troilite and daubreelite, each 1-5 μ thick. When different troilite-daubreelite nodules in the same section are compared, the daubreelite lamellae show random orientation, i.e., the troilite orientation with respect to the parent austenite crystal is also random.

A few troilite-daubreelite intergrowths have assumed plate shapes and reach dimensions of 500 x 1 μ in cross section. They are enveloped in 1-2 μ wide creamcolored austenite, bordered on either side by 10-15 μ wide martensitic-bainitic zones.

No silicates, graphites or carbides were detected in the sections.

Tlacotepec is a nickel-rich ataxite of group IVB which is closely related to Iquique, Hoba and Cape of Good Hope. However, it appears to be slightly less weathered than these.

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

2,400 g full slice (no. 872, 40 x 16 x 0.8 cm; Figure 2 in Nininger 1931d).

Tocavita. See Salt River

Toconao. See Imilac (in the Supplement)

Tocopilla. See North Chile (Tocopilla)

Toluca, Mexico
19°27'N, 99°35'W; 2700 m

Polycrystalline, coarse octahedrite, Og. Bandwidth 1.40±0.20 mm. Neumann bands. HV 235±20.

Group I. 8.14% Ni, 0.49% Co, 0.16% P, 0.7% S, 70 ppm Ga, 246 ppm Ge, 1.9 ppm Ir.

Synonyms: Xiquipilco, Michigan, Amates, Tejupilco, Tacubaya and others.

HISTORY

The important Toluca shower comprises many thousands of fragments which have been recovered from a rather small area on the hillsides around the village of Xiquipilco (present name Jiquipilco), which is situated in a remote branch of the Toluca Valley network some 25 km north-northeast of Toluca. The cumulative weight of all specimens in registered collections is about 2,100 kg, but it is quite certain that much more material has been found and distributed. However, the estimate that 22 tons of material has been shipped out of Mexico before 1929 (Nininger 1952b, based upon interviews in Mexico) appears exaggerated. Before 1850 very little material from the Toluca fall had been acquired in the U.S.A. or Europe. Since then, starting with Krantz (1857), major collecting activities have occurred at intervals: Ward was active from 1890 to 1904, Foote about the same time, and Nininger in 1929 and

1952. It is likely that these collectors more or less absorbed the specimens discovered by the immediately preceding generation while they were tilling fields. It may be estimated that Kranz, Ward and Foote purchased 100, 500 and 300 kg, respectively, while Nininger (1952b) reported that he acquired 325 and 180 kg in 1929 and 1952, respectively. If we add to this the weight of the collection of specimens in Mexico City, i.e., about 900 kg which has not passed through the hands of the foreign collectors, and an additional 500 kg representing the material collected by Humboldt, Stein, Burkart and minor dealers, we end up with a total of about 2.8 tons as an estimate of what has actually been removed from the Toluca region. To this we must add the numerous fragments which have been forged into agricultural implements or have otherwise been lost, having been utilized by the local population "from time immemorial" (Ramirez, as quoted by Fletcher 1890a: 165). It will be understood that we only have very vague ideas as to the total amount discovered. It appears however, that the area is still yielding material, as the erosion on the hillsides cuts farther down and as the soil is worked. Electronic devices have apparently not yet been taken into use in the search for fresh material.

Various reviews of the Toluca fall have appeared. The best are, in order of publication date, Chladni (1819: 339), Ramirez (1831), Partsch (1843: 99), Burkart (1856: 297), Rose (1864a: 60), Fletcher (1890a: 164), Farrington (1915: 436), and Nininger (1952b). In addition, Buchner (1863: 139), Wülfing (1897: 357), and Hey (1966: 483) have bibliographies comprising most of the relevant literature.

Toluca first came to be known as a meteorite locality in 1784 (Gazeta de Mexico, as quoted by Chladni 1819: 339). The natives of Xiquipilco searched for the iron fragments after each new rainstorm, and they needed no other supply of iron for the forging of their agricultural implements. Ramirez (1831) reported, "The Indians of Xiquipilco collect what they can, for it is not abundant. The owners of the haciendas of Indege and Santa Isabel

Figure 1760. Toluca (Institute of Geology, Mexico City, no. 67). A 13.4 kg weathered mass which is typical of the medium-sized fragments from the strewnfield. Ruler is 10 cm. See also Figure 23.

barter for it with the Indians who chance to find it, generally at the beginning of the rains, when it becomes visible among the soil. The Indians of Xiquipilco make spades and axes of the iron, and the owners of the said haciendas use it for plows. About the year 1776, I went to Xiquipilco to see with my own eyes the famed native iron. I found two smiths established in the town who worked the native iron; and in my sight they forged it and worked it into the shape demanded of them." To this may be added that Ward (1900: 29) acquired several kilogram-sized masses which had been in use as pounding stones, while Nininger & Nininger (1950: 120) acquired specimens that had been in use for roughening the grinding surfaces of their metates (millstones). Nininger (1933c: figure 33) was even fortunate enough to secure a 3.96 kg barretta, a Mexican crowbar, which allegedly had been forged in the village from meteoritic iron.

From the very beginning it has been well-known that the meteorites did not actually come from Toluca but from the village of Xiquipilco 25 km further north-northeast (see, e.g., Chladni 1819: 339; Burkhart 1856: 297). The two names, therefore, occur as synonyms together with a host of other less well-known names. Nininger and Glen Huss of The American Meteorite Laboratory, Denver, Colorado, have in all their publications and sales lists consistently preferred the Xiquipilco name for Toluca. The attractiveness of the precise location name is, however, more than counterbalanced by the fact that by far the major part of the literature applies the name Toluca. All major collections and relevant catalogs use Toluca, and the use of the name Xiquipilco must, therefore, be discouraged. We have several other meteorites which, with equally good right, could be renamed after their exact location, but where common usage has established a less precise geographic location as the name. The Cape York meteorites were, thus, found 50 km east of Cape York near the Savigsavik village, and the Krasnojarsk pallasite was found 200 km south of Krasnojarsk, between the Ubei and Sisim Rivers. The dropping at this late date of well-established — and easily spelled — names would serve little purpose. After

all, the meteorite names are names only and all workers in meteoritics should know that they do not necessarily specify the exact locality, while they do specify the exact meteorite.

Nininger (1952b) published the results of his two visits in 1929 and 1952 and gave several photographs of the general area, which is entirely volcanic with rocks and tuffs mainly of Tertiary Age. His topographical reconnaisance, supplemented with interviews with the local population, indicates that the strewnfield is a broad ellipse with the village plaza of Xiquipilco near the center. The long northeast-southwest axis is about 5 km, the other axis perhaps 4 km, estimating from the available field data. It appears that no craters occur; a few circular structures turned out to have a volcanic origin.

The first figure of a polished and etched section was produced by Schreibers (1820: 78 and plate 8) who owned a fragment which had been deformed, and perhaps heated, by a blacksmith. Other early descriptions were given by Partsch (1843: 99), Wöhler (1856), Reichenbach (1858-62, in numerous places), Brezina (1896: 274) and Cohen (1894; 1899; 1900a). Excerpts of some of these papers are translated into English in Farrington (1915: 436).

