display α_2 structures – and then only in near-surface parts, – it should be easy to avoid this kind of material for any kind of serious work.

Tombigbee is an unusual shower-producing iron meteorite. It exhibits pseudo-hexahedrite portions with prominent schreibersite inclusions, *and* minor portions with remnant Widmanstätten structure. Its secondary structure varies widely from mass to mass. It has been classified as a nickel-poor ataxite by Cohen (1905) and Hey (1966: 485), but this classification is unfortunate because it does not take into consideration the fact that large parts of the mass are only slightly altered, and that remnants of Widmanstätten structure are present. It is, therefore, proposed that Tombigbee be classified as a "hexahedrite, transitional to the coarsest octahedrites."

After its primary cooling, a cosmic shock event severely distorted the schreibersite lamellae, produced Neumann bands, shear zones with intense deformations, and micromelted troilite. Later, or perhaps immediately afterwards, as a result of the relaxation heating, annealing decorated the Neumann bands and caused the strained kamacite to recrystallize. Surprisingly, the degree of *recrystallization* varies extremely from mass to mass; it appears, however, that all masses are annealed to *recovery*.

At least one mass (VI) has, in addition, been exposed to artificial reheating.

Tombigbee is related to Bellsbank and La Primitiva and, distantly, to El Burro, Summit, Santa Luzia, São Julião and other meteorites of group IIB.

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

2,347 g endpiece (no. 252, 17 x 10 x 3 cm)
140 g part slice (no. 252, 10 x 7 x 0.25 cm)
95 g various slices (nos. 252, 1679)
} all from mass III Plate III in Foote (1899a)

262 g part slice (no. 3104, 7 x 5 x 0.9 cm; Figure 1 in Brezina & Cohen, 1904) from Mass I.

157 g part slice (no. 3105, 6 x 4 x 0.9 cm) from an unidentified mass

Tonganoxie, Kansas, U.S.A.

39°5′N, 95°7′W; 250 m

Medium octahedrite, Om. Bandwidth 1.10±0.10 mm. Neumann bands and ε-structure. HV 270±25.

Group IIIA, judging from the structure. 7.82% Ni, 0.50% Co, 0.13% P.

HISTORY

A mass of 26.5 pounds (12.0 kg) was found in 1886 by Mr. Quincy Baldwin on his farm a mile west of the town of Tonganoxie, Leavenworth County. The corresponding coordinates are given above. Baldwin manufactured a fishhook from a small fragment of the mass; but, disappointed that it was not an iron ore, he sold the meteorite in 1889 to a friend who again sold it to the University of Kansas. It was examined and described by Snow (1891) and by Bailey (1891) who also produced a good analysis and a figure of the exterior and of an etched section. Photomacrographs with brief descriptions of other sections have been published by Ward (1904a: plate 2), Mauroy (1913: plate 2) and Nininger (1933c: figures 11 and 12), but otherwise the meteorite has apparently not been examined.

COLLECTIONS

Chicago (945 g), Utrecht (about 400 g), Vatican (349 g), Leningrad (336 g), New York (321 g), London (260 g), Helsinki (258 g), Tübingen (245 g), Washington (230 g), Vienna (224 g), Rome (222 g), Tempe (222 g), Harvard (220 g), Prague (204 g), Paris (173 g), Oslo (163 g), Calcutta (140 g), Strasburg (130 g), Yale (128 g), Hamburg (128 g), Bally (119 g), Moscow (71 g), Budapest (16 g, previously 139 g), Berlin (8 g), Denver (*x* g).

Farrington (1915: 458) and Hey (1966: 486) stated that the main mass was still in the University of Kansas. This is evidently not correct, since it appears that the whole mass was sliced at an early date – before 1900 – and distributed as parallel slices of 100-400 g weight. The cumulative weight of the known slices is 5.5 kg. The loss in cutting, grinding and polishing to produce all these sections may be estimated to amount to 4 kg. This allows for a maximum of 2.5 kg in other, unregistered collections, such as the University of Kansas, Lawrence.

DESCRIPTION

According to Snow (1891) and Bailey (1891), the mass was irregular of shape, resembling a "lion couchant," and measuring 24 x 16 x 9 cm. The entire exterior was covered with a reddish-black coating of iron oxide-shale, and polished sections were noted to exude minute droplets of iron chloride from near-surface cracks and from under the oxide crust.

Although, as mentioned above, the meteorite now only exists as a number of parallel 2-10 mm thick slices, the general description of the weathered state can be confirmed. No fusion crust and no heat-affected α_2 zone were detected on the sections. However, hardness tracks perpendicular to the surface exhibited, in the last two or three millimeters, a significant drop to 220 from interior values of 270. This may be interpreted as a hardness curve type I (or IV) where the left leg has been lost by corrosion; probably 3-4 mm has been lost on the average. In many places this loss has occurred through the spalling off of

TONGANOXIE – SELECTED CHEMICAL ANALYSES

	percentage			ppm								
Reference	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Moore et al. 1969	7.82	0.50	0.13	85	225		170					

Figure 1779. Tonganoxie (Tempe no. 120a). A medium octahedrite which probably belongs to group IIIA. The section is almost parallel to $(111)_\gamma$ and the fourth set of Widmanstätten lamellae appear as irregular wide plumes. Millimeter-sized troilite nodules occur in several places (black). Deep-etched. Scale in centimeters. (Courtesy C.B. Moore.)

parallel kamacite platelets, so that the surface now has a distinct Widmanstätten pattern. Corrosion also pervades along grain boundaries, phosphides and sulfides to a depth of several centimeters, and the troilite is locally penetrated by 2 μ wide pentlandite veinlets.

Etched sections display a medium Widmanstätten structure of straight, long ($\frac{L}{W} \sim 25$) kamacite lamellae with a width of 1.10±0.10 mm. The kamacite shows subboundaries with less than 1 μ phosphide precipitates. It is shock-hardened to a somewhat variable level of 270±25; this variation is also detectable under the microscope since the kamacite displays a mixture of Neumann bands and ϵ-structure. Around some troilite inclusions the Neumann bands are visibly bent and distorted, and the microhardness reaches peak values just below 300 here.

Taenite and plessite cover about 25% by area, mostly as comb and net plessite, as duplex unresolvable, dark-etching fields and as fields with martensitic interiors or with interiors of a felt of 1-2 μ wide α-sparks. The stained taenite borders have a hardness of 365±15. The zone of martensitic transformation products which follows immediately has a hardness of 480±25, and a typical duplex interior of $\alpha + \gamma$ ($< 1\ \mu\ \gamma$) has a hardness of 325±20.

Schreibersite is not present as large crystals but is common as 10-50 μ wide grain boundary veinlets and as 5-50 μ irregular particles inside the plessite fields. Tetragonal rhabdite prisms, 1-10 μ thick, are common in the kamacite lamellae. Many schreibersite veinlets are severely brecciated and offset by thrust faulting.

Troilite occurs as nodules up to 11 mm across, and as lenticular or plate-shaped bodies, typically 5 x 1 or 3 x 0.6 mm across. These smaller bodies occur with a frequency of about one per ten cm^2. The troilite is monocrystalline and contains about 20 volume % daubreelite, mainly as 1-100 μ thick platelets parallel to (1000) of the troilite. Daubreelite also occurs as 20-40 μ subangular particles in the kamacite lamellae.

Some troilite-daubreelite aggregates are sheared and brecciated, and 5-25 μ fragments may be found shattered through 10-50 μ wide fissures radiating from the nodule. These fissures must be of old date, preterrestrial and probably cogenetic with the event that shock-hardened the kamacite and taenite phases, and brecciated the minerals. If so, the fissures have been open for millions of years, loosely filled with debris, and only recently have been recemented by limonite through terrestrial weathering processes.

