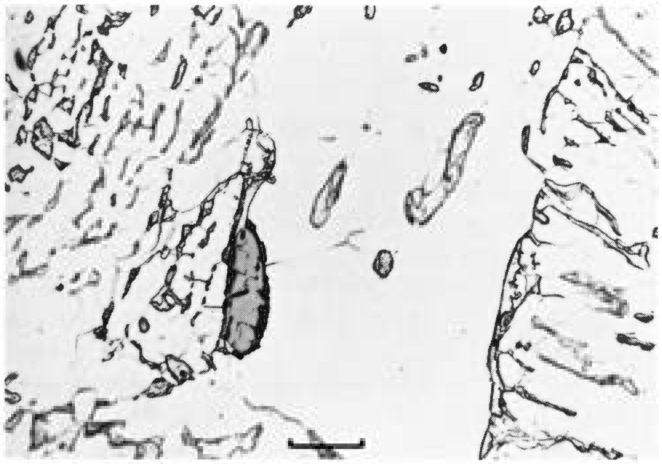

Figure 2025. Ysleta (New York no. 271). Nonmetallic inclusions are rare in Ysleta. Here, in a grain boundary, is a small brecciated crystal, probably daubreelite. Etched. Scale bar 20 μ.

219±10, except where chiseling has cold-worked the material to a high hardness of 270-290.

The kamacite phase is rich in Neumann bands, many of which are twisted and faulted. It appears that the Neumann bands are genuinely preterrestrial, but a final conclusion could not be reached because the only specimens available had been chiseled. Several deep fissures and violently cold-worked material to a depth of at least 3 mm bear witness to the artificial alteration of the material. No reheating was detected, however.

Schreibersite, cohenite, graphite and silicates were not present. The only inclusions seen were very small, blue subangular grains, 5-20 μ across, in the austenite grain boundaries. They probably consist of daubreelite or some other sulfide. The bulk phosphorus content is apparently below 0.05%.

Iron meteorites with 7.6% Ni and a low phosphorus content normally display very large parent austenite grains and well developed Widmanstätten structures. According to the relative cooling rates, the structures may be coarse (e.g., Bischtübe), medium (e.g., Henbury) or fine (e.g., Gibeon). The small austenite grain size of Ysleta indicates that only a limited time for grain growth at high temperature (1000° C) was available. The fine-grained plessitic matrix suggests a cooling rate (around 600-500° C) several orders of magnitude larger than that of Gibeon and other normal octahedrites. Both observations would indicate that Ysleta came from a parent body of smaller dimensions than other irons, or perhaps from an isolated "raisin" at a smaller depth on the parent body than other irons.

Ysleta is chemically and structurally an anomalous iron. No relatives are known; N'Goureyma and Nordheim have certain structures in common with it, without being chemically related.

Specimen in the U.S. National Museum in Washington:

19 g chiseled slice (no. 1357, 3 x 3 x 0.3 cm)

Yudoma, Khabarovsk Region, USSR

60°0'N, 140°48'E

A mass of 7.4 kg was found in 1946 and transferred to the Geological Museum in Yakutsk (Krinov 1947; Meteoritical Bulletin, No. 6, 1957; Krinov 1962). The structure was described, with a sketch, as that of a fine octahedrite (Zavaritskij & Kvasha 1952: 70), and Bergman (1955) reported 8.0% Ni.

A brief examination of a deep-etched sample in Moscow (No. 274, 2.8 g) indicates that Yudoma is a fine octahedrite with a bandwidth of 0.32±0.05 mm. Taenite and plessite cover about 40% by area, the plessite forming a variety of fields which apparently are similar to those of Gibeon and other irons of group IVA. Schreibersite is only present in minor amounts as blebs in the grain boundaries. It may cautiously be concluded that Yudoma is a fine octahedrite of group IVA which may turn out to be related to Muonionalusta and Seneca Township.

Zacatecas (1792), Zacatecas, Mexico

22°48'N, 102°33'W; about 2000 m

Anomalous. Polycrystalline, troilite-rich iron with indistinct Widmanstätten structure. HV 177±13.

Anomalous. 5.95% Ni, 0.49% Co, 0.6% P, about 0.5% S, 84 ppm Ga, 307 ppm Ge, 2.2 ppm Ir.

HISTORY

Only one mass is known, the original weight of which has been given from 2000 libras (Gazeta de Mexico, 1792) to 24 Zentner (1200 kg, Burkart 1856: 293). The former value of about 1000 kg appears to be the more reliable because it was obtained by an actual weighing. The mass was probably found during silver prospecting shortly after the conquistadores arrived in the region about 1520. As to its origin, there is only the belief that it was found by one of the first colonists when working the Quebradilla mine. This was situated on the western outskirts of the city of Zacatecas and is known to have been worked immediately after the conquest by the Spaniards (Burkart 1856: 288; Fletcher 1890a: 162). The coordinates given above are, therefore, for the city of Zacatecas.

The mass was brought to scientific attention by Sonneschmid (1804: 192) who saw it "exhibited" in the

Figure 2026. Zacatecas (1792). The main mass as exhibited in Tacuba No. 5, Old School of Engineering, Mexico City. The parallel drill holes indicate how a – roughly – 200 kg endpiece was removed by Burkart in the 1830s. White ruler is 15 cm long.

San Domingo Street in Zacatecas and sent the first small specimens to European collections. In the 1830s Burkart succeeded in separating a large chunk from the main mass by drilling many holes, and cutting and chiseling the remaining walls between the holes. This mass was subdivided and came to Reichenbach (about 8 kg), Bonn (about 4 kg), London (3.85 kg), Vienna (about 2 kg) and several other foreign collections (Burkart 1856: 288; Laspeyres 1895: 204). According to the present museum label, the main mass was moved from Zacatecas to Mexico City by Antonio del Castillo in 1890.

Partsch (1843: 122) described one of the specimens obtained from Burkart. Müller (1859) investigated a specimen cut from a 9.5 kg mass that had belonged to the mining director of Zacatecas earlier but which was transferred to London (now in the Geological Society, London). Müller performed the first reliable analysis and gave an excellent electrotyped facsimile of the etched section. Rose (1864a: 66 and plate 2) presented some very instructive drawings of the microstructure based on deep-etched slices. Fletcher (1890a: 162) reviewed the information and related it to what was known of the other Mexican meteorites. Brezina (1896: 289 and plate 9) gave a short structural description, as did Klein (1906: 128); and Cohen (1897a: 47) presented a new analysis on a surprisingly chromite-rich specimen. The early literature was collected by Laspeyres (1895: 205), Wülfing (1897: 392) and Farrington (1915: 498). Vogel discussed Zacatecas on several occasions (1932, 1943, 1952), and Perry (1944) presented two micrographs. Haro (1931: 71) mainly quoted Fletcher (1892a), but the short attached report by Nininger included a good photograph of the main mass in Mexico City. Farrington (1907: plate 33) had also presented a photograph of the exterior of the mass. Buchwald (1966: 40) discussed the microstructure and gave three micrographs. Modern analyses have been performed by Moore et al. (1969, on specimen No. 232.1 in Tempe) and Wasson

Figure 2027. Zacatecas (1792) (Tempe no. 232.1). Inch-sized precursor taenite grains have each transformed to an indistinct Widmanstätten pattern. In the grain boundaries are troilite and schreibersite inclusions. Deep-etched. Scale in centimeters. (Courtesy C.B. Moore.)

Figure 2028. Zacatecas (1792). An instructive drawing by Rose (1864a) that shows the polycrystalline nature and the numerous streaks of rhabdite crystals. Black nodules are troilite. Scale bar 10 mm.

ZACATECAS (1792) – SELECTED CHEMICAL ANALYSES

Cohen (1897a) did not succeed in separating iron and cobalt quantitatively, so these results are not used. Cohen analyzed separated fractions of the meteorite. He identified chromite and found that the phosphides were unusually low in nickel (about 10%). These results were confirmed on the electron microprobe during the present study. Cohen further inferred the presence of taenite, daubreelite and silicate. These observations could not be confirmed; if present at all, these components must be very irregularly scattered and only add up to insignificant quantities.