Fraenkel & Tammann (1908) conducted various re-heating experiments on Toluca specimens. Merrill (1916a: plate 35) produced a photomacrograph, and Böggild (1927), from crystallographical examinations, supported Young's (1926) conclusion as to the relative orientation of taenite and kamacite. Nininger & Nininger (1950: plates 3, 6, 8, 18) showed sections through various Toluca specimens and noted individuals with twinning. Axon & Faulkner (1967) further examined one of the twinned specimens. Buddhue (1957: 126) presented an analysis of the oxidized crust. Beck (1951) believed he had identified lawrencite, but the documentation is insufficient and the chloride found (0.96%) had presumably been introduced by perco-lating ground water.

El Goresy (1965) studied the troilite-graphite nodules and presented typical photomicrographs. He identified clinoenstatite and olivine in myrmekitic intergrowths with troilite, and also found sphalerite and an unidentified sulfide in minor amounts in the troilite. Laspeyres (1897) described zircon occurring in insoluble residues from Toluca, but later investigators assumed that the zircon had been located in the oxide crust and was of terrestrial origin. Marvin & Klein (1964) proved, however, that small grains are present in some troilite nodules and found the optical properties of an 0.08 mm long crystal to correspond to unmetamict zircon. Frondel & Klein (1965) described ureyite, $Na\,Cr\,Si_2\,O_6$, a new meteoritic pyroxene; evidently another confirmation of an observation by Laspeyres (1897), who had called the emerald-green mineral kosmochlor. The bulk chemical composition of four differ-ent troilite nodules was examined by Nichiporuk & Chodos (1959).

Feller-Kniepmeier & Uhlig (1961) produced nickel profiles across typical plessite fields, and further electron

Figure 1761. Toluca (Institute of Geology, Mexico City, no. 69). An 11 kg irregular mass from the Toluca strewnfield. Scale bar approximately 4 cm.

microprobe work was reported by Massalski & Park (1962), Wood (1964), Short & Andersen (1965) and Goldstein (1967). Reed (1965b; 1969) reported a rather inhomogeneous kamacite with 7.0-7.6% Ni and 0.09% P in solid solution. Lovering & Parry (1962) included Toluca in their thermomagnetic reconnaissance.

Chackett et al. (1953) presented helium data from various specimens; further noble gas data have been provided and discussed by Schaeffer & Zähringer (1960), Fisher & Schaeffer (1960), Signer & Nier (1962), Bauer (1963), Hintenberger & Wänke (1964) and Fisher (1965). The potassium-argon age of about 6.3×10^9 years (Müller & Zähringer 1966) is now believed to be too high, mainly due to potassium leaching during terrestrial exposure (Rancitelli & Fisher 1968; Kaiser & Zähringer 1968). Rubidium-strontium datings (Burnett & Wasserburg 1967a) on diopside inclusions yielded the probably much more correct date of 4.6×10^9 years. A similar age had already been found by the osmium-rhenium method (Herr et al. 1961). Alexander et al. (1969) measured ^{128}Xe, ^{129}Xe and ^{130}Xe and the ratios of these, as determined by extraction from silicates at various temperatures. They concluded that

Toluca's silicates formed about 65 million years before the chondrites and the Shallowater achondrite.

Vilcsek & Wänke (1963) found a ^{36}Cl/^{39}Ar cosmic ray exposure age of 600±40 million years, while Chang & Wänke (1969) by the ^{10}Be/^{36}Ar method found 570±100 million years. The same authors estimated the terrestrial age to be about 60,000 years, but quoted large limits of uncertainty.

Several papers have appeared, examining the isotopic composition of a large range of elements. Of the more interesting are those of Starik (1960) and Ostic (1966) who found that the lead isotopes correspond to a primordial composition, with little contamination of radiogenic lead isotopes, indicating very low amounts of uranium and thorium. Fossil fission tracks in diopside were studied by Fleischer et al. (1965) and were shown to be due to spontaneous fission of extinct plutonium-244, and to a much smaller degree to uranium. No detectable gamma radioactivity was found by Rowe et al. (1963), who attributed the result to the fact that the major gamma ray emitting isotopes, ^{46}Sc, ^{48}V, ^{51}Cr, ^{54}Mn, ^{56}Co, ^{57}Co, ^{58}Co and ^{60}Co, produced by cosmic rays in meteorites are short-lived (half-lives $\leq$ 5.27 years) and had decayed below
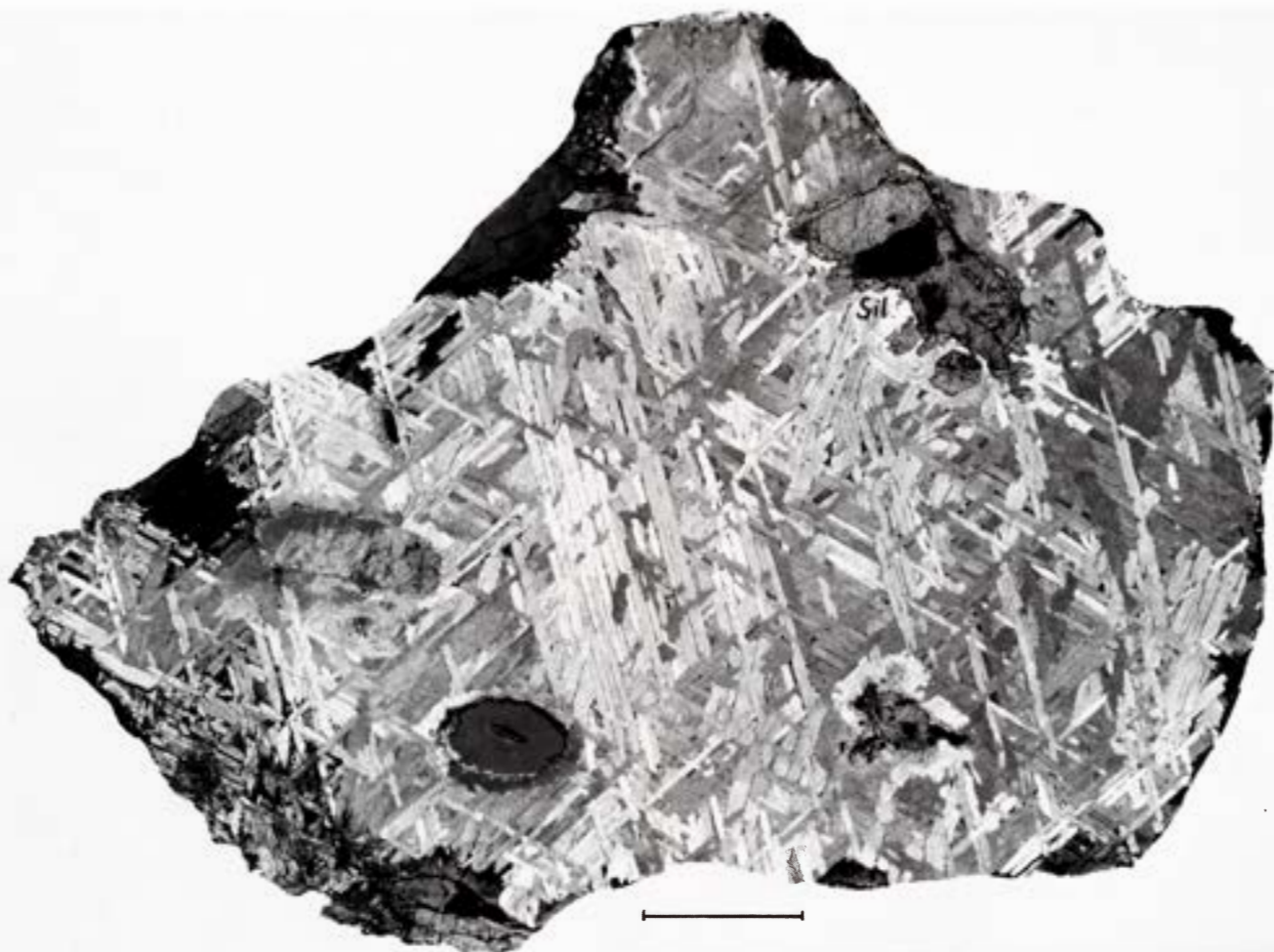

