depression into the tunnel. We regard this tunnel to be as much a primary feature as the hole through the Tucson, Ariz. (Ring), meteorite shown in pictures by Merrill (1929).

It is impracticable to measure or illustrate in detail all the cavities; therefore, a few of the important types were selected for a more detailed study. With the assistance of W. E. Salter of the United States Geological Survey, latex molds of these cavities were prepared and plaster casts made of the molds. After a plaster mold was avail-

able, we investigated methods of measuring the volumes. By the method finally used, it is now possible to measure the volume of cavities in some large meteorites too heavy to be reorientated so that the cavities would be in position to be filled with either a liquid or sand.

After trying various methods, we found that "Climax" wallpaper cleaner (Simmons, 1942) could be successfully used to measure cavity volume. A film of oil was first applied to the walls of the cavity, then the opening was filled by inserting small wads of cleaner from a weighed amount. Each time the cleaner was added, it was pressed down with all the force that could be exerted with the fingers. After the hole was filled to the original surface of the meteorite, the weight of the excess cleaner was subtracted from the original weight. The density of the cleaner was obtained by packing it into various combinations of plumbing connections, such as elbows and tees. These simulated the cavities in the meteorite very nicely because certain combinations gave a sizable cavity with a small opening. After these were filled with cleaner, the material was removed and weighed, and the volume was then measured with water. As the cleaner absorbs oil from the walls of the cavity, its density varies and should be checked after several measurements. After a little practice we were able to determine the volumes of the cavities with sufficient accuracy for our needs.

TABLE 2.—Measurements of a few cavities in the Goose Lake meteorite

Depth (cm.)	Width (cm.)	Width/depth ratio	Volume (cc.)	Estimated weight of Ni-Fe needed to fill cavity (gm.)
10	11	1.10	686	5451.5
11	7	0.63	340	2657.0
8	2	0.25	60	468.0
11	5	0.45	215	1677.0

Many mineralogists believe that the cavities in iron meteorites were formed during flight when some included mineral burned out. The largest inclusions usually found in iron meteorites are troilite and schreibersite, with occasionally a carbon nodule, although generally the carbon is concentrated around the troilite. Usually the troilite and carbon inclusions are rounded masses with a diameter of less than 1 inch, whereas the schreibersite ordinarily is more elongated and irregular. The schreibersite is more uniformly dispersed in this iron than is troilite. In the slices so far cut from the Goose Lake iron, no single inclusion or aggregate occurs that approaches the dimensions of the cavities.

As troilite and schreibersite melt at approximately 1000° C. and are brittle, it is possible that they would be easily ablated by the air stream. If these minerals melted out to form a deep, narrow cavity, considerable iron around the inclusion must also have been removed, because, as stated above, the cavities in this iron are much larger than any of the inclusions thus far found. It is difficult to understand how a cavity 8 cm. deep with an opening of 2 cm. could be formed by melting out some included mineral, and possibly an equal volume of Ni-Fe alloy around the inclusion, without widening the opening to the surface. If the air within the tube is somewhat stabilized, it would retard the flow of heat toward the bottom of the hole, since air is an insulating medium.

Sections cut through some iron meteorites show cavities in which troilite still occurs at the bottom. If such cavities were formed by burning out the sulfide, it seems unlikely that troilite would be found in the bottom of some cavities. Its occurrence there may indicate that troilite is not as easily removed during the fall as has been assumed by some workers in this field.

As stated above, there are no inclusions in any of the sections of the Goose Lake, Canyon Diablo, or Willamette meteorites that even approach the dimensions of the cavities. This would seem to rule out the theory that the large cavities on the surface of these irons were formed by the burning out of troilite, schreibersite, or carbon inclusions except for one possibility. Perhaps the zone around the outside of these irons contained larger included masses of these minerals than now occur in these meteorites; consequently, size alone might not eliminate the burning-out theory. This possibility would introduce a new concept of iron meteorites, for in the past it has been tacitly accepted that the portion removed from the surface of a meteorite during flight had a composition and structure similar to that in the mass that fell.

Those who claim that the cavities were formed by the burning out of inclusions must account for the formation of large cavities at very high altitudes. Such cavities would have to be formed in a fraction of the time it takes the meteorite to pass through the atmosphere. The meteorite must pass part way through the rarefied upper atmosphere before collision with the air can have much effect on the surface. Toward the end of the flight, the velocity is so retarded that no changes take place on the surface. When these two time intervals are subtracted from the number of seconds required for a meteorite to fall through our atmosphere, we do not believe that enough time remains for a tumbling iron to undergo sufficient heat penetration to form the deep cavities on all sides.



The greatest changes that take place on a falling meteorite occur during the period of their maximum deceleration, which is but a fraction of the atmospheric passage. The size and shape of a meteorite affect the velocity it will retain during the fall. The Goose Lake meteorite has a rather wide cross section and therefore was probably decelerated rapidly. There is evidence that less heat was applied to the surface of the Goose Lake meteorite than to the surface of certain other meteorites. For example, there are no delicate stringlike markings of fused metal flowing away from the front face, and the cross sections through this iron fail to show any appreciable evidence of heat penetration, as the internal pattern of the metal continues to the edge without loss of detail. The failure to find a zone of modified structure near the edge of the Goose Lake iron supports our contention that these cavities were not burned out during flight.

If the Goose Lake iron entered our atmosphere with a high velocity, one would expect its surface to show some features similar to those found on the Freda, North Dakota (Henderson and Perry, 1942a), and the Pima County, Arizona (Henderson and S. H. Perry, 1949), irons. The external forms of these two meteorites indicate that more heat was applied to them than to the Goose Lake iron. There is no evidence that heat penetrated the Goose Lake iron as it did the Reed City, Michigan (Henderson and Perry, 1942b), the Bruno, Saskatchewan (Nininger, 1936), or the Murnpeowie, Australia (Spencer, 1935), meteorites.

The highest temperature on a falling meteorite occurs on the front face, while the thermal action on the rear surface is much less severe. A shock wave follows the outline of the front face, and the molecules of air which strike the iron pass through this wave and are compressed into the lateral flow moving toward the edges of the body. It is this lateral flow which ablates the iron. The hot gas that is compressed against the iron moves with a high velocity and is the agency that cuts obliquely across the cavities in the Canyon Diablo iron. It partially removed the cavities on the conical sides of the Willamette iron.

The temperature within a hole may be different from that which exists on the surface of the meteorite, and we are not sure that it would be below the temperature on the exposed surface. It can be argued that the temperature within a hole would be lower because air is a poor conductor and because the walls of the cavity would absorb heat.

It is possible also to argue in the opposite direction. Heat is lost from the outside surface by radiation, but the heat within the cavity cannot escape that way. Thus, if energy can be supplied through the opening in amounts which will produce an exothermic reaction,

possibly a higher temperature could exist within the cavity than on the outside surface. Furthermore, if an element in the included minerals could produce an exothermic reaction, additional heat would be generated within the cavity.

The collision between the air molecules and the meteorite would ablate the surface, but the metal on the side walls ("bc" and "ef" of fig. 2) is both heated and ablated. As the lip of the cavity is ablated from two sides, the rim would recede faster than any other part.

A flow of considerable force exists on the front surface of a meteorite. This flow originates at the center and radiates in all directions from this point, producing the layers of displaced metal previously referred to as a type of flight marking. Thus, on the forward face of a falling meteorite we think that a depression should widen faster than it deepens. The diameter of an opening (fig. 2) should increase because the shaded areas are heat-softened from two sides. This perhaps explains why broad shallow depressions are more abundant than tubular cavities on iron meteorites.

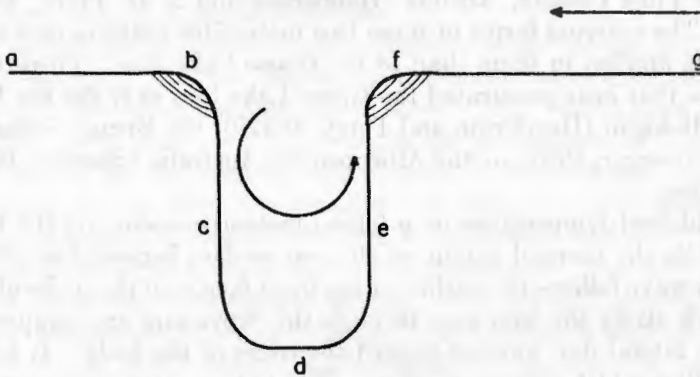


FIGURE 2.—Cross section of theoretical cavity in a meteorite, showing how the width of the opening increases faster than the depth. The shaded area probably would ablate faster than the outside surface of the meteorite between "a" and "b" as well as "f" and "g." The sides of the cavity, "c" and "e," may be ablated faster than the bottom, "d," because there should be a vortex established within the cavity. The arrow indicates the direction of the lateral flow, and the vortex within the cavity should rotate as the arrow indicates; thus, the sides "c" and "e" may be undercut.

The above explanation accounts for those shallow but wide depressions called "thumbmarks." Sometimes these "thumbmarks" are closely spaced on the surface but are separated by narrow ridges of metal. The fact that the separating ridges are irregular suggests that their position was constantly changing. A ridge has a large exposed surface compared to its volume; consequently the metal in it would be heat-softened to a point where it could be mechanically ablated more rapidly than the metal on a flat surface.

The surfaces of some meteorites pass obliquely across tubelike cavities leaving outlines of parts of these cavities still preserved. When a surface cuts obliquely across a cavity, the evidence indicates that the cavity was being modified at the surface rather than within the hole. It also means that the deep and narrow cavity existed when the meteorite had a high velocity. These oblique cuts provide a method of estimating the thickness of metal that was lost, although possibly they give a value closer to the minimum than the maximum.

Two Canyon Diablo irons in the U. S. National Museum have oblique cuts across cavities. Probably no specimen better shows how much metal was removed after the cavities existed than the Willamette, Oregon, iron. Pictures of the large cavities in the base of that conical mass are well known, but few observers have noted the remnants of cavities on the conical sides of the specimen. The conical-shaped meteorites are cited as having held a fixed position through most of their flight. If that is true, the shallow depressions on the conical surface of the Willamette iron are probably remnants of cavities similar in size and shape to those on the rear surface. The rear face of a meteorite undergoes little change during flight. Thus, the rear side of the Willamette iron, which exhibits deep craters, may have some topographic similarities to the surface that existed there before the iron entered our atmosphere.

Although this is not a discussion of the Willamette iron, it should be mentioned that the specimen needs to be restudied. It was described as a medium octahedrite and continues to be so listed, although none of the specimens we have seen contains a trace of the Widmanstätten structures; instead all have granulated structures. Possibly these pieces were heat-treated at the time they were removed from the main mass or afterward. If further study of the Willamette iron were to show that the heat penetrated deeply into the main mass, this might be an indication that the meteorite was heated before it entered our atmosphere.

Although the Social Circle, Georgia, iron (Henderson and Perry, 1951) has no cavities, it is a sizable iron and is granulated throughout. In this case the granulation apparently did exist before the specimen entered our atmosphere. Since the cavities in the Goose Lake meteorite are enclosed in metal with a normal Widmanstätten structure and since the etched structure extends to the edge of the slice, there is no evidence visible to the naked eye of thermal changes in the outside zone of this iron.

The velocity of all meteors entering our atmosphere is high enough so that sufficient heat is developed by the collision with the air to fuse the surface and change the shape. The Canyon Diablo individuals

mentioned above and the Willamette iron show a loss of metal after the formation of the cavities. There are no conspicuous oblique cuts across the cavities in the Goose Lake meteorite, which indicates that it traveled with less velocity through the air than either of the two above-mentioned meteorites.

The two large Canyon Diablo individuals have deep cavities on one side but no holes on the side that was next to the ground. The upper surface still shows some flight markings, indicating that almost no metal was lost since its fall. An examination of the under surface gives the impression that the specimens are very old, but an opposite opinion would be gained if only the exposed surface were examined.

It is reasonable to believe that there were cavities on all sides of these Canyon Diablo specimens when they entered our atmosphere, and we are certain that these cavities existed before the meteorite hit the earth. Since the fall, corrosion has removed enough iron from the under surface to obliterate the cavities. Just when the Canyon Diablo iron fell is unknown; it may have been 10,000 or even 50,000 years ago.

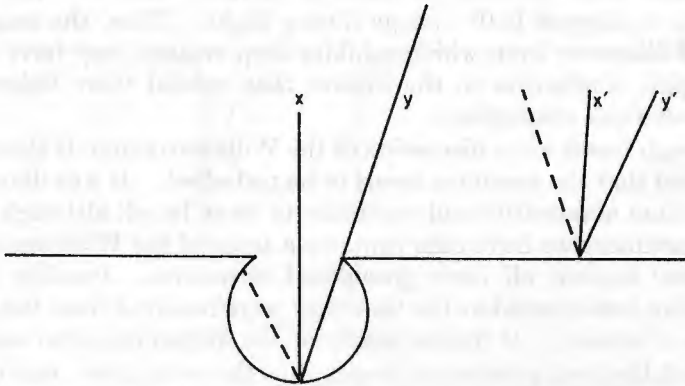


FIGURE 3.—Cross section of theoretical cavity in a meteorite, showing how its size may increase below the surface by the bombardment. Particles colliding along directions indicated by "x" and "x'" will rebound along the same direction, but those striking parallel to "y" and "y'" will rebound in a different direction. Since most of the particles falling within the cavity will rebound against the side walls, this action may produce the undercutting.

But the difference between the corroded under surface and the top of the specimen shows how slow atmospheric corrosion is compared to the corrosion that takes place on the under side.

The lateral flow over the forward side produces the overhanging rim of metal on one side of a cavity, but there is no satisfactory explanation for an overhanging rim of metal entirely surrounding the cavity. If the moving air pushes metal into the cavity, we are unable

to understand why the air which has to escape will not bend some metal the other way.

Although it is our belief that the shape of these cavities and their overhanging rims of metal point to the existence of the cavities before the meteorite entered our atmosphere, R. N. Thomas<sup>3</sup> has a different and interesting explanation for the shape of the cavities. He considers that if a hole existed, it acted as an energy trap (fig. 3). The particles that collided with the outside of the meteorite were reflected away, while those that hit within the cavity were reflected against the side walls; this bombardment undercut the sides.

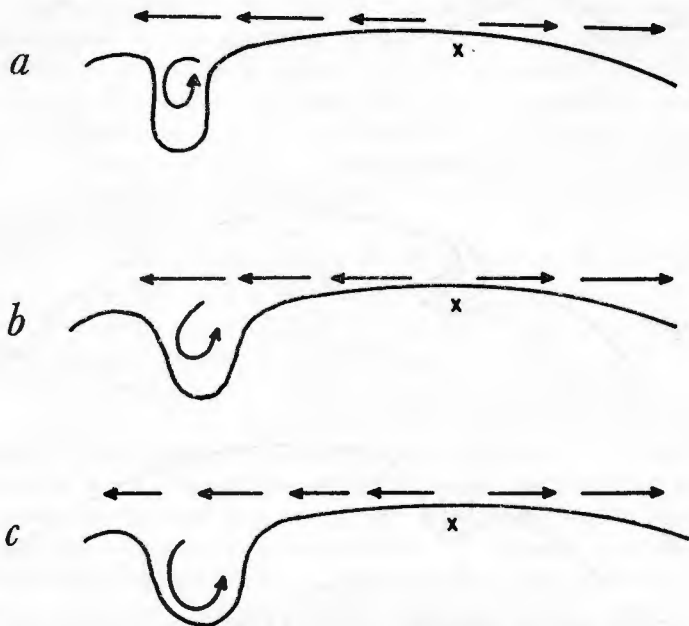


FIGURE 4.—Cross sections of theoretical cavity in a meteorite representing the progressive changes (*a*, *b*, *c*) when the long axis lies parallel to the direction in which the mass is falling. The stagnation point is indicated by the "x." The small arrows indicate the direction of the lateral flow. The ablation, at the opening to the cavity, is greater on the side towards which the flow is directed.

A bombardment such as Thomas suggests probably does occur, but we believe that the lateral flow of hot air on the front of the meteorite is the predominating force. The progressive changes shown in figure 4 illustrate our conception of what happens to a deep but narrow cavity, essentially normal to the lateral flow, which holds a fixed position on the front of a falling iron. Since the air flow originates at the center of the front face, the stagnation point, and moves

<sup>3</sup> Personal communications.

in all directions, the cavity rim farthest away from the stagnation point would get the direct impact of the lateral flow. The metal in the rim would be heated from the top and from within the cavity, with the result that the rim would be ablated much faster than the surface of the meteorite. It seems clear that this blast of hot air would widen the opening of the hole faster than the general surface of the meteorite would recede and faster than the cavity would be deepened.

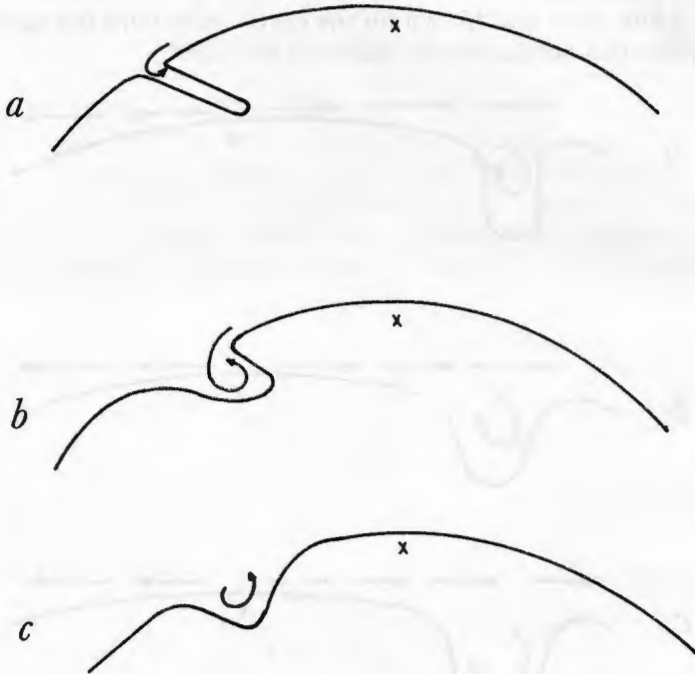


FIGURE 5.—Cross sections of theoretical cavity in a meteorite representing the progressive changes when the long axis is oblique to the direction in which the mass is falling. Similar conditions exist here as in figure 4 except for the incline of the long axis. The thin, overhanging lip would be ablated more rapidly than the opposite side. The stagnation point is indicated by the "x."

Although ablation is probably greatest on the rim farthest from the stagnation point, the opposite rim is also heat-softened and ablated. The lateral current of air blowing across the opening of the cavity would establish an eddy in the mouth of the hole. This eddy would direct hot gas against the inside wall for a distance down in the cavity about equal to the diameter of the opening. The turbulent gas must contain solid particles torn from the surface of the meteorite, and these particles should ablate the metal on the side walls as fast as heat

softens it. Almost simultaneously this lateral flow of hot-air heat would soften and ablate the rim around the cavity with the result, we believe, that the cavity would be widened faster than it is deepened.

When the long axis of the cavity makes an acute angle with the plane of the lateral flow (fig. 5), the side nearest the stagnation point, or the upstream rim, would be widened more rapidly than the opposite side. In this case, the eddy established in the cavity opening would direct heated air against the inside wall on the upper side of the opening. As the overhanging metal is thin, it would be softened and more quickly ablated than the lower side. This process could change such a cavity into something like that which exists on the Canyon Diablo meteorite (see p. 351), or, if there is enough time, the lateral flow could make a wide and shallow depression, or "thumbmark."