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Müller 1859	5.81	0.48	0.24		1000							
Cohen 1897a	5.94	0.91	1.02	300		230	170					
Moore et al. 1969	6.15	0.49	0.61	285	240		140					
Wasson 1970a	5.88								83.8	307	2.2	

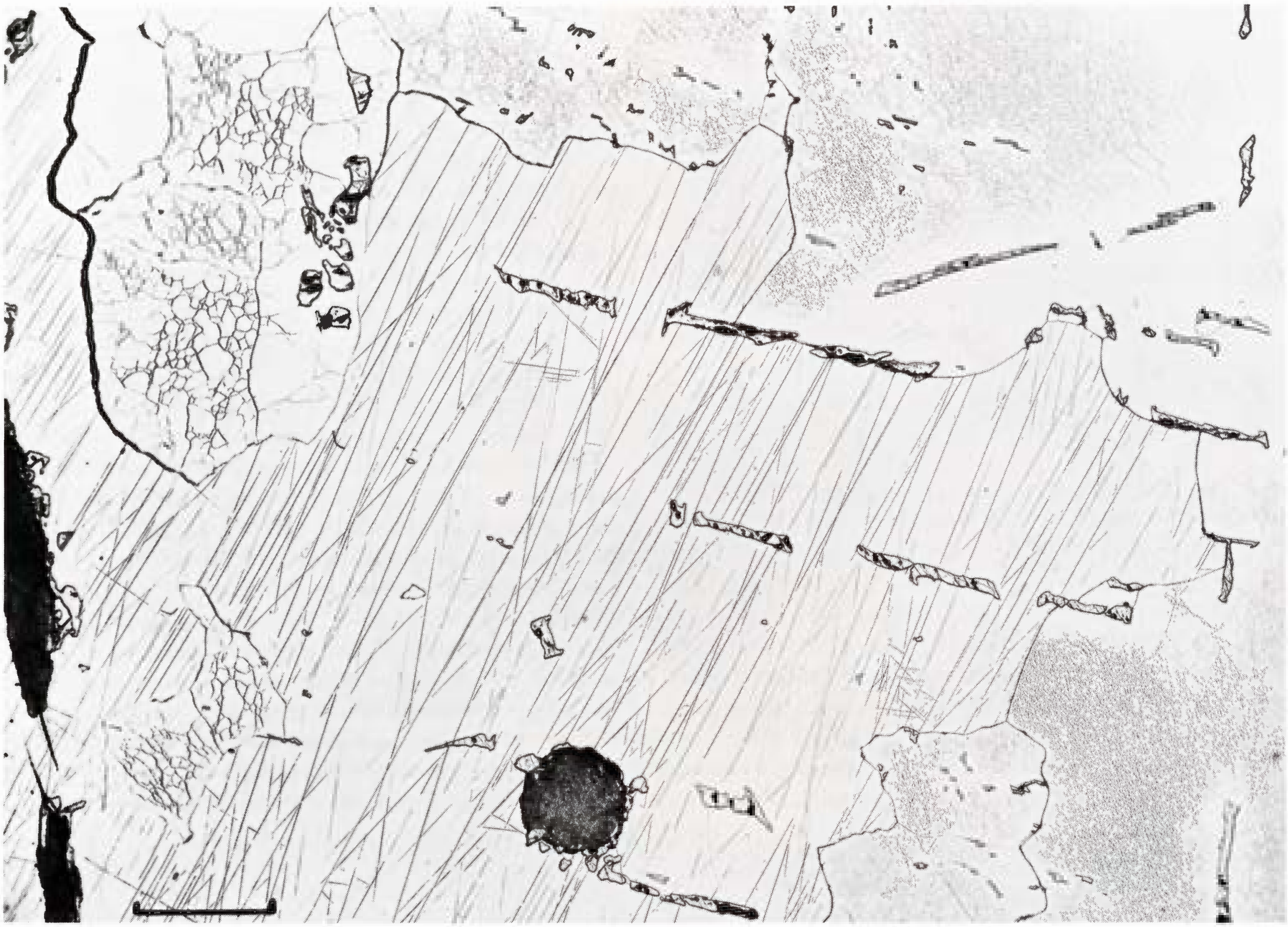

Figure 2029. Zacatecas (1792) (Copenhagen no. 1906, 145). Grain growth on part of the kamacite. To the left two areas with polygonization which resist recrystallization. Shock-melted troilite (black) with shattered schreibersite rims. Prominent rhabdites and Neumann bands. Etched. Scale bar 2 mm.

(1970a), who designated Zacatecas I-An3, indicating a remote relationship to the resolved chemical group I.

COLLECTIONS

Main mass of about 780 kg in Mexico City (Old School of Engineering, Palazzo Mineria, Tacuba Nr. 5). Specimens in London, Geological Society (9.5 kg), Tübingen (3.9 kg), London, Brit. Mus. (3.87 kg), Bonn (2.55 kg), Vienna (1.90 kg), Heidelberg (1.41 kg), Chicago (1.34 kg), Paris (1.32 kg), Calcutta (645 g), Washington (444 g), Amherst (427 g), Munich (376 g), Tempe (336 g), Budapest (331 g), Harvard (277 g), Canberra (263 g), Vatican (242 g), Strasbourg (219 g), Leningrad (160 g), Rome (123 g), Fort Worth (100 g), Philadelphia (99 g), Uppsala (98 g), Dresden (86 g), New York (71 g), Helsinki (62 g), Ann Arbor (59 g), Prague (58 g), Braunschweig (56 g), Göttingen (53 g), Los Angeles (50 g), Hamburg (39 g), Stockholm (34 g), Copenhagen (27 g), Dorpat (27 g). There are numerous mislabeled specimens in the various collections. The Tempe specimen No. 232.1 (275 g) was thus erroneously labeled Wichita County, while other Zacatecas specimens have been identified by me in this book in the sections on Toluca and Rancho de la Pila.

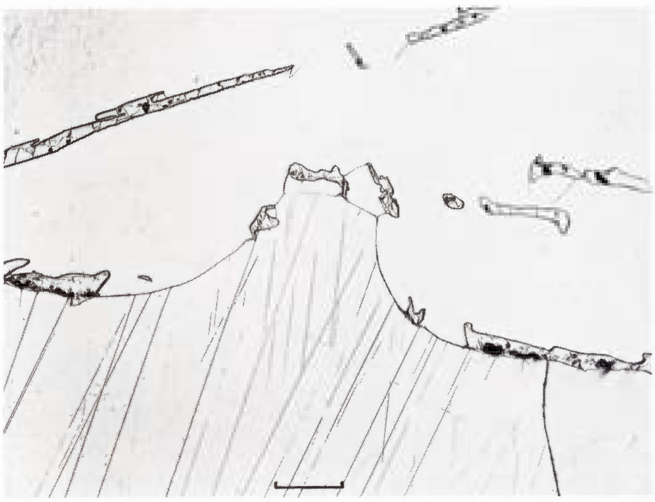

Figure 2030. Zacatecas (1792). Detail of Figure 2029 showing a moving grain boundary that was pinned by rhabdite crystals. Neumann bands are present in both grains, but due to orientation not so sensitive to the etching reagent (Nital) in the upper grain. Etched. Scale bar 500 μ.

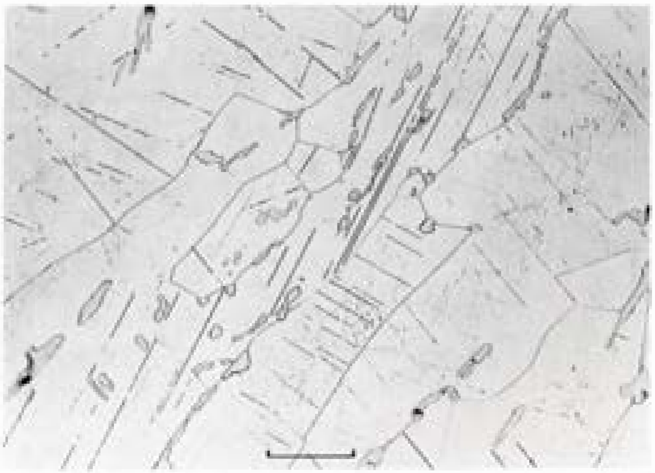

Figure 2031. Zacatecas (1792). (Copenhagen no. 1906, 145). An area with elongated kamacite grains. Schreibersite (or rhabdite) particles are common, while taenite is absent. Etched. Scale bar 300 μ. See also Figure 173.

DESCRIPTION

The main mass as it is preserved at present in the hall of The Old School of Engineering, Tacuba Nr. 5, Mexico City, weighs 780 kg, according to the label. It is an irregular rectangular block of 106 x 56 x 30 cm overall dimensions. The thickness varies between 20 and 30 cm because several large shallow depressions indent the mass. A typical depression measures 20 x 12 x 4 cm, and this is divided into smaller depressions about 9 x 5 x 1 cm in size.

Eighteen centimeters from one end is a heavy chiseled furrow, 52 cm long, 5 cm deep and 10-15 mm wide, which must be evidence of a vain attempt to divide the mass. According to an old Mexican story the mass was originally supposed to consist of silver, so it was brought by the finder to his house in order to create a figure of a Saint. However, later when he altered his decision and tried to split the mass by chiseling in order to sell it, the silver transformed to iron and all attempts to penetrate it were in vain (Burkart 1856: 289). The other end still bears evidence of Burkart's successful drilling operatons. The end face of 39 x 23 cm is furrowed by 22 parallel, cylindrical drillholes ½" in diameter. It may be estimated from the exterior faces that the meteorite was originally at least 20 cm longer; thus 130 x 56 x 30 cm. This is in accordance with the dimensions given by Burkart (1856: 293): 4 1/2' x 2 1/4' x 3/4'.

The corners around the surface worked by Burkart have later been removed by hacksawing, leaving smooth sections of 12 x 10 cm and 19 x 11 cm respectively. It is surprising that most of the specimens removed by all the mentioned cutting operations seem to have disappeared. A conservative estimate gives 20 x 20 x 50 cm removed, that is about 150 kg, but as shown above only about 32 kg can be accounted for in "registered" collections. Wülfing (1897: 392) could only account for 24 kg outside Mexico.