Figure 1762. Toluca (U.S.N.M. no. 931). A 2.0 kg full slice showing the typical group I structure with a number of troilite-graphite nodules. One of them, at Sil, with a large angular silicate inclusion. Ragged rims of schreibersite and cohenite, and subdivided wide rims of swathing kamacite. Deep-etched. Scale bar 30 mm. S.I. neg. 331.

the limit of detection between the time of fall and the time of measurement.

COLLECTIONS

Mexico City, Institute of Geology, (535 kg, maximum about 400 kg), Mexico City, Museum de Chopo (250 kg, maximum 150 kg), Chicago (227 kg, maximum 46.0 kg), Vienna (178 kg, maximum 52.9 kg), Tempe (153 kg, maximum 90.8 kg), Hamburg (107.6 kg, maximum 107 kg), Washington (102 kg, maximum 30.4 kg), London (94 kg, maximum 74.1 kg), Nantes (69 kg), Amherst (62.5 kg, maximum 42.7 kg), Bonn (61.4 kg, maximum 12.5 kg), Berlin (54.8 kg, maximum 33.0 kg), Budapest (35.8 kg, maximum 17.0 kg), Prague (32.1 kg, maximum 18.3 kg), Harvard (21.2 kg, maximum 18.4 kg), Tübingen (15.5 kg), Paris (13.8 kg), Vatican (10.0 kg), New York (9.6 kg), Calcutta (7.7 kg), Naples (7.6 kg), Albuquerque (6.1 kg), Göttingen (5.2 kg), Leningrad (4.3 kg), Copenhagen (2.2 kg), Stockholm (1.7 kg), Uppsala (1.6 kg), Oslo (1.3 kg), Helsinki (0.6 kg). Specimens are also to be found in numerous other public and some private collections. There are many mislabeled Toluca specimens. One of the most intriguing cases was discovered by the author in 1965 in the collection of the late F.A. Paneth which was acquired by the Max Planck Institute at Mainz. A 13 kg endpiece, apparently from a mass larger than 100 kg and labeled "Toluca, Calvert's Iron," was found to have a structure deviating from that of genuine Toluca material. Later research revealed that the beautiful 26.1 kg slice (No. 47192) in the British Museum, also labeled Toluca, had been cut from the same mass; see, e.g., Chackett et al. (1953). Assisted by Dr. Hutchison and the staff of the British Museum, the author was able to trace the origin of the controversial material back to 1873. It has been decided to enter the material as an independent new meteorite, Paneth's Iron; see Supplement.

DESCRIPTION

The largest known individual is in Mexico City in the hall of the Institute of Geology. It measures 46 x 44 x 44 cm and weighs approximately 400 kg. Another large specimen, of 150 kg, is in the now abandoned Museum de Chopo, also in Mexico City. In the list above I have noted the weight of the largest individuals in the major collections. However, the largest number of specimens probably fall in the 0.5-5 kg range, and the smallest recognizable masses are generally 0.05-0.2 kg in size. The parent meteorite evidently disintegrated thoroughly in the atmosphere and spattered the slopes with thousands of fragments ranging from 0.1-400 kg in size. A somewhat comparable event produced the Magura shower and, in recent time, the Sikhote-Alin shower. While the impact holes of the Siberian meteorite may still be seen, those of Toluca and Magura appear to have been removed by erosion long ago. All specimens come from the cultivated small fields around Xiquipilco or from the ravines and, mostly dry, streams of the area. Since the masses have been buried, they are corroded and often covered with 5-10 mm thick oxide-shales. In places they are disintegrating along octahedral planes so that the Widmanstätten structure becomes exposed. One of the largest specimens in Washington, No. 3376 of 28.9 kg, is a typical example of the unattractive weathered specimens. Such masses may have lost anything between 2 and 20 mm of the surface during the terrestrial exposure.

In some instances the masses may, however, be surprisingly well-preserved. Number 858A of 1.36 kg is a typical, angular individual measuring 10 x 7 x 4 cm and only covered with 0.1 mm thick terrestrial oxides. Upon cutting, a weathered fusion crust, 0.03-0.1 mm thick, was found in places, and a heat-affected α_2 zone was present along most of the circumference. The α_2 zone was very narrow, ranging from 0.4-0.2 mm only, but micromelted phosphides were present in the exterior part, and the α_2 zone was not wider where the overlying fusion crust was

TOLUCA – SELECTED CHEMICAL ANALYSES

Smales et al. (1967) reported an extensive set of trace-element determinations, but it appears that their specimen was some group IIIA meteorite rather than Toluca. Hawley's asterisk-marked value below includes all platinum metals.

| References | percentage | | | ppm | | | | | | | | |
	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Hawley 1939	8.15											14.7*
Goldberg et al. 1951	8.31	0.53							55.2			
Lovering et al. 1957		0.45				4.9	125		61	170		
Nishimura & Sandell 1964								33				
Nichiporuk & Brown 1965											2.0	6.5
Moore et al. 1969	8.02	0.49	0.16	240	20		160					
Wasson 1970a	8.07								70.6	246	1.8	
De Laeter 1972									71.0			
Rosman 1972								33				

preserved. This seems to indicate that, after fragmentation, the mass had only a limited, rather low velocity flight in the atmosphere, insufficient to produce the normal wide α_2 zones. The hardness of the α_2 phase is 190±5; it drops to 175±5 at the transition to the unaffected interior which has a hardness of 235±15 (hardness curve type I).