*Were cavities formed by shrinkage?*—H. C. Urey and G. P. Kuiper<sup>4</sup> independently suggested that cavities in iron meteorites might be due to shrinkage when the metal solidified. Although depressions occur in cast metals, there are so many differences between the shape and location of cavities in ingots and in meteorites that this hypothesis seems very unlikely.

A liquid conforms to the shape of its container, so that only its upper surface is free. Thus the cavities in ingots occur in the upper part or close to the upper surface. This point was comprehensively discussed by Camp and Francis (1951), and their illustration indicates that the cavities in ingots usually resemble inverted cones. In all but a "killed ingot" the conspicuous shrinkage features and cavities occur in the core of the upper part. "Killed ingots" cool rapidly, and inasmuch as such cooling has no place in the history of meteoritic iron we believe that the features of such ingots need not be discussed.

*Were cavities formed by gas or liquids?*—The metallic portion of a meteorite solidifies at a lower temperature than the silicates. If gas or liquid phases are given off as a metallic portion solidifies, these would escape through the enclosing silicates as long as they remained porous. When the mobile phases can no longer escape and as they do not combine with the metallic or silicate constituents, they must accumulate somewhere. The most likely place would be between a large iron mass and the enclosing zone of silicates. Thus, possibly these mobile phases accumulated near the outside edges of the large metallic masses.

The occurrence of metallic phases in stony meteorites indicates that the metal was injected after the silicates were formed and in the position they now occupy.

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<sup>4</sup> Personal communications.

In iron meteorites, usually some schreibersite occurs around the troilite inclusions. It seems reasonable to assume, therefore, that around a large concentration of metallic iron in a silicate body, a swathing zone of some type existed which now is completely gone. Such an enclosing zone could be rich in chlorides, sulfides, phosphides, etc. Such phases may have filled the embayments or cavities in the iron and through some unknown process subsequently vanished. Although at the present time this is pure speculation, there is a reasonable possibility that such a zone existed.

Nash and Baxter (1947) studied the gas within six meteorites and found that four of them contained less than 10 cubic millimeters of total gas under normal temperature and pressure per gram of meteorite. The Canyon Diablo iron had much more gas than the average of the six meteorites they studied, and it may be significant that the Canyon Diablo individuals contain cavities.

If Baxter's values for the Canyon Diablo iron are taken for the Goose Lake meteorite, there would be about 35.01 cubic meters of gas (N.T.P.) within the latter.

$$\frac{30 \text{ cu. mm.} \times 2573 \text{ lbs.} \times 453.59 \text{ gm. per lb.}}{10^6} = 35.01 \text{ cu. m.}$$

An ultraconservative estimate of the liberated gas would be between 5 and 10 times the amount of residual gas in a meteorite; for the Goose Lake iron, this would give between 175 and 350 cubic meters of liberated gas under N.T.P. Considering the pressure and temperature the gas would be under when the cavities formed, probably there was enough liberated gas to fill these cavities.

When iron is cast it conforms to the enclosing mold, so that the gas cavities or shrinkage features develop only on the upper surface, whereas in the Goose Lake meteorite there are cavities on all sides. Ingots are, of course, made in the earth's gravitational field, but possibly meteoritic iron formed in a gravitational field which was not as strong as that of the earth, and therefore cavities might occur around the entire mass.

*Were cavities formed by weathering?*—The corroded surface of a buried iron meteorite differs from a weathered exposed surface. The pitting on the buried side is usually wide and shallow, and the metal ridges separating corrosion pits are generally sharp. Furthermore, the iron oxide on the buried surface is rough and usually thicker than that on an exposed surface. Corrosion acts on the side of the iron next to the ground, or all over a buried iron meteorite, much faster than it does on the upper exposed surfaces.

Many arguments can be marshalled against the formation of cavities in the Goose Lake meteorite by weathering. The cavities occur on



all sides of the specimen instead of chiefly on the side next to the ground where corrosion would be expected to be the greatest. Corrosion on an exposed surface is slow, and during the great length of time that would have been required to weather out such deep holes on exposed surfaces of the meteorite, the surface next to the ground would surely have developed the characteristic corrosion pattern of the under side of a meteorite; this it did not do.

If the cavities in the Goose Lake iron were made by weathering, those in the upper side would have been full of oxide when the specimen was found. We know, however, that the cavities were free from oxide because many trained observers were present when the iron was relocated and their published accounts contain no mention of rust filling any holes. The field notes that the observers published contained descriptions of the size and shape of the meteorite, its cavities, nature of the terrain, the depression around the iron, the altitude and slope of the ground where the specimen was found, but not a word about rust in the cavities. Surely these men would have mentioned rust if it were abundant in the cavities or if it were found on the ground near the meteorite.

Linsley (1939a) wrote:

The side which rested on and was partly in the soil has the characteristic appearance of rusty iron, but is smooth and nowhere crumbling in disintegration. The prominent external pits characteristic of iron meteorites were far less numerous on this protected side. On the exposed side the external pittings had developed into holes, many of which were several inches deep; some extending through the specimen. There were no sharp edges or angles on the meteorite. There was no accumulation of rusty pieces on the ground around it.

Deep holes such as those occurring in this meteorite are less common on other irons than the shallow, wide depressions or "thumbmarks." However, on the Goose Lake iron there are more deep holes than "thumbmarks." We disagree with Linsley's observation about the exposed pits developing by weathering, and we do not see any conspicuous "thumbmarks." Furthermore, no surface of this iron indicates prolonged weathering, and the flight markings on the sides exhibiting the deep holes make it seem extremely unlikely that weathering produced these cavities.

One surface of each of the two large Canyon Diablo specimens in the National Museum is deeply corroded, with considerable metal removed. This is the part that was either buried or next to the ground. The oxide on that side is thick, rough, and different in appearance from that which occurs on the exposed side. Yet the Canyon Diablo irons, like the Goose Lake iron, show flight markings on the side with the cavities. We regard this as a significant fact,

because the flight markings were made after the cavities. The surface of a meteorite that is exposed to the air apparently is extremely inert compared to the side next to the earth.

Everyone who has examined the Goose Lake iron with us agrees that no side shows extensive corrosion. It has the appearance of being a recent fall, although we have no definite evidence that it is. It is definitely not an old fall.

*Are the cavities impact scars?*—If a small meteorite collided with a large iron, we believe that the impact would make a craterlike scar. The material composing the small meteorite is not as important as the velocity with which the two bodies collide. If the large mass were iron, the impact shock would be absorbed without fracture, as meteoritic iron is malleable. We suspect that the impact scar the small body would make on the larger mass would resemble the meteor craters on this earth, because both are produced by a small body with high velocity striking a larger mass.

Most meteor craters are bowl-shaped and have upturned rims around their edges. The diameter across the opening is greater than that below the opening. The ratio between the width and depth of terrestrial meteor craters and the cavities in the Goose Lake iron are different (see table 3). Probably the shape of the terrestrial meteor craters has been modified by weathering, and possibly to some extent so have the holes in this iron. The difference in shape between the meteor craters and the cavities in the Goose Lake meteorite becomes conspicuous when the width/depth ratios are compared.

TABLE 3.—*Comparison of terrestrial meteor craters with four typical cavities in the Goose Lake iron*

<i>Crater</i>	<i>Width (in feet)</i>	<i>Depth (in feet)</i>	<i>Width/Depth ratio</i>
Canyon Diablo, Arizona	3,900	570	6.8
Wolf Creek, Australia	2,800	170	16.5
Boxhole, Australia	575	52	11.1
Odessa, Texas	530	18	29.4
Henbury, Australia	360	60	6.0
Henbury, Australia	240	25	9.6
Henbury, Australia	30	3	10.0
Warbar, Arabia	328	40	8.0
<i>Goose Lake cavities</i>	<i>(in cm.)</i>	<i>(in cm.)</i>	
1	11	10	1.1
2	7	11	0.63
3	2	8	0.25
4	5	11	0.45

Since a small meteorite striking a larger one would penetrate the large body and possibly volatilize, there might be nothing left to be identified. It is likely that the impact would not disturb the structure of the Ni-Fe alloy in the large body very far beyond the limits of the crater, but we are not certain of this point.

*Wave action within a cavity.*—If cavities existed in an iron before it entered our atmosphere or if they formed quickly after the iron entered, we must not neglect the changes that wave action would make within a hole. The lateral flow of heated air over the forward side would pass over the opening to the hole, inducing wave action. The crests of these waves would strike the sides and be reflected back from the bottom of the cavity.

Solid particles ablated from the surface would get into the cavity and be hurled against the side walls and bottom. More work would be done on the side walls than on the bottom. Possibly the ablation on the walls would exceed that on the exposed surface of the meteorite. The reasons for this could be: (1) The heat might be higher within the cavity than on the exposed surface; (2) the side walls would be both heated and to some degree ablated with a bombardment of heated particles; and (3) perhaps the frequency of impacts against the side walls would be greater than the collisions on the surface of the iron.

The wave action within a cavity during the fall of a meteorite is complex, and our limitations prevent us from fully analyzing the reactions. However, we believe that the most violent action would occur just inside the opening, and if this is true, the tendency would be to widen the opening faster than the cavity is deepened.

*Are the cavities primary structures?*—Since we seem to have no satisfactory explanation for the formation of a cavity in an iron meteorite during its fall, the possibility must be considered that cavities existed before the meteorite entered the atmosphere.

More metal is ablated from the forward side of a falling meteorite than from any other surface. But on a tumbling body no surface receives the extensive ablation that the front side does when the mass holds a fixed position. The Goose Lake iron has no truncated cavities and no zone of granulated metal along any of its edges. These facts, together with the features previously discussed, to us constitute evidence that this iron fell with a lower velocity than many of the other meteorites.

We believe that the surfaces of the Canyon Diablo specimens discussed previously were ablated after the cavities were made. Their shape and the fact that several of their cavities are truncated by the surface, exposing 2 inches of a tubelike depression on the down-slope

side, indicate that these holes already existed when the outside surface was being ablated.

It is unrealistic to assume that the cavities in the Canyon Diablo irons were much deeper than the combined length of the trough and the depth of the present holes. If it is assumed that these holes were 4 inches deeper than they are now, the cavities would have been about 6 to 10 inches deep and possibly less than an inch wide. A hole of such dimensions would seem most improbable.

If 2 to 4 inches were lost from one side of the meteorite, the diameter of the meteorite would have decreased 4 to 8 inches. If that much metal were ablated from an iron such as the Goose Lake specimen, the percentage of weight lost would be large. But if our assumption of the metal lost by ablation is high—and it probably is—the dimensions of the meteorite would not have been greatly reduced in flight, in which case the present mass may still have some of its primary cavities.

Cavities, as far as we know, do not occur within iron meteorites. If these are preflight features, it means that no sizable piece was broken from the Goose Lake iron during its fall through our atmosphere. Also, it is unlikely that this meteorite came from the metallic core of some planet, for if it had, the implication would be that cavities existed there, and such a condition seems improbable.

It might be suggested that these cavities were filled with some mineral which has since vanished, but it is generally assumed that meteorites rather reliably represent the body in which they formed and also that the composition and structure of the portion that was lost in flight are essentially the same as those of the mass still remaining. There is no evidence that any low density minerals were concentrated near the outside edges of the larger meteorites.

The metallography of the metal in the overturned rims of cavities needs further study. In a section cut through the rim of a cavity in the Goose Lake iron (pl. 6), the Widmanstätten pattern was neither obliterated nor granulated. Granulated zones have been found around the outside edges of several iron meteorites, and those zones are usually wider than the overhanging lips of metal around the cavities. In general there is little evidence that heat penetrated the Goose Lake meteorite; the limited evidence found is discussed in the section dealing with the metallography. However, the feature which did indicate a thermal change was found near the surface of this iron.

After reviewing all the evidence or possibilities outlined in this paper relative to the origin of cavities, we are inclined toward the view that the deep, narrow holes in the Goose Lake iron existed before it entered our atmosphere. The specific manner in which they were

formed is not understood, but our basic reasons for thinking that they are preflight may be summarized as follows:

The most common flight markings on iron meteorites are the broad, shallow depressions called "thumbmarks" which definitely originated during the fall through the atmosphere. The Goose Lake meteorite has many more deep, narrow cavities and fewer "thumbmarks" and threadlike flight markings on its surface than most iron meteorites. The fact that this iron lacks the surface features which suggest a high velocity of fall favors the preatmospheric origin for its cavities.

No evidence was found that heat penetrated this specimen to any appreciable depth. The depth of the cavities, their peculiar shape, and the overturned rims around them cannot be explained by the thermal penetration we observed, by the original shrinkage of the metal, or by terrestrial weathering. The possibility that cavities represent something that was burned out during the flight through our atmosphere seems most unlikely because in the many sections cut through this iron, no inclusions were found that even approached the dimensions of the cavities. Furthermore, the length of time this iron was in flight through the atmosphere seems insufficient for enough heat to penetrate to the depth of the cavities and melt the quantities of metal that might have filled them.

Cavities are narrower at the openings than within; if they were made by air streaming over the surface of a meteorite during its flight, surely the openings would be widened faster than the cavity was deepened. Finally, if cavities like these originated during the flight in our atmosphere, it seems strange that they occur in only a small percentage of the known iron meteorites.

### Summary

A 2,573-pound iron meteorite from Goose Lake, Modoc County, Calif., found in 1938, is described, and a general discussion of the cavities in iron meteorites is presented. The chemistry, metallography, and physical features of this and seven other meteorites from widely scattered places are given. The cavities in this iron, a conspicuous feature, are discussed, and reasons are stated why they are believed to be primary features. The cavities are compared with those in other meteorites. A study of the cavities indicates: (1) That this meteorite is not much smaller now than when it formed in some primordial body; (2) that no large piece broke off during flight; and (3) that this probably is not a portion of the metallic core of the planetlike body where it was formed.

The origin of cavities is a complex subject, and only the general theories of their formation are here outlined. It is our hope that this

generalized discussion will stimulate further investigations of cavities in iron meteorites. Although we believe that the cavities in this meteorite existed before it entered our atmosphere, we do not infer that all meteoritic cavities are preflight.

### The Cincinnati, Ohio, Meteorite

PLATES 10, 12

This iron meteorite was said to have been found near a dwelling in Cincinnati, Ohio, and was classified as a nickel-poor ataxite. It was first mentioned by Wulff in 1897, and later by Cohen in 1898 and 1905; a summary of the former descriptions was published by Farrington in 1915.

When Perry in 1944 studied this specimen, which was obtained from the American Museum of Natural History, he observed numerous inclusions and identified them as phosphide bodies. Most of these small inclusions were rounded and gave the appearance of having been diffused by preterrestrial reheating. Since these particles were abundant, we suspected that there was more phosphorus in this iron than was shown in the analysis. Because of this and of the possibility that other chemical determinations might be unreliable, a restudy of the meteorite was made.

A 16.33-gram slice was removed from the sample lent by the American Museum of Natural History and was dissolved in HCl (1 part HCl, 2 parts H<sub>2</sub>O). The gas given off was passed through a solution of lead acetate. The lead sulfide was recovered, converted into lead sulfate, and calculated to sulfur. The residue, which weighed 0.0067 gram, was so small that it was impossible to make an analysis, but chemical tests proved that this residue was rhabdite.

TABLE 4.—*Chemical composition of the Cincinnati, Ohio, meteorite*

	1	2
	<i>Sjostrom (in Cohen, 1898)</i>	<i>New analy- sis</i>
Fe	94.47	94.12
Ni	5.43	5.33
Co	0.68	0.74
Cu	0.01	n. d.
P	0.05	0.19
S	0.05	0.006
Rhabdite	—	0.05
Total	100.69	100.436
Density	7.68	7.71
Mol. ratio	$\frac{\text{Fe}}{\text{Ni}+\text{Co}}$ 16.41	16.51

The agreement between the densities of the two samples indicates that the sample we restudied was similar to the one Sjoström had. However, these densities are low for meteoritic iron. The pieces restudied came from a small specimen that was somewhat altered, and it was therefore impossible to avoid including some altered material. There was not enough oxidization to make a significant difference in the analysis, but the included phosphide and the oxide reduced the density of the iron.

The main difference between these analyses is in the phosphorus content; the reanalysis has almost four times as much phosphorus as Sjoström reported. The higher value is more consistent with the metallography shown in plate 12.

The amount of schreibersite or rhabdite in the analyzed sample may be calculated from the phosphorus reported. To simplify the calculation, the phosphorus content of the mineral was rounded off at 15 percent. Thus, the sample reported in analysis 2 contains 1.26 percent of phosphides by weight. For some reason most of the phosphide inclusions are soluble in dilute hydrochloric acid, which is contrary to the usual finding.

The photomicrographs of the Cincinnati iron (pl. 10) indicate that the rhabdite reacted with the matrix. This reaction, we believe, occurred subsequent to the original segregation of the rhabdite and either before the meteor entered our atmosphere or during its fall through the air. When the temperature of the mass was raised, the inclusions partly redissolved in the matrix. The cooling process which followed was so rapid that the material taken up from the matrix in the reheating process could not be rejected. We suspect that the reheating had something to do with making the phosphide soluble. Also, we found in other meteorites, where similar metallographic evidence of reheating occurs, that an appreciable amount of phosphorus dissolved in the same strength of acid.

Because many old analyses of iron meteorites are inaccurate, it is worthy of note when one which seemed to be incorrect was found to be good.

We express our appreciation to Dr. Frederick H. Pough, formerly of the American Museum of Natural History, for making this meteorite available for restudy.

### Summary

A new analysis confirms the old analysis with the exception of the phosphorus determination. The phosphide mineral in the meteorite is largely soluble in acid. This iron apparently was reheated after it originally cooled.

## The Pittsburgh, Pennsylvania, Meteorite

PLATES 11, 13-15

This 292-pound iron was found in a field along Miller's Run, Allegheny County, Pa., in 1850. Shortly thereafter the main mass was carried to Pittsburgh and wrought into a bar; thus most of the meteorite was lost to science before it was studied. Since there are conflicting statements in the descriptions of this iron, a reinvestigation was desirable.

When the Pennsylvania meteorites are plotted on a map, the Pittsburgh, New Baltimore, Mount Joy, and Shrewsbury irons lie on a line starting near Pittsburgh and extending eastward for about 180 miles. Because of this alinement it might be suspected that the falls are related. Our reexamination of the Pittsburgh meteorite makes it possible to compare the four Pennsylvania irons and also one from Wooster, Ohio, lying on the same line but to the west of Pittsburgh.

The data on the Pittsburgh meteorite were summarized by Farrington (1915b) and by Stone (1932), and, since their publications are more readily accessible than the original descriptions, no references are made to the earlier work on this meteorite.

We were fortunate in having two specimens because they differ in some respects. The Yale sample is granulated, indicating that it had been reheated, whereas the Harvard sample apparently had undergone no thermal treatment.

The Pittsburgh meteorite has been classified as both a coarse octahedrite and a hexahedrite by Farrington (1915b), but it is definitely a coarse octahedrite. Most of its kamacite occurs in irregular masses, but one area in the Yale specimen shows a Widmanstätten structure (pl. 11, top). The Yale sample is granulated, so that the outline of many of its kamacite areas are not sharply defined; thus measurements of the widths of those bands are unsatisfactory. The average width for several of the lamellae in plate 11 is 2.08 millimeters. The orientation of the cut was not determined, but the lamellae are wide enough to place the Pittsburgh iron among the coarse octahedrites.