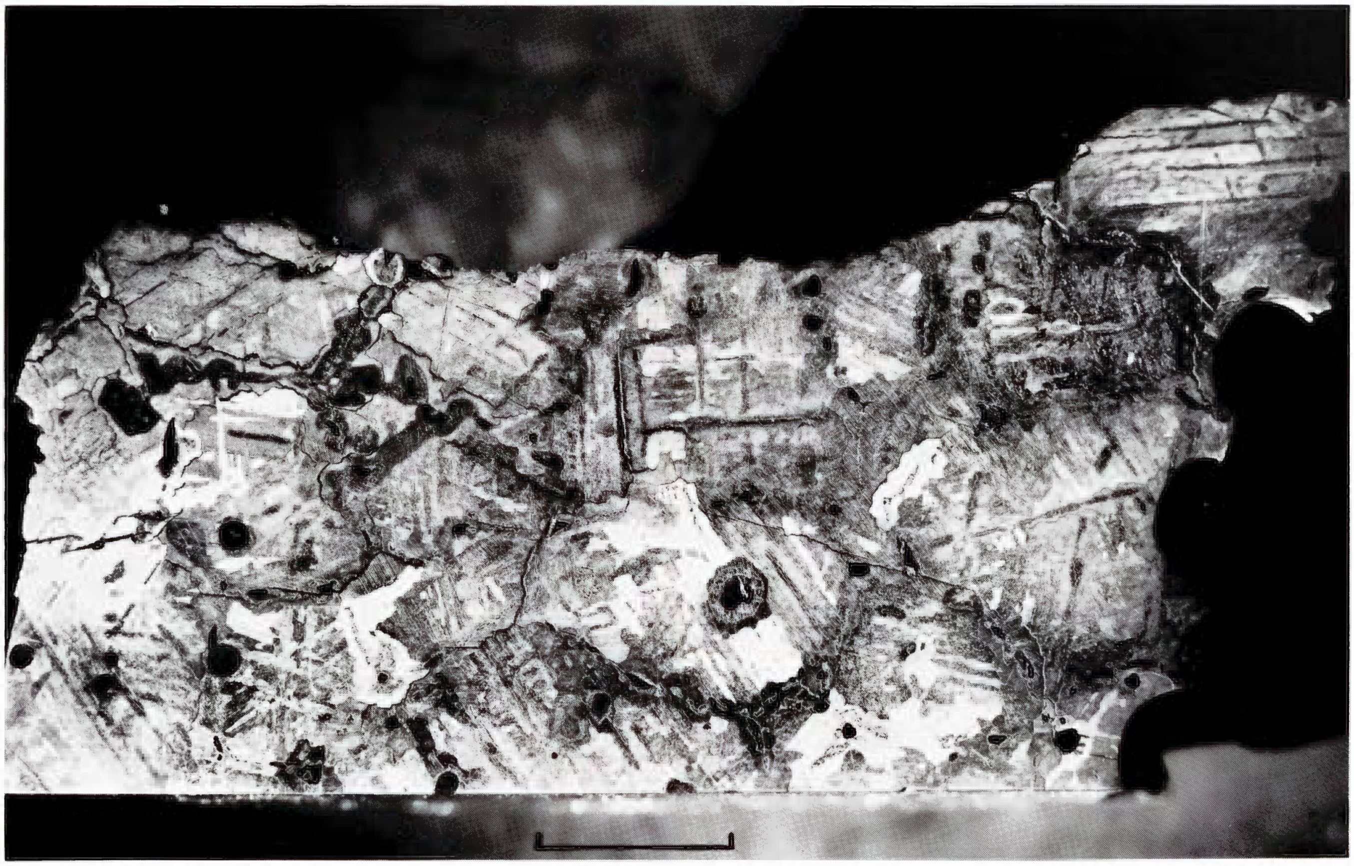

Figure 2032. Zacatecas (1792).(Brit. Mus. no. 28296; 2,570 g). A fine picture that shows the polycrystallinity, with troilite filaments at grain boundaries and troilite globules in the grain interiors. To the right, part of the drill holes shown in Figure 2026. Deep-etched. Scale bar 2 cm. B.M. neg. 5576.

Zacatecas is remarkable in that it belongs to the rather few polycrystalline iron meteorites. The grain size ranges from 1 to 5 cm, a variation which is partly due to the random sectioning through many almost equiaxial grains. The average grain size is 3 cm. At high temperature each grain was an independently oriented austenite crystal. A few of them were evidently twinned. The grain boundaries are marked by numerous elongated troilite bodies, surrounded by skeleton crystals of schreibersite. The grain boundaries are also conspicuous because of the copious development of very irregular 1-3 mm wide zones of swathing kamacite. This kamacite was nucleated by the troilite and schreibersite precipitates, and by the boundary itself, and grew significantly before the bulk of the grains transformed during the primary cooling period.

Each austenite grain transformed independently to ferrite and simultaneously precipitated a considerable amount of phosphide. Indications are that the cooling rate was significantly higher than for the normal group I irons and for group IIB which has similar nickel and phosphorus contents. Zacatecas may have shown a kamacite bandwidth at one time of 0.6-1.0 mm, but since all taenite eventually disappeared and significant grain growth in the kamacite took place, no well defined Widmanstätten pattern is present now. In this respect Zacatecas resembles New Baltimore, Santa Rosa and Chihuahua City. In Zacatecas irregular bulky patches of clear kamacite are intercalated with lamellar kamacite with pronounced networks of subgrains. Under crossed Nicols, etched sections of Zacatecas show an unusually strong anisotropy of the individual ferrite grains. Since they themselves are isotropic and cubic, the anisotropy must be due to some thin, anisotropic layer precipitated upon the differently oriented kamacite grains during etching. The effect is, as far as I know, quite common, but very substantial in Zacatecas. It is, e.g., also present in Joel's Iron.

Both grain boundaries and subboundaries are richly decorated with phosphide precipitates ranging from 10 μ in width downwards to submicroscopic sizes. The zones near the larger schreibersite crystals are depleted in phosphorus and show clear kamacite without phosphide precipitates. Farther away, rhabdites occur in profusion as 1-5 μ thick tetragonal prisms. Neumann bands are abundant, but somewhat annealed, since they have almost parallel sides and are discontinuous, especially near inclusions and grain boundaries. The microhardness of the kamacite is 177±13, a range which probably mainly reflects the varying quantities of nickel and phosphorus in solid solution. In near-surface regions, the outermost 0.5-1 mm may show severe distortion and kneading, with hardnesses up to 250. These effects are from the artificial hammering on the mass.

Taenite and plessite are not present. Perhaps the kamacite, which is now richest in cellular networks, represents those areas which retained a plessitic structure for the longest length of time.

Troilite occurs as elongated bodies, typically 4 x 2 mm in size, in the old austenite grain boundaries, and as spheroidized inclusions 0.5-3 mm in diameter, in the grain interiors. No daubreelite or graphite are present. By planimetry of a 4500 mm^2 section it was found that 23 grain boundary inclusions had a total area of 85 mm^2. Five spherules in the interior had a total area of 15 mm^2. The troilite inclusions thus totaled 100 mm^2 which corresponds to a sulfur content of approximately 0.5%. This is a better average for sulfur than the values obtained by chemical analysis (quoted above) because the shavings were, for analytical purposes, deliberately chosen to avoid troilite inclusions.

The troilite is micromelted and solidified to fine aggregates of sulfide grains, with or without dispersed iron. The two main types occur together as intricate mixtures of 0.5-1 mm size patches. They are best examined both before and after etching. Type A consists of aggregates of almost equiaxial sulfide grains, 5-10 μ across. It attains a glossy, solid appearance by polishing and is not attacked by etching. Type B consists of aggregates of 2-5 μ sulfide grains with large quantities of minute beads (0.5-2 μ) of dispersed iron. Upon etching the iron is dissolved and leaves a matte,

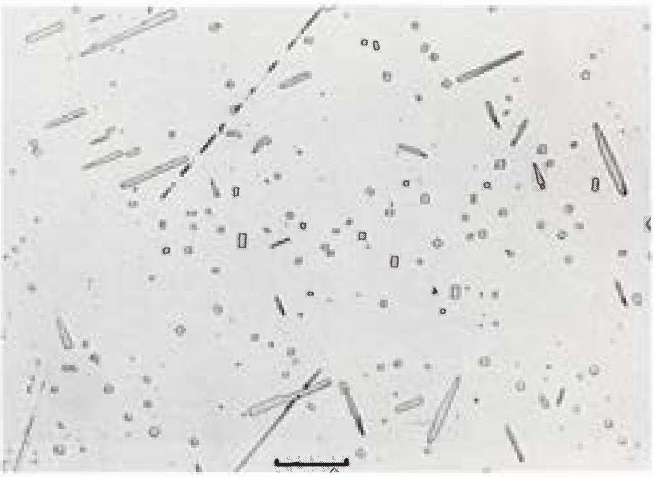

Figure 2033. Zacatecas (1792). (Copenhagen no. 1906, 145). A kamacite crystal with prismatic rhabdites. An annealed Neumann band above left. Etched. Scale bar 100 μ.