Etched sections display a coarse Widmanstätten structure of straight, long ($\frac{L}{W} \sim 15$) kamacite lamellae with a width of 1.40±0.20 mm. Only in rare cases are the kamacite lamellae visibly bent. Superficial distortion is seen on some of the 0.4-2 kg masses used as hammer stones, while a more penetrating deformation is present in U.S. National Museum No. 347 and Tempe Nos. 128.177 and 128.178 (two halves of the same mass of approximately 0.8 kg). The Tempe specimens show large scale faulting of the lamellae and several subparallel shear zones across the sections. The schreibersite and cohenite crystals are locally displaced 1.5 mm by shear, and the Neumann bands are twisted. The deformation is preterrestrial and may be due to the breakup in the atmosphere which in other irons, such as Canyon Diablo, Gibeon, Glorieta Mountain, Kaalijärv and Henbury is known to produce violent distortions. The reason that no more deformation is present in Toluca's metallic parts appears to be that the major amount of fissures preferred to follow paths along the large number of brittle and weak inclusions, such as schreibersite, troilite and graphite. In Gibeon and Henbury the major inclusions are troilite, and they occur with a much lower frequency than in Toluca, so that a significant part of any fracture zone will have to proceed by straining and necking of the metallic matrix.

Some Toluca specimens, notably Tempe No. 128 ee, are polycrystalline. This particular sample shows a 13 cm long, curved grain boundary between two original austenite crystals, each 5-15 cm in size. The boundary is rich in elongated bodies and other precipitates such as schreibersite and graphite. The two crystals appear to be randomly oriented with respect to each other. It is likely that the fragmentation in the atmosphere followed, to a significant degree, the mineral-rich grain boundaries, which may already have been partly cracked as the result of the early cosmic event when Toluca was dislodged from its parent body.
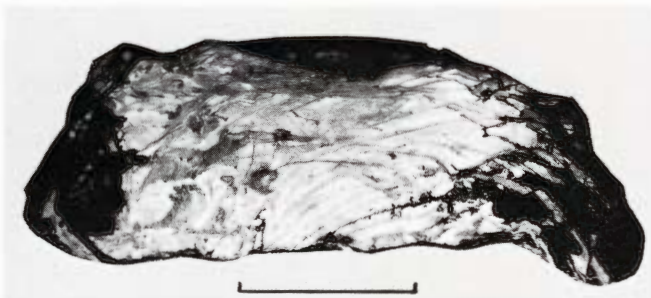
A few Toluca specimens show large austenite twins. This is the case with Tempe No. 128xx and London No. 1949, 1048, presented in figures by Nininger & Nininger (1950: plate 8) and Axon & Faulkner (1967: figure 2), and actually halves of the same original 1.5 kg mass. Parts of four twins may be identified, 20, 6, 30 and 35 mm wide, respectively, and with straight, rather inclusion-free boundaries. The twinning plane is, as usual, the $\{111\}$ plane of the cubic face centered structure.

The kamacite has subboundaries, richly decorated with 0.5-2 μ rhabdites. Neumann bands are common, and they are locally deformed. Near the surface the deformation may be excessive and some necking of the metal, with several lenticular deformation bands, becomes apparent. These are the microscopic indications of plastic deformation before final fracturing in the atmosphere. The hardness of the kamacite ranges from 205 to 260 with the bulk of the measurements giving 235±15. The hardness is that of a plastically worked kamacite and not necessarily due to any excessive shock.

Taenite and plessite cover about 15% by area, mostly as comb plessite and as taenite ribbons and wedges that show various stages of decomposition. One of the characteristics of Toluca are the tarnished taenite bands (HV 320±25) which – on long stretches – are decomposed to pearlitic textures (HV 310±30). The hardness of the pearlite decreases with increasing thickness of the subparallel gamma lamellae (0.2-2 μ thick). Locally, pearlitic areas interchange with spheroidized areas with gamma spherules 2-20 μ across. Some fields have a significant proportion of carbide and approach – in texture – the carbide roses described in Staunton, Mungindi and many other irons. In

Figure 1763. Toluca (Tempe no. 128.177). One of the rather rare distorted Toluca fragments. The deformations and shears were caused by the breakup of the main body in our atmosphere. Scattered cohenite crystals are visible in the kamacite lamellae and in the black corroded surface zone. Etched. Scale bar 20 mm.
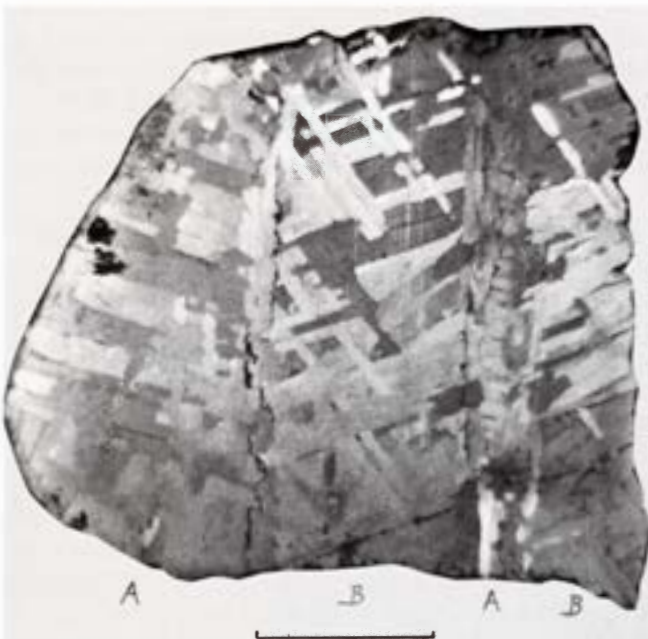

Figure 1764. Toluca (Tempe no. 128xx). A 925 g section through a twinned sample. The precursor taenite grain had the twin parts A, B, A, B. Each part transformed to the corresponding Widmanstätten pattern, one $(111)_\gamma$ plane being mutually common and parallel to the twin plane. Etched. Scale bar 21 mm.

Toluca they may completely fill plessite wedges up to 3 x 1 mm in size with an intricate intergrowth of carbide, kamacite and 1-5 μ wide lamellae and spherules of taenite. Depending on the actual ratio of these components, the hardness ranges from 700 to 950; it appears that the carbide contains 4-5% Ni in contrast to the massive cohenite discussed below. Scott (1971) has shown that the carbide is a new mineral, haxonite, $(Fe,Ni)_{23}C_6$.

A typical taenite field will have a tarnished taenite rim with carbon in solid solution (HV 320±25). Then follows light-etching acicular martensites which may be extremely hard (HV 410-585). The interior is often partially decomposed, exhibiting pointed kamacite plates, 1-5 μ wide.

Schreibersite occurs as skeleton crystals up to 30 x 5 x 1 mm in size. They are often brecciated and have a hardness of 920±20. Schreibersite is common as 10-100 μ wide grain boundary precipitates and as 5-50 μ irregular blebs inside the plessite. Rhabdites are ubiquitous as 2-15 μ tetragonal prisms, except in 1 mm wide zones around the primary skeleton crystals.