The irregular kamacite areas in the Harvard sample are partly bounded by taenite. Open fractures occur between some of these kamacite granules, but this is a common feature for coarse octahedrites. One small trigonal plessite area was found. The kamacite in the Harvard specimen shows three sets of Neumann lines, but none was found in the Yale sample. Possibly they were lost when the piece was heated.

Most of the kamacite areas in this meteorite are not enclosed by a continuous band of taenite. When the taenite thickens, its centers



consist of dark, untransformed alpha-gamma iron. Numerous rhabdite needles occur in some of the kamacite (pl. 13); cohenite inclusions were identified (pl. 15), and a few plessite areas were found (pls. 14, 15).

Since both the Harvard and Yale sections were small, neither contained much of the original crust of the meteorite; the small amount that remained was similar on both. The surface oxide and other features show clearly that the two samples came from the same meteorite.

Our analysis was made on a piece taken from the Yale specimen. The sample was dissolved in HCl (1 part HCl, 2 parts H<sub>2</sub>O), and the magnetic part of the insoluble residue was retained in the flask by attaching a strong magnet to the bottom of the container while the solution was filtered to recover the carbon. By counting the grains in a portion of the magnetic residue, we estimated that there was about 10 percent cohenite and 90 percent rhabdite in the residue, and both minerals were later identified by X-ray.

TABLE 5.—*Chemical composition of the Pittsburgh meteorite*

	(1)	(2)	(3)	(4)
	<i>New analysis by E. P. Henderson</i>	<i>Calculated composition after correcting for rhabdite and cohenite</i>	<i>Genth's analysis (Farrington, 1915b)</i>	<i>Hildebrand's analysis (Farrington, 1915b)</i>
Fe	* 91.6	92.15	92.80	93.38
Ni	6.77	6.99	4.66	5.89
Co	0.66	0.67	0.39	1.24
P	0.12	0.22	0.25	0.15
S	0.018	0.018	0.03	0.05
Cu	—	—	0.03	0.05
C	—	0.001	—	—
Cr	—	—	—	0.2
Mn	—	—	0.14	—
Rhabdite } Cohenite }	0.76	—	—	—
	100.00		98.30	100.80

\* By difference.

As the residue contained rhabdite as well as a small amount of cohenite, and as some loss occurred during the picking operations, we decided to correct the figures for Fe, Ni, Co, and P for the quantities contained in the residue. The nickel content of rhabdite was arbitrarily set at 25 percent, the phosphorus at 15 percent, and the cobalt at 0.75 percent. The difference between the sum of these elements and 100 was taken to be iron. Incompleted studies by the authors show that cohenite has a fixed composition, with a carbon

content of approximately 6.5 percent; therefore, the iron it contains can be obtained by difference. Thus, if our estimates for the proportions of rhabdite and cohenite and the assumed compositions are about right, it is possible to correct the analysis in column 1 of table 5, for these two minerals. The adjusted analysis is given in column 2 of the table.

The specimen analyzed had a density of 7.89, which is low for a meteorite belonging to the coarsest octahedrite group (Henderson and Perry, 1954). But the sample selected contained traces of oxide and some included minerals, and it had been thermally treated, all of which reduce the density of meteoritic iron.

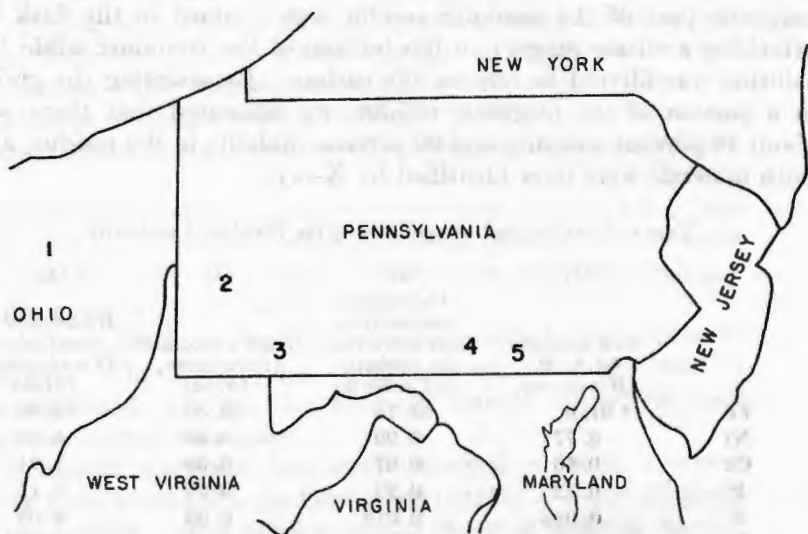


FIGURE 6.—Map showing the locations of the iron meteorites that have been found in eastern Ohio and in Pennsylvania. 1, Wooster, Wayne County, Ohio; 2, Pittsburgh, Allegheny County, Pa.; 3, New Baltimore, Somerset County, Pa.; 4, Mount Joy, Adams County, Pa.; 5, Shrewsbury, York County, Pa.

The five iron meteorites plotted in figure 6 were found almost on a straight line extending about 275 miles eastward from and slightly south of Wooster, Ohio. There are no historical records of the date of fall of any of these irons, but the pattern of distribution might suggest that all five represent a meteor shower. Their analyses are listed in table 6.

The Wooster, Ohio, meteorite apparently has not been reinvestigated since Smith (1864) described it. He gave the density of this iron as 7.901, and by calculating the density from the analysis we got 7.903. Such agreement indicates that the analysis is consistent with the density Smith reported; hence the analysis is essentially correct.

This reanalysis of the Pittsburgh iron, the reanalysis of the Mount Joy iron (Henderson, 1941), and the analyses of the New Baltimore (Merrill, 1923) and the Shrewsbury (Farrington, 1910) irons are all

TABLE 6.—*Chemical composition of the five meteorites located in figure 6*

	Wooster, Ohio	Pittsburgh, Pa.	New Balti- more, Pa.	Mount Joy, Pa.	Shrewsbury, Pa.
Fe	93.61	92.15	93.25	92.93	90.84
Ni	6.01	6.99	6.42	5.76	8.80
Co	0.73	0.67	0.32	0.61	trace
P	0.13	0.22	0.037	—	0.29
S	—	0.018	—	—	0.01
C	—	0.001	0.015	—	—
Si	—	—	0.01	—	—

sufficiently different to make it certain that these are independent meteorites. Furthermore, when sections of the five irons are compared, structural differences can be seen in their etched patterns.

### Summary

This reanalysis brings the composition of the Pittsburgh iron into agreement with that of other meteorites having similar structures. The Pittsburgh iron differs from other iron meteorites that have been found along the southern border of Pennsylvania. The metallography of the meteorite is discussed.

### The Breece, New Mexico, Meteorite

#### PLATE 16

An iron meteorite weighing approximately 50 kilograms from near Breece, McKinley County, N. Mex., was described by Beck, La Paz, and Goldsmith (1951) as a medium octahedrite containing lamellae of cohenite. This is the first reported occurrence of cohenite lamellae. Previous to that study, we had examined the Breece meteorite without recognizing cohenite, and after the above-named authors reported cohenite in Reichenbach lamellae we restudied the sample of that iron in the U. S. National Museum.

Our specimen (pl. 16) is very similar to the one pictured by Beck, La Paz, and Goldsmith. We tested each of the lamellae shown in plate 16 by etching tests without getting any typical reactions for cohenite. Powders from these lamellae were also X-rayed, and in each case the pattern proved to be that of schreibersite.

Perry (1944, pl. 47) pictured inclusions similar to those in our plate 16 and referred to them in a way which indicated that he believed them to be troilite. Although he did not call them troilite, Perry described

them "as an example of Reichenbach lamellae remarkable for their fineness and regularity." Since all the other illustrations in Perry's plate 47 were troilite, the inference is that he considered the lamellae in the Breece iron to be troilite.

Two samples, together weighing 21.69 grams and both containing the elongated inclusions which had once been identified as cohenite, were prepared for analysis. Since the densities of these pieces were 7.86 and 7.87, apparently both portions had about equal quantities of these lamellar inclusions. Both samples were dissolved in HCl (1 part HCl, 2 parts H<sub>2</sub>O), as a result of which the cohenite and schreibersite should concentrate in the residue. After the kamacitic iron dissolved, a strong magnet was attached to the bottom of the flask to hold the magnetic residue in the container while the solution was decanted off.

A visual examination of this residue showed that it contained two minerals. The most abundant one had the color and luster of the mineral which occurred in the lamellae shown in plate 16. The other was a dark carbonlike particle, feebly magnetic, brittle, and very soft.

#### Cohenite and Carbon Pseudomorphs of Cohenite

This dark component was unlike anything we had seen in a meteorite. Because of the size of some of these aggregates, it was difficult to believe that they could be common in iron meteorites and have escaped detection until now. Others who had examined this iron apparently had not observed these carbon aggregates. We found them because our sample was dissolved so that the analyst could observe the progress of the acid attack on the meteorite.

Cohen (1897c) found a carbon compound in the Cranbourne meteorite that may have been similar to the carbon we recovered. As the Cranbourne iron contains cohenite, possibly the black carbon aggregate that Cohen noticed was iron carbide that had become graphitized. When some silicate minerals are attacked by acid they will leave a skeleton made of one of their constituents, and carbon in cohenite may behave in the same way.

The color and luster of these dark bodies from the residue of the Breece iron were remarkably constant. Some were soft, black, and slightly magnetic, others were nonmagnetic. The X-ray pattern was different from those of graphite, cohenite, or schreibersite.

Thus, if cohenite is slightly soluble in dilute hydrochloric acid, possibly it existed in the portion we analyzed from the Breece iron. Its decomposition products may have escaped unnoticed as hydrocarbons, and perhaps those carbonlike aggregates were a product of the reaction of the acid on cohenite.

Cohenite obtained from another meteorite was given a prolonged treatment in dilute hydrochloric acid. Detectable amounts of hydrocarbons were liberated, but, what is more unusual, some carbon pseudomorphs of cohenite formed. Since these had the shape and color of cohenite, the unaided eye could not distinguish them from that mineral. However, these pseudomorphs are essentially nonmagnetic, while cohenite is strongly magnetic. A characteristic

TABLE 7.—*Spacings of unknown black residue from HCl solution of the Breece, N. Mex., meteorite*<sup>1</sup>

Fe Radiation, Fe K $\alpha$  = 1.9373 Å

Intensity	d (Å)	Intensity	d (Å)
3	4.46	1	2.51
3	4.23	1	2.34
2	4.13	5	2.18
1	3.73	5	2.11
1	3.44	2	2.06
7	3.35	3	2.00
10	3.06	5	1.97
9	3.01	4	1.93
9	2.96	3	1.91
1	2.88	4	1.86

<sup>1</sup> By George Switzer.

feature of most cohenite inclusions is the small island of kamacite enclosed within the grains. These carbon pseudomorphs had a sharply defined hole, which must be the place where some kamacite dissolved out.

The soft aggregates of carbon found when the Breece iron was dissolved are possibly similar in origin to the carbon pseudomorphs of cohenite, but perhaps these should be called skeletons or aggregates of carbon.

Although we obtained no such well-defined carbon pseudomorphs when the Breece iron was dissolved, we will concede that these black carbon aggregates indicate that some cohenite was concealed in the sample we dissolved. Although we failed to detect cohenite in that portion of the Breece iron, Beck, La Paz, and Goldsmith isolated and identified some from this meteorite. Those authors, however, were mistaken in reporting that cohenite made up the Reichenbach lamellae, because we tested all the lathlike inclusions and found them to be schreibersite.

Beck recovered enough cohenite to analyze and identify it by X-ray. Because the density Beck reported for cohenite was closer to schreibersite than to cohenite, we became suspicious of the identification. His X-ray film of cohenite matched the lines in our standard

cohenite film, but we could not understand why the lines in his film were indistinct. Now we suspect that the cohenite Beck X-rayed was partly graphitized or carbonized.

Although present in limited amounts in the Breece meteorite, cohenite is difficult to detect; yet it is a rather common mineral in coarse octahedrites. Cohenite apparently becomes less and less abundant as the Ni content increases above that which is normal for the coarse octahedrites. Nickel apparently partly graphitizes or carbonizes the cohenite; thus it is unlikely than an iron meteorite like the Breece would contain more than a trace of cohenite. Furthermore, since carbon pseudomorphs are made by prolonged treatment of cohenite in dilute HCl, possibly the carbon aggregates we found originated from cohenite. Thus, the acid treatment given the sample may have partly carbonized the cohenite that Beck X-rayed.

#### Chemical Analyses of the Matrix and the Schreibersite in the Breece Meteorite

Table 8 contains all the reported analyses of this meteorite. The failure of Martin (analysis 2) to report phosphorus probably influenced Beck, La Paz, and Goldsmith to call these lamellae cohenite. All the other analyses show phosphorus, and all except No. 5 show only traces of sulfur. Possibly, Carlisle's sample contained a bit of troilite.

TABLE 8.—*Findings, by various analysts, of the chemical composition of the Breece, N. Mex., meteorite*

	(1) <i>Henderson</i> <i>(new analysis)</i>	(2) <i>Martin</i> <sup>1</sup>	(3) <i>Herpers</i> <sup>2</sup>	(4) <i>Nichols</i> <sup>2</sup>	(5) <i>Carlisle</i> <sup>3</sup>
Fe	89.627	89.87	89.97	90.06	88.69
Ni	9.167	9.26	9.46	8.67	9.58
Co	0.635	0.89	0.19	0.62	1.02
S	trace	0.11	trace	0.03	0.23
C	trace	0.03	—	—	0.10
P	0.571	0.00	0.219	0.47	0.46
Cl	—	0.00	—	—	—
Cu	—	0.00	0.002	0.02	—

<sup>1</sup> In Beck, La Paz, and Goldsmith (1951, p. 537).

<sup>2</sup> Personal communication from S. K. Roy, Chicago Museum of Natural History.

<sup>3</sup> Personal communication from L. La Pax, University of New Mexico.

The magnetic portion of the insoluble residue makes up 3.63 percent of the meteorite by weight. If the schreibersite in the material represented by analyses 1, 4, and 5 of table 8 is calculated, all these analyses contain about the same amount of schreibersite.

TABLE 9.—*Chemical composition of the insoluble residue (schreibersite) from the Brece meteorite*

	<i>Analysis by Carlisle</i>			<i>Analysis by Henderson</i>	
		<i>Ratio</i>			<i>Ratio</i>
Fe	60.82	1.09	} 3.52	<sup>a</sup> 59.93	1.071
Ni	24.52	0.418		24.18	0.412
Co	0.15	0.002		0.014	0.002
P	13.19	0.425	1	15.75	0.507
S	0.00	0.00		—	—
C	1.06	0.09		<sup>b</sup> 0.002	—

<sup>a</sup> By difference.

<sup>b</sup> Carbon not determined, but observed.

The carbon that Carlisle reported, 1.06 percent, was not all derived from the decomposition of cohenite by acid used to dissolve the sample, because if there is 1.06 percent carbon and all of it came from cohenite, the Brece meteorite would contain about 7 percent cohenite. Such quantities of cohenite are not present in this meteorite. Although some of the carbon Carlisle reported may have been derived from cohenite, most of it represents disseminated carbon in the meteoritic iron.

### Summary

The mineral in the lamellar inclusions formerly was incorrectly identified as cohenite. This restudy proves that the mineral is schreibersite and confirms the presence of cohenite in this meteorite.

### The Tombigbee, Alabama, Meteorite

#### PLATE 17

The Tombigbee meteorite was restudied because the old analyses reported less nickel than we believed should occur in a hexahedrite. Since hexahedrites are essentially kamacitic iron and usually contain about 5.5 percent Ni, it seemed important to check the accuracy of some analyses reporting low nickel percentages. If such analyses are correct, some explanation must be given for the apparent deficiency of nickel.

This meteorite contains many large schreibersite inclusions as well as rhabdite needles; therefore, it is particularly suited to an investigation of the composition of the phosphide inclusions, the kamacitic groundmass, and the kamacite adjacent to the large schreibersite bodies.

Since the areas to be analyzed were selected from a slice about one-eighth inch thick (pl. 17), it was possible to have some control over the homogeneity of the selected samples. The findings reported

are based upon studies of special areas, thus they do not truly represent the composition of the meteorite. A representative analysis of a meteorite such as this one is possible only if special attention is given to the selection of the sample. To sample the Tombigbee iron properly, it is necessary to get the actual proportion of inclusions and matrix in the main mass. Because of this difficulty the analyses of such a meteorite may vary more than those of the normal hexahedrites or fine-grained octahedrites.

Farrington (1915b) gave a comprehensive summary of the historical and descriptive data on this iron, which he called De Sotoville. Foote (1899) described six specimens that were found along a straight line about 16 kilometers long. Three pieces were from south of De Sotoville in Choctaw County, Alabama, and three from farther north, in Sumter County. It is important to note that the heaviest of the six was the one farthest north and the smallest was at the south. All were found between 1858 and 1886 and were extensively altered when discovered.

#### Classification

This meteorite has been classified in three different ways: Berwerth (1903) called it an ataxite; Klein (1903) called it a finest octahedrite; and Farrington (1903) noted its cubic character. Brezina and Cohen (1904) observed that different pieces of this iron had different structures. They said:

Mass I considered by itself alone, may be regarded as hexahedral iron; Mass VI, as the same, though possessing in places a granular structure, while in Mass III only traces of Neumann lines are visible . . . . It must be assumed that various masses of the De Sotoville iron were originally normal hexahedrites and in varying degree of extent were subject to agencies which wrought a change of structure. Probably different degrees of heating may account for the difference, which in the case of some of the masses may have been carried to the extent of softening or complete melting of the entire mass . . . . It cannot be determined with certainty whether the masses in question were heated by the finders, as so often happened in the case of meteoric iron, or whether a secondary softening took place before or during their fall . . . . Since, however, in the neighborhood of the displacement and veins, occur structural changes similar to those of the apparently thermally altered portions, the conclusion may be drawn that the thermal process is also not of artificial or terrestrial origin, but of the same cosmic nature as the mechanical changes; and that through heating and pressure there was a gradual change of a hexahedral iron into an ataxite . . . .

Perry (1944) classified the Tombigbee iron as a hexahedrite. It has a clear primary granulation and shows no diffusion around the phosphide needles. Neumann lines are profuse but delicate, and their diverse orientation in the grains is similar to that occurring in typical hexahedrites.

Although taenite and plessite may be present in this iron, they were not observed. The numerous dark spots scattered through the



meteorite are, we assume, phosphide particles; however, they are visible only in higher magnification and are distinct from rhabdite. The kamacite shows a microscopic granulation, but no evidence was found of any octahedral arrangement.

### Chemical Composition

An area containing a large schreibersite inclusion and a narrow zone of enclosing kamacitic iron was selected from the prepared slice for an analysis of both the kamacite and schreibersite. The portion selected, which weighed 23.379 grams, was placed in HCl (1 part HCl, 2 parts H<sub>2</sub>O) until all the kamacite dissolved. The analysis of the acid-soluble part gives the composition of the kamacite adjacent to the schreibersite. The insoluble residue, the schreibersite, was then dissolved in HNO<sub>3</sub> and separately analyzed, table 10.

TABLE 10.—*Chemical composition of swathing kamacite and schreibersite in the Tombigbee meteorite*

	<i>Swathing kamacite</i>	<i>Ratio</i>	<i>Schreiber- site</i>	<i>Ratio</i>
Fe	95.64	1.712	71.78	1.285
Ni	3.78	0.064	12.03	0.205
Co	0.58	0.009	0.58	0.009
P	—	—	15.59	0.503

$$\text{Mol. ratio } \frac{\text{Fe}}{\text{Ni} + \text{Co}} = 23.45$$

\* By difference.