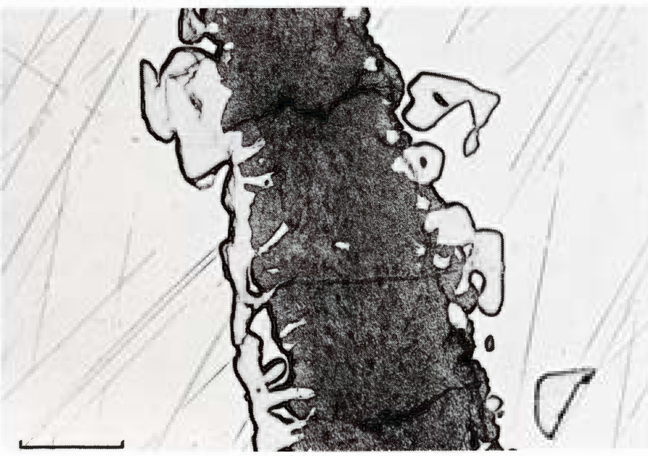

Figure 2034. Zacatecas (1792). Detail of left edge of Figure 2029. Shock-melted troilite (gray) and brecciated schreibersite bodies, apparently healed by a subsequent annealing period. Etched. Scale bar 300 μ.

porous aggregate. Upon natural etching (corrosion) this type is converted to a sulfide aggregate with bluish-black limonite in beads and veins. Both type A and B contain numerous angular fragments of schreibersite and chromite, which originally occurred as massive rims and crystals upon and in the troilite. Partsch (1843) also noted the peculiar appearance of troilite and assumed that two different sulfides were involved. However, this is not the case. The morphology is no doubt due to shock reheating whereby the original troilite melted and partially dissolved the encasing metal walls and shattered and dispersed the associated schreibersite and chromite minerals. It appears that the event created two slightly different melts which were unequilibrated and, therefore, when rapidly solidifying, formed intricate intergrowths.

Schreibersite is present as 0.1 mm wide rims around the troilite nodules; however, it is partially shattered as mentioned above. It also occurs as skeleton crystals, e.g., 2 x 0.5 mm in size, with deeply indented surfaces and frequently with associated, detached blebs, 10-50 μ in size. This morphology is pronounced along the old austenite grain boundaries and near troilite, around which the skeleton crystals are often arranged in rays. The morphology is peculiar and probably indicates rather rapid cooling which prevented formation of the typical massive schreibersite crystals. Published analytical data show a wide range of phosphorus, 0.24, 0.61 and 1.02%. From planimetry it appears that the true bulk content is near the average of these values, 0.6% P.

Chromite occurs frequently both in kamacite and troilite. It forms cubic crystals, 10-500 μ across, and often encloses minute blebs of troilite, kamacite and schreibersite.

Silicates, carbides and graphite were not observed. Nowhere on the available sections was there any fusion crust or reheated α_2 zone from atmospheric penetration identified. Corrosion penetrates to a depth of many centimeters, particularly along the original troilite- and schreibersite-rich austenite grain boundaries.

A note of caution may be given in connection with several old museum specimens, e.g., in Tübingen and London. By the standard procedure of the mid-nineteenth century they were etched by heat-tinting, whereby individual metal phases acquired yellowish-purple-blue colors. Since the heat application was not well controlled, such specimens may show minor deviations in hardness and microstructure compared with untreated specimens.

Zacatecas is a rare and complex meteorite which has no immediate relatives. The polycrystalline structure with dispersed troilite is such that the whole mass may be interpreted as a powder-aggregate which has been sintered at about 1000-1100° C but was never melted in bulk. Indications are that it cooled at a faster rate than other irons on the 6-7% Ni level, such as group IIA, IIB and some of group I. Otherwise it is difficult to understand the unequilibrated phosphides (with special morphology and low-nickel content) and the peculiar kamacite types. After the primary cooling on its parent body, the mass was subjected to a shock which produced Neumann bands and micromelted troilite. An associated (?) mild reheating partially annealed out the Neumann bands and imperfect recrystallization occurred.

Chemically, the Ga-Ge-Ir content points to an association with group I (Wasson 1970a); however, the nickel content is much too low for a good correlation and also the phosphorus content is much too high. In connection with this, it should be pointed out that the metallic structure is very different from other group I irons. And finally, Zacatecas has no silicates, carbides or graphite inclusions – minerals which otherwise are so characteristic for group I. Zacatecas is, therefore, both structurally and chemically an anomalous meteorite.

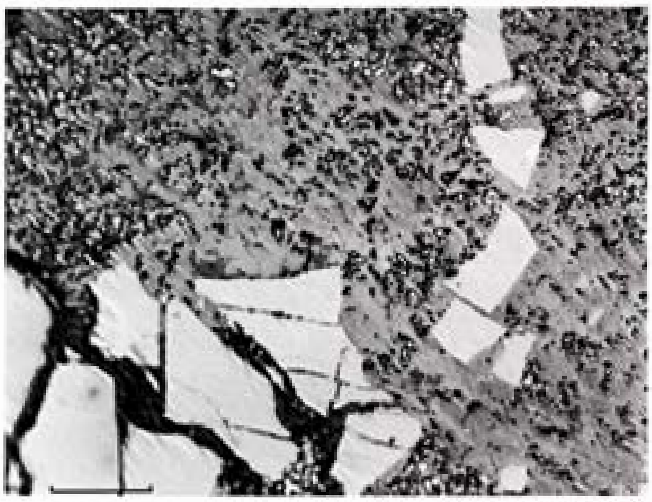

Figure 2035. Zacatecas (1792) (Copenhagen no. 1906, 145). Shock-melted polycrystalline troilite in which are embedded angular fragments of schreibersite, previously located along the troilite-kamacite interface. Etched. Scale bar 20 μ.

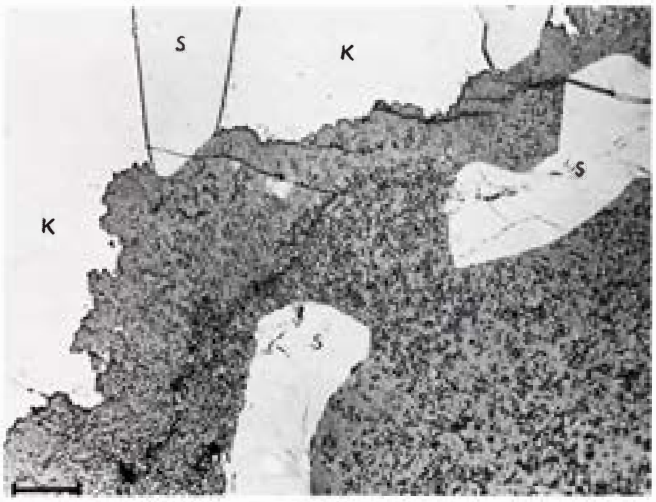

Figure 2036. Zacatecas (1792) (Brit. Mus. no. 33917). Another sample of shock-melted troilite with dispersed schreibersite fragments (S). Serrated, unequilibrated interface with kamacite (K). Etched. Scale bar 50 μ.

Specimens in the U.S. National Museum in Washington:

14.7 g part slice (no. 57)
56 g part slice (no. 666)
73 g part slice (no. 783, 4 x 4 x 0.5 cm) found in the collection, mislabeled Otumpa
274 g part slice (no. 1780, 6 x 5.5 x 0.9 cm with parts of three of the old characteristic drillholes).
27 g part slice (no. 3014, 4 x 3 x 0.2 cm, divided into two specimens)

Two specimens were mislabeled:

A 175 g endpiece no. 1185, 5 x 3.5 x 2 cm) turned out to be a medium octahedrite of group IIIA, not further identifiable.
A 37 g nodule (no. 3158, 3.5 x 2.5 x 2 cm) turned out to be a nineteenth century artificial product, probably cast steel.

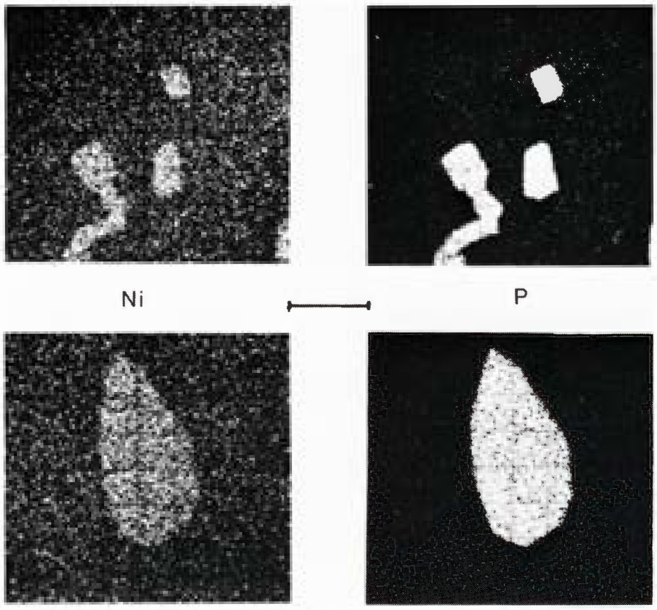

Figure 2037. Zacatecas (1792) (Copenhagen no. 1906, 145), X-ray scanning pictures of various inclusions, large and small, confirmed that they were essentially phosphides with relatively low (<15%) nickel contents. This, and their peculiar morphology, is probably the result of cosmic annealing. NiK_α and PK_α pictures at 15KV. Scale bar 100 μ.