Cohenite is present as 4 x 0.5 mm rounded, cavernous crystals, located centrally in the kamacite lamellae. They are, however, not as common as in Cosby's Creek, Canyon Diablo and Odessa. Cohenite is also present as rather continuous 0.1-0.5 mm wide rims around most of the larger schreibersite crystals. The cohenite shows the usual windows of kamacite, taenite and schreibersite; it is not under decomposition to graphite and has a hardness of 1065±40. Various studies have shown that the coarse cohenite crystals contain 1.4-1.7% Ni.

Troilite and graphite occur as mixed nodules that range from almost 100% troilite to 100% graphite. The troilite is monocrystalline or composed of 5-10 mm large units; it shows some twinning or undulatory extinction from plastic deformation, but is rarely, if ever, micromelted. Its hardness is 255±20. Daubreelite lamellae are only present in very minor amounts. An isotropic mineral, somewhat darker blue than daubreelite, occurs as 25-100 μ frayed units, frequently at the very edge of the troilite. It is possibly the same mineral which El Goresy (1965: 1143) preliminarily described as a new mineral $(Fe,Mn,Mg)_x Cr_y S_z$. The graphite forms almond-shaped nodules which are composed of a mixture of poorly defined cliftonite units and palmette-shaped graphite bundles with horsetail extinction. The compound nodules generally have a troilite-rich center and a graphite-rich rim, but rhythmic, more or less concentric shales of graphite also occur within the troilite. A typical nodule, 15 x 10 mm in size, is composed of two troilite crystals, slightly tilted with respect to each other. The graphite, covering about 10% of the area, is concentrated along the rim as a continuous, laminated sleeve, 50-200 μ thick. In places it increases to 5 x 1 mm or 0.5 x 0.2 mm irregular pockets, still in contact with the rim. Everywhere, the graphite forms cliftonite-like skeleton crystals, 10-50 μ across, which protrude inwards into the troilite.

The troilite-graphite nodules cover 15% by area of some large sections, e.g., on Amherst's 42 kg specimen. In order to reach an estimate of the bulk sulfur content an arbitrarily selected number of Toluca sections were measured. A total of 55 nodules with a combined area of 106 cm^2 were encountered on 3,100 cm^2, indicating an average sulfur content of about 0.7%. Some nodules may be very large, e.g., 5 x 3 x 2 cm in size. In rare cases they contain conspicuous silicate fragments, similar to what is observed in Campo del Cielo. The U.S. National Museum specimen No. 931 thus shows a 16 x 8 mm angular silicate fragment embedded in troilite. The silicate fragments appear to be aggregates of olivine, diopside and, to a minor extent, plagioclase, which in a complex way mutually enclose each other. In addition, reports indicate that orthoclase, zircon and ureyite are present. Laspeyres (1897) also reported augite and quartz, but these occurrences have never been substantiated. Native copper may occasionally be found as beautiful red, easily tarnishing specks. They are 0.1-0.3 mm in size, irregular, and usually located at the troilite rim; they appear to be of primary, not terrestrial, origin.

The troilite-graphite nodules have served as a nucleating substrate for schreibersite and cohenite. These minerals form 0.5-1 mm and 0.1-0.5 mm thick continuous, but ragged, rims around most nodules. They, in turn, are followed by a 1-2 mm rim of swathing kamacite, as are the schreibersite-cohenite skeleton crystals. The swathing kamacite shows a nickel- and phosphorus gradient and is depleted in rhabdites; a hardness gradient is present showing a peak ($\sim$ 250) midway in the rim.

Toluca contains several preterrestrial fissures. On No. 858 there is a branching system, several centimeters long and partially filled with an unusual component. A close examination reveals that the fissures mainly follow 0.1-0.5 mm wide schreibersite crystals and that these — in varying degrees — are micromelted and solidified to a mosaic of 1 μ grains (HV 385±20). The immediate kamacite surroundings are transformed to α_2 or annealed and exhibit hardnesses as low as 115. Evidently some violent event concentrated the energy in the grain boundary schreibersite, partially melted it and opened up the fissures. Whether the event was associated with the atmospheric breakup or dates back to cosmic collisions is difficult to decide.

Corrosion has, of course, had easy access to such preterrestrial cracks, and they are partly filled with limonitic products. Corrosion also selectively attacks the α-phase of the plessitic and pearlitic areas, and the near-surface rhabdites are enveloped by halos of corrosion products. The troilite is beset with 1-3 μ wide pentlandite veinlets.

Toluca is remarkable for its relatively small range of structures, compared to e.g., Canyon Diablo, Magura, Gibeon and Henbury. The Tempe specimens Nos. 128.177 and 178 appear to represent the extreme in deformation.

Toluca is a polycrystalline, inclusion-rich coarse octahedrite which, structurally, is closely related to Bischtübe, and more distantly to Odessa, Canyon Diablo and Campo

del Cielo. Common characteristics are the graphite-troilite nodules, frequently rich in silicate inclusions, and the cohenite crystals. As a result of the rich carbon concentration, the taenite and plessite show distinct pearlitic morphologies and in places even exhibit intricate intergrowths of plessite with carbide, the so-called carbide roses (haxonite). Chemically, Toluca is a normal member of group I, forming the most important of the 8% Ni members.

See also the entries that follow, as well as Cuba and Southern Arizona.

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

735	g individual, "hammer stone" (no. 347A, 7 x 6 x 4 cm)
30.4	kg individual, divided into 28.1 kg and 1.28 kg (no. 396, 36 x 18 x 12 cm)
4.13	kg endpiece (no. 714, 21 x 17 x 3 cm)
1.36	kg individual (no. 858A, 10 x 7 x 4 cm)
2.00	kg full slice (no. 931, 23 x 16 x 1 cm)
17.7	kg individual (no. 1160, 22 x 16 x 13 cm)
28.7	kg individual (no. 3376, 31 x 17 x 17 cm)
About 26	kg individuals, slices and part slices (nos. 16, 75, 204, 396, 517, 638, 704, 708, 792, 801, etc.)

Toluca (Amates fragment), Morelos, Mexico
18°30'N, 99°22'W

Coarse octahedrite, Og. Bandwidth 1.40±0.25 mm. Neumann bands. HV 245±15.

Group I. About 8% Ni and 0.2% P, judging from the structure.

No doubt a transported fragment of the Toluca shower.

HISTORY

A small individual was found in a mineral collection, coming from Rancho de los Amates, in the state of Morelos (Castillo 1889: 3). Fletcher (1890a: 169) suggested that it was a transported mass, but did not see the iron. Ward (1904a: 3) acquired a 3 g fragment and gave the coordinated quoted above. Nininger cut 62 g from the mass in 1929 and suggested that it was, in fact, a Toluca fragment (Nininger & Nininger 1950: 28). Haro (1931: plate 19) reproduced a photograph of the exterior.

The iron has apparently never been described. On a visit to Mexico City in 1967 the present author examined the piece. According to an old label, the original weight was 327 g; but on three occasions (Ward, Nininger and Haro) material had been cut from it, leaving about 225 g. The macrostructure was verified as being the same as that of the specimens in London, Tempe and Washington.