The average molecular ratio  $\frac{\text{Fe}}{\text{Ni} + \text{Co}}$  for hexahedrites is about

16.50. This average does not include several octahedrites that have been incorrectly classified as hexahedrites. It does include several analyses which we suspect are not entirely accurate. Thus, a molecular ratio of 23.45 for swathing kamacite is so different from the average kamacite in a hexahedrite that some reason must be given in explanation.

The material analyzed in table 10 consisted of 16.8 percent schreibersite and 83.2 percent kamacite. Probably the material analyzed as swathing kamacite was a mixture of kamacite adjacent to the phosphide and some of the groundmass. In some unpublished studies we found that the swathing kamacite around schreibersite bodies contained several percent less Ni than the groundmass of the meteorite.

A composite analysis, calculated from the analyses of the matrix and the schreibersite in table 10, shows that the abundance of Fe, Ni, and Co in an area made up of both kamacite and schreibersite is similar to that in a normal hexahedrite.

TABLE 11.—A composite analysis of an area in the Tombigbee iron consisting of kamacite and schreibersite, and an average analysis of hexahedrites

	(1)	(2)
	Composite analysis of an area consisting of kamacite and schreibersite	Average of hexahedrites
Fe	91.86	93.76
Ni	5.10	5.51
Co	0.64	0.56
P	2.64	—
FeS	0.016	—
Insol.	0.01	—
Mol. ratio $\frac{\text{Fe}}{\text{Ni} + \text{Co}}$	17.13	16.45

A comparison of the molecular ratios of a composite analysis of a section of the Tombigbee iron with that of an average of 39 iron, 41 nickel, and 39 cobalt determinations on different hexahedrites shows that the Tombigbee iron is a hexahedrite rich in phosphide inclusions.

Other areas from the matrix in this iron were analyzed to verify the composition of the matrix. These analyses are given in tables 12 and 13. Swathing kamacite contains 0.55 percent less Ni than the average of the analyses of the ground mass (table 14). However, it is more than likely that the swathing kamacite studied was contaminated by some of the matrix. Possibly the kamacite adjacent to the phosphide contains less Ni than our findings report.

TABLE 12.—Chemical composition of the average kamacite in groundmass in the Tombigbee meteorite, remote from any schreibersite inclusions

	Grams	Percent	Ratio
Fe	10.5570	94.19	1.687
Ni	0.4927	4.39	0.074
Co	0.0773	0.69	0.011
P	—	—	
Insol.	0.0070	0.06	
	11.1340	99.33	

$$\text{Mol. ratio } \frac{\text{Fe}}{\text{Ni} + \text{Co}} = 19.84$$

Weight of original sample, 11.208 gm.

Weight of recovered material, 11.134 gm.

Unaccounted for, 0.074 gm. (0.66 percent).

All the unaccountable portion in table 12 should not be assigned to an error in the iron determination, although some of it may belong there. After all the soluble material had dissolved, the insoluble

residue had such a low density and was so finely divided that the solution could not be decanted without carrying off some of the residue. Unfortunately, this solution was decanted onto a paper filter and when an effort was made to recover the residue enough was embedded in the filter to account for most of the loss.

Another sample of the matrix was selected at some distance from a schreibersite body to confirm the composition of the matrix and to get enough rhabdite to determine its nickel and cobalt content.

The portion selected, weighing 28.603 grams, was dissolved in 1 part HCl and 4 parts H<sub>2</sub>O in a flask. The vapors were condensed and returned to the solution to prevent the acid from concentrating. The insoluble residue weighed 0.2425 gram and consisted of magnetic particles that had the identical form and color of the rhabdite we had recovered from other meteorites. Thus, the matrix of the Tombigbee iron contains about 1 percent of rhabdite.

This residue was dissolved in HNO<sub>3</sub> and HCl so that the nickel and cobalt determinations could be made. The matrix of this iron, the portion that dissolved in the 1-4 HCl, was partially analyzed. Both analyses are given in table 13.

TABLE 13.—*Partial analyses of the kamacite and rhabdite in groundmass in the Tombigbee meteorite*

	<i>Kamacite</i>	<i>Rhabdite</i>
Fe	95.09	—
Ni	4.28	19.53
Co	0.63	0.58
P	None	<sup>b</sup>
Cu	—	trace
Insol.	—	0.83

<sup>a</sup> By difference.

<sup>b</sup> Qualitatively confirmed but not determined.

The point we desire to prove is that the kamacite adjacent to the schreibersite is essentially different from the matrix that is remote from these large phosphide bodies. The data for the preceding tables that support this contention are summarized in table 14.

Table 14.—*Comparison of analyses of the Tombigbee meteorite*

	<i>Composite analysis</i>	<i>Kamacite in groundmass</i>		<i>Swathing kamacite</i>
	(Table 11)	(Table 12)	(Table 13)	(Table 10)
Fe	91.86	94.19	95.09	95.64
Ni	5.10	4.39	4.28	3.78
Co	0.64	0.69	0.63	0.58
P	2.64	—	—	—

TABLE 15.—*Summary of Analyses on the Tombigbee meteorite*

	<i>Kamacite</i>						<i>Schreibersite</i>		<i>Rhabdite</i> <sup>1</sup>	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	<i>Foote, 1899</i>	<i>New data (Swathing kamacite)</i>	<i>Brezina and Cohen, 1904</i>	<i>New data</i>	<i>New data (Partial analysis)</i>	<i>Cohen, 1905</i>	<i>Cohen, 1905</i>	<i>New data</i>	<i>Cohen, 1903</i>	<i>New data</i>
Fe	95.86	95.64	95.40	94.19	95.09	95.22	95.60	71.78	71.70	60.98
Ni	3.62	3.78	3.83	4.39	4.28	4.02	4.34	12.03	12.58	19.53
Co	0.36	0.58	0.71	0.69	0.63	0.65	—	0.58	0.32	0.58
P	—	—	—	—	—	—	—	15.59	15.45	—

<sup>1</sup> See discussion on page 377.

A comparison of the nickel content of the swathing kamacite with that of the kamacitic groundmass shows that the kamacite adjacent to the schreibersite contains less nickel. We believe this to be the first time that this has been shown. In table 15 the nickel content of the schreibersite is shown to be between 12.03 and 12.58 percent and that of the rhabdites 19.53 percent. Thus, the rhabdite contains about 7 percent more nickel than the schreibersite.

All available previous analyses of the Tombigbee meteorite are given in table 15.

The Ni content of the kamacite in the matrix of this iron ranges between 3.62 and 4.39. The analyses of schreibersite agree fairly well. Brezina and Cohen (1904) noted that the Tombigbee schreibersite was unusually low in Ni and asked if the rhabdite in this iron contained more Ni than the schreibersite. The new analysis confirms the low Ni content of the schreibersite, and the partial analysis of the rhabdite shows that the smaller phosphide bodies contain much more Ni than the schreibersite.

Farrington (1915a) listed 24 schreibersite analyses. The one with the lowest Ni, 10.72 percent, came from the Zacatecas meteorite (Cohen 1897a, p. 49). Only five of those analyses had less than 15 percent Ni. In the Tombigbee iron the Ni is near the average of the hexahedrites, the schreibersite contains slightly more than twice as much Ni as the matrix, and the rhabdite has between four and five times as much as the matrix. It will be interesting to see if similar differences exist in other meteorites of this type.

### A Theory for the Origin of Swathing Kamacite

The partition constant governing the distribution of Ni between kamacite and schreibersite is unknown. We suspect that the phosphide molecule which existed while the matrix was at higher temperatures was essentially an iron phosphide. At temperatures just below those at which the Ni-Fe alloy solidified, the phosphide probably was a liquid and was deficient in Ni.

At temperatures above 1000° C. the Ni-Fe matrix is a solid and in the gamma phase, but the phosphide is still a liquid. At this temperature the nickel entering the phosphide and replacing iron is assimilated by the phosphide. The replaced iron solidifies because the temperature is below its melting point. These particles of rejected iron migrate to the edge of the phosphide.

The above process happens simultaneously with the formation of the Ni-impoverished zone surrounding the phosphide inclusion. The diffusion rate of iron into the matrix must be slower than the rate at which nickel enters the phosphide; otherwise these swathing zones

would not exist. Thus, we suspect the following theory outlines the origin for the swathing kamacite around schreibersite inclusions.

The swathing zone represents a reaction zone. Possibly the liquid phosphide that segregated at a high temperature was essentially  $\text{Fe}_3\text{P}$ , and the Ni-Fe matrix that enclosed it was in the gamma phase. As Ni migrates from the matrix into the phosphide, Fe is replaced. The rejected Fe which migrated to the edge of the phosphide together with the enclosing Ni-impoverished zone effectively sealed off the available source of Ni. Thus, the swathing kamacite may represent two processes, the rejection of the iron from the phosphide and the formation of a zone of Ni-impoverished iron in the matrix that enclosed the schreibersite.

Perry (1944) reports eutectic structures in schreibersite bodies in the Chesterville, Cincinnati, and Rio Loa meteorites. He explains the structures by saying that the schreibersite bodies were remelted and that the liquid phosphide absorbed kamacite from the groundmass. Then, as the liquid cooled, the absorbed Fe, in the excess of the Fe- $\text{Fe}_3\text{P}$  eutectic ratio, was rejected in the form of droplike particles in the interior and in a border around the periphery.

Whatever process produced these droplike kamacite particles that occur within the phosphide inclusions, we suspect their presence indicates that the temperature was lowered too rapidly for the drops to migrate the short distance to the periphery of these bodies. This idea is supported by the way these features occur in the Cincinnati and the Rio Loa irons, although in those meteorites the structures were found in the zone of alteration.

In all probability the swathing kamacite is made during the original cooling. The metal in the zone containing both Ni-impoverished iron and the iron rejected from the schreibersite is in the gamma phase and, being Ni-poor, transforms to kamacite at higher temperatures than those at which the matrix will transform. The swathing zones around sizable schreibersite bodies are wider than the kamacite lamellae within the Widmanstätten structures because the displaced iron from the phosphide accumulated against the Ni-impoverished iron.

There is no difference in the appearance of the matrix in the Tombigbee iron and the swathing kamacite because both are kamacitic iron. However, the matrix and the zone adjacent to the phosphide inclusions have different hardnesses (table 16). We have also observed differences in the chemical composition of swathing zone around schreibersite and the matrix in other meteorites.

At the time the Ni-Fe alloy solidified, most of the phosphide had been rejected as large liquid blobs. Some phosphide, however, dissolved in the matrix and that portion became enriched in nickel.

Phosphide is more soluble in taenite than in kamacite. Both the taenite and rhabdite, which separate as the temperatures are lowered, contain increased percentages of nickel. The information needed to follow the changes in composition that occur in the phosphide that separates from the matrix as cooling takes place is not available.

#### Hardness Measurements on Swathing Kamacite

A series of Knoop hardness tests were made on the Tombigbee meteorite at the Department of Metallurgy, Massachusetts Institute of Technology, through arrangements made by Prof. H. H. Uhlig. These values, given in table 16, show a progressive increase in hardness as the distance from the phosphide increases. The Knoop hardness

TABLE 16.—*Knoop hardness numbers on swathing zone around schreibersite, load 100 grams, in Tombigbee meteorite*

<i>Test</i>	<i>Knoop No.</i>
1	211.6
2	253.0
3	246.3
4	253.0
5	233.9
6	246.3
7	253.0
8	274.5

values confirm the analytical results by showing that there is a difference in the composition of the metal in the swathing zone around schreibersite bodies and in the matrix.

The lowest value reported was 211.6, and the highest 274.4. The higher value we suspect is essentially that of the matrix. Dalton (1950) reported that the hardness of hexahedrites is consistent at about 180 on the Knoop scale and that the hardness of kamacite in octahedrites is approximately 260.

#### Hexahedrites Containing an Abundance of Schreibersite

The La Primitiva, Chile, iron (Cohen, 1897b, p. 123) is rich in schreibersite and was classified as an altered hexahedrite. We assume that Cohen meant the meteorite had a structure modified by reheating rather than weathering or chemical alteration. Prior (1914), in a description of the Angela, Chile, meteorite, said this iron "is honey-combed by schreibersite, which on one piece is estimated to amount to nearly a quarter of the mass." La Primitiva and Angela are now regarded as the same meteorite.

The kamacite in the Soper, Oklahoma, iron (Henderson and Perry, 1948b) is unusually low in nickel. Here the numerous phosphide inclusions occur as small masses between kamacite grains. Apparently,

this iron solidified before the phosphide could coalesce. With the phosphide scattered as small bodies, the contact between the schreibersite and kamacite is greater than if the schreibersite is segregated into one large body. Hence, a favorable opportunity existed for the phosphide bodies in the Soper to acquire more nickel than did the schreibersite in the Tombigbee iron. The Soper schreibersite contains 15.61 percent Ni, while the large inclusions in the Tombigbee contain only between 12.02 and 12.58 percent.

TABLE 17.—*Chemical composition of kamacite in the Soper, Angela, and La Primitiva meteorites*

	<i>Soper</i>	<i>Angela</i>	<i>La Primitiva</i>
Fe	93.35	95.03	94.72
Ni	4.11	4.52	4.72
Co	0.51	0.65	0.71
P	—	trace	0.18

Since the above analyses of the groundmass of the Soper and Angela meteorites are free from phosphorus and were made on material containing no schreibersite, all the nickel belongs to the kamacite. The La Primitiva analysis shows 0.18 percent P, or about 1.2 percent schreibersite. If this mineral contains the same percentage of nickel as the Soper schreibersite, and if the La Primitiva analysis was corrected for that amount of schreibersite, then the nickel content of the kamacitic groundmass in La Primitiva is approximately the same as that found in Angela.

### Summary

Analyses of the matrix, the metal adjacent to the large schreibersite bodies, the large schreibersite, and the rhabdite needles of the Tombigbee meteorite are given. The distribution of Ni in the matrix is uniform, but the zone of swathing kamacite immediately enclosing the large schreibersite contains less Ni than the matrix. The evidence indicates that large schreibersite bodies became enriched in Ni. The diffusion of Ni from the matrix into the swathing kamacite zone or the diffusion of the rejected iron from the phosphide into the matrix was not fast enough to equalize the abundance of Ni in the matrix and the swathing kamacite. The hardness measurements show a difference between the matrix and the swathing kamacite. Thus, the matrix of those hexahedrites which have many large phosphide bodies enclosed within them may contain less nickel than the average hexahedrite. A few analyses of other meteorites of this type are given.



## The Soroti, Uganda, Africa, Meteorite

PLATES 18, 19

### Fall and Description

The Soroti meteorite fell about 12 miles northeast of Soroti, Uganda, Africa (lat.  $1^{\circ}41' N.$ , long.  $33^{\circ}38' E.$ ) at 1.10 (probably p. m.) on Sept. 17, 1945. It was named after the native village of Soroti by R. O. Roberts (1947), who first described it and to whom we are indebted for both the historical records and the samples we studied.

The District Commissioner at Teso, in a report dated Sept. 22, 1945, stated:

... at almost exactly 10 minutes past one on Monday 17th of September, a low rumble, as of thunder, but without claps, was heard. It was, indeed, so similar to thunder that people indoors took little notice for half a minute. It rose slightly in volume and its persistence soon drew everyone to look skyward. Many thousands of feet high (wild guess is 20,000) a vapor trail could be seen. This trail extended across the sky which was clear as it could be. After about a minute the sound abruptly stopped. The trail disintegrated after about 5 minutes. Everybody had a different idea as to the direction, I personally thought north-south, another European thought south-north, and all points of the compass were mentioned.

A woman from Melok village, about 3 miles southwest of Katine Etem (Gombolola) Headquarters said, "I was sitting in my hut with my three children yesterday morning. I heard something like thunder. So I went out of my hut and went to a tree nearby with my oldest child. I told him to kneel down and pray to God. We had just knelt down, when a thing came from the sky and went into the ground near the tree. I and my child were blinded by smoke for a little while. When we could see again, I went to the place where the thing had fallen."

There was found a small crater a foot deep and only 3 feet from the spot where they had been praying. Other pieces of metal were found scattered around within a radius of a mile or more. Some are believed to have fallen in Omunyal Swamp.

Pieces brought to the District Office evoked great interest and some 500 people had seen it within an hour of the arrival in Soroti. Many hundreds more have come to see them since.

Summarizing, it may be stated that the phenomenon was observed in Eastern Buganda, at Aloi, 18 miles to the East of Lira in Lango District, at Budaka, 17 miles west-south of Mbale, in Mbale District, and at Soroti and Tosoma, in Teso District, that is, within an area of at least 4,200 sq. miles. Fragments of the meteorite are known to have fallen only in Teso, particularly near Soroti.

The velocity of the Soroti meteorite at the time the native woman heard the noise may have been greater than the speed of sound, although the terminal velocity of the piece which struck near her was not high. Of course it is impossible to prove that the sounds first heard originated when those pieces were sheared off, for probably

many pieces were broken off the meteorite while it was decelerating. Most of these pieces either were essentially consumed in the air or fell unnoticed and have not as yet been found.

Thus, possibly the noise that the woman heard originated back along the path of the meteorite. Sound waves travel at greater speeds than those at which the fragments would fall, so that the noise could be heard several seconds before any of the pieces landed. The sounds that were heard may have been produced when the meteorite encountered or passed through the sound barrier. The noises which alerted the native mother possibly were made after the pieces were broken off.

We were given<sup>5</sup> the two small specimens for restudy and a picture of all four specimens. The approximate weights of the four Soroti specimens are 1,000, 700, 190, and 170 grams.

The specimens consist of nickel-iron and troilite and have rough surfaces similar to that of a pallasite. Numerous bits of metal protrude from the surface of the specimen, some of them partly coated with a black fusion crust in which delicate flight markings are preserved. The troilite is covered with a thicker crust of fusion products than the Ni-Fe alloy, probably because troilite melts at a lower temperature.

The cross section through the two Soroti specimens (pl. 18, top) shows that the distribution of the metallic veins determined the shape of the meteorite. The troilite is held by the Ni-Fe alloy in the same way that olivine is held in the pallasites.

Apparently the troilite on the surface receded by ablation during the flight slightly faster than did the metallic phase and for reasons given on page 392. The troilite exposed on the surface is badly fractured, indicating that mechanical action probably had as much to do with the loss of troilite as thermal action.

The black crust covering many of the troilite areas on this meteorite may be essentially the fusion product of troilite, although possibly some material from the Ni-Fe alloy contaminates it. In color and texture, the fusion crust on the troilite is indistinguishable from the crust on the Ni-Fe alloy, but there is no reason to suppose that it should be otherwise.

The unique character of this meteorite, we believe, makes it worthy of a class name. The name sorotiite is proposed for meteorites consisting of Ni-Fe and troilite which have structures similar to those of the pallasites.

Normally one studies the polished surface of a slice through a meteorite and then selects a typical area from that slice for the chemical analysis. As it did not seem desirable to slice either of these

two small specimens and consume the material in the chemical analysis, we decided to cut them in half with a hacksaw and use the cuttings in the analysis.

A few of the pieces of metal that fell off during the cutting had some troilite attached to them. These were picked out, and with the use of a steel needle we then removed much of the troilite. These pieces were next hammered on a steel block in an attempt to break off more troilite, and although most of the remaining troilite was removed, possibly some of it was beaten into the iron. After the battered pieces of metal were brushed to remove the loosely attached troilite, they were added to the magnetic portion of the saw cuttings. Dust from the hacksaw blade may possibly have contaminated the sample, and some troilite may have been lost as a fine powder, but we estimate that these disadvantages were more than offset by the advantages of having cross sections from two pieces of this iron available for study and of preserving more material.