Carlsbergite is present in the kamacite as 15 x 1 μ oriented platelets. No silicates, carbides or graphite were observed on the available sections.

Tonganoxie appears to be a normal shocked medium octahedrite closely related to Cape York, Casas Grandes and Augusta County. An examination of the trace elements Ga, Ge and Ir will probably show it to be a member of group IIIA.

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

191 g slice (no. 253, 14 x 8.5 x 0.3 cm)
39 g part slice (no. 3107, 6 x 4 x 0.3)

Tonopah. See Quinn Canyon (Tonopah)

Toubil River, Krasnojarsk Region, RSFSR
55°N, 93°E

Medium octahedrite, Om. Bandwidth 1.15±0.15 mm. α_2 matrix. HV 210±25.

Group IIIA. 7.76% Ni, 0.54% Co, 0.18% P, 19.8 ppm Ga, 38.1 ppm Ge, 5.0 ppm Ir.

The whole meteorite has been artificially reheated to about 1000° C.

Figure 1780. Toubil River (Leningrad no. 58/53). Artificially reheated medium octahedrite of group IIIA, closely related to Cape York. Fused troilite lenses (black). Deep-etched. Scale bar 20 mm.

HISTORY

A mass of about 22 kg was found in 1891 by a miner in the gold-bearing sand by the banks of the rivulet Tubil. The finder chiseled off a sample and examined the nature of the mass by various heating and forging experiments. Disappointed to find that it was not a gold nugget, he gave the mass to the museum in Minusinsk. Four years later it was transferred to the Mining Museum in St. Petersburg (Leningrad), where it was described by Khlaponin (1898) who also presented figures of it.

A small sample which came to Vienna around 1895, was briefly described under the name Tajgha by Brezina (1896: 284, 307, 364). Berwerth (1903: 18 and 19; 1905: 353) also kept Tajgha as an entry entirely separate from Toubil River. However, it was shown by Kupffer (1911) that the Tajgha samples were fragments detached from the Toubil River mass, originating from and assuming the name of the Tajgha railway station 400 versts (400 km) west of Krasnojarsk. Kupffer gave a description and a photograph of an etched section.

Berwerth (1905; 1914) noted the peculiar flimmery appearance of the kamacite; since he was able to reproduce this structure experimentally by heating to 950° C in a furnace, he concluded that the meteorite had been artificially reheated by the finder. This conclusion was also arrived at by the present author (quoted in Hey 1966: 487), but has apparently not been accepted by the Russian authors.

Zavaritskij & Kvasha (1952: 60) gave a brief description and a sketch of the macrostructure, and Krinov (1960a: figure 115) gave a figure. On the authority of Khlaponin (1898), the locality has hitherto been given as 55°53′N, 89°6′E (Krinov 1962; Hey 1966), but recently Yavnel (1969) has shown that the finding place was much further east, corresponding approximately to the coordinates 55°N, 93°E. According to Yavnel, the Tubil River is a tributary of the Derbin River, which again is a right tributary of the Yenisey. The locality is in the Artemovsk-Daurskoye gold district, at an altitude of 1000-1500 m.

A small mass of 190 g, later divided in samples of 144 and 27 g, has been listed as the independent meteorite Abakan by Krinov (1945a), Kvasha (1962) and Hey (1966). However, Yavnel (1969) showed that Abakan is nothing more than a fragment of the Toubil River mass which was detached early and which, through different channels, ended up in Moscow while the main mass went to Leningrad. The Abakan material has been described by Zavaritskij & Kvasha (1952: 40) who gave a photomacrograph and a sketch of etched slices.

COLLECTIONS

Leningrad (10.6 kg, 2.1 kg and 447 g), Paris (750 g), Chicago (543 g), London (463 g), New York (343 g), Stockholm (282 g), Moscow (171 g labeled Abakan, 64 g labeled Toubil), Washington (174 g), Vatican (147 g), Vienna (11 g labeled Tajgha, 80 g labeled Toubil), Harvard (41 g), Prague (29 g), Yale (28 g), Bonn (24 g).

DESCRIPTION

The original mass has been described as an irregular, somewhat flat and rounded block. At an early date it was cut into two almost equal halves, and one half was further subdivided and distributed (Kupffer 1911; Kuznetsova 1955).

In the present examination, samples from Leningrad, Moscow, Washington, Vienna and Chicago were incorporated. It was confirmed that Abakan and Tajgha were samples from the Toubil River mass, so all the following structural details, therefore, apply equally well to the different samples.

No fusion crust and no heat-affected α_2 zone could be detected. Corrosion has penetrated to a depth of several

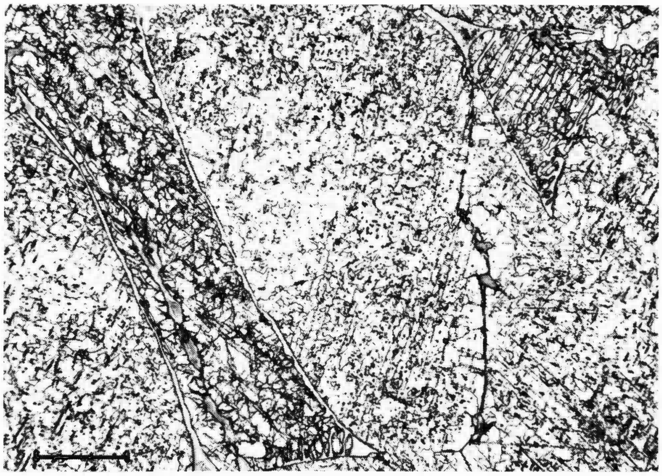

Figure 1781. Toubil River (Moscow no. 2485). Two open-meshed comb plessite fields and a kamacite matrix that has been transformed to unequilibrated α_2 grains. Etched. Scale bar 400 μ.

TOUBIL RIVER – SELECTED CHEMICAL ANALYSES

The first two analyses were performed upon material labeled Abakan, and the two last analyses upon material labeled Toubil River. However, all the material comes from the same 22 kg meteorite.

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Trofimov 1950				110								
Dyakonova & Charitonova 1960	7.88	0.53	0.23				200					
ibid., Toubil River	7.81	0.55	0.13				200					
Scott et al. 1973	7.59								19.8	38.1	5.0	

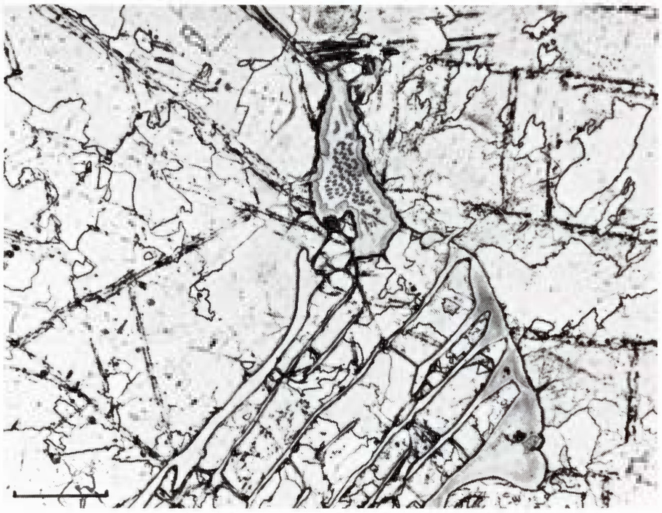

Figure 1782. Toubil River (Moscow no. 2485). A comb plessite field and, above it, a fused schreibersite crystal. The Neumann bands were evidently decorated by small precipitates, since they did not disappear when the kamacite was transformed to unequilibrated α_2 by the artificial reheating. Etched. Scale bar 100 μ.

centimeters along certain α - γ grain boundaries and along some schreibersite inclusions. Corrosion has also selectively attacked the Neumann bands, because these are sensitized by microscopic precipitates of nickel-rich particles, consisting either of taenite or, to a minor extent, of phosphides.