Zacatecas (1969), Zacatecas, Mexico

Approximately 22°48'N, 102°33'W

Medium octahedrite, Om. Bandwidth 0.70±0.10 mm. Recrystallized. HV 175±5.

Group IIIB. 9.0% Ni, about 0.5% P, 20.3 ppm Ga, 38.8 ppm Ge, 0.029 ppm Ir.

HISTORY

A mass of 6.66 kg was purchased by Richard E. Dalsin of Minneapolis, Minnesota, from a Mexican in the city of Zacatecas in February 1969. Mr. Dalsin reported that "the Mexican told he had found it in the area," but more could not be learned. The complete specimen was donated to the Smithsonian Institution in December 1969.

COLLECTION

Washington (6.66 kg).

DESCRIPTION

The mass has the shape of a low triangular pyramid with a height of 7 cm and a base of 15 x 16 cm. The base is a fracture surface that is rather flat, partially following one set of Widmanstätten planes and partially some of the large schreibersite inclusions. The mass is evidently a corner piece of a much larger main mass which has either not been found yet or has not been reported. As will be seen from the structural discussion below, the mass cannot be a fragment of any of the recorded Mexican meteorites.

The surface is weathered and covered with 0.1-1 mm terrestrial oxides. Regmaglypts, 3-5 cm across and up to 1 cm deep, are present however; even a little, weathered fusion crust may be identified in the bottom of some of the regmaglypts. The size of the regmaglypts suggests that the unknown main mass is 30-50 cm in diameter. The fragment is severely hammered over an area of several square centimeters, but there are no indications of an artificial

Figure 2038. Zacatecas (1969) (U.S.N.M. no. 5291). A 6.7 kg endpiece of a larger mass, the whereabouts of which are unknown. The sample shows indistinct regmaglypts and a little fusion crust. Scale bar 3 cm. S.I. neg. 1606B.

ZACATECAS (1969) – SELECTED CHEMICAL ANALYSES

	percentage			ppm								
Reference	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Scott et al. 1973	9.0±0.3								20.3	38.8	0.029	

reheating. There are distinct marks indicating work with hammer and chisel, so it cannot be ignored that the fragment might have been broken from the main mass by the finders. It appears that the finders have widened a deep, preexisting crack and after some efforts finally detached the 6.7 kg fragment.

Etched sections show a medium Widmanstätten structure of straight, long ($\frac{L}{W} \sim 25$) kamacite lamellae with a width of 0.70±0.10 mm. The kamacite is fully recrystallized to equiaxed grains, 50-300 μ in diameter. Each grain displays an independent set of Neumann bands; there are no longer any indications of previously existing sets of Neumann bands. The hardness is 175±5. The recrystallized grains are rather pure; no rhabdites are present, but small amounts of 1-3 μ wide wedges and blebs of phosphides occur in the grain boundaries.

Taenite and plessite cover 50-60% by area, mostly as comb plessite and as decomposed, duplex fields. The taenite phase is altered by the same cosmic annealing that recrystallized the kamacite. It has frayed edges and numerous angular windows of kamacite. These are generally 1-5 μ across and occur in the 20-40 μ wide taenite ribbons and in the rim zone of the plessite fields. The hardness is as low as 180±8, indicating thorough annealing. Where this type of meteorite normally exhibits martensitic or poorly resolvable, duplex phases (compare, e.g., Grant), Zacatecas (1969) has decomposed duplex $\alpha + \gamma$ structures. The parent martensite zone is now a 1:1 mixture of 1 μ $\alpha + \gamma$ (HV 190±10), while the poorly resolvable black taenite regions are 3:1 mixtures of $\alpha + \gamma$ with 2-3 μ wide γ-particles

Figure 2039. Zacatecas (1969). The same from the opposite side showing that the base is a hackly fracture surface with distinct parting along schreibersite-rich Widmanstätten boundaries. Scale bar 3 cm. S.I. neg. 1606C.

(HV 180±10). The kamacite phase is recrystallized to 10-50 μ grains, and the taenite is located mainly at the grain boundaries. The hardness of the open-meshed plessite fields approaches that of the adjacent kamacite lamellae.

Schreibersite is common as skeleton crystals, e.g., 10 x 1.5 mm in size. These large crystals have a high hardness of 890±30 and were relatively low in nickel (~ 15%) from the beginning; they show no reaction rims against the metal. Schreibersite is further common as 10-100 μ wide grain boundary precipitates and as 5-50 μ blebs inside the plessite. These crystals were originally rich in nickel (30-40%) but have, upon the cosmic annealing, reacted with the adjacent kamacite and formed 1-5 μ wide zones of kamacite and taenite. They have adjusted their nickel content downwards to 20%, corresponding to the equilibrium content at the annealing temperature. The rejected nickel has mainly been incorporated in tiny taenite globules along the edges of the frayed schreibersite crystals. The schreibersite hardness is 850±25, significantly harder than similar-sized crystals in unannealed iron meteorites which still have their original high-nickel content. From the ternary Fe-Ni-P diagram (Buchwald 1966: 12), the reheating temperature that led to recrystallization of the kamacite phase and readjustment of the schreibersite composition may be estimated to be 600-650° C.

Troilite occurs in one place as a 2 mm nodule encased in a 400 μ wide schreibersite ring. It is shock-melted and solidified to 1-3 μ eutectics of iron and sulfur. The surrounding schreibersite is shattered and 5-50 μ rounded fragments have become dispersed and trapped in the sulfide melt. The troilite and the skeleton schreibersite crystals have nucleated 1-2 mm wide rims of swathing kamacite.

A small amount of the heat-affected α_2 zone is present in the section. It displays a hardness of 205±10, decreasing to 175±5 within a few millimeters (hardness curve type II). Corrosion has removed, on the average, 1-2 mm of the surface. It proceeds along the recrystallized grain boundaries and along deep fissures that probably date back to a cosmic shock event. Corrosion also selectively attacks the minute alpha grains in the reaction zones around schreibersite, the alpha windows of the annealed taenite and the nickel-depleted, 0.5 mm wide zones around the large schreibersite crystals. That these zones really are nickel- (and phosphorus-) depleted is clearly seen in the steep hardness gradient, going from 175±5 in the matrix to 130±4 at a distance of 40-80 μ from the schreibersite. Nickel and phosphorus are known to be the major elements responsible for solid-solution hardening of kamacite (Dieter 1962; Buchwald 1966); so when they are removed for the building of the schreibersite, the hardness must drop significantly.

The fracture surface that presently terminates the specimen may have been initiated at the remote preatmospheric shock event but was probably first fully opened after the main mass arrived on the Earth. Many similar cases of irons with deep, but incomplete, fissures are known, e.g., Navajo, Bacubirito, Lazarev and some Sikhote-Alin specimens. Other irons split into unequal parts very late in their flight, probably mainly along preexisting cracks, e.g., Glorieta Mountain, Grant, Loreto and Wallapai. It shall be interesting to see the main mass of Zacatecas (1969).

Zacatecas (1969) is a medium octahedrite which is related to Cleveland, Apoala and Grant, and possibly to Hopper. It is, however, unusual in that it shows a very thorough annealing which is present in all phases. The cause appears to have been a violent shock with a subsequent relaxation temperature of the order of 600° C. Although it bears some resemblance to Apoala, Chupaderos and other Mexican irons, Zacatecas (1969) is unique in its secondary structure and may, with confidence, be said to be different from these falls.

Specimen in the U.S. National Museum in Washington:

6.66 kg endpiece of unknown main mass (no. 5291, 16 x 15 x 7 cm)

Zaffra, Oklahoma, U.S.A.

Approximately 35°N, 94°45′W

Coarse octahedrite, Og. Bandwidth 2.5±0.6 mm. Decorated Neumann bands. HV 162±7.

Group I, judging from the structure. About 6.7% Ni and 0.23% P.

HISTORY

A mass of about 3 kg was found in 1919 near Zaffra, Le Flore County. It was discovered in Section 1, Township 1S, Range 26E, by Messrs. Moore and Hesperling who were prospecting for zinc. They broke the specimen apart on an anvil, each finder retaining about half of the mass. The part owned by J.L. Hesperling (of 1,430 g) was purchased in 1930 by the American Museum of Natural History and classified as a coarse octahedrite (Reeds 1937: 639). A preliminary note had already appeared 15 years earlier (Shead 1922) but which omitted the name of the location, however, and assumed that the original weight was 15 pounds (i.e., 7 kg), and not 3 kg.

COLLECTIONS

New York (1,229 g), London (180 g).