The magnetic material from the saw cuttings, consisting of Ni-Fe alloy and schreibersite, was placed in a flask and covered with 1 part of HCl and 3 parts of H<sub>2</sub>O. The gas given off was passed through acidified lead acetate solution. The portion that dissolved in hydrochloric acid was decanted off for analysis. The magnetic residue, later identified as schreibersite, made up 0.98 percent of the sample. The lead sulfide that formed in the lead acetate solution was converted to lead sulfate and calculated as sulfur.

The results given in table 18 closely approximate the composition of the Ni-Fe phase and the troilite. Roberts (1947) gives Fe as 91.13 and Ni as 8.87. As our sample was of necessity prepared in a manner not entirely satisfactory, we prefer to consider the results as a partial analysis.

TABLE 18.—*Partial analysis of the Soroti meteorite*

	<i>Ni-Fe phase</i>	<i>Ni-Fe phase including schreibersite</i>	<i>Troilite</i>	<i>Schreibersite</i>
Fe	83.51	84.21	62.80	—
Ni	12.67	12.80	—	13.75
Co	0.62	0.62	—	n. d.
P	0.00	0.15	—	15.65
S } {	0.81	0.81	35.84	—
Fe } {	1.41	1.41	—	—
Schreibersite	0.98	—	—	—
Cr	—	—	<sup>b</sup> 0.062	—
Insol.	—	—	0.53	—

<sup>a</sup> Calculated from sulfur.

<sup>b</sup> Determined on separate sample.

The percentages of Fe, Ni, and Co in the metallic phase of the Soroti iron agree with the composition of the meteorites in table 19. Metallographically the Alt Bela (Smycka, 1899) and the Illinois Gulch (Cohen, 1900) irons are different. The Widmanstätten structures of the Carlton (Howell, 1890), Edmonton (Henderson and Perry, 1947), and Soroti meteorites are so similar that it would be difficult to distinguish between them if only the Ni-Fe phases were compared.

TABLE 19.—Iron, nickel, and cobalt content of four meteorites that are similar chemically to the Soroti.

	<i>Soroti</i>	<i>Edmonton</i> <sup>1</sup>	<i>Carlton</i> <sup>1</sup>	<i>Alt Bela</i> <sup>2</sup>	<i>Illinois Gulch</i> <sup>2</sup>
Fe	84.21	86.61	86.54	85.34	86.77
Ni	12.80	12.57	12.77	12.89	12.67
Co	0.62	0.79	0.63	0.41	0.81

<sup>1</sup> Also similar metallurgically to Soroti.

<sup>2</sup> Different metallurgically from Soroti.

Roberts (1947) reported the density for the largest Soroti specimen to be 5.86. The density of a meteorite like the Soroti would vary depending upon the proportion of Ni-Fe to troilite. The measured densities of the four halves of our two specimens were 5.98, 6.11, 6.16, and 6.24. An average of all the reported densities on this meteorite is 6.07, but since there was a little oxide on each specimen, the true density would be slightly higher than 6.07. Henderson and Perry (1954) demonstrated that the densities of hexahedrites, coarsest octahedrites, and nickel-poor ataxites can be calculated very closely from the chemical analyses. It is not known, however, whether the density of a meteorite containing as much plessite as the Soroti can be accurately calculated. The density of the magnetic portion was found to be 7.864 by substituting the needed data in the following formula, but a density so determined may be low because the magnetic portion contained 2.22 percent of troilite.

Where S=schreibersite, T=troilite, and d=density:

$$\text{Density of magnetic portion} = \frac{100}{\frac{\% \text{ of Fe}}{d \text{ of Fe}} + \frac{\% \text{ of Ni}}{d \text{ of Ni}} + \frac{\% \text{ of Co}}{d \text{ of Co}} + \frac{\% \text{ of T}}{d \text{ of T}} + \frac{\% \text{ of S}}{d \text{ of S}}}$$

The analysis of the Ni-Fe portion probably should be corrected for the 2.22 percent FeS before the density is calculated, because there is not that much troilite in the metallic portion of this meteorite. Table 21 gives the analysis of the magnetic portion of the Soroti meteorite before and after it was corrected for troilite.

TABLE 20.—Recalculation of the partial analysis (table 8) of the Soroti meteorite

	<i>Ni-Fe phase including schreibersite</i>	<i>Composition of schreibersite deducted</i>	<i>Percentage of components in Ni-Fe analysis</i>
Fe	84.21	0.71	83.50
Ni	12.80	0.137	12.67
Co	0.62	0.01	0.61
P	0.15	0.15	—
FeS	2.22	—	2.22
Schreibersite	—	—	0.99

TABLE 21.—Analysis of the magnetic part of the Soroti iron before and after deducting the troilite; also, the calculation of the density of the metallic phase

	<i>Percentage of components in Ni-Fe analysis</i>	<i>Analysis after deducting FeS, calculated to 100%</i>		<i>Density of constituents</i>		<i>Quotient</i>
Fe	83.50	85.41	÷	7.86	=	10.866
Ni	12.67	12.96	÷	8.90	=	1.456
Co	0.61	0.62	÷	8.90	=	0.069
Schreibersite	0.99	1.01	÷	7.00	=	0.144
Troilite	2.22	—		—		—
						12.535

$$\text{Density corrected for troilite} = \frac{100}{12.535} = 7.977$$

Roberts (1947) calculated the density for the metallic phase at 7.95, but the formula he used is not entirely reliable.

The relative proportions of Ni-Fe and troilite in the Soroti can be obtained by the following formula, where

$$\begin{aligned} x &= \text{weight percentage of troilite} \\ 100 - x &= \text{weight percentage of Ni-Fe} \\ 6.07 &= \text{average density of meteorite} \\ 7.977 &= \text{calculated density of Ni-Fe} \\ 4.77 &= \text{density of troilite} \end{aligned}$$

we have

$$\frac{x}{4.77} + \frac{100-x}{7.977} = \frac{100}{6.07}$$

By the above calculation, the troilite makes up 46.727 percent and Ni-Fe 53.274 percent by weight of this meteorite. To make the percentage more useful to the reader who examines plate 18 (top), the weight percentage of troilite has been recalculated to volume percentage as follows:

$$\frac{\text{Weight percentage of troilite}}{\text{Density of troilite}} = \text{Volume proportion of troilite} \quad (1)$$

$$\frac{\text{Weight percentage of Ni-Fe}}{\text{Density of Ni-Fe}} = \text{Volume proportion of Ni-Fe} \quad (2)$$

Substituting in equation (1) we have

$$\frac{46.727}{4.77} = 9.796,$$

and substituting in equation (2) we have

$$\frac{53.274}{7.977} = 6.678.$$

Thus, the total volume proportion of troilite and Ni-Fe is 16.474. Reducing to volume percentage of troilite we have

$$\frac{9.796}{16.474} \times 100 = 59.46.$$

And reducing to volume percentage of nickel-iron we have

$$\frac{6.678}{16.474} \times 100 = 40.45$$

Summarizing, the Soroti meteorite has 46.727 percent of troilite and 53.274 percent of nickel-iron by weight; and it has 59.46 percent of troilite and 40.54 percent of Ni-Fe by volume.

#### Metallography

The unique feature of this iron is the ratio between the troilite and the Ni-Fe, although neither phase by itself is unusual. Of all the many meteorites that have been studied, none resembles this iron. It is therefore unlikely that numerous examples of this type will be found, but it does not necessarily follow that such meteorites could not be relatively abundant among those that enter our atmosphere.

The kamacite bands in the Soroti, measured in the direction of the cut, have a width of less than 1 millimeter. Schreibersite, which so commonly occurs between the troilite and the metal in other irons, in this case is essentially within the Ni-Fe alloy. The zone of swathing kamacite that encloses the entire Ni-Fe portion is nearly twice as thick as the average kamacite lamella in this meteorite. Since nickel does not replace iron in troilite, as it does in schreibersite, the additional widths of swathing kamacite must have a different explanation from that given for the swathing kamacite around the schreibersite in the Tombigbee iron (p. 379). Possibly troilite at higher temperatures had some excess iron which, as cooling took place, was rejected and the swathing kamacite was produced.

Troilite is both immiscible in molten Ni-Fe and of lower density than Ni-Fe. Hence, if FeS and Ni-Fe were slowly cooled from a melt, the FeS, or troilite, should completely segregate from the Ni-Fe phase and exist as a liquid above the solidified Ni-Fe phase. The abundance of plessite and the narrow kamacitic lamellae are interpreted to indicate a rather rapid cooling or perhaps a sudden relief of pressure.

Although the mechanism of producing a meteorite containing about 50 percent troilite dispersed in a network of Ni-Fe alloy is not understood, the process should be no more complicated than that which produces a pallasite. If an acquiescent body of molten material with the composition of a pallasite slowly cooled, olivine would solidify before the Ni-Fe. As the density of olivine is lower than that of Ni-Fe, it should completely separate itself from the metal if the cooling takes place slowly in an appreciable field of gravity. Due to surface cohesion, the olivine might carry up some metal, but surely not enough to account for the Ni-Fe in pallasites.

Apparently such a simple condition did not exist in the case of the Soroti. Thus, it is pertinent to speculate about the conditions that did exist and those which seem to be consistent with the structures and mineral assemblages found in pallasites and in meteorites like the Soroti. Pallasites probably cooled from a magna, with the olivine solidifying first. Regardless of its lower density, the olivine in pallasites is mixed with Ni-Fe alloy, indicating either that the body in which the pallasites formed was small or that there were no appreciable gravitational forces. Pallasites or meteorites like the Soroti iron could, however, be made in a large body if the process took place near the center, because there the gravitational forces would be negligible.

Troilite in the Soroti meteorite is analogous to the olivine in pallasites, and for this reason the comparison of the occurrence of olivine and troilite in meteorites should be pursued further. Olivine is much more abundant than troilite in stony meteorites, but less so in iron meteorites. Occasionally olivine occurs in an iron meteorite which is not a pallasite, but such an iron could originate adjacent to a pallasitic aggregate.

#### Abundance of Troilite in Meteorites

Troilite is relatively abundant in meteorites. According to Daly (1943), the chondrites contain about 5 percent FeS and the achondrites about 1.5 percent. According to these figures troilite is 4 times more abundant in chondrites and 12 times more abundant in achondrites than it is in metallic meteorites. However, the sections of meteorites in museum collections and the pictures of sections in published descriptions do not support Daly's figures.

A preliminary investigation of the abundance of troilite in a few irons was made. If there were more troilite than the above data indicate, it would support our contention that material such as that occurring in the Soroti iron could exist in quantities in the body from whence meteorites came.

Daly probably obtained his figures for sulfur from the chemical analysis, but our experience indicates that this is the wrong place to get such information. An author describing an iron meteorite is generally more interested in the metallic matrix than in an inclusion like troilite. Thus, the analyses of most of the irons are not suited for the calculation of sulfur because the troilite areas were not included in the portion selected for study.

To investigate this, the sulfur in a number of irons was calculated. The sulfur content of four coarse octahedrites (table 22) was established by measuring the width across a section and then measuring the total distance occupied by troilite along that line. Similar parallel traverses were made at one-eighth inch intervals.

TABLE 22.—*Comparison of sulfur percentages determined chemically by analyses of coarse octahedrites with sulfur percentages determined statistically by measuring sections from the same meteorites*

(The sulfur chemically determined is a weight percentage and is not equivalent to sulfur reported in the last column, which was obtained after estimating the percentage of troilite in the total area of a slice.)

Meteor	Chemical determination		Statistical determination	
	Reference	% Sulfur	% Troilite in section	% Sulfur in section
Coolac, Australia.....	Hodge-Smith, 1937.....	1.27	4.76	1.73
Canyon Diablo, Ariz.....	Henderson, 1951.....	none	5.95	2.17
	Noissan, 1904.....	trace		
	Barringer, 1905.....	0.004		
	Merrill & Tassin, 1907.....	0.005		
	Merrill, 1913.....	0.01		
Odessa, Tex.....	Buddhue, 1950.....	0.13	3.43	1.15
	Merrill, 1922.....	0.03		
	Beck & La Paz, 1951.....	0.02		
Osseo, Canada.....	Marble, 1938.....	None	3.42	1.25
Wichita County, Tex.....			2.72	1.00

When more than one section of a specimen was measured, a weighted average was calculated for the percentage of troilite. We do not claim that the coarse octahedrites selected are representative for that group. Only a small number of sections have been measured through the Canyon Diablo and the Odessa meteorites, whereas there are tons of the Canyon Diablo and possibly many hundreds of pounds of the Odessa iron. Also the areas that were measured on both were too small to represent either meteorite. Yet the percentages so obtained appear to be more reliable than the values Daly reported after calculating the analysis of a sample weighing but a few grams.



The measurements reported in table 22 were made on the same meteorite that the chemist analyzed but not on the same sample.

Troilite (stoichiometric FeS) with NiAs crystal structure is exclusively a meteoritic mineral, with the one exception of the Del Norte, Calif., occurrence. According to Eakle (1922), the California troilite occurs in a serpentine in an old copper mine. Apparently no specimens were found with the troilite in the matrix. We are not challenging the terrestrial origin of the California troilite, but it is important to keep its uniqueness in mind. If the theory proposed in the following pages for the disintegration of a meteorite made of about 50 percent troilite and 50 percent Ni-Fe is correct, possibly meteoritic troilite is scattered over the earth; however, the chances of finding such specimens would be very slim indeed.

### Meteorites Like the Soroti Are Likely To Be Consumed in Flight

All meteorites are fragments of some large cosmic body. It would be impossible for a meteorite such as the Soroti to be broken from its parent mass without acquiring a rough and hackly surface, with projecting veins of metal extending slightly beyond the troilite. Also, the troilite occurring all over the surface and perhaps that occurring slightly below the surface would be fractured, as troilite is brittle at normal temperatures. In the Soroti, such troilite probably was brittle at the temperature existing when the original body broke up. (Gunard Kullerud, of the Geophysical Laboratory, reports in personal communications that FeS made at 550° C. appeared to be more brittle than FeS made at 400° C.)

Most meteorites seen in collections have rather evenly rounded surfaces, but this does not mean that they entered our atmosphere with a smooth surface. Possibly a prominent external irregularity on a mass entering the atmosphere is removed during the interval the meteorite undergoes its maximum deceleration. After the meteorites with homogeneous textures become rounded, their dimensions probably decrease only slightly during the remainder of their flight.

A surface made up of either troilite or olivine held in a network of metal will not become smooth because of stresses and strains. The mechanical forces applied to such a surface supplements the loss of material by normal thermal ablation; hence the vapor trails from such meteorites should be more pronounced and enduring than those from homogeneous meteorites.

The most violent reactions occur on the forward face of a falling meteorite. Enough energy was released in the collision of the air molecules with the Soroti meteorite to vaporize both the Ni-Fe alloy and the troilite. Many irons show that heat-softened metal flowed over their surfaces. Troilite, which has a lower melting point than

the Ni-Fe alloy and is brittle, was either burned away or mechanically lost at a faster rate than the Ni-Fe alloy. Thus an aggregate of minerals like the Soroti, in which small veins of metal protrude from the surface, loses more material from its surface than the average meteorite. Furthermore, the reduction possibly continues through more of the flight than in the case of a homogenous meteorite.

After the velocity of the Soroti meteorite was decelerated to a point where the temperature on its front face was not high enough to heat the sides, possibly physical action continued to disintegrate the brittle troilite. A spine of Ni-Fe alloy extending beyond the surface might, by means of the atmospheric drag, be bent backward. If this happened, the spine of Ni-Fe would fracture the sulfide against which it is pressed, with a simultaneous breaking of the bond between the metal and the troilite on the forward side of the metallic spine.

Such a falling meteorite may undergo major changes in its form during flight, and, if so, it probably would not hold a fixed position. If such a body tumbles during its high-velocity flight, fractures would be produced and widened between the metal and the troilite over all surfaces. Such violent action may shatter more of the troilite and cause the loose pieces to fall out. As the troilite is lost, more rough metal surfaces would become exposed, and these, in turn, would be subjected to the shearing-off process.

Thus, the stresses and strains applied to these meteorites with hackly surfaces, such as those of the Soroti type and the pallasites, cause material to be lost as long as the mass is moving with a velocity high enough to cause bending of the metallic veins. Troilite, because of its low melting point, should react to the temperatures on the front of such a meteorite after the other minerals have ceased to react. In addition, the FeS and Ni-Fe portions have different thermal conductivities and coefficients of expansion. Therefore, both thermal and mechanical stresses are operating simultaneously on the surface of such a meteorite during its fall.

### Summary

This meteorite fell Sept. 17, 1945, at 1.10 (probably p. m.) near Soroti, Uganda, Africa. Four pieces were recovered, together weighing 2,060 grams. The composition and metallography of the meteorite are given. The abundance of sulfur in iron meteorites is discussed, and a probable reason is given for the variety of such meteorites as the Soroti iron. This iron represents a new type of meteorite, analogous to the pallasites, with troilite taking the place of olivine. The name sorotiite is proposed for this type.

## The Keen Mountain, Virginia, Meteorite

PLATES 20-22

A 14.75-pound iron meteorite, a new hexahedrite, was found in 1950 by Fred Matney at approximately 30 feet from the crest of the south face of Keen Mountain, Buchannon County, Virginia, near the head waters of Pigeon Branch. The coordinates of the point of discovery are lat.  $37^{\circ}13' N.$ , long.  $82^{\circ}0' W.$

Mr. Matney observed this dark object along a path he frequently used. It attracted his attention because it was noticeably different from the other rocks. When he discovered it was metallic he cut off a small piece and sent it to the U. S. Geological Survey, Washington, D. C. Dr. Charles Milton, of the Survey, suspected it was a meteorite and referred the correspondence to the U. S. National Museum.

When Mr. Matney learned that his specimen was a meteorite and that the National Museum was interested in it, he offered to bring it to Washington on his next trip north or hold it until someone from the Museum would visit him. Gordon Davis of the Geophysical Laboratory, Washington, D. C., was in the Museum shortly after this specimen was identified, and, since he was going to Buchannon County, Virginia, he offered to negotiate with Mr. Matney for the meteorite.

When Mr. Davis delivered the iron to Washington, Stuart H. Perry bought it and presented it to the National Museum.

### Description

The Keen Mountain meteorite probably fell recently, although the fall was not witnessed. On its surface there are sizable patches of unaltered black fusion crust that contain flight markings. In a few places the silver color of the Ni-iron alloy can be seen through the fusion crust. However, on the surface of this iron, patches of loosely attached oxide as well as some small corrosion pits occur. The meteorite, according to Mr. Davis, was found at a place where it would be wet by ground seepage for about four months of each year. Probably no iron meteorite would remain fresh in such an environment very long. Although it is impossible to establish the year it fell, we suspect its weathered surface could develop within five or ten years if it was wet as much of the time Mr. Davis estimates. Thus, the Keen Mountain iron possibly fell between 1940 and 1950.

Apparently this fall attracted no local attention. Mr. Matney, who lived close to where the meteorite was found, did not associate it with any meteor display. Finding this iron near the top of the southern slope of Keen Mountain indicates that it did not come from a northerly direction.

The rough areas shown in plate 20 are due to surface alteration. Some of the corrosion pits range between 2 and 4 millimeters in width and are about the same in depth. When this meteorite was received the pits were nearly filled with loosely bonded brown iron oxide. The rust was removed from most of these places to probe the depth of the oxidization.