Several jagged fissures, mainly following the Widmanstätten pattern or which jump stepwise between schreibersite-rich grain boundaries, are conspicuous. In places the near-surface kamacite lamellae are visibly bent due to hammering, and over significant parts of the exterior surface the normal limonitic oxides from terrestrial corrosion are visibly altered as a result of late artificial reheating. It appears that most – if not all – of the interior fissures were formed when the finder hammered, chiseled, and otherwise probed the mass, as reported by Khlaponin (1898).

Etched sections display a medium Widmanstätten pattern of straight, long ($\frac{L}{W} \sim 20$) kamacite lamellae with a width of 1.15±0.15 mm. The kamacite has numerous subboundaries and many Neumann bands. These are decorated by tiny (0.5-1 μ) precipitates of taenite and phosphide particles.

Taenite and plessite cover about 30% by area. There are fields of comb and net plessite and duplex almost unresolvable black taenite.

Schreibersite is present as 10-100 μ wide grain boundary veinlets and as irregular, 5-50 μ blebs inside the open plessite fields. No large schreibersite crystals were detected. Rhabdites occur in profusion as 1-5 μ tetragonal prisms in the kamacite lamellae. The bulk phosphorus concentration is estimated to be 0.15±0.02%, i.e., somewhat lower than the average of the two quoted chemical analyses.

Troilite is common as nodules up to 8 mm across and as lenticular bodies typically 5 x 1 or 3 x 1.5 mm in size. The troilite contains 5-25% daubreelite in the form of

Figure 1783. Toubil River (Moscow no. 2485). A fused schreibersite crystal (S), and a plessite field (P) and unequilibrated α_2 grains. Etched. Oil immersion. Scale bar 20 μ. See also Figure 28.

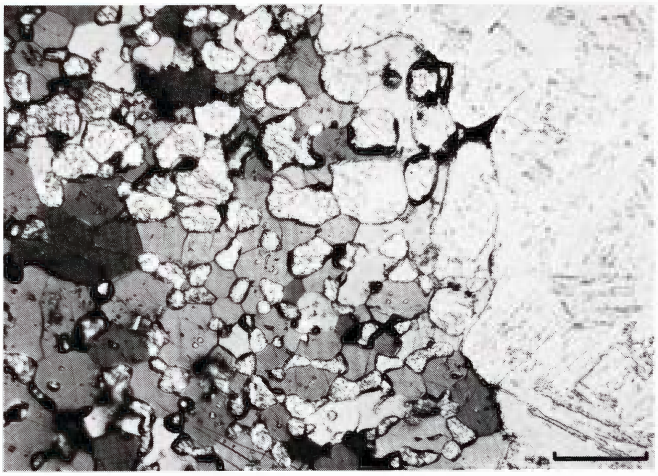

Figure 1784. Toubil River (Moscow no. 2485). Fused troilite nodule. It is decomposed into metallic dendrites and polycrystalline sulfides (gray in shades). The metal is transformed to α_2. Etched. Oil immersion. Crossed polars. Scale bar 20 μ.

parallel lamellae, generally 1-100 μ wide. Daubreelite also occurs – isolated in the kamacite as 5-50 μ rounded particles. The troilite has served as a nucleus for the precipitation of small amounts of schreibersite. The phosphide rims are only 10-30 μ wide and discontinuous because of the low bulk phosphorus content of the meteorite. The larger troilite crystals are enveloped in 1.0-1.5 mm wide rims of swathing kamacite.

Carlsbergite, the chromium nitride, is present in the kamacite phase as scattered platelets, typically 30 x 2 μ in size. Graphite has been reported by Kupffer (1911), but this observation could not be confirmed. If at all present, it is certainly on an insignificantly low level.

The above observations indicate that Toubil River is a normal medium octahedrite of the resolved chemical group IIIA. Its nearest relatives are such well-known meteorites as Cape York, Casas Grandes and Glasgow.

Toubil River has, however, been thoroughly reheated and somewhat worked by the finder. Macroscopically, the

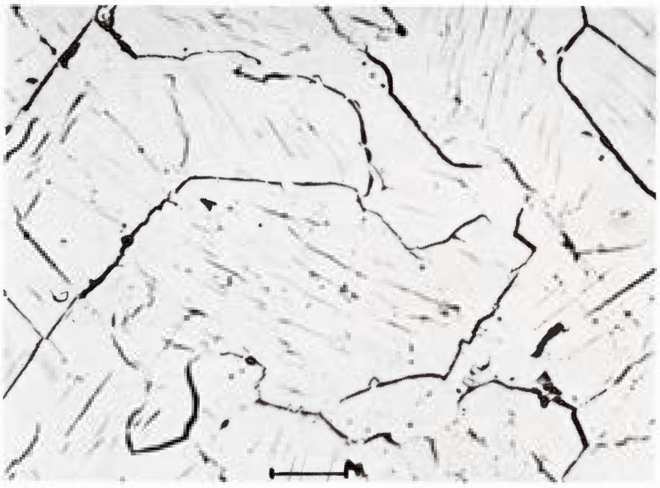

Figure 1785. Toubil River (Moscow no. 2485). Polycrystalline aggregate of lamellar sulfides, caused by artificial reheating. Polished. Oil immersion. Scale bar 10 μ.

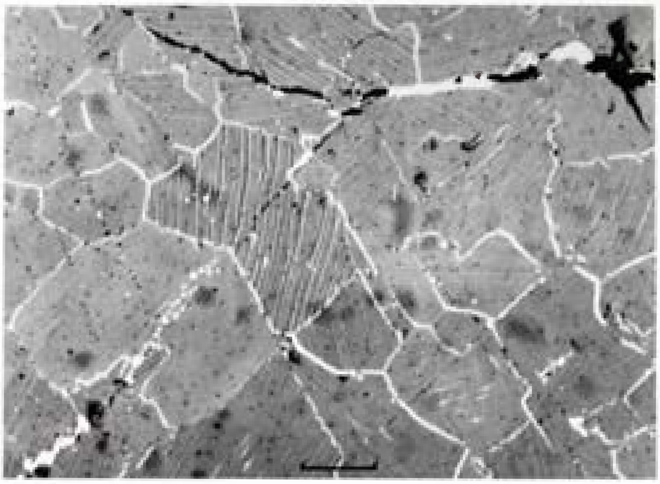

Figure 1786. Toubil River (Moscow no. 2485). Polycrystalline aggregate of lamellar sulfides, as in Figure 1785. Each grain is composed of extremely thin lamellae of alternating sulfides, while the grain boundaries appear metallic. Polished. Crossed polars. Scale bar 10 μ.

etched sections display a diffuse and blurred pattern with no oriented sheen. The reason for this is that all kamacite has been through the $\alpha \rightarrow \gamma \rightarrow \alpha_2$ transformation, and the numerous newly formed α_2 crystallites are randomly oriented. The α_2 crystallites are generally 25-100 μ in size and exhibit ragged borders. To a casual observer the Neumann bands seem to be preserved, which would be impossible if the above quoted transformation had taken place. High magnification (e.g., a 40x objective) reveals that it is not the Neumann bands proper which are preserved, but rather the lined up, microscopic precipitates which have not been resorbed by the heat treatment and, therefore, still indicate the location of the Neumann bands. The hardness of the α_2 phase is rather variable, 210±25, presumably because equilibrium conditions have not been achieved, so that the concentration of solute atoms such as Ni, P and C vary widely from place to place.