COLLECTIONS

Mexico City (225 g), London (29 g), Tempe (28 g), Washington (14 g), Chicago (3 g).

ANALYSIS

No analysis has been performed, but the author would estimate about 8% Ni and 0.20% P, from structural observations.

DESCRIPTION

The original Amates individual measured approximately 6 x 4 x 4 cm and weighed 327 g. It is rather smoothly rounded, mainly due to terrestrial weathering that also covered the mass irregularly with a 1 mm thick crust. The fusion crust and heat-affected rim zone are lost, and corrosion penetrates along grain boundaries in 100-500 μ wide, limonitic veinlets.

Etched sections display a coarse Widmanstätten structure of straight, long ($\frac{L}{W} \sim 15$) kamacite lamellae with a width of 1.40±0.25 mm. The kamacite has subboundaries decorated with 1 μ phosphides and shows Neumann bands and, locally, more heavy distortion with deformation bands. The microhardness is 245±15, corresponding to a cold-worked kamacite. Taenite and plessite cover about 15% by area, mostly as comb, net and acicular plessite. The comb plessite fields may reach 2 x 2 mm in size, and taenite wedges in these fields may have martensitic or duplex interiors. The taenite frames and ribbons etch brownish because of carbon in solid solution. Near corroded fissures the taenite etch grayish, evidently due to incipient alteration caused by oxidation. The acicular taenite has numerous pointed kamacite needles, 2-10 μ wide.

Schreibersite occurs as 25-100 μ wide grain boundary precipitates and as 5-20 μ blebs inside the plessite fields. Inside the coarsest comb plessite the schreibersite may even reach sizes of 100 x 50 μ. Rhabdites are ubiquitous as sharp prisms, 5-15 μ in cross section. All the phosphides are brecciated or sheared, due to considerable plastic deformation.

Troilite, cohenite and graphite were not observed on a combined area of 32 cm².

The description above fits in every detail the inclusion-poor variety of Toluca. Furthermore, since the state of corrosion corresponds to Toluca, it is concluded that Amates is one of the numerous small Toluca fragments which, undeserved, has become listed as an individual fall.
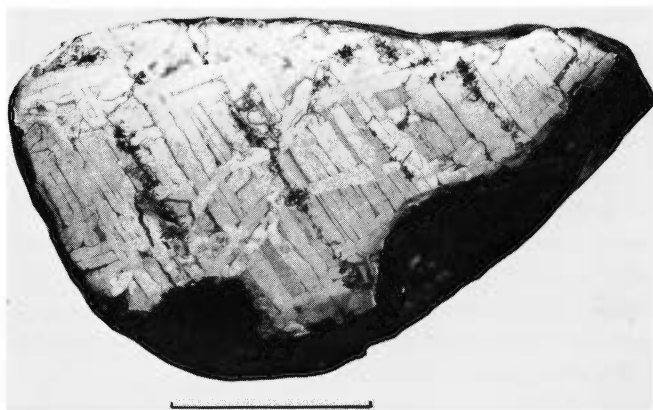

Figure 1765. Toluca (Institute of Geology, Mexico City, no. 38). The Amates fragment now weighs about 225 g. It is a typical coarse octahedrite of group I, however, it only contains few inclusions on the exposed section. Black diffuse lines are corrosion filaments that developed on the surface after the section was prepared. Deep-etched. Scale bar 20 mm.

Rancho de los Amates is about 100 km south of Xiquipilco, the village around which the Toluca meteorites are found.

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

14 g slice (no. 912, 4 x 1.9 x 0.5 cm, by exchange from J.C. Haro 1935)

Toluca (Michigan fragment)

Coarse octahedrite, Og. Bandwidth 1.45±0.20 mm. Neumann bands. HV 220±15.

Group I, judging from the structure. About 8.0% Ni, 0.20% P, 0.05% C.

A 360 g individual which appears to be a mislabeled Toluca specimen.

HISTORY

A small individual of 360 g was found unlabeled in the museum of the University of Michigan (S.H. Perry: Meteorite Collection, Adrian, 1947: 13). It was provisionally listed as "Michigan Iron" in the records of the U.S. National Museum and in Hey's Catalog (1966: 304), but no information as to date of find or locality could be found. It was sliced in 1947, and 110 g was donated to the U.S. National Museum.

COLLECTION

Washington (110 g).

ANALYSIS

None. From the structure, the present author would estimate 8.0% Ni, 0.20% P, 0.05% C.

DESCRIPTION

The mass appears to have been a small individual of 360 g with the overall dimensions 5 x 4 x 4 cm. It is weathered and locally covered with 1.5 mm of terrestrial oxides. Nevertheless, the original fusion crust is distinctly visible locally in sections, and it is underlain by an unusually thin, 200 μ wide zone of α_2. Micromelted phosphides are present in the exterior 50% of this zone.

Etched sections disclose a coarse Widmanstätten structure of bulky ($\frac{L}{W} \sim 15$) kamacite lamellae with a width of 1.45±0.20 mm. The kamacite has subboundaries, decorated with 1-2 μ phosphides; and Neumann bands are abundant. The microhardness (100 g Vickers) is 220±15. Taenite and plessite cover about 15%, partly as comb plessite, partly as pearlitic and spheroidized fields. The taenite rims are stained – except in the heat-affected rim zone, – and many martensitic interiors have irregular, dark-etching patches of high carbon concentration.

Schreibersite is present as scattered 1-2 mm skeleton crystals and as 10-50 μ wide grain boundary precipitates. Rhabdites are ubiquitous as sharp prisms, 1-20 μ in cross section. Plastic deformation of the metallic matrix has resulted in considerable brecciation and shearing of the phosphides.

Troilite occurs as an 8 x 5 mm nodule with a 100 μ wide schreibersite rim. The troilite is monocrystalline and contains a few 300 x 30 μ bars of an unidentified, bluish isotropic, opaque mineral. The troilite is veined by pentlandite from terrestrial corrosion.

Cohenite and graphite were not present on the sections examined (a combined area of 70 cm^2), but they are expected to be present in other sections.

"Michigan" is clearly not a fragment of any of the other known Michigan irons. It is hardly even related to any other iron from the United States. It does, however, closely correspond in size, structure, hardness and state of corrosion to Toluca; and it also shows a little fusion crust and a uniquely thin heat alteration zone, something which is typical of the small Toluca individuals and absent in other individual falls. There is, therefore, little doubt that "Michigan," surprisingly, is a purchased specimen of Toluca, that later lost its label by carelessness. [J.T. Wasson, personal communication 1974: Group I with about 8.16% Ni, 69.7 ppm Ga, 251 ppm Ge and 2.2 ppm Ir. This supports the conclusions above].