The depression in the central part of plate 20 (top) is about 7 or 8 millimeters deep. After 2 or 3 millimeters of oxide were removed from this cavity, troilite was exposed at the bottom. The bottom dimensions of this cavity are approximately 8 by 10 millimeters, while the diameter at the surface is nearly 15 millimeters. Apparently, during the flight of this iron through our atmosphere, this depression increased in diameter faster than it deepened.

The surface of the iron surrounding this cavity is covered with fusion crust containing flight markings. However, some oxidization is superimposed on some parts of the fusion crust. Since the surface of the iron surrounding this depression has a black crust over it, this feature was made during the flight of the meteorite in our atmosphere. Some of the troilite in this depression was burned away during the flight, so the heat generated on the surface was not sustained long enough to remove all the sulfide.

The delicate striae preserved in the glossy fusion crust and the shape of this meteorite indicate that the forward face during most of its flight through the atmosphere is the one shown in plate 20 (bottom).

A study of the surface features of unaltered meteorites is important but unfortunately this topic has not attracted much attention. Plate 20 shows the surface features of the Keen Mountain iron and permits others to interpret these features.

The Keen Mountain meteorite cannot be paired with any other meteorite. If other pieces fell they have not been found, and if such pieces are not discovered soon they will be weathered and it will be difficult to relate them to this iron.

The other known hexahedrite from Virginia was found 100 miles east of Keen Mountain, at Indian Valley, Floyd County, in 1887. It was described by Kuntz and Weinschenk (1892) who said:

In the spring of 1887 a mass of meteoritic iron was turned up by John Showalter while plowing his tobacco patch, situated in Indian Valley Township near Carroll and Pulaski lines and near the base of the south side of Floyd Mountain, 6 miles south east of Radford Furnace, Virginia . . . . This meteorite weighs 31 pounds . . . . The surface of the iron is very much corroded and is entirely covered with a limonite crust, only a little of the original crust is visible. On the exterior are deep depressions from 2 to 4 cm. in diameter.

Although both hexahedrites were found on the southern face of mountains we believe this is only a coincidence.

A slice 2.5 millimeters thick was cut for study (plate 21, bottom) and three areas were selected for density determinations. We assumed that the area with the highest density was the purest kamacite, so this portion was analyzed.

TABLE 23.—Density measurements of three areas from one slice of the Keen Mountain meteorite before and after the oxide was removed

Area	Density of piece as it was removed	Density of piece after oxide was removed
1	7.766	7.907
2	7.908	7.908
3	7.859	7.895

### Composition

All but a small proportion of area 2 (table 23) dissolved in dilute HCl. The insoluble part was filtered off, weighed, and found to have the crystal habit of rhabdite. A partial analysis of this residue is shown in table 24. The rhabdite in this section of the Keen Mountain iron makes up 0.98 percent by weight.

The nickel content of the rhabdite was determined. We obtained phosphorus by calculation, because rhabdite has a fixed phosphorus content.

TABLE 24.—Analysis of the acid soluble part of the Keen Mountain meteorite, a partial analysis of the residue, and a calculated composite analysis of the meteorite

	(1)	(2)	(3)
	Portion that dissolved in HCl	Partial analysis of rhabdite	Composite analysis of the meteorite
Fe	<sup>a</sup> 92.92	<sup>a</sup> 46.80	93.38
Ni	5.28, 5.27	37.7	5.65
Co	0.72	<sup>b</sup> 0.50	0.73
P	0.04	<sup>b</sup> 15.00	0.19
S	none	none	none
C	0.06	—	0.06
	100.00	100.00	100.00

$$\text{Molecular ratio } \frac{\text{Fe}}{\text{Ni} + \text{Co}} = 16.46$$

<sup>a</sup> By difference.

<sup>b</sup> See discussion (p. 397).

The composition of the meteorite may be estimated by combining the analyses in columns 1 and 2 of table 24. The cobalt content in several rhabdite analyses averaged about 0.50 percent; therefore, that value was assumed to be present. The iron in each case was

obtained by difference. Chemically the composite analysis is similar to other hexahedrites.

Both the Cincinnati (pl. 10) and the Keen Mountain (pl. 22) meteorites have eutectic structures; also, some phosphorus in both irons dissolved in acid. Possibly the process that produced these eutectic structures had something to do with the making of the phosphides soluble. Certainly the phosphorus in both meteorites originally was either in a rhabdite or schreibersite body and was insoluble in dilute hydrochloric acid. In the analyzed specimen of the Keen Mountain iron, 25 percent of all the phosphorus dissolved in dilute acid.

All the insoluble residue, which consisted of rhabdite needles, was used in a nickel determination. Unfortunately, there was not enough material for a complete analysis. The rhabdite in the Keen Mountain iron contains about 37 percent nickel.

The sulfur content was determined by estimating the volume of troilite in the slices shown in plate 21 (bottom). The volume percentages (3.49 and 4.25, obtained by two different methods) were averaged, and 3.91 percent is reported for the troilite content of this meteorite.

Since only a few slices have been removed from this meteorite, we do not know whether they represent an average for this iron. More sulfur than phosphorus is present in the slices thus far removed. However, there may be more phosphorus in the Keen Mountain iron than sulfur because the phosphides are uniformly dispersed through the metal while sulfur occurs as localized troilite.

Hexahedrites as well as all iron meteorites probably contain much more sulfur and phosphorus than their analyses indicate. Possibly the error in the abundance of sulfur is greater than the error in the abundance of phosphorus.

### Metallography

The zone of granulated metal immediately underlying the crust (pl. 21) usually is assumed to represent the penetration of heat into the meteorite during its flight. It is important to establish where the greatest thermal penetration occurs on oriented meteorites. Nininger (1940) said that it was unreasonable to expect the front face of oriented meteorites to show the deepest penetration of heat because the maximum ablation occurs on the front of a falling meteorite.

Two sections cut through the Keen Mountain meteorite (pl. 21) show a zone of granulation around the edges of the cuts. The thickness of the zone is not uniform in both slices. The slice with the widest zone of granulated metal was removed where section AA'

crosses the specimen (pl. 20, top). The place where the granulation is the widest corresponds to the lower edge of what we believe was the front face. Our opinion about the orientation of this specimen was based on the shape of the meteorite and on the flight markings.

The Bruno, Canada, iron (Nininger, 1936) is another example of thermal alteration within a hexahedrite. Unfortunately, the illustration Nininger used did not show the magnification; therefore, it gives one the impression that the heated zone around this iron is unusually thick. On a recent visit to the American Meteorite Museum in Sedona, Ariz., we examined the iron and found that the pictures Nininger published in both 1936 and 1952 were enlarged nearly three times. Thus the thermal penetration into the Bruno iron is about the same as occurs in the Keen Mountain specimen.

The Neumann lines in plate 21 (top) are curved, but this is not the first time such Neumann lines have been observed. Such lines indicate some deformation after the Neumann lines formed because originally they were straight.

Some normal rhabdite occurs in the kamacite in this meteorite but two unusual habits for rhabdite are shown in plate 22 (top). Both rhabdites are made up of fragmented particles. One consists of a localized path of similarly orientated particles separated by a narrow channel of kamacite. The other phosphide inclusion is an elongated wavy-body, but in place of being a continuous unit it consists of a series of broken segments.

When these phosphides formed they possibly were no different from the normal phosphides seen in most meteorites. We think these unusual habits indicate a thermal reaction: the matrix was heated high enough for the phosphide particles to react with the surrounding alloy. Since these peculiar phosphide inclusions occur close to the surface, they may have been made during the flight of the iron through the atmosphere. This and other evidence indicates that a study of the phosphide inclusions within meteorites may provide an excellent means of determining the thermal penetration into iron meteorites.

The manner in which the rhabdite was obtained for the analysis precluded it from being anything but an average of the phosphide particles in this meteorite. The Keen Mountain rhabdite, which contains 37 percent of Ni, falls within the upper limits of the nickel values for rhabdite. Unfortunately, there are not enough analyses of this mineral to determine if this rhabdite is unusually rich in nickel.

The rhabdite from the Annaheim, Canada, meteorite (Johnston and Ellsworth, 1921) had 41.36 percent Ni; and the rhabdite in the Cranbourne, Australia, meteorite (Cohen, 1897c) had 42.16 percent Ni.

Both of these irons are coarse octahedrites, so there is more nickel available for the rhabdites to acquire than there is in the Keen Mountain meteorite.

Plate 21 (top) shows a phosphide body consisting of a cluster of orientated particles separated by channels of kamacite. Some structural features, possibly Neumann lines, extend to the border of these phosphide bodies. Some acicular features existing in the kamacite may be structures of a rapidly cooled metal. Such cooling would arrest the solution of the phosphide in the kamacite.

While a high temperature is sustained in the Ni-Fe alloy, nickel may migrate from the kamacite into the phosphide where it replaces iron that is returned to the kamacite. All Ni-Fe phase diagrams show that the solubility of nickel in kamacite decreases as the temperature is raised. The nickel content of schreibersite varies; thus, as the temperature is increased, nickel must enter this mineral from the kamacite because there is no other place for nickel to come from.

The solubility of the phosphide in kamacite apparently increases as the temperature is raised. To understand the thermal changes observed in this iron, some knowledge of the temperature-time relationship for the structures in meteoritic iron is needed.

There are rhabdites in the center of this piece that have a normal habit. Their presence indicates that reheating took place after the mass was broken from the body in which it was formed. Although reheating may have occurred prior to the flight through our atmosphere, most likely these changes were made during the flight in our atmosphere. The thermal changes noted in the Keen Mountain iron are not as extensive as those described in the Social Circle, Georgia, meteorite (Henderson and Perry, 1951) or the Murnpeowie, Australia, meteorite (Spencer, 1935).

Since the diffusion of Ni and Fe is slow, there is a possibility that the changes noted in the phosphide inclusions in the Keen Mountain meteorite took place outside our atmosphere. Although almost everyone will agree that the thermal changes noted around the outside of the Keen Mountain iron were made during flight within the atmosphere, there is a possibility that the zone of metal in which these thermal changes are preserved is the remains of some more extensive thermal reaction that took place around the outside of the mass prior to its entry into our atmosphere.

The increased solubility of the phosphide in the kamacite probably has more to do with the formation of the jagged boundaries of these phosphide bodies than the molecular exchanges of Ni and Fe. In the Cincinnati, Ohio, iron (pl. 10) we found eutectic structures similar to those in the Keen Mountain iron. We believe the eutectic structures resulted from the phosphide particles reacting with the kamacite



when the temperature was raised. The cooling which followed apparently was rapid, and since all the iron that separated as blebs did not get beyond the limits of the phosphide body, some small blebs of iron were trapped (pl. 22, bottom).

All the various structures described in the Keen Mountain meteorite were observed in a single slice. However, the phosphide inclusions arranged parallel to the Neumann lines in the center of the slice are enclosed by a zone of granulated metal around the edge; this means that the reheating occurred after the Keen Mountain iron was small.

There is no data on the rate heat will penetrate a hexahedrite, and we do not know the temperature at which the peculiar features noted in these phosphides will form. Moreover, the zone of granulated metal around the edges of the section indicates that no sizable pieces were broken off during the flight of this mass in our atmosphere.

Apparently most students of meteorites think that iron meteorites fall as single bodies, but it is possible a large hexahedrite could separate along a cleavage and produce several smaller bodies. A fusion crust would form over the fragments and perhaps some thermal penetration would start the moment the larger mass breaks into pieces. Stony meteorites break during their fall and produce individual pieces that are covered with fusion crust, so why can't irons occasionally behave in the same manner?

### Summary

A new 14.75-pound hexahedrite from Buchanan County, Virginia, is described. Chemical analyses of the matrix and the rhabdite inclusions are given. Certain metallographic features resulting from the penetration of heat into the meteorite are described.

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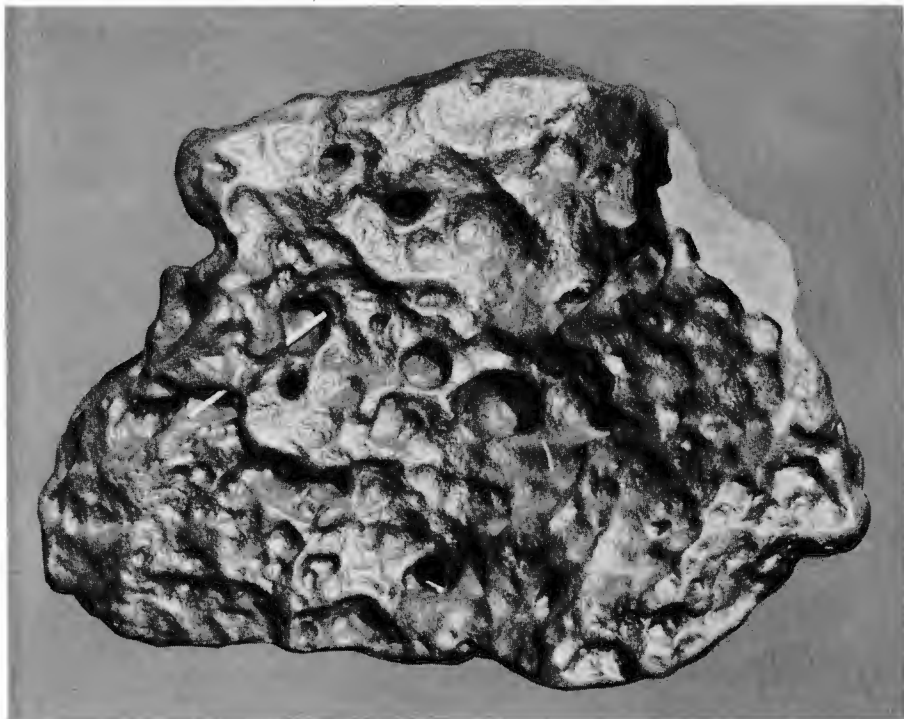
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General view of the Goose Lake meteorite. Note the rim of curled metal bending into the large cavity at the left. (Chabot Observatory photograph.)

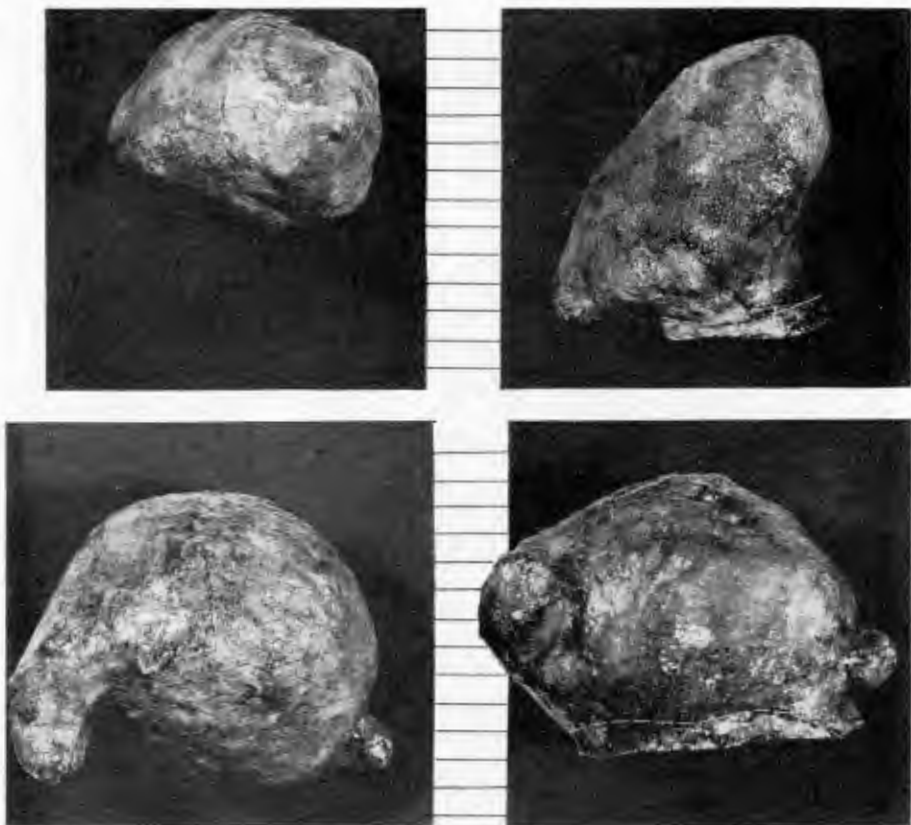


View of the Goose Lake meteorite. This probably is the rear face of the meteorite because it has fewer layers of deformed metal than the opposite side. Both white rods are 8 inches long. The upper one shows two cavities, which are connected below the bridge of metal. The hole below the upper end of the rod connects with the cavity under the metal bridge. A model of the large cavity at the center of the picture is shown in the bottom photographs of plate 4; its volume is 686 cc. The small round hole near the bottom center with one end of the white rod showing is the opening of the tunnel through the meteorite. The flat area, upper right, is where the slices were cut off.



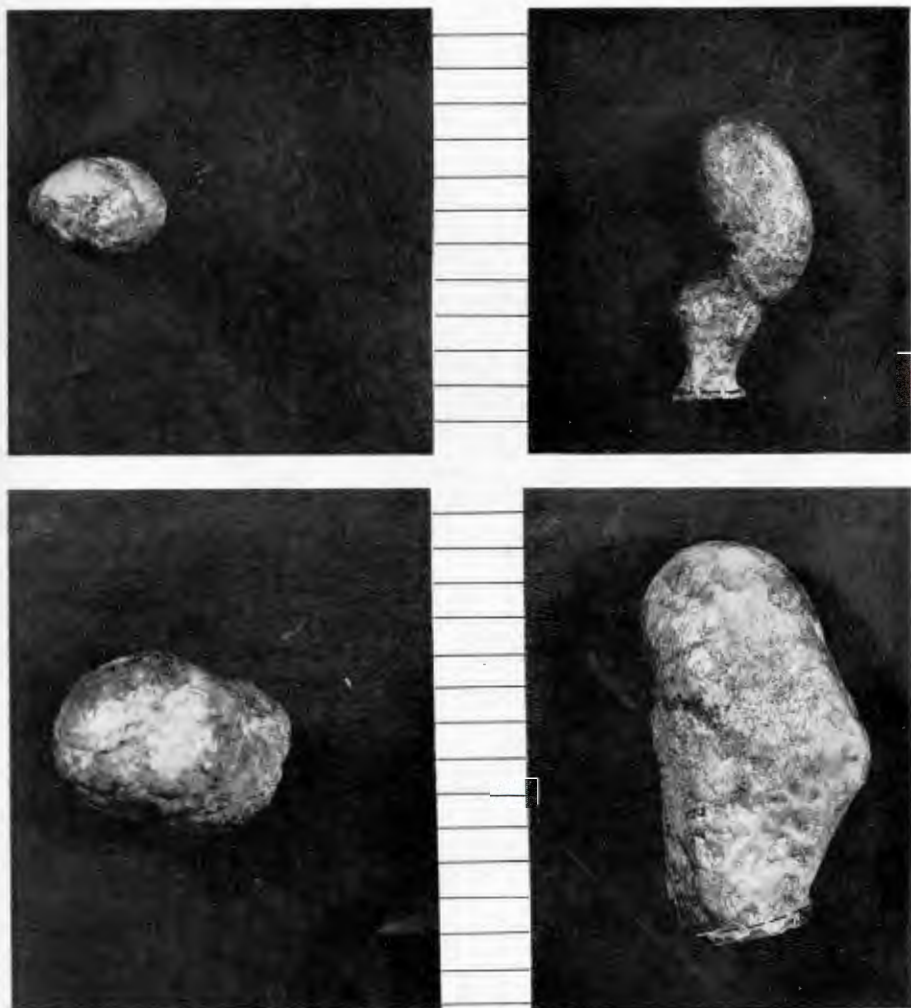
A view of a portion of the face of the Goose Lake meteorite. It is assumed that this portion was part of the front face during most of the fall because there are more layers of deformed metal. A model of the cavity, left of center, is shown in the lower photographs of plate 5. The arrow locates the large cavity leading to the tunnel.