The taenite etches in cloudy yellowish nuances and exhibits diffuse borders against the α_2 phase, sending thorny spikes out along grain boundaries. The taenite hardness is extremely variable, from about 170 to 340, presumably for the same reasons as given above. The finer taenite lamellae are partially resorbed, and the plessite interiors are altered. Around several taenite fields on the etched section one can distinguish with the naked eye a diffuse, dark halo. At high magnification, these halos are seen to be zones of bainitic-martensitic transformation products, which must be due to the outward diffusion of nickel and carbon from the central taenite particle. The microhardness of these 50-100 μ wide zones is about 100 points above that of the adjacent α_2 phase, as would be expected from a carbon-rich nickel bainite. The bulk carbon content of Toubil River is 0.01% (Trofimov 1950), but most of this carbon appears to have been in solution in a minor part of the taenite fields. From point counting, it is estimated that the major part of the carbon is concentrated in taenite fields constituting less than 1% of the volume; i.e., the carbon concentration may in these fields reach the astonishing weight percent of one.

The schreibersite is micromelted and solidified to complex eutectics of very small grain size. The rhabdites are melted and partially resorbed. The troilite is melted and has dissolved part of the surrounding metal, whereupon it has solidified to eutectics with 5-10 μ grain size. Near-surface troilite nodules have either sweated out or reacted with oxygen. Such nodules have, upon solidification, created beautiful Fe-S-O eutectic intergrowths. The daubreelite has decomposed to a polycrystalline aggregate, each grain of 10-30 μ diameter apparently being a stack of extremely thin parallel lamellae of alternating decomposition products, one of which is easily dissolved in dilute acid and may be iron.

That the reheating was artificial and not cosmic is proved by the fact that the corrosion products are also heat-treated. Lace-like reaction zones of high temperature oxides and fine metal particles (½-2 μ across) line the corroded grain boundaries, and high temperature intercrystalline oxidation attacks may also be detected on several samples.

While the metallic matrix alone indicates reheating above 750° C, the micromelted phosphides and sulfides prove that the reheating was still more efficient and apparently continued to about 1000° C for about an hour. There is only a very remote possibility that the main mass, now in Leningrad, escaped the reheating.

Toubil River is another of those irons which, like Chesterville, Cacaria and Rodeo, were thoroughly reheated by the finders or early owners. While all microstructural features are completely altered, the macrostructural appearance is only little changed, and a close examination still allows us to reach a conclusion as to the microstructure and genetical relationships before the artificial reheating took place.

Specimens in the U.S. National Museum in Washington:
43 g part slice (no. 632, 4 x 3 x 0.5 cm)
64 g endpiece (no. 1153, 3.5 x 2.5 x 1.5 cm)
67 g corner (no. 3108, 4.5 x 2 x 2 cm)

Toubil River (Abakan), Siberia

A mass of 190 grams was found and incorporated in the collection of the Academy of Sciences, Moscow, as Abakan (Krinov 1947; Hey 1966). As shown by Yavnel (1969) the Abakan sample is, in fact, a fragment of Toubil River, and, therefore, it will not be treated separately here.

Trenton, Wisconsin, U.S.A.

43°22′44″N, 88°6′30″W; 275 m

Medium octahedrite, Om. Bandwidth 1.15±0.20 mm. ε-structure. HV 330±15.

Group IIIA. 8.34% Ni, 0.48% Co, 0.17% P, 20.8 ppm Ga, 44.5 ppm Ge, 2.4 ppm Ir.

HISTORY

Long believed to be a rather small fall, it was recently proven by Read & Stockwell (1966) that the Trenton shower comprises several large specimens, too, so that today 13 specimens totaling 505 kg are known.

The first four masses were plowed up by Louis Korb before 1868 and were described by Brenndecke (1869) and Smith (1869). Smith gave the location as the town of Trenton, which, however, should be the township of Trenton, about 45 km north-northwest of Milwaukee and 8 km southeast of West Bend. The next two masses, Nos. 5 and 6, were plowed up later, in the same field, and were described by Lapham (1872). These specimens were somewhat cut and distributed, mainly through J.L. Smith, around 1870 and Ward's Natural History Establishment after 1892. Almost all examinations published before 1965 have been based on material from the first four. Brezina (1880b) described the Reichenbach lamellae and gave a photomacrograph. Later (1885: 211) he used Trenton as a type member for the Trenton subgroup in his classification system. Perry (1944) gave excellent photomicrographs of the crosshatched kamacite and Wood (1964) examined the kamacite-taenite relationship with the microprobe and gave several photomicrographs. El Goresy (1965) examined a troilite nodule. Axon & Boustead (1967) and Axon et al. (1968: 535) discussed the shock-hardened structure in more detail and presented photomicrographs of twinned troilite.

In the meantime it had occurred to H.O. Stockwell, of Hutchinson, Kansas, that the area might yield more specimens if searched with his wheelbarrow-mounted electronic metal detector. He identified the old 40-acre Louis Korb farm, now owned by Reuben Gauger, and by systematic searching in 1952 found two large masses, of 187 and 239 kg, respectively. They were buried under 60-65 cm of earth (Read 1962; Read & Stockwell 1966). The authors, in addition, found the small specimens Nos. 12 and 13, and received information on Nos. 7-9 which had been found previously. In unpublished notes from 1868 (I.A.Lapham 1962) Lapham stated that "other fragments are said to have been found, which have been used by blacksmiths in the neighborhood." Thus, more than 13 individuals have been recovered from the shower.

No.	Discovered	Weight Pounds	Weight kg	Present Location
1	1858	62	28.1	Cut and distributed
2	1858-68	16	7.2	Cut and distributed
3	1858-68	10	4.5	Cut and distributed
4	1858-68	8	3.6	Cut and distributed
5	1869	16.2	7.3	University of Wisconsin, Milwaukee
6	1871	33	15.0	Cut and distributed?
7	1880	10	4.5	Milwaukee Public Museum
8	1885	6.5	3.0	R.A.E. Morley, Salem, Oregon. Purchased by University of California, Los Angeles, in 1971.
9	1933	3	1.35	
10	1952	413	187	151 kg in U.S. National Museum
11	1952	527	239	In U.S. National Museum Subdivided by 4 cuts in 1964
12	1952	1.5	0.7	One half sold to R.A.E. Morley, Salem, Oregon
13	1964	9.5	4.3	Lawrence University

The first nine (and additional, unrecorded fragments) were found accidentally, mainly by plowing. The last four were found by systematic search with a metal detector. For detailed information and photographs, see Read & Stockwell (1966).

All masses have apparently been found close together, within the same field. According to Read & Stockwell (1966), who presented a detailed map, ten of the masses were found within 30 m of each other, while Nos. 7 and 9 were found 150 and 300 m, respectively, farther northeast. Trenton thus forms an unusually dense shower.

Herr et al. (1961) examined the Os/Re ratio and estimated that Trenton, as most other iron meteorites, was formed about 4.5 x 10^9 years ago. Schultz & Hintenberger (1967) and Hintenberger et al. (1967) presented data on numerous occluded, noble gases. Vilcsek & Wänke (1963) estimated the cosmic ray exposure age to be 450±100 million years; while Lämmerzahl & Zähringer (1966) found 670±220 million years. Voshage (1967) found, with the reliable $^{40}K/^{41}K$ method, 575±60 million years; while Chang & Wänke (1969), with the $^{10}Be/^{36}A$ method, found 410±50 million years. The latter pair of authors estimated the terrestrial age to be lower than 10^5 years because both ^{36}Cl and ^{10}Be were present in significant amounts. Buchwald (1971d) discussed the gas content and the metallographic structure and presented three photomicrographs.