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

62 g slice (no. 1446, 5 x 4 x 0.4 cm)
48 g slice (no 1680, 5 x 4 x 0.3 cm)

Toluca, (Tacubaya) Mexico State, Mexico

Approximately 19°21'N, 99°5'W

A mass of about 7 kg was found in 1931 near Tacubaya (Nininger 1933a; Nininger & Nininger 1950: 97, plate 10). It has never been described, but Nininger suggested, in 1950, that Tacubaya might be an artificially reheated Xiquipilco specimen (i.e., Toluca specimen). This is fully supported by the present examination.

COLLECTIONS

London (994 g), Washington (405 g), Tempe (401 g), Chicago (276 g). Nininger originally acquired an endpiece

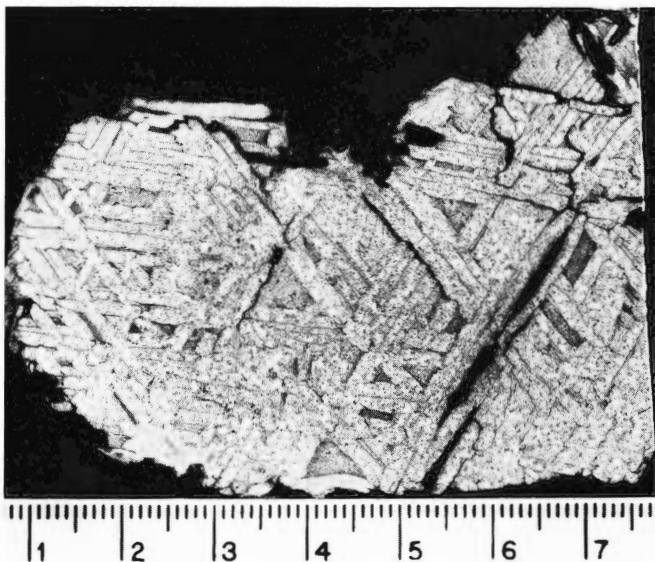**Figure 1766.** Toluca. The Tacubaya specimen (Tempe no. 115.1x). Artificially reheated Toluca sample with unequilibrated α_2 matrix and fissures with high temperature oxidation products. Deep-etched. Scale in centimeters. (Courtesy C.B. Moore.)

of about 2 kg which was divided into the listed samples. The repository of the remaining 5 kg is unknown.

DESCRIPTION

The following is based upon a study of the two slices in Tempe (No. 115.1x, 401 g, 7 x 5 x 4 cm corner piece), and Washington (No. 1214).

To begin with, the material has all the primary macro- and microstructural details of typical Toluca samples: 1.40 mm bandwidth, 1-4 cm troilite nodules with minor silicate inclusions and with rims of schreibersite and cohenite, and 3 x 0.5 mm cohenite crystals centrally in some kamacite lamellae. The chemical analysis by Wasson is, within analytical and sampling error, identical to that of Toluca.

All structural elements of Tacubaya are, however, severely but inhomogeneously altered, due to a secondary reheating. The kamacite is transformed to unequilibrated serrated α_2 grains throughout the mass, suggesting peak temperatures above $750°$ C. The troilite is unmelted, but completely recrystallized to 0.1-1 mm angular blocks, the boundaries of which are mainly determined by preexisting corroded fissures. The cohenite is slightly decomposed and surrounded by 10-50 μ wide, optically unresolvable black zones of what appears to be fine martensitic-bainitic products. The terrestrial hydrated weathering products (limonite) are imperfectly decomposed by high-temperature reactions to lace-like intergrowths of metal and oxides.
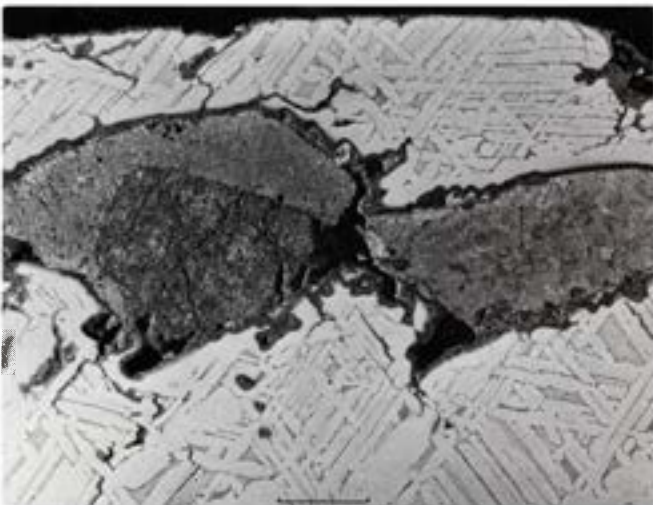
Nininger's assumption that Tacubaya is a Toluca specimen, artificially reheated and therefore difficult to recognize, is fully supported by the analysis and the structural details. The peak temperature was apparently $750\text{-}850°$ C, perhaps attained rather inhomogeneously through the mass.

Toluca (Tennant's Iron), Mexico

A few small samples, totaling less than 100 g, have for many years been listed in various catalogs as "Tennant's Iron, Coarse octahedrite. Found 1784," see, e.g., Prior (1927; 1953), Mason (1964), Horback & Olsen (1965) and Hey (1966). Practically nothing is known of this meteorite, not the origin, composition, nor the original size. According to Hey, who based his information on a note by Ward (1904a: 25), the samples were originally part of a mineral collection formed by Smithson Tennant (1761-1815, Professor of Chemistry at Cambridge). Hey suggested that the material was similar to the material labeled Agricultural College and acquired by H.A. Ward from Moscow in 1898. However, as discussed on page 248, the Agricultural College material is wrought iron while Tennant's Iron is certainly genuinely meteoritic — but of what origin?

The following specimens are preserved: Chicago (29 g), London (9 g), Berlin (9 g), New York (4.1 g).

The largest fragment is No. 1166 in Chicago, a 29 g wedge-shaped mass measuring 4.5 x 1.5 x 1.5 cm. It is slightly corroded, without fusion crust and heat-affected α_2 zones. It is a coarse octahedrite with a bandwidth of 1.4 ± 0.3 mm. The kamacite shows Neumann bands. Taenite and plessite cover 10-15% by area, as comb and net plessite fields and as acicular and martensitic wedges.

Figure 1767. Toluca. Tacubaya (U.S.N.M. no. 1214). Altered troilite-graphite nodules with black rims due to decomposed cohenite. Along the surface above, high-temperature oxidation products which are artificial and different from the genuine fusion crust. Deep-etched. Scale bar 10 mm. S.I. neg. 1365A.
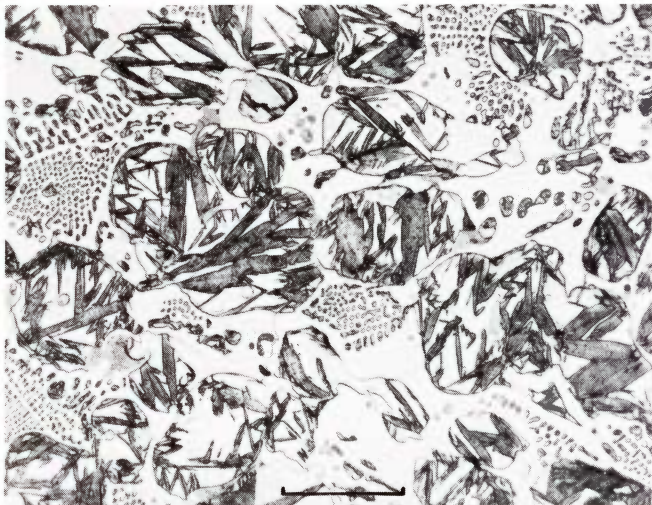
Figure 1768. Toluca. Tacubaya (Tempe no. 115.1x). An artificially fused cohenite-schreibersite aggregate that solidified with austenite dendrites ("rounded windows") in a steadite eutectic. The nickel- and carbon-rich dendrites transformed upon cooling to martensite, but retained austenite is common. Etched. Scale bar 30 μ.