TOP.—Two views, normal to each other, of a cast of a depression on the rear face of the Goose Lake meteorite. In the photo at right, the lower left corner of the cavity is close to the surface of the meteorite; the broken line at bottom indicates where the surface of the meteorite crosses at the opening.

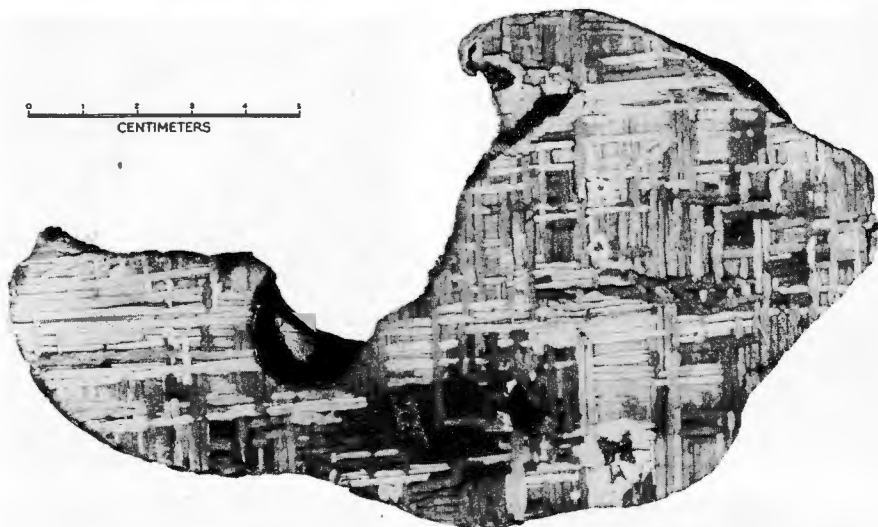
BOTTOM.—Two views, normal to each other, of a cast of a hole in the meteorite. The dotted line on photograph at right locates the opening to the surface of the meteorite. The space between lines in the center strip represents 1 cm.



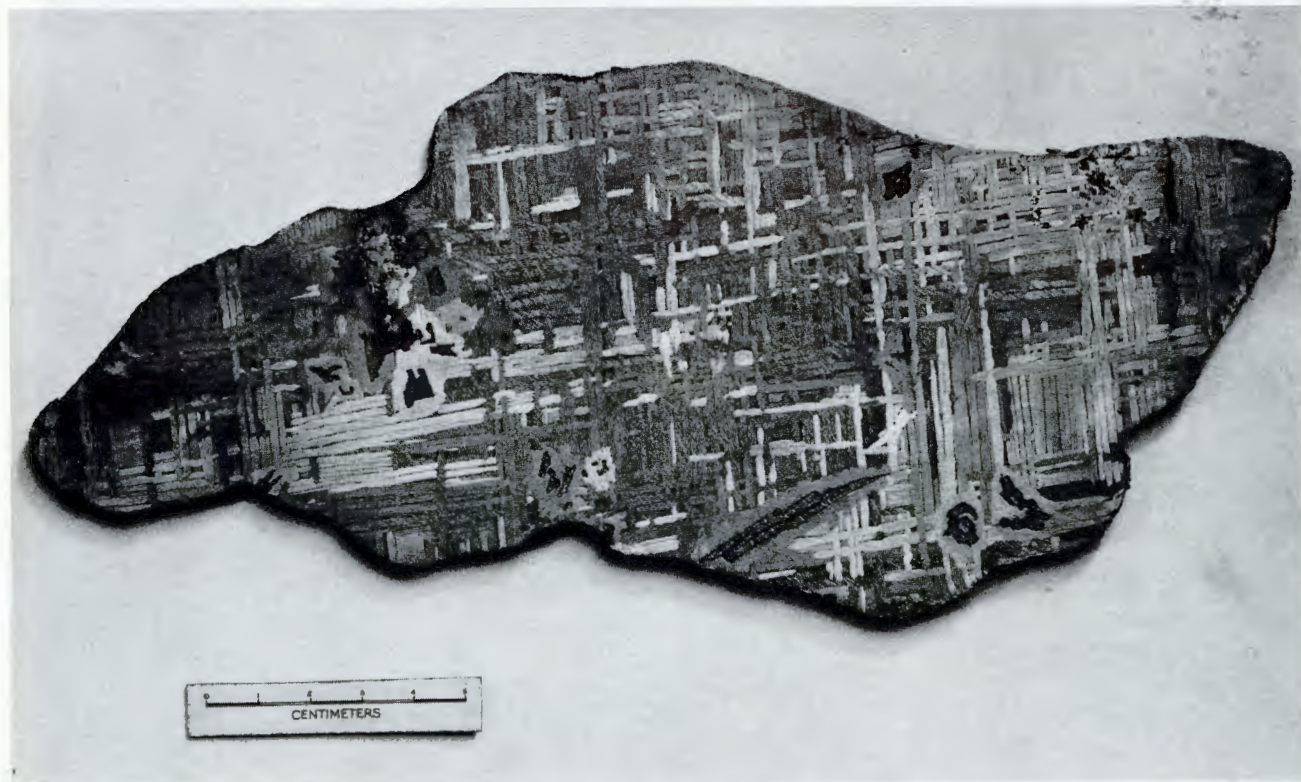
TOP.—Two views, at right angles to each other, of a cavity in the Goose Lake meteorite that appears to be twisted and restricted in width about midway of its depth. The diameter of the opening at the surface is approximately 50 percent of the maximum width of this cavity.

BOTTOM.—Two views, at right angles to each other, of a cast of a cavity in the forward face of the meteorite. The width of the cross section at the widest point is about double the diameter of the surface opening.

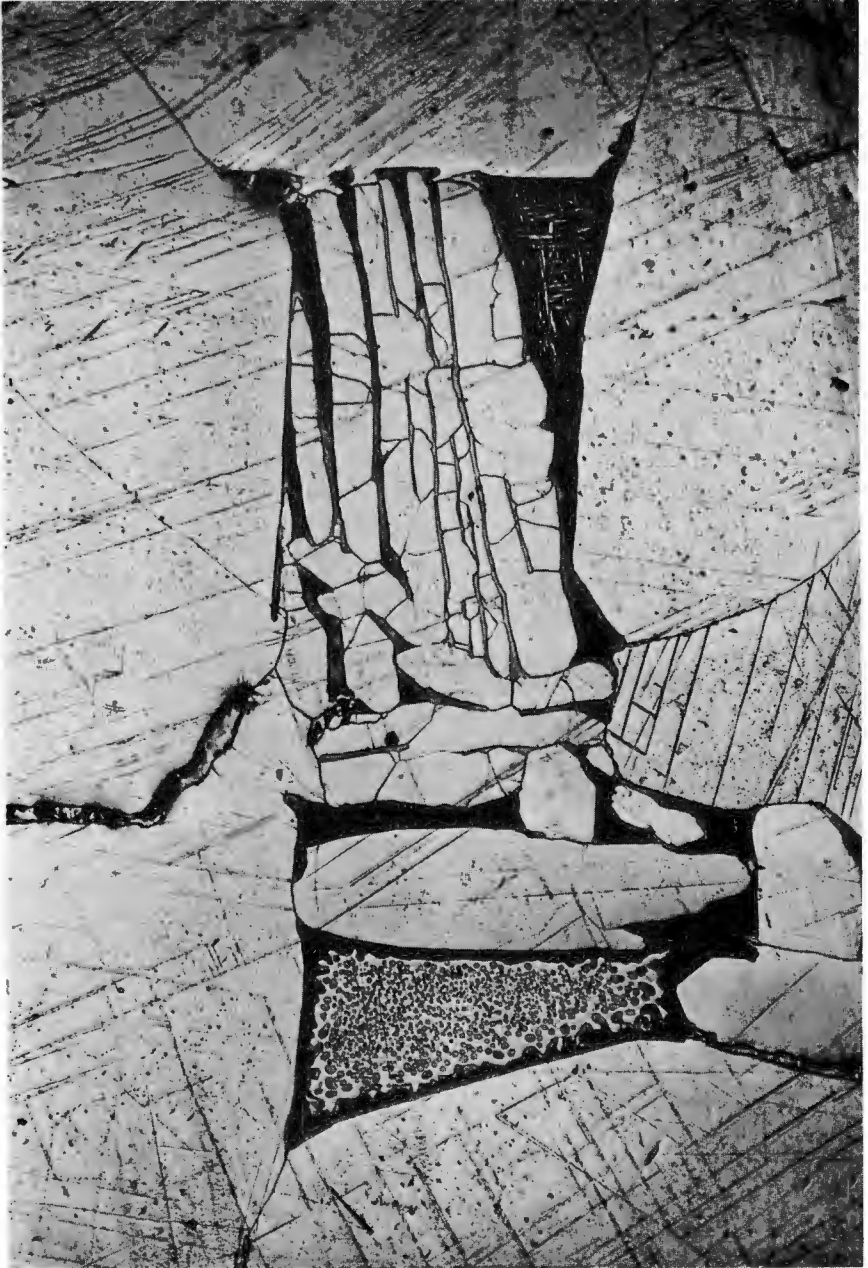
The space between lines in the center strip represents 1 cm.



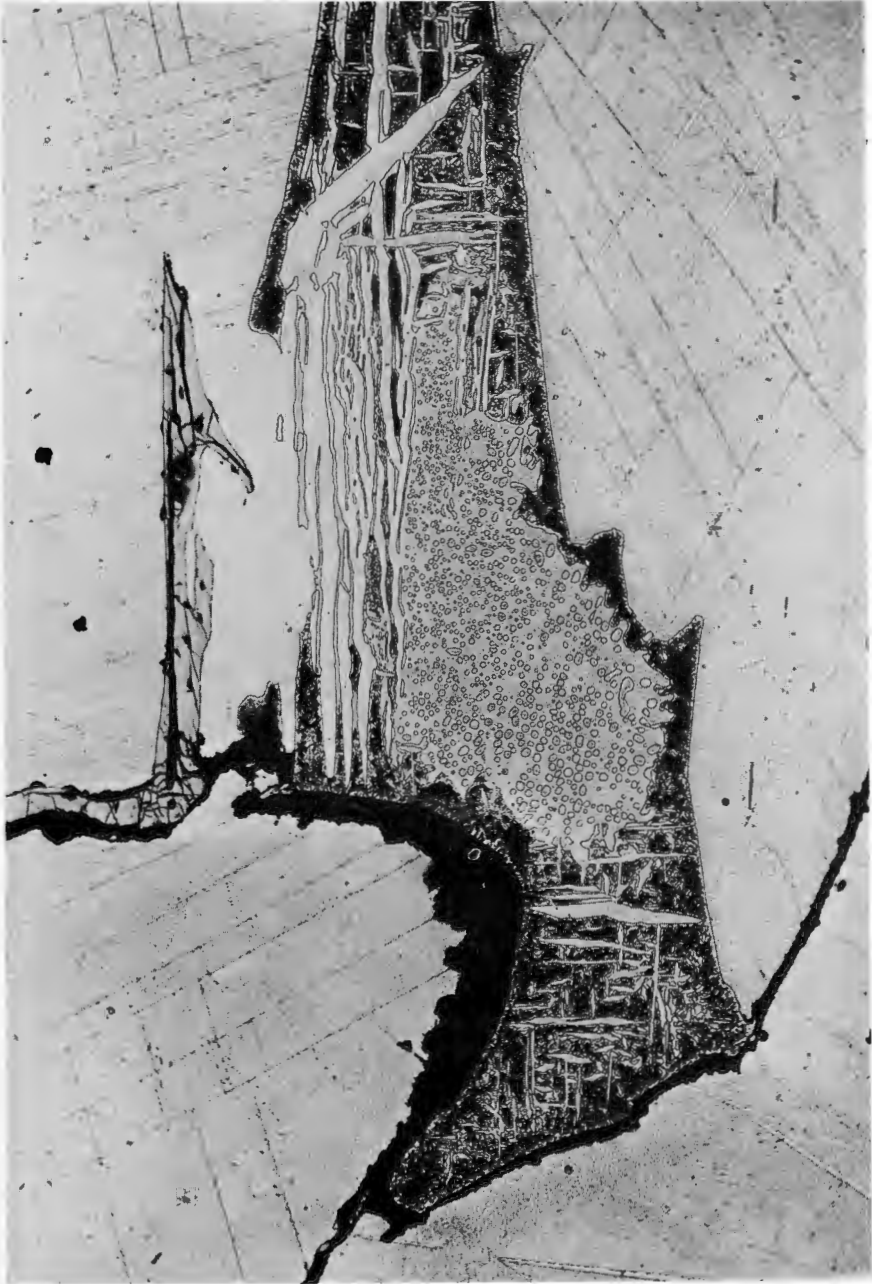
A cross section through a wide but shallow cavity in the Goose Lake meteorite. The dark crescent is the shadow formed by the bent lip, which has curled back into the depression until it reaches the plane of the cut. Note the curved kamacite at the upper edge of the cavity. The Widmanstätten structure runs to the limits of this cavity. At the edges, the structure appears slightly distorted because the metal is so thin that it was deformed by the grinding and polishing.



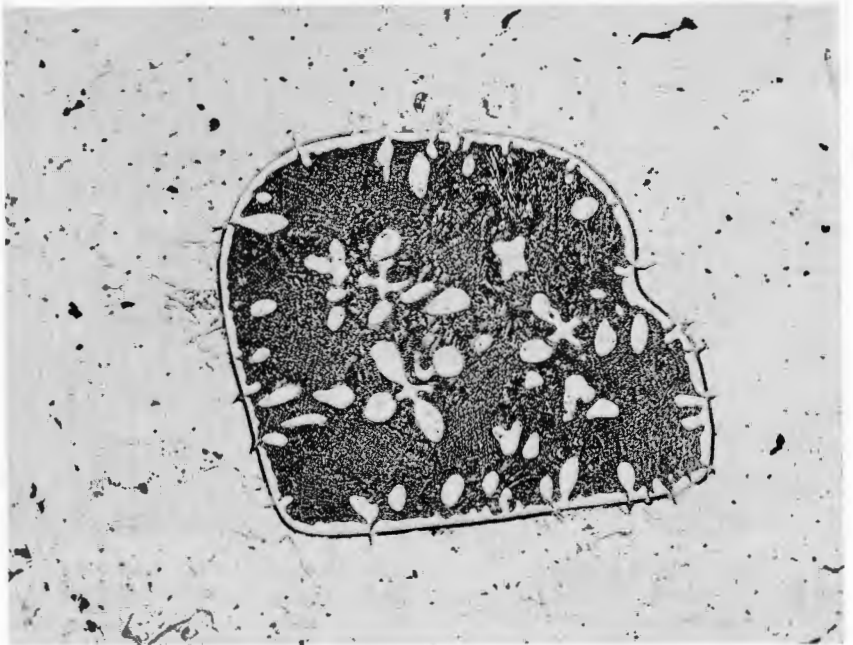
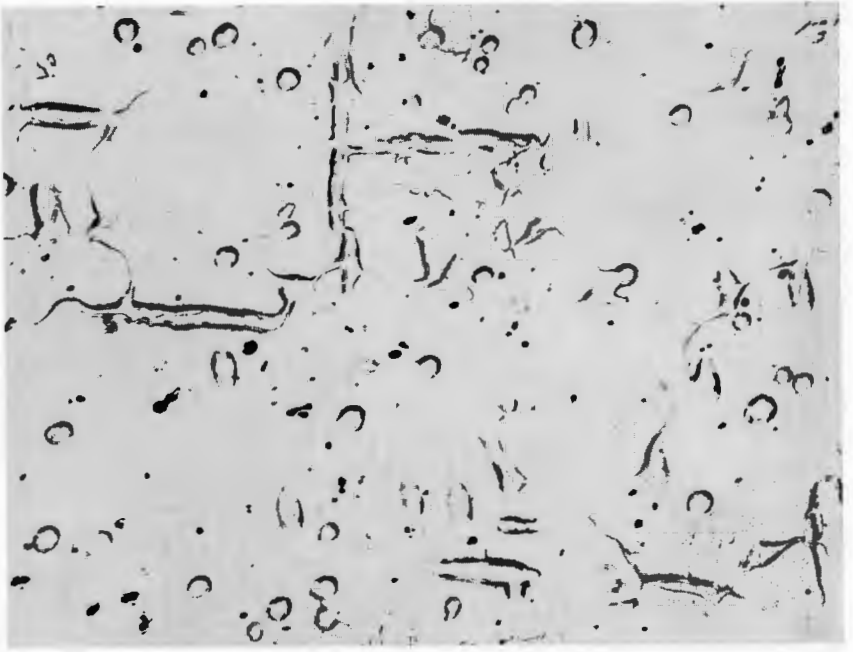
The Goose Lake meteorite is a coarse octahedrite. Numerous plessite areas occur between the kamacite bands. Elongated schreibersite bodies disrupt the Widmanstätten pattern. The thin dark veins lying between the kamacite lamellae were injected during flight.



An irregular atypical plessite field about 1 inch below the surface of Goose Lake meteorite. Area at bottom is filled with spheroidized taenite and enclosed by a dark border of imperfectly transformed taenite. Rest of the field is kamacite with some darkened taenite. Dark area in the upper right corner is imperfectly transformed gamma-alpha mixture with orientated (white) kamacite lamellae. Small schreibersite bodies are at the left and at the upper left corner of the plessite field. (Picral applied for 30 seconds; magnification, 100.)



A plessite field in the Goose Lake meteorite, the central part of which shows spheroidized taenite. At the top, left, and bottom, the kamacite lamellae are orientated. At center left is an irregular schreibersite body. Invading hydroxide, due to weathering, appears as dark area along a grain boundary (lower right), a border along the lower end of the plessite field as a much thicker curved area, and adjacent to the schreibersite body. (Picral applied for 30 seconds; magnification, 100.)



The Cincinnati meteorite. Explanation on facing page.