COLLECTIONS

Washington (390 kg), Harvard (5.2 kg), Chicago (3.6 kg), Berlin (1,420 g), Vienna (1,109 g), Paris (962 g), New York (761 g), Tempe (654 g), Budapest (604 g), Los Angeles (597 g), London (446 g), Copenhagen (398 g), Vatican (348 g), Tübingen (339 g), Amherst (214 g), Ottawa (211 g), Leningrad (165 g), Canberra (154 g), Yale (132 g), Prague (101 g). Also in numerous other collections. Quite recently about 35 kg from block No. 10 has been subcut and offered for sale from Ward's Natural Science Establishment.

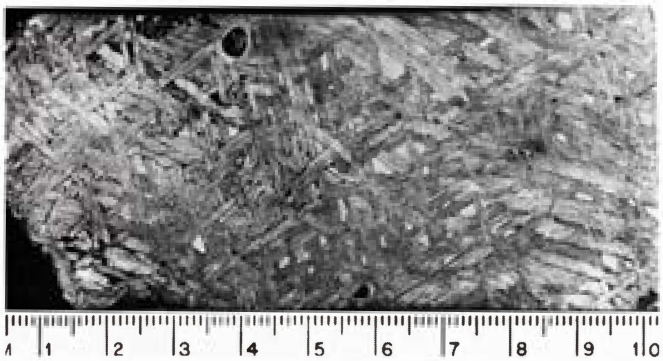

Figure 1788. Trenton (Tempe no. 136). A shock-hatched medium octahedrite of group IIIA. One large and several small troilite nodules appear black. Deep-etched. Scale in centimeters. (Courtesy C.B. Moore.)

Figure 1787. Trenton. Mass number 11, of 239 kg, while being cut in Professor Hintenberger's laboratory in Mainz, Germany. Marks of the 8 mm wide drilling holes are distinctly seen on the sections. The central slab measures 50 x 38 x 3 cm.

DESCRIPTION

The two largest masses, Nos. 10 and 11, have the average dimensions 45 x 33 x 30 cm and 55 x 38 x 30 cm, respectively. In 1964 No. 11 was shipped to Mainz, Germany, and – in the Max-Planck-Institute under supervision of Professor H. Hintenberger – divided by four parallel cuts, aided by preliminary drilling of densely spaced, 8 mm wide holes. The center section, which was 50 x 38 x 3 cm in size, has been milled, ground, polished and etched on one side, while some of the other cut faces have, as yet, only been partly finished.

The masses apparently present a very corroded exterior with ocher colored terrestrial oxides building up locally to a thickness of 10 mm. A close examination of the surface reveals, however, that a significant part of the original regmaglypts are preserved as 2-5 cm wide depressions. Also deep pits, e.g., 2 cm deep and 2 cm wide, occur in several places. They are due to ablational melting of troilite. In the

TRENTON – SELECTED CHEMICAL ANALYSES

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Sen Gupta & Beamish 1963											3.4	8.4
Nishimura & Sandell 1964								3				
Cobb 1967		0.47					165		18.5		2.1	
Wasson & Kimberlin 1967	8.34								20.8	44.5	2.4	
Lewis & Moore 1971	8.34	0.49	0.17	220								

bottom of some of the pits part of the troilite is still preserved. On several sections the heat-affected zone is present as a 1-2 mm thick rim of very fine-grained α_2 units. The hardness of this rim is 200±10; the hardness increases rapidly inwards; at a depth of 5-10 mm it attains the unaffected interior level of 330±15 (hardness curve type I).

Along part of the periphery of some etched sections, e.g., on No. 11, the kamacite lamellae are visibly bent and distorted. The corrosion products around them are undamaged so the deformation cannot be artificial. It is probably an indication of the torsional-tensional fracturing which occurred during atmospheric breakup, as seen on, e.g., Gibeon, Glorieta Mountain and Wabar. Read & Stockwell (1966) have also noted features suggesting late, atmospheric ruptures on specimens Nos. 5 and 13.

The various masses are somewhat corroded. Besides the superficial attack corrosion preferentially attacks the near-surface brecciated Reichenbach lamellae and the nickel-poor surroundings of the phosphides. Some pentlandite veining occurs in the troilite nodules.

Trenton is a medium octahedrite with straight, or locally slightly undulating, kamacite lamellae ($\frac{L}{W} \sim 25$) with a width of 1.15±0.20 mm. Subboundaries are common, but somewhat obscured by the superimposed, cross-hatched ϵ-structure. The hardness of the shock-hardened structure is high, 330±15, and suggests shock pressures of about 200 k bar.

Taenite and plessite cover about 30% by area, mostly as comb and net plessite in which individual taenite ribbons and wedges may have dark-etching, martensitic or duplex interiors. A typical, partially decomposed taenite wedge will exhibit a yellow or stained taenite rim (HV 400±50) followed by a light-etching martensitic transition zone (HV 485±30). Then follow dark-etching martensites (HV 400±40) and finally very fine-grained duplex mixtures of alpha and gamma grains (HV 350±25). These central, best decomposed parts are barely resolvable with a 40x objective and their hardness approaches that of the adjacent kamacite lamellae, as do their average nickel content; see, e.g., Wood (1964).

The phosphorus content of Trenton is too low for schreibersite to occur as large crystals, and schreibersite is almost absent around the troilite nodules. Schreibersite is, however, common as 20-80 μ wide grain boundary precipitates and as 5-50 μ irregular blebs inside the plessite fields. Rhabdites are rare or absent. Chromite is rather common, e.g., as 2 x 0.05 mm lamellae or as 0.1-0.3 mm thick euhedral, cubic crystals. They are situated in the α-phase or have served as nuclei for some troilite blebs.

Troilite is common as lamellar, lenticular and globular inclusions, which range in size from a tenth of a millimeter to 6.5 x 3.5 x 3 cm. On sections totaling 3,000 cm^2 a total of 10 inclusions larger than 10 mm and 25 between 1 and 10 mm across were noted. They cover 2.1% by area, corresponding to a bulk sulfur content of 0.47%. The troilite is rather pure, and no macroscopically visible schreibersite rims occur. Asymmetric, 0.1-1.5 mm thick rims of swathing kamacite are common. Some nodules are single crystals, but most show various degrees of damage. A typical troilite nodule may be 15 mm across, and it may be divided into passive, monocrystalline units, 0.5-2 mm across. These units are separated by irregular shear zones which display undulatory extinction or sharp, lenticular twins. Where the deformation intensity in the shear zones was higher, the troilite is recrystallized or shock-melted and solidified to 1-3 μ wide grains. A few fragments of shattered schreibersite may be identified in the shock-melted troilite. The single crystals of troilite have a hardness of 260±25.

The large troilite nodules appear to be elongated and oriented in a roughly parallel manner on several sections. Some are indented by metallic tongues. The small nodules show no preferred orientation.

Reichenbach lamellae are very common; on a 1500 cm^2 section I noted 88 lamellae, typically 15 x 15 x 0.1 mm in size. Brezina (1880b) concluded that they were crystallographically arranged in the three cubic planes

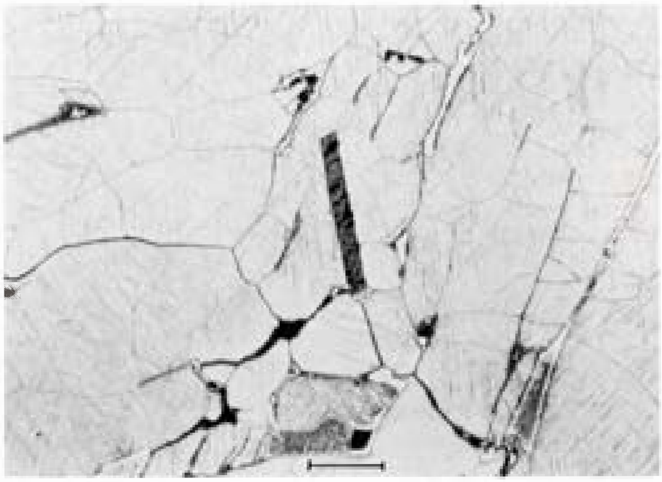

Figure 1789. Trenton (Copenhagen no. 1876, 2246). Centrally, a chromite bar with schreibersite and troilite precipitates at its lower end. Etched. Scale bar 500 μ.