ANALYSIS

Shead (1922) reported 7.23% nickel, trace of cobalt, 0.234% phosphorus and 0.22% chlorine. In addition he found graphite. The chlorine was assumed to be present as lawrencite, but the mineral was not observed. It was the normal staining after the preparation of polished surfaces that led him to this conclusion. It appears more likely, however, that the chloride was introduced by terrestrial ground waters.

From the structural observations below, it is estimated that the composition is 6.7±0.2% Ni and 0.5% Co. This is in harmony with Shead's analysis if we assume that he did not succeed in separating nickel and cobalt analytically, but instead reported all as nickel.

DESCRIPTION

The dimensions and shape of the main mass are unknown. Reeds (1937) stated that the material in New York was weathered and covered with jagged, sharp metallic points. The 180 g sample (B.M. No. 1963, 529), which has been cut from the New York sample, was put at my disposal by Dr. Hutchison. It is an irregular piece of 6 x 3 x 3 cm; it appears that the jagged, rough surface is mainly due to artificial handling. When the finders divided the mass, it opened along already weathered intercrystalline cracks so that the resulting surfaces became very rough.

Fusion crust and heat-affected zones were not detected. The surface is covered with 0.5-1 mm thick limonitic crusts, and on sections the corrosion is seen to penetrate deep into the interior along grain boundaries. The shattered schreibersite crystals are recemented by limonitic products, and the decorated Neumann bands are selectively

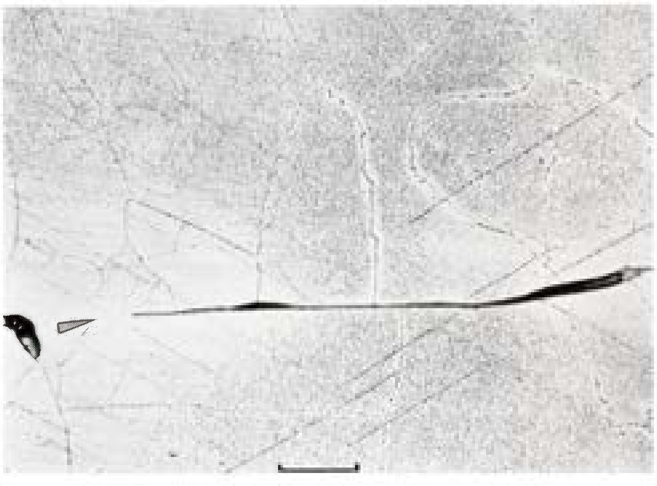

Figure 2040. Zaffra (Brit. Mus. no. 1963, 529). Cloudy taenite lamella with grain boundary schreibersite at either end. Kamacite with subboundaries that are pinned by phosphide particles. Etched. Scale bar 500 μ.

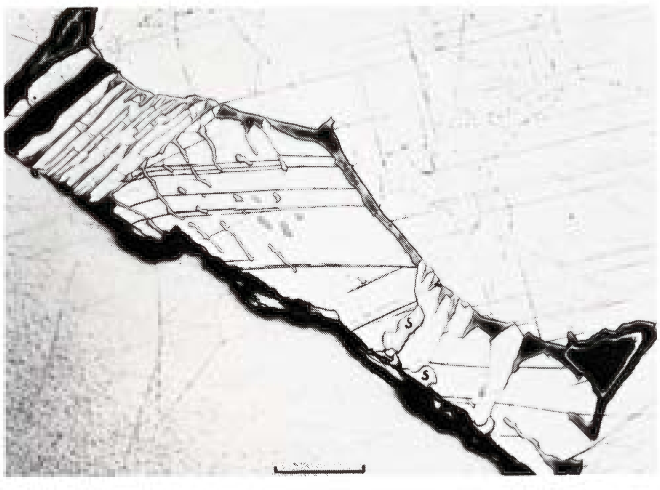

Figure 2041. Zaffra (Brit. Mus. 1963, 529). Open-meshed degenerated plessite field with schreibersite inclusions (S). Terrestrial limonite along lower interface. Neumann bands in the kamacite. Etched. Scale bar 400 μ.

corroded. The martensitic plessite interiors are selectively corroded in much the same was as in Tishomingo, albeit on a smaller scale. No natural hardness gradient towards the present surface was detected. On the other hand, where there were structural indications of chiseling (bent Neumann bands and lenticular deformation lamellae), the hardness increased to above 200.

Etched sections display a coarse Widmanstätten structure of irregular, bulky ($\frac{L}{W} \sim 6$) kamacite lamellae with a width of 2.5±0.6 mm. Grain growth has created a number of almost equiaxial kamacite grains, 7-15 mm across. The kamacite is rich in subboundaries, decorated with 0.5-5 μ phosphides, sometimes giving the appearance of barbed wire. Neumann bands are common. After they formed, slight annealing must have occurred, since they are densely crowded with almost submicroscopic precipitates, presumably of phosphides. The kamacite hardness is 162±7, also suggesting imperfect annealing.

Taenite and plessite cover 1-2% by area. The comb plessite is open-meshed and almost resorbed but still forms distinct fields up to 3 x 4 mm in size. The massive wedges display cloudy taenite rim zones (HV 300±25) that terminate abruptly against brownish-black tempered martensite (HV 370±30). In the taenite rim zones and in the taenite lamellae a distinct grid of slipplanes is clearly visible, probably as a result of deformation followed by slight annealing and precipitation.

Schreibersite occurs as 25-150 μ wide grain boundary veinlets and as 5-50 μ irregular particles inside the plessite fields. Rhabdites proper were not observed, but a large population of almost submicroscopic precipitates (0.5 μ) appears everywhere in the kamacite and is presumably microrhabdites. Some of the plate-shaped precipitates, typically 20 x 0.5 μ in size, are apparently carlsbergite.

Graphite was reported by Shead (1922) but was not present in the sample examined here. Troilite was seen once, as a small 100 μ particle associated with a daubreelite crystal of similar size. The troilite was shock-melted, had dissolved part of the adjacent metal and then solidified to a 1-2 μ eutectic of metal and sulfide. The interface with the metal was consequently very jagged, and fine veinlets of sulfide had been injected into the daubreelite.

Carbides and silicates were not detected but may be found when other sections become available. There are no indications of significant artificial reheating; it appears that the finders restricted themselves to the use of a hammer when they split the mass.

Zaffra is a coarse octahedrite, which has been shocked and slightly annealed in space, judging from the decorated Neumann bands, micromelted troilite and "tempered martensite." It is related to Sardis, Bolivia and Yardymly but shows several structural differences, being somewhat unique with respect to the taenite-plessite development and the absence of large rhabdites. Chemically, it will probably prove to be a member of the resolved group I. It is unrelated to the other iron meteorites found in Oklahoma and adjacent states.

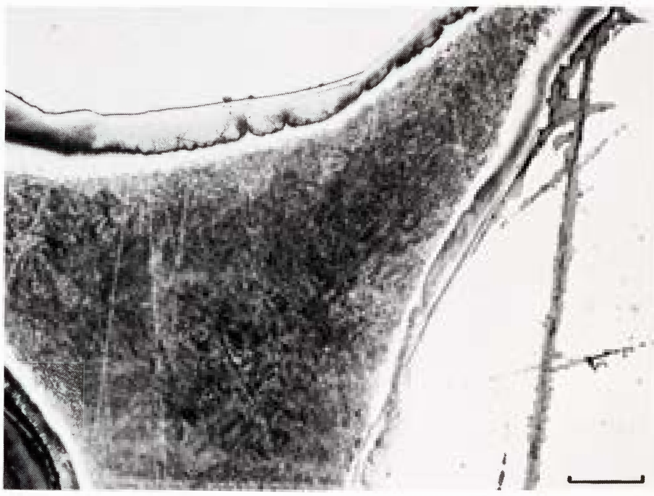

Figure 2042. Zaffra (Brit. Mus. no. 1963, 529). Martensitic plessite field with cloudy taenite edges. Terrestrial corrosion has attacked the duplex interior and the cloudy rim zone. The decorated Neumann bands (right) are also selectively attacked. Etched. Scale bar 50 μ.

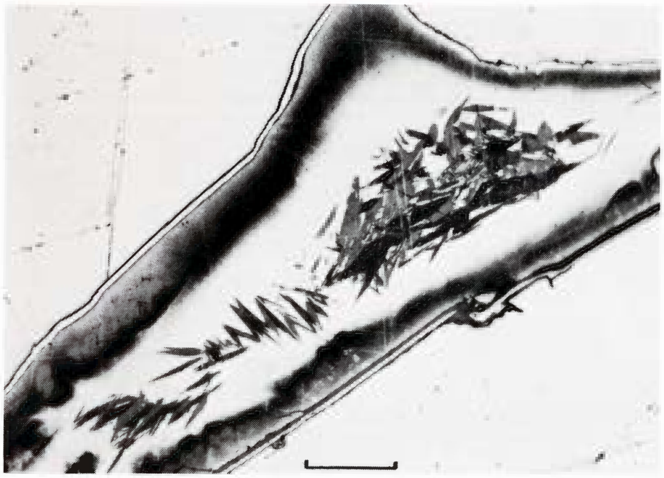

Figure 2043. Zaffra (Brit. Mus. no. 1963, 529). Taenite field with a high nickel content, presumably above 30% everywhere. The interior shows acicular carbon-nickel martensite. Terrestrial corrosion has selectively attacked along the interface with kamacite and along the inner edge of the 2-3 μ wide yellow high-nickel taenite rim, so that this has become detached as a narrow uncorroded strip. Etched. Scale bar 40 μ.