TOLUCA (TACUBAYA) — SELECTED CHEMICAL ANALYSES

Reference	percentage			ppm								
	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Wasson 1971, pers. comm.	8.13								66.9	249	1.9	

Schreibersite is common as cuneiform skeleton crystals up to 10 x 5 mm in size, and as 10-100 μ wide grain boundary precipitates. Cohenite is common too, both as 0.2 mm wide rims around the large schreibersite crystals and as individual 3 x 0.4 mm rounded blebs centrally aligned in the Widmanstätten kamacite lamellae. The 9 g sample in Berlin (Klein 1906: 113; Wappler & Hoppe 1969: 379) is in all respects similar to the preceding one. It contains a considerable amount of cohenite and some graphite.

From the examination it must be concluded that Tennant's Iron is a coarse, inclusion-rich octahedrite of the resolved chemical group I. It is estimated to contain 8.0±0.3% Ni and 0.20±0.05% P. Graphite and cohenite are significant minerals.

With regard to its origin there are two possibilities: (i) either the iron is a fragment of another already registered fall, (ii) or it represents the major part of an independent fall. In the first case, which is by far the most plausible, a search must be made for a similar meteorite with which to compare it.

Toluca is one of the few candidates which is completely similar in macro- and microstructure and in corrosion characteristics. It was also the only coarse iron octahedrite known to Science when Professor Tennant, before 1815, worked on his collection. Moreover, Tennant's Iron is usually reported as having been discovered in 1784, which is the year accepted for the first report on the Toluca shower. The assumption that Tennant's Iron was originally acquired from Mexico is supported by a cursory remark by Reichenbach (1862b: 579) who had seen "a section of Tennant's Iron *from Mexico* in the University Collection at Berlin." As can be deduced from the works of Chladni (1819) and Schreibers (1820), a few small samples of the Toluca iron were in circulation and available for collectors when Tennant lived.

It must, therefore, be concluded that Tennant's Iron is a typical Toluca fragment that lost its label at some early date.

Tombigbee River, Alabama, U.S.A.
32°15′N, 88°12′W; 60 m

Hexahedrite, transitional to a coarsest octahedrite. H-Ogg. Neumann bands. Partly recrystallized. HV 135-180.

Anomalous. Bulk analysis: 5.1% Ni, 0.58% Co, 1.8% P, 38 ppm Ga, 62 ppm Ge, 0.06 ppm Ir.

HISTORY
Six individual masses, totaling 43.8 kg, were purchased in 1899 by the mineral dealing firm, A.E. Foote, Philadelphia. According to W.M. Foote (1899a) who described the material and gave a map and three photographs, the masses had been discovered at intervals since 1859 when the smallest (VI) was found by Ben Johnson. Because Foote took great pains to establish and record the places where the individual masses were found, today we are able to reconstruct the strewnfield (see Figure 1769) which shows an approximate north-south line with the three heaviest masses at the southern end — not northern, as stated by Brezina & Cohen (1904) and Henderson & Perry (1958). The coordinates for the midpoint of the line are given above. The distance between IV and I at the extreme ends is 14 km.

I Found 1878.	15,019 g.	Found next to an uprooted pine tree by R.Y. Smith
II Found 1886.	11,976 g.	Plowed up by R.Y. Smith
III Found 1886.	9,215 g.	Found by W. Howington on top of a hill.
IV Before 1899.	3,568 g.	Found by H. Wilkerson where a road cuts into a small hill.
V Before 1899.	3,260 g.	Plowed up by W.C. Moore.
VI Found 1859.	757 g.	Found by Ben Johnson. Part of it forged.

Material from I, III and VI was examined by Brezina & Cohen (1904) who gave three photomacrographs. They noted that the blocks were different in their structure, but similar in their composition, and concluded that the masses had suffered cosmic reheating to varying degrees, producing a hexahedrite (I) that gradually merged into a nickel-poor ataxite (III). The examination was reprinted by Cohen (1905: 208) and translated by Farrington (1915: 164). Mauroy (1913: plate 1) gave a photomacrograph, and Merrill (1916a: plate 36) gave another macrograph of an endpiece of III (U.S.N.M. No. 252).

Perry (1944) and Henderson & Perry (1958: 373) reexamined the meteorite, being particularly interested in the composition of the phosphides and the kamacite. Since they did not state which mass they studied, I have checked their material and found it to have come from mass III. They presented several analyses, photomicrographs and a photomacrograph. Buchwald (1966: 29) discussed the structure and gave a photomacrograph. Berkey & Fisher (1967) examined the chlorine distribution and found an extremely steep gradient from the surface inwards. The chlorine content drops from about 150 ppm at the surface to below 0.015 ppm within millimeters, strongly suggesting that the chlorine is of terrestrial origin. Bauer (1963) determined the ^{3}He/^{4}He ratio to be 0.142 and found it significantly lower than the lowest ratio of 0.18, calculated for pure, cosmogenic helium. This low ratio may somehow be associated with the cosmically annealed and partly recrystallized structure.

COLLECTIONS
London (7,730 g of either I or II), Vatican (3,950 g), Washington (3,000 g), Chicago (2,211 g), Rome (1,886 g), Berlin (1,535 g), New York (1,008 g), Bally (893 g), Yale (497 g), Paris (358 g), Dublin (334 g), Greifswald (325 g), Philadelphia (300 g), Vienna (285 g), Ottawa (275 g), Copenhagen (253 g of I), Tucson (226 g), Helsinki (225 g), Stockholm (204 g), Los Angeles (136 g), Bonn (117 g), Harvard (98 g), Strasbourg (35 g), Amherst (33 g).

DESCRIPTION
The largest mass, I, of 15 kg is angular and has the average dimensions of 18 x 16.5 x 13 cm. The other pieces are irregular, spheroidal or oval masses with no indications of fracture faces where they could be joined to one mass. It is apparent that long, independent flight paths and subsequent corrosion have effectively rounded these faces.

An endpiece of 2,954 g from III came to the U.S. National Museum in 1901; it is weathered and covered with 0.1-2 mm thick, terrestrial oxides. It shows a certain relief with shallow pits about 1 cm in diameter; they resemble regmaglypts that are modified by terrestrial corrosion. If