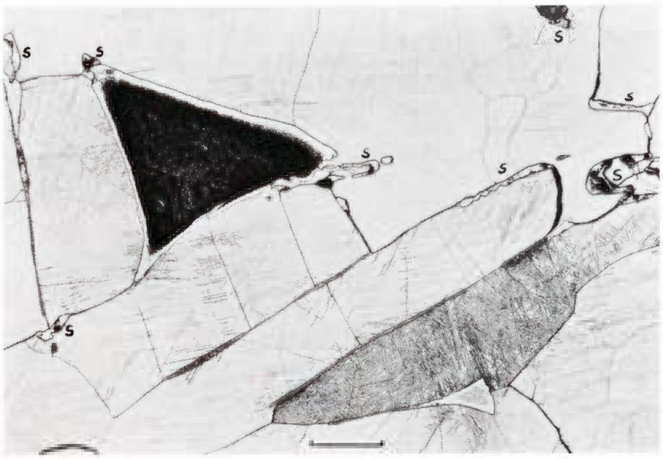

Figure 1790. Trenton (Copenhagen no. 1876, 2246). Shock-hatched kamacite in various shades. Schreibersite (S) at grain boundaries. Plessite and taenite with cloudy edges and a chromite crystal above right. Etched. Scale bar 500 μ. See also Figure 124.

{100}. From an examination of the large sections made available recently it appears to me that the lamellae rather arbitrarily cut through the Widmanstätten structure in at least eight different directions, none of which coincide with {111} planes. Some of them may coincide with {100} planes. The lamellae are mainly composed of troilite, with small amounts of daubreelite and schreibersite. In many instances they are heavily brecciated on a microscale, and terrestrial oxides have cemented the individual fragments together. The lamellae apparently represent high temperature sulfide fillings of limited fissures in the parent taenite single crystal. At the late shock event that formed the metallic ε-structure, the sulfides were deformed, brecciated or, sometimes, micromelted.

In addition, a rather rare troilite variety occurs. From several of the large troilite nodules 0.1-1.5 mm wide, troilite-filled veins extend for many centimeters into the metal, mainly following the Widmanstätten planes or jumping in a zigzag fashion from plane to plane, sometimes even cutting through plessite fields. These veins appear to be original fissures in the metal which at an early date were cemented together by troilite, perhaps injected in a liquid or semiplastic condition into the cracks.

Trenton is a medium octahedrite of group IIIA which is related to Drum Mountains, Kayakent, Susuman, Tamarugal and Thunda. The somewhat oriented troilite nodules, and the various troilite-filled fissures suggest that the mass on its primary place was subject to plastic deformation and shearing by compression. The adjustments of the overburden may have continued to quite low temperatures, after the meteorite was wholly transformed to a Widmanstätten structure, since the α-lamellae show some distortion and the minerals are brecciated. These secondary deformations may, however, also have occurred in connection with the ε-producing shock event that presumably dislodged the mass from its surroundings. When Trenton decelerated in the atmosphere, the breakup was assisted by the presence of the numerous, weak, troilite-filled cracks, so a shower was the result. Only very limited deformation took place with the atmospheric rupture, and virtually none at the impact with the Earth.

Figure 1791. Trenton (Copenhagen no. 1876, 2246). Shock-hatched kamacite in various shades. Schreibersite (S) at grain boundaries. Plessite field with martensitic interior (P). Subboundaries in the kamacite. Etched. Scale bar 200 μ.

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

322 g slice (no. 65, 8 x 7 x 0.8 cm) (Shepard Collection no. 65)
103 g part slice (no. 668, 4 x 4 x 0.7 cm)
61 g fragments (no. 1163, two pieces) (Shepard Collection no. 66)
666 g slice subdivided (no. 2164, 12 x 9 x 0.8 cm)
151 kg Mass No. 10 with one cut face 30 x 22 cm (no. 2173, 36 x 33 x 30 cm)
"239 kg" Mass No. 11, divided in three thick slices and two, insignificant endpieces; weights only known approximately (no. 2173, originally 55 x 38 x 30 cm)
102 g slice, subdivided (no. 3111, 6 x 6 x 0.5 cm)
179 g part slice (no. 3379, 6 x 4 x 1 cm) (J.L. Smith No. 144)

Treysa, Hesse, Germany
50°57'N, 9°10'E

Medium octahedrite, Om. Bandwidth 0.85±0.10 mm. ε-structure. HV 290±15.

Group III – Anomalous. 9.51% Ni, 0.57% Co, 0.40% P, 20.4 ppm Ga, 43.1 ppm Ge, 1.2 ppm Ir.

HISTORY

A mass of 63.28 kg fell April 3, 1916 at 1525 (1425 Greenwich time) (Wegener 1917). Numerous eyewitnesses saw a fireball that moved, in four seconds, with an average (geocentric) velocity of 16.3 km/sec in a trajectory inclined 55° to the horizontal from N 15° W to S 15° E. The intensity of the light from the fireball gradually decreased until it disappeared at the unusually low altitude of 16.4 km. The heliocentric velocity was calculated to 37.5 km/sec corresponding to an elliptic orbit within the

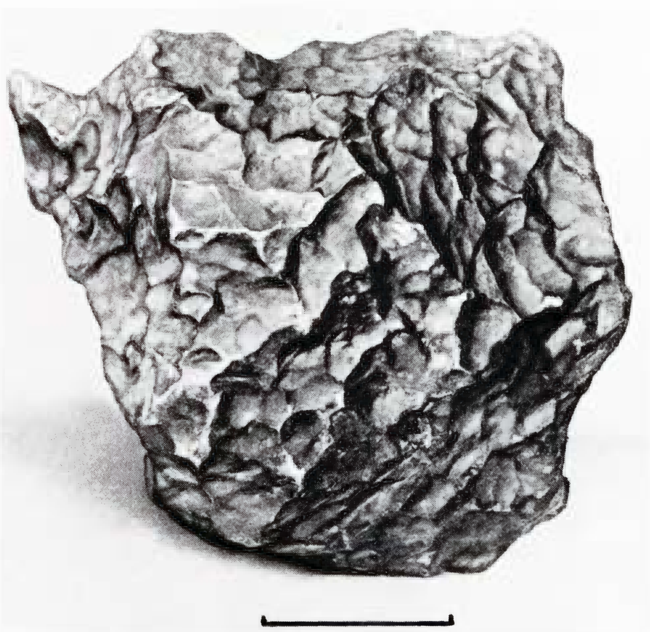

Figure 1792. Treysa. The 63.3 kg mass is beautifully covered with regmaglypts. Scale bar approximately 10 cm. (From Richarz 1918.)

solar system. Due to fine weather the meteorite was observed from an area 135 km in radius. The whole train, 81 km long, was visible as a whitish band that slowly became blurred until it vanished after 10 minutes. Eyewitnesses within a radius of 50 km heard a detonation a few minutes after the fireball had disappeared, and some witnesses near the end point of the trajectory allegedly observed a black body falling. Wegener collected these observations and concluded in a remarkable paper (1917) that a single iron had fallen in the forest region northwest of Treysa.