Zapata County, Texas, U.S.A.

An octahedrite found in Zapata County in about 1930 was listed by Mason (1962: 244). No further details have become available. The possibility that Zapata County is a synonym for some other Texas meteorite – or is a transported Odessa or Canyon Diablo fragment – should be considered.

Zenda, Wisconsin, U.S.A.

42°30′48″N, 88°29′22″W

Medium octahedrite, Om. Bandwidth 0.90±0.15 mm. Neumann bands.

Group I – Anomalous. About 8.5% Ni, 0.25% P, 55 ppm Ga, 214 ppm Ge, 2.1 ppm Ir.

HISTORY

A mass of about 3.7 kg was plowed up in 1955, a quarter of a mile northwest of Zenda, in Walworth County. The material was not described but was classified as a medium octahedrite (Read 1962; Meteoritical Bulletin No. 26,1963; Hey 1966: 534).

COLLECTIONS

Lawrence College, Appleton, Wisconsin (2,791 g and 770 g), Tempe (60 g).

DESCRIPTION

The following few notes were taken during a brief examination of the deep-etched 60 g endpiece in Tempe (No. 666.1; 5 x 3 x 1 cm).

Zenda is a medium octahedrite with straight, long ($\frac{L}{W} \sim 25$) kamacite lamellae with a width of 0.9±0.15 mm. The kamacite is rich in subboundaries, and Neumann bands are common. Taenite and plessite cover about 20% by area, as comb and net plessite, and as acicular areas.

Schreibersite is common as cuneiform skeleton crystals, up to 4 x 2 mm in size. They are usually enveloped in 1-2 mm wide rims of swathing kamacite. This is divided into several grains, evidently because each grain grew from differently oriented nuclei. Schreibersite also occurs as 0.05-0.1 mm grain boundary veinlets and as minor blebs in the plessite fields. Rhabdites, 5-15 μ across, are apparently present. The bulk phosphorus content may be estimated to be 0.25±0.10%.

Troilite occurs as 1-2 mm nodules with a little graphite; schreibersite forms 0.5-1 mm wide rims.

The mass is somewhat weathered. Fusion crust was not identified, but heat-affected α_2 zones occur as about 1 mm wide rims in several places.

Zenda is an inclusion-rich medium octahedrite related to Mazapil, Shrewsbury, Toluca and Bischtübe. On a graph where the kamacite bandwidth is plotted against the nickel content, Zenda falls significantly below the band defined by the meteorites mentioned, indicating that Zenda is somewhat anomalous. A similar conclusion was reached by Wasson (1970a), when comparing trace elements of Zenda to those of the resolved chemical group I.

ZENDA – SELECTED CHEMICAL ANALYSES

Reference	percentage Ni	Co	P	ppm C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Wasson 1970a	8.5±0.3								54.7	214	2.1	

Zerhamra, Algeria

Approximately 30°N, 2½°W

Medium octahedrite, Om. Bandwidth 1.10±0.15 mm. Recrystallized to 0.25 mm grains. HV 168±6.

Probably group IIIA. About 7.8% Ni and 0.12% P.

HISTORY

A mass of 630 kg was discovered in 1961 by the geologist, F. Arbey, Faculté d'Orsay, Paris, when he was mapping an area of the Algerian Sahara about 50 km southwest of Beni Abbès. The accurate circumstances of finding are not reported, but the approximate coordinates are given above. In the late 1960s the mass was transported to Paris.

During a visit to the Museum National d'Histoire Naturelle, Paris, in 1972, I had the opportunity to examine the large number of iron meteorites preserved there; I was shown the new meteorite by Professor J. Fabriès and it was discussed whether Tamentit and Zerhamra could be a paired fall. The exterior, the state of preservation and the general place of discovery could not immediately rule out this possibility. In order to solve the question, it was decided that a portion should be cut for examination and comparison with Tamentit. A wedge-sized sample of just over a kilogram was removed by hacksawing where the domed part met the posterior flattened surface. Previously nothing had been removed except a few grams at one or two exposed sites. The examination showed conclusively that Zerhamra is an independent meteorite of a very interesting type.

COLLECTIONS

Paris (main mass of 629 kg), Copenhagen (91 g).

Figure 2044. Zerhamra. The 630 kg main mass in Paris. The mass is of irregular shield-shape. Its regmaglypts are large and very well preserved. In many of them warty fusion crusts are seen. The examined section was sawed at the V-shaped notch above. Scale bar approximately 20 cm. (Photo courtesy Professor J. Fabriès.)

Figure 2045. Zerhamra (Copenhagen no. 1972, 1680). A recrystallized medium octahedrite, probably belonging to group IIIA. The equiaxial kamacite grains are slightly smaller within the degenerated plessite fields than within the kamacite lamellae. Etched. Scale bar 500 μ.

ANALYSIS

No analysis is available as yet. From the structural examination Zerhamra may be estimated to contain 7.6-8.0% Ni and 0.10-0.14% P, with Ga, Ge and Ir traces that place it in group IIIA.

DESCRIPTION

The large meteorite is shield-shaped, i.e., forms a rather irregular, low cone. The base of the cone measures approximately 80 x 65 cm, while the height reaches a maximum of 40 cm. A narrow crack may be followed on the surface for a distance of about 50 cm; at the surface it is at no point wider than 1 mm; its depth is unknown.

The entire meteorite is covered with conspicuous elongated regmaglypts which are indistinctly aligned and radiate away from the apex of the cone. The regmaglypts are typically 8 x 2, 8 x 5 or 9 x 6 cm in size, and 1-2 cm deep. On the posterior face the regmaglypts are somewhat shallower and less elongated, measuring for example 5 x 3 and 4 x 3 cm. The development resembles that of large Henbury specimens and of Quinn Canyon, to which the oriented, stabilized flight through our atmosphere is common. A few cylindrical depressions, 8-25 mm in diameter and 10-20 mm deep, indicate where troilite nodules have been partially or entirely removed by ablation melting during this flight.

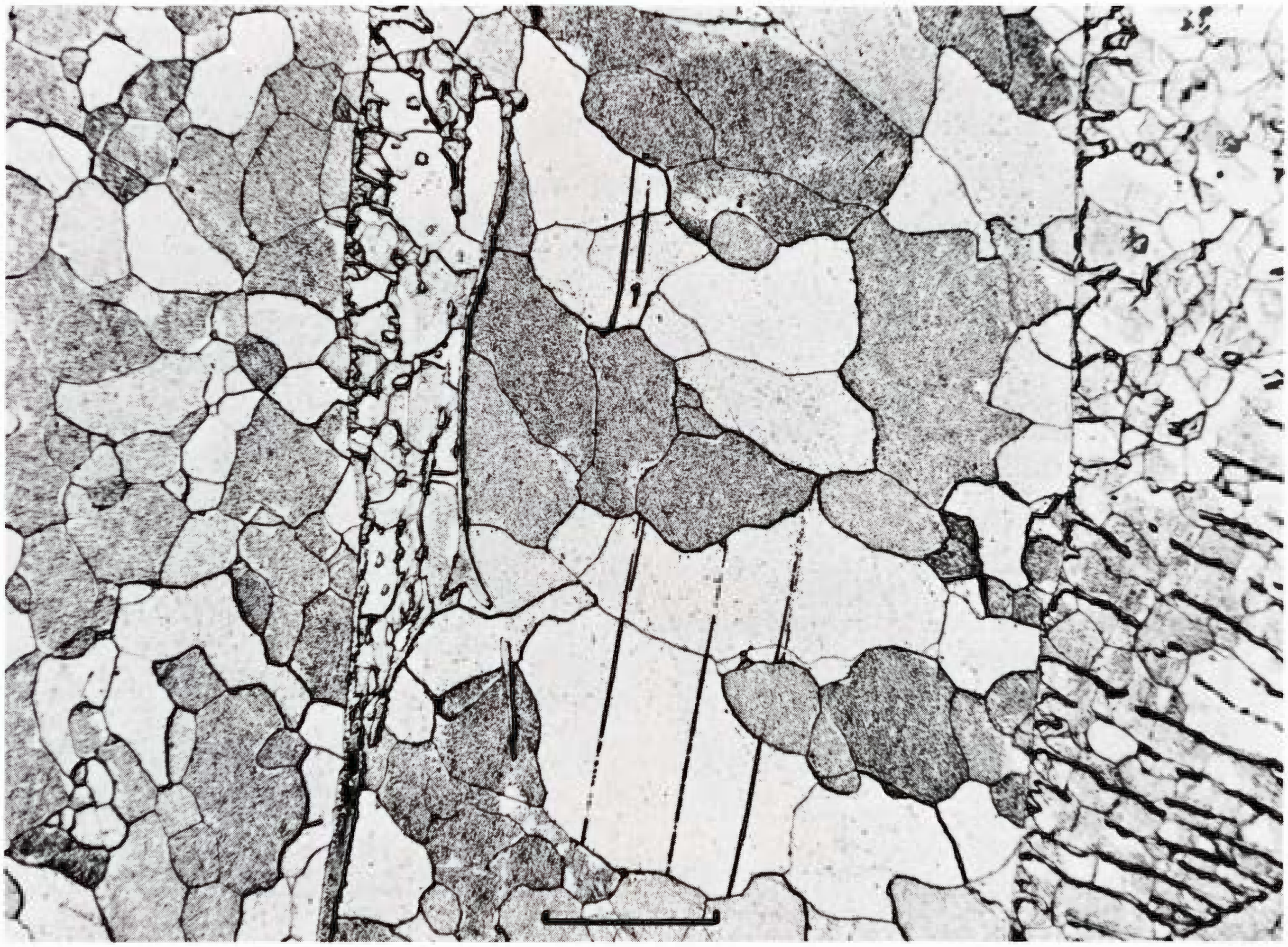

Figure 2046. Zerhamra (Copenhagen no. 1972, 1680). Near some of the surface cracks a few of the recrystallized kamacite grains contain a new generation of Neumann bands, probably dating from the atmospheric deceleration. Etched. Scale bar 300 μ. See also Figure 100.