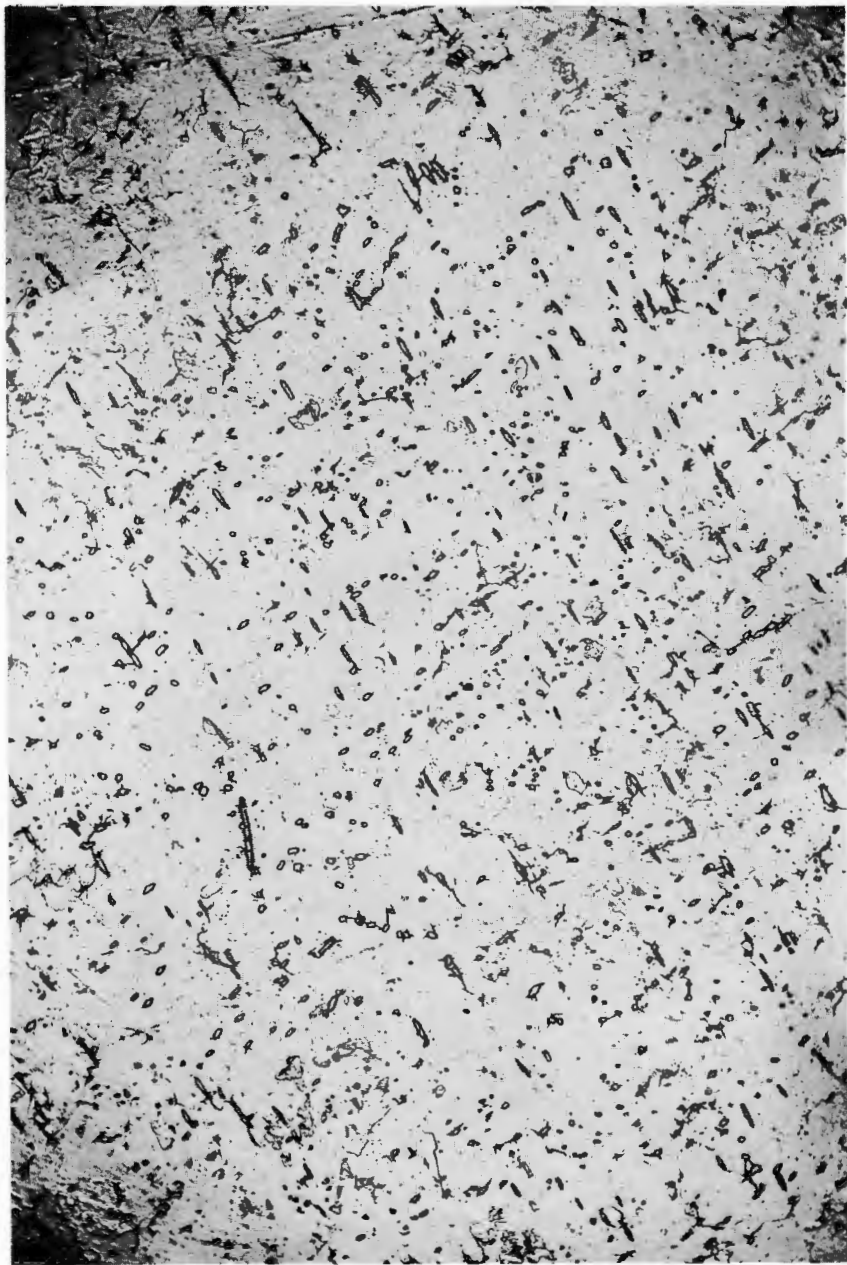
Slices of the Pittsburgh meteorite. The slice shown at top was lent by Yale University; that shown at bottom was lent by Harvard College. (Magnification, 2.)

EXPLANATION OF PLATE 10 (Opposite)

The Cincinnati meteorite. **TOP.**—The phosphides in the Cincinnati meteorite are rounded and appear to have been diffused by reheating. This structure indicates that reheating was for a brief interval and was followed by quick cooling. (Picral applied for 40 seconds; magnification, 150.)

**BOTTOM.**—An iron phosphide eutectic of unusual fineness and regularity. The excess of iron that was rejected in the cooling was unable to migrate to the edge of the structure. A feature with such perfect structure is indicative of slow cooling. (Picral applied for 60 seconds; magnification, 100.)

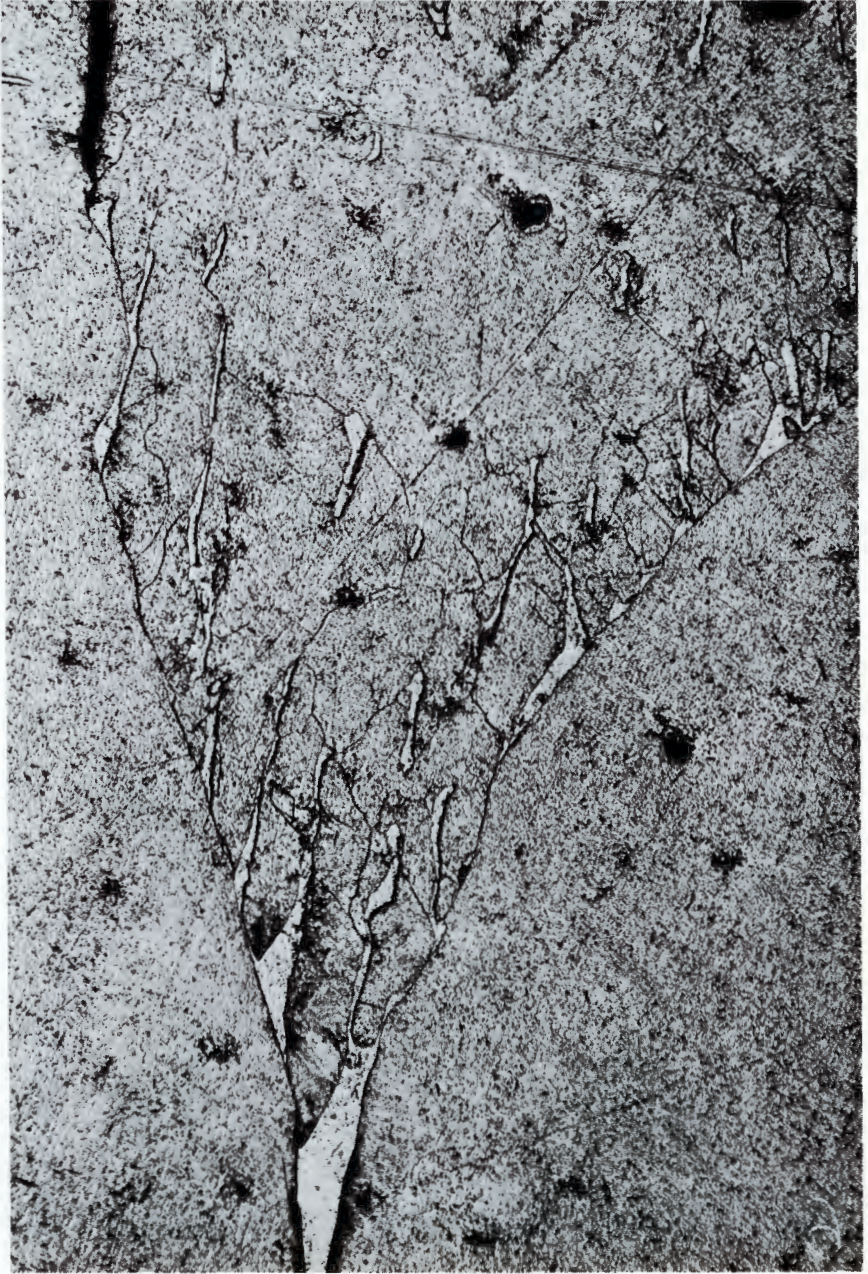




An area in the central part of the Cincinnati meteorite showing numerous rhabdites. Many of these have frayed ends and some have irregular sides, indicating only that these inclusions had undergone little change in the reheating. (Picral applied for 80 seconds; magnification, 50.)



Kamacite containing rhabdite inclusions in a parallel arrangement, Pittsburgh meteorite.  
(Magnification, 100.)



Coarse plessite surrounded by granulated kamacite, Pittsburgh meteorite. (Sodium picrate applied for 70 seconds; magnification, 100.)



A large cohenite with the characteristic kamacite inclusions, Pittsburgh meteorite. Above this cohenite there occurs an elongated plessite area, in one corner of which is a dark island of gamma-alpha iron; in the opposite upper corner there are some delicate acicular kamacite needles. The kamacitic groundmass is granular, and small dark grains are localized along the boundary of the kamacite. (Picral, 5 percent, applied for 130 seconds; magnification, 50.)



View of the Breece meteorite. Samples were taken from five of the long lathlike inclusions, Reichenbach lamellae, for X-ray, and in every case the film matched the lines on the standard schreibersite film. (Natural size.)

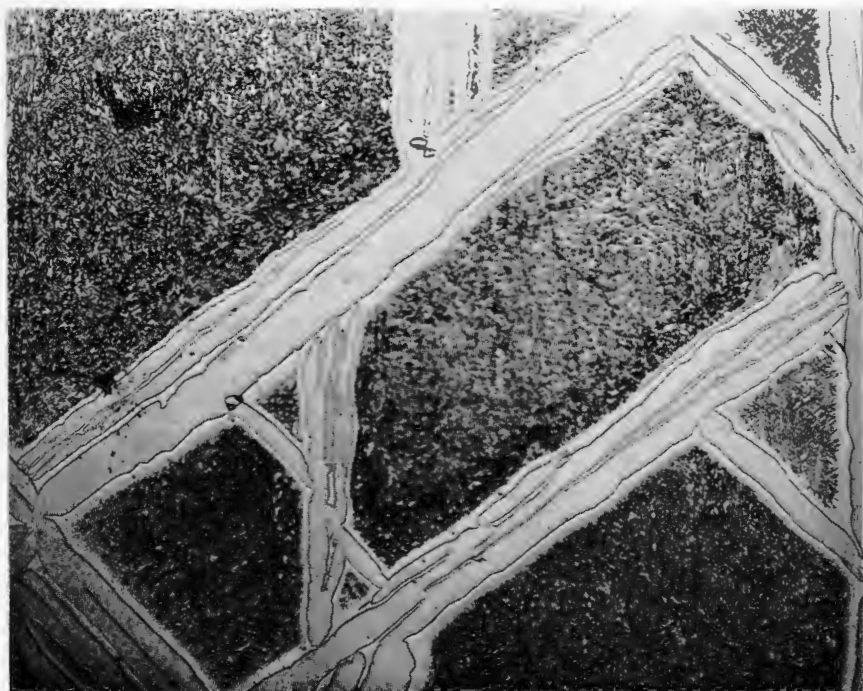


An etched cross section of the Tombigbee meteorite. Numerous irregular schreibersite bodies are dispersed in the matrix; the rhabdite inclusions are not shown. The areas selected for analysis are outlined. (Natural size.)

EXPLANATION OF PLATE 18

The Soroti meteorite. TOP.—Macrophotographs of two specimens taken in reflected light so that the plessite fields appear white. (Natural size.)

BOTTOM.—An area of fine octahedrite structure, the kamacite bands enclosing lamellae of taenite. Dense (imperfectly transformed) plessite in the interstices. (Picral, 4 percent, applied for 12 seconds; magnification, 50.)



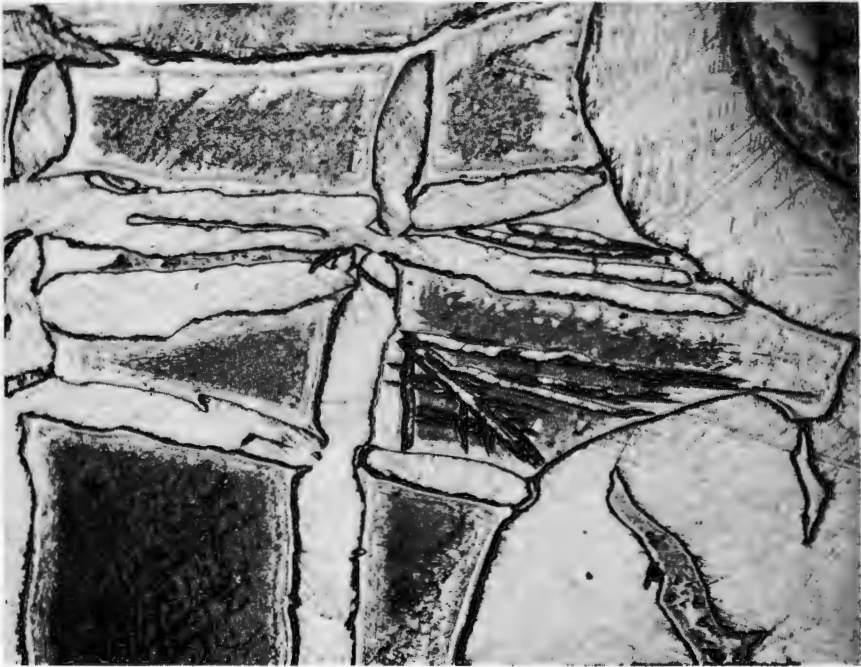
The Soroti meteorite. Explanation on facing page.



#### EXPLANATION OF PLATE 19

The Soroti meteorite. **TOP.**—The central inclusion with the dark spots is schreibersite and it contacts a dark hexagonal body, troilite. The kamacite practically surrounding the schreibersite and extending downward to the lower right and left corners of the plate contains transformation structures. The large inclusion below the troilite and kamacite was not positively identified, but its chipped surface suggests schreibersite. The light area at the lower right also may be schreibersite. The dense plessite fields at the left, right, and top have lamellae of kamacite. (Picral 5 percent, applied for 40 seconds; magnification, 50.)

**BOTTOM.**—A plessite area with needles of kamacite. Much of the kamacite shows lines which may be transformation structures or Neumann lines. Transformation structures may simulate Neumann lines very closely. The dark area at the upper right corner is troilite. (Picral, 5 percent, applied for 40 seconds; magnification, 50.)



The Soroti meteorite. Explanation on facing page.

#### EXPLANATION OF PLATE 20

The Keen Mountain meteorite. TOP: Troilite is exposed on the bottom of the depression in the center of this face after about two millimeters of oxide were removed. The surface of the meteorite immediately surrounding this depression is partly corroded and some of the oxidization products rest on an unaltered fusion crust. The cuts, at the right end, were made by the finder before the object was identified. The slice used in the analysis (pl. 21, bottom) was cut along the line made by projecting A to A'. (About two-thirds natural size.)

BOTTOM: This meteorite lacks the typical "thumbmark" depressions common to most iron meteorites. The shallow cavity at the lower right is surrounded with unaltered fusion crust in which flight markings are present. The file mark above the depression exposes fresh metal. The rougher surfaces represent corrosion. If the guide lines (at the sides and bottom of the picture) were projected they would cross over the spot believed to be the center of the forward face (stagnation point) during the fall of this meteorite. (Natural size.)

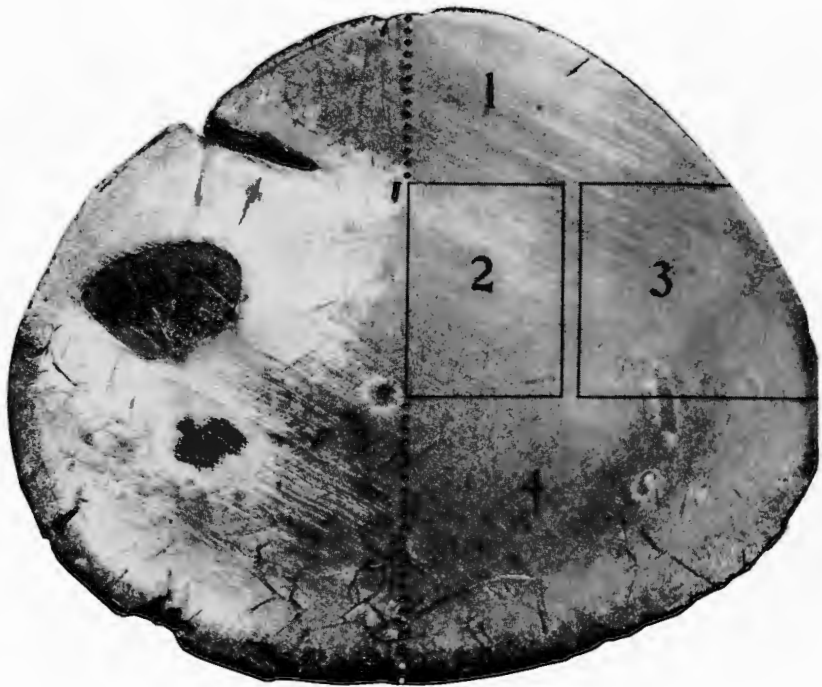


The Keen Mountain meteorite. Explanation on facing page.

#### EXPLANATION OF PLATE 21

The Keen Mountain meteorite. **TOP.**—The curved Neumann lines in the central portion end abruptly at the inner edge of the granulated zone. Sufficient heat was absorbed by this iron to granulate the metal from 7 to 9 millimeters in from the existing surface and to obliterate the Neumann lines. The fractures in the thermally altered zone possibly represent a volume adjustment made when the outside shell was reheated. The reheating and rapid cooling of the outside zone may have had something to do with the deformation of the Neumann lines and the displacement of the phosphide lamellae shown in plate 22 (bottom). (Magnification, 1.2.)

**BOTTOM.**—This thin slice was removed about 15 millimeters further into the meteorite than the slice pictured at top, and the thermally granulated zone around the edges is not as wide as the zone shown in that slice. The Neumann lines in the center are slightly deformed. This slice was cut along the dotted lines and the density of sections 1-3 was determined. The analysis was made on section No. 2. (Magnification, 1.3.)

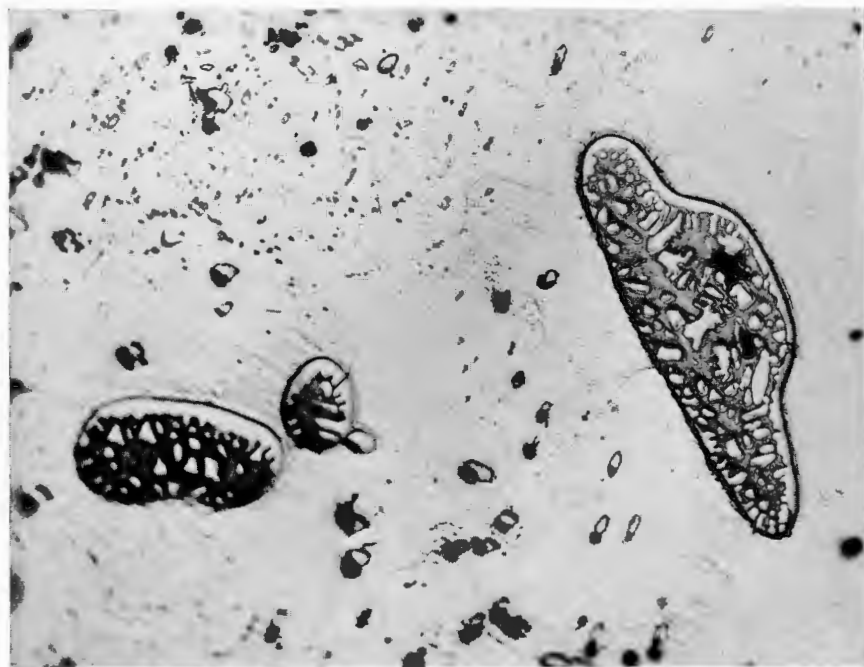


The Keen Mountain Meteorite. Explanation on facing page.

#### EXPLANATION OF PLATE 22

The Keen Mountain meteorite. **TOP.**—A group of phosphide particles with their pointed ends lying in the same direction and separated by channels of kamacitic iron. This habit suggests that these phosphides reacted with the matrix. The phosphide in the lamella at the left is broken into small segments but the particles are not separated very far. There are many such lamellae in this slice. Fewer rhabdites occur in the kamacite immediately adjacent to these long lamellae than are found in the kamacite some distance away. Many of these long lamellae are not straight and we assume that they have been deformed by movement of the kamacitic matrix. (Magnification, 150.)

**BOTTOM.**—These inclusions indicate Fe-Fe<sub>3</sub>P eutectic structures which formed by reheating. The rhabdite lost its original form and became rounded. This eutectic inclusion could be formed by melting but possibly these bodies never became liquid. After their reheating, they cooled so fast that the excess iron could not migrate beyond the limits of the inclusion. (Magnification, 150.)



The Keen Mountain meteorite. Explanation on facing page.