In January 1917 a reward of 300 marks was promised by the "Naturgesellschaft" in Marburg and a short note was distributed to the rangers of the district in the hope that they would report anything unusual. In March 1917 this resulted in the locating of a funnel-shaped hole in the forest. It was about 1 m across and 25 cm deep. Rain had partially washed in the walls of the original hole, but, by excavation, the iron was found at a depth of 1.6 m. The upper soil consisted of 75 cm loose forest debris mixed with sandy loess; the lower was a soft, clayey sandstone, presumably considerably weathered (Richarz 1918; Wegener 1918; Hoffmeister 1918).

If we assume that Wegener's calculated point of retardation (see map in Wegener 1917; Richarz 1918) is approximately correct, we here have a well documented example of an almost vertical fall of the meteorite after it had lost its cosmic velocity: the meteorite was found only about 800 m from the vertical projection of the point of retardation; i.e., in a fall of 16 km it only proceeded another 0.8 km. Lamar & Romig (1964) discussed the anomalous sounds and electromagnetic effects associated with fireball entry and used Treysa as an example. The trajectory of Treysa is included in the catalog of bright meteors by Nielsen (1968).

Buchwald (1966: figure 33; 1967a: figure 4) noted the shocked structure and argued that the shock event must have been preatmospheric in this meteorite – and numerous others – which were not associated with craters. Jaeger & Lipschutz (1967b) reached a similar conclusion.

Martin (1953) estimated, from helium determinations, that Treysa's preatmospheric mass had been approximately 600 kg, thus having lost 90% in the atmosphere. Fechtig et al. (1960) gave two photographs and estimated the preatmospheric mass at 600 kg. Fireman & De Felice (1960) measured the tritium and argon-39 isotopes and discussed the short-time variations in the cosmic ray flux. Herr et al. (1961) calculated from the Os/Re ratio a total age of 4 x 10^9 years for Treysa. The noble gas concentrations and various nuclides have been reported by Hintenberger & Wänke (1964), Honda & Arnold (1964), Schaeffer & Heymann (1965) and Müller & Zähringer (1966). Cosmic ray exposure ages have been estimated to be 450±30 million years (Vilscek & Wänke 1963), 370±30 million

Figure 1793. Treysa (Copenhagen no. 1963, 648). A shock-hatched medium octahedrite of group IIIB. Several schreibersite skeleton crystals (dark) enveloped in swathing kamacite. Etched. Scale bar 3 mm.

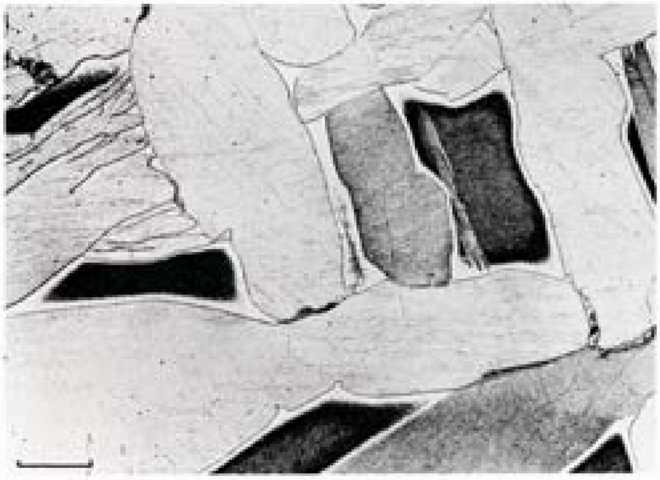

Figure 1794. Treysa. Detail of right part of Figure 1793. Shock-hatched kamacite in various shades. Plessite fields with martensitic or unresolvable black interiors. Schreibersite (S) at grain boundaries. Etched. Scal bar 500 μ.

TREYSA – SELECTED CHEMICAL ANALYSES

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Bothwell in Hey 1966	9.44											
Buchwald 1967 unpubl.	9.55	0.60	0.20		50		130		21	36		
Wasson & Kimberlin 1967	9.1±0.4								20.4	43.1	1.2	
Lewis & Moore 1971	9.55	0.53	0.40	140								

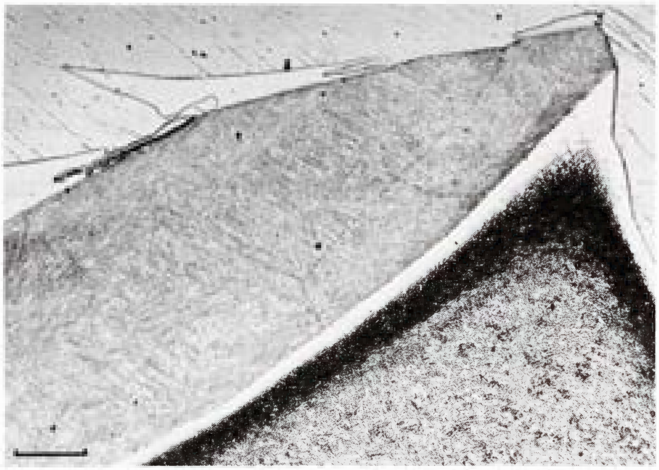

Figure 1795. Treysa. Detail of lower right part of Figure 1793. The plessite field has a taenite edge, a martensitic transition zone and a duplex $\alpha + \gamma$ interior. Etched. Scale bar 200 μ.

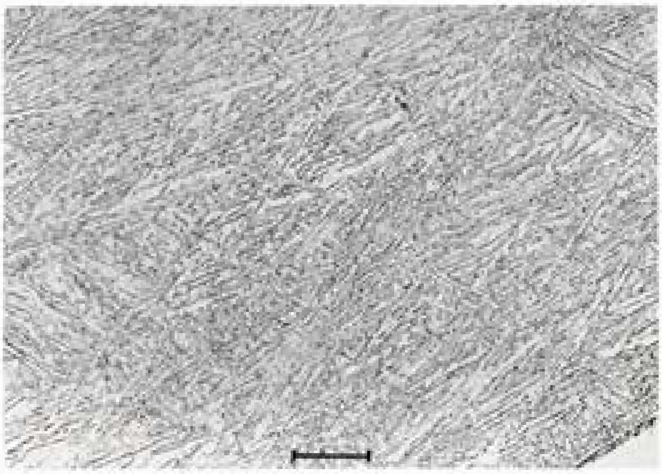

Figure 1797. Treysa (Copenhagen no. 1967, 648). Shock-hatched kamacite at high magnification. Below right, the edge of a taenite lamella. Etched. Scale bar 30 μ.

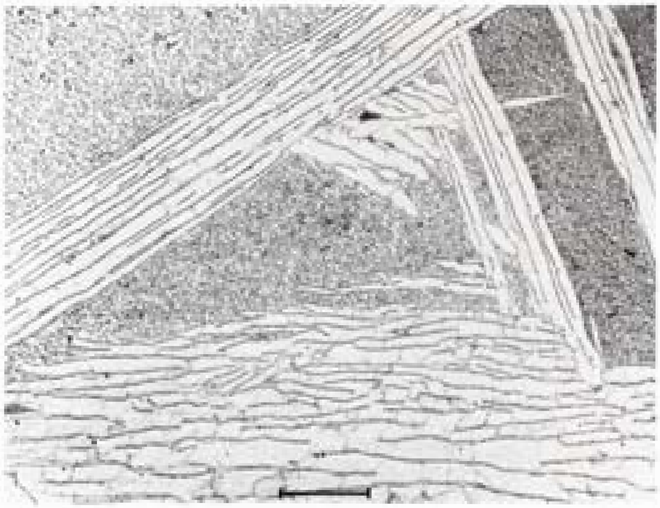

Figure 1796. Treysa (Copenhagen no. 1963, 648). A plessite field of a somewhat unusual character. Comb areas repeat all four Widmanstätten directions while intercalated areas are finely granular. Schreibersite particles are common and stand in high relief. Etched. Scale bar 300 μ.

years (Schaeffer & Heymann 1965), 530±70 million years (Lipschutz et al. 1965), 620±60 million years (Voshage 1967) and 440 million years (Chang & Wänke 1969). In these papers references to several others, dealing with trace element determinations in Treysa, will be found.