The visual inspection of the surface reveals a "soil-line" above which very little terrestrial corrosion has occurred. Above, the metal is glossy and chocolate-brown and the fusion crust is easily distinguished over more than 50% of the surface. Below the "soil-line" slight corrosion has partially removed the fusion crust. Occasional pits, 1-3 mm in diameter, indicate the start of corrosion-pitting. The metal is of a matte brown color and slight incrustation with sand has occurred. Generally, however, Zerhamra is in a very good state of preservation and belongs to the best preserved finds.

The few sections examined to date suffice to classify Zerhamra as a medium octahedrite with straight long ($\frac{L}{W} \sim 25$) kamacite lamellae with a width of 1.10±0.15 mm. All kamacite is fully recrystallized and subsequent grain growth has led to a grain size of 0.1-0.4 mm, with an average grain size of 0.25 mm. The kamacite units are equiaxial and well-equilibrated and there is no indication of preexisting Neumann bands. Grain growth was in progress when all diffusion was finally stopped by cooling. Many small two-, three- and four-sided grains are clearly diminishing in size and on the verge of being wholly eliminated in the grain growth process. The grains display densely spaced phosphide particles of an almost submicroscopic size, apparently precipitated during annealing. The grains have been pinned in many places by these and other precipitates.

The thorough recrystallization and grain growth must have required a substantial plastic deformation followed by a prolonged annealing at perhaps 500° C. The microhardness of 168±6 is in accordance with the interpretation of the kamacite as a recrystallized and annealed structure.

Taenite and plessite cover about 30% by area. Most plessite is of the comb and net varieties, while martensitic and acicular types are almost absent because of the annealing. Straight taenite lamellae and wedges have been imperfectly spheroidized or pearlitized and the cloudy types have been eliminated. The slip systems $(111)_\gamma$ which presumably were activated by the same early cosmic shock event that produced the deformed kamacite have become decorated by minute α-particles, or occasionally entirely decomposed to α-globules arranged along the previous slipplanes. The taenite hardness is difficult to measure because of its incipient decomposition, but it is about 195±15.

Schreibersite occurs as 10-40 μ wide veinlets in the grain boundaries, and as 5-30 μ irregular blebs inside the plessite. It is brecciated and occasionally exhibits fine (0.5-2 μ) γ-particles along the periphery. These were produced during annealing when the phosphides adjusted their composition in accordance with the Fe-Ni-P diagram. Rhabdites, 2-4 μ thick, are only indistinctly seen because they have been partly resorbed by the annealing. On subsequent more rapid cooling, the resorbed phosphorus was precipitated as densely spaced phosphide particles of

Figure 2048. Zerhamra (Copenhagen no. 1972, 1680). Another annealed plessite field and a schreibersite crystal (S) with fine γ-particles along its periphery. Etched. Scale bar 50 μ.

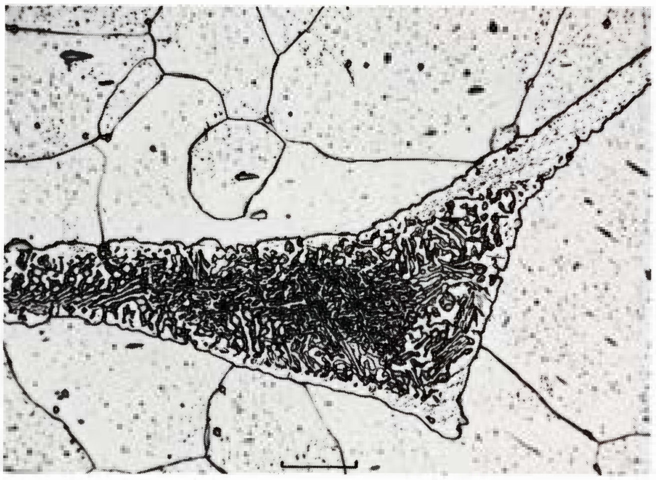

Figure 2047. Zerhamra (Copenhagen no. 1972, 1680). An annealed and decomposed plessite field. The interior is pearlitic or spheroidized, while the nickel-rich edge shows a dense $(111)_\gamma$ grid with fine α-precipitates. Etched. Scale bar 50 μ.

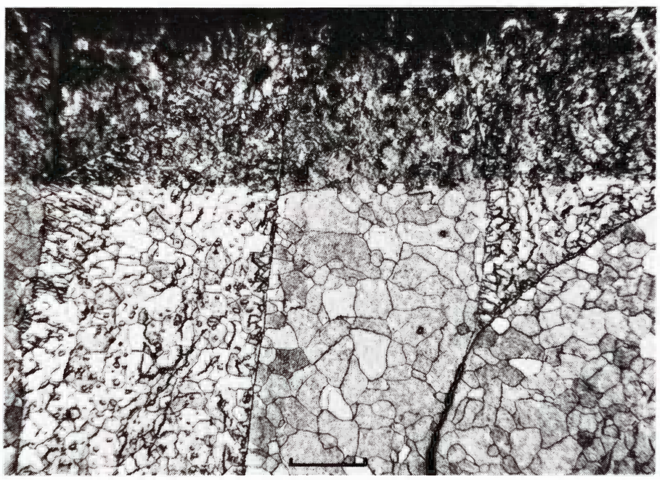

Figure 2049. Zerhamra (Copenhagen no. 1972, 1680). Heat-affected α_2 zone (above) and unaffected interior. It is quite clear that the kamacite is annealed and without Neumann bands. Etched. Scale bar 500 μ.

almost submicroscopic size between the remaining rhabdite crystals.

Troilite is present as occasional centimeter-sized nodules as evidenced by the cylindrical holes in the surface. Only minute (0.1-0.3 mm) troilite bodies were detected on the sections. They all showed the effects of an intense shock reheating, having been melted and solidified to fine-grained sulfide-metal textures with fringed borders against the metal. Original daubreelite had become shattered and was partially melted, and it is now present as 3-6 μ particles with rounded contours, dispersed through the sulfide-metal eutectic.

Apart from a few 0.1 mm daubreelite crystals in the kamacite or as nuclei for schreibersite, no other meteoritic minerals were detected.

The heat-affected rim zone is very well-preserved. The fusion crust forms a 60 μ thick layer of magnetite and wüstite, underlain by a 1-100 μ thick, dendritic, columnar, laminated metallic layer. The layers are slightly altered by corrosion and have occasionally spalled off. The α_2 transformation zone is 1-2 mm thick and displays hardnesses of 195±15. In the exterior half micromelted phosphides are present. The recovered transition zone between α_2 and recrystallized kamacite has the low hardness of 155±10 (hardness curve type II). Occasional cracks are present in the examined 1 kg sample. The recrystallized kamacite is along these cracks – and only here – studded with sharp Neumann bands. It appears that they developed when the meteorite was decelerated in the atmosphere and started to crack open.

Zerhamra is a shocked and thoroughly annealed medium octahedrite. The annealing was caused by cosmic reheating, probably while Zerhamra was still part of a larger body. A shell of no more than 10 mm of reheated material from the atmospheric flight is superimposed on the cosmic structures. Zerhamra is still unanalyzed, but it appears to belong to group IIIA and to be related to, e.g., Cape York, Willamette, Youanmi and Canyon City. In its secondary, annealed structure it resembles Durango, Joel's Iron, Cachiyual, Willamette, Roebourne and Ruff's Mountain.

(Zerhamra was examined after the statistics and the curves were prepared for the handbook and is thus not included. J.T. Wasson (personal communication 1974) reported the following analysis: 8.00% Ni, 18.2 ppm Ga, 33.5 ppm Ge and 10 ppm Ir, which shows that Zerhamra is a slightly anomalous member of group IIIA).

In this work, when it shall be found that much is omitted,
let it not be forgotten that much likewise is performed.

– Samuel Johnson,
Dictionary of the English Language,
London, 1755