COLLECTIONS

Marburg (main mass), London (1,173 g), New York (214 g), Washington (195 g), Tübingen (143 g), Copenhagen (114 g), Tempe (108 g), Chicago (89 g), Ottawa (84 g).

DESCRIPTION

The mass is an irregular, polyhedric monolith with the approximate dimensions of 36 x 30 x 24 cm. It weighed 63.28 kg; and its volume was measured at 8.02 liters, giving a specific gravity of 7.88. From this it was rightly assumed that the nickel content was somewhat higher than 8% (Richarz 1918: 109), but it would be 50 years before the first analyses were published; see the table. The surfaces are indented by regmaglypts, 1-5 cm across, the most common being 3 cm wide and about 5 mm deep. On one face there is a large cavity, 6 cm deep and about 10 cm across. In one place there is a pit, 2 cm wide, which marks where a troilite nodule was partially melted by ablation. Most of the surface is covered by a paper-thin black crust of magnetite and wüstite. It is rust-stained due to the year it was exposed in the forest, but corrosion has not penetrated into the interior. In the crust there are some hair-lines and warty parts. The oxidic crust is underlain by a 0-400 μ thick metallic fusion crust. It is cellular-dendritic with an armspacing of 1-2 μ and includes scattered, 1-20 μ thick globules of fused oxides. The metal is transformed to a fine-grained martensitic α_2 phase with a hardness of 400±15. The metallic fusion crusts are intimately intergrown with each other and with the underlying, unmelted matrix. It is clearly seen how the nickel-rich taenite, because of its lower melting point, is melted before the plessite and kamacite: the fusion crust penetrates 20-30 μ deeper where taenite is present than elsewhere.

Under the fusion crusts there is a 1.5-2.5 mm wide, heat-affected α_2 zone, and micromelted phosphides are present in the exterior 50% of this zone. The serrated α_2 units are rather small, 5-50 μ across, as is always the case when α_2 forms from a shock-hardened ϵ-phase. The hardness is correspondingly high, 220±10. The hardness drops to a minimum of 200±5 at the transition from α_2 to ϵ-structure and then increases steeply to the interior level of 290±15, which is reached at a depth of 6-10 mm (hardness curve type I).

Etched sections display a medium Widmanstätten structure of straight, long ($\frac{L}{W} \sim 20$) kamacite lamellae with a width of 0.85±0.10 mm. The kamacite has subboundaries with 1 μ phosphides, but these are inconspicuous due to the marked, crosshatched, shock-hardened ϵ-structure. The micrographs clearly show how different lamellae, all of the same hardness, 290±15, etch in various shadings. The ϵ-structure responds to etching in much the same way as Neumann bands in less shocked meteorites. The effects are mainly due to different orientation of the kamacite lamellae.

Taenite and plessite cover about 35% by area, mostly as comb and net plessite and as dark-etching fields. A typical dark, rhombic field will exhibit a tarnished taenite edge (HV 350±20) followed by a light-etching martensitic transition zone (HV 450±20). Then follow a brown-etching martensite – developed parallel to the bulk Widmanstätten structure (HV 510) – and than a darker etching, but similar, martensite (HV 425±25). Finally come duplex interiors of $\alpha + \gamma$ – first fine-grained (HV 350±10) and then coarse-grained, approaching net plessitic development (HV 295±15).

Schreibersite is common as hieroglyphic or rosette-shaped crystals, typically 5 x 0.5 mm in size. They are monocrystalline but somewhat brecciated. Point counting of a typical area (57 cm^2) resulted in an average of 0.25% P as visible phosphides. Since phosphorus is also present in microscopic phosphides and in solid solution the P-determination by Moore seems to be a better bulk value than mine, which was obtained on a small portion of shavings. The schreibersite has a 1-1.5 mm wide rim of swathing kamacite. Schreibersite is also common as 20-50 μ wide grain boundary precipitates and as 2-20 μ thick blebs in the plessite fields, but island-arcs are absent. Rhabdites are numerous, but very small, generally 0.5-1 μ across. They are best identified in the exterior heat-affected α_2 zone where they are micromelted. Around several of the martensitic, dark-etching fields there are numerous slipplanes decorated by less than 0.5 μ wide phosphides; compare Thule, Welland and others.

Troilite was not observed on sections totaling 400 cm^2, however, it is present, as noted above in the discussion of the crust.

Treysa is a medium octahedrite that resembles Ilinskaya Stanitza, Grant and several other irons of group IIIA-IIIB. It is a little anomalous in its detailed Ni-Ga-Ge ratios, and also in its P-Ir ratio.

Specimen in the U.S. National Museum in Washington:
195 g part slice (no. 1881, 10.5 x 8 x 0.3 cm)

Tucson, Arizona, U.S.A.

Approximately 31°48'N, 110°48'W

Polycrystalline ataxite with flow pattern of olivine inclusions. HV 225±20.

Anomalous. 9.53% Ni, 0.45% Co, 0.09% P, 0.21% Cr, 0.8% Si, 0.94 ppm Ga, 0.05 ppm Ge, 2.1 ppm Ir.

The Ring mass is the best preserved. The Carleton mass has been significantly reheated artificially.

HISTORY

When first reported in scientific literature, by Velasco (1850) and LeConte (1852), the two Tucson iron meteorites had already been known to the local population of the then Spanish-Mexican southern Arizona for some time. The remarkable irons, which at one time were both in use as anvils, are now in the Smithsonian Institution, Washington. The ring-shaped Irwin-Ainsa mass weighs 621.5 kg, while the ear-shaped Carleton mass weighs 282 kg. The original weights are unknown but may be estimated to have been about 635 kg and 287 kg (about 1,400 pounds and 635 pounds), respectively; see page 1241. Previous estimates for the original masses are 688 kg and 287 kg (Hey 1966).

Much has been written about these meteorites, but it is only fair to say that very little more is known of the circumstances and place of discovery now than in 1850. Excellent reviews have been presented by Fletcher (1890b), Wülfing (1897: 367), Cohen (1900e; 1905), Farrington (1915: 460) and McGough (1943; 1944) to which the reader must refer for detailed information. Here I shall only quote and discuss a few of the original reports, as these are felt to be pertinent to the history of the masses and to contain valuable information as to the sites and dates of discovery. Numerous other reports exist, but in my opinion they are based upon second- and third-hand information and, consequently, best omitted. Some, e.g., the contributions by Santiago Ainsa, appear unreliable and are apparently improved upon to draw attention to the Ainsa family.

The first record is the following, which was originally in Spanish and consequently unnoticed for a long time.

> Between the presidio of Tucson and Tubac is a mountain range called Sierra de la Madera and (a pass called) Puerto de los Muchachos. In it are several enormous masses of native iron, and many have rolled to the foot of the said sierra. One of the masses, of a moderate size, was transported to Tucson and has stood for many years in the plaza of the said presidio. (Velasco 1850.)

Tubac – until 1751 an Indian village – is believed to have been the first permanent white settlement in Arizona; it was made a presidio (i.e., the site of a garrison) by the Spanish after the Pima Indian revolt in 1751. The Indian

Figure 1798. Tucson. The Ring specimen, or Irwin-Ainsa mass, now weighing 621.5 kg, in the old exhibition rooms of the Smithsonian Institution. (To the left, the Casas Grandes mass, to the right a Canyon Diablo mass). S.I. neg. 15720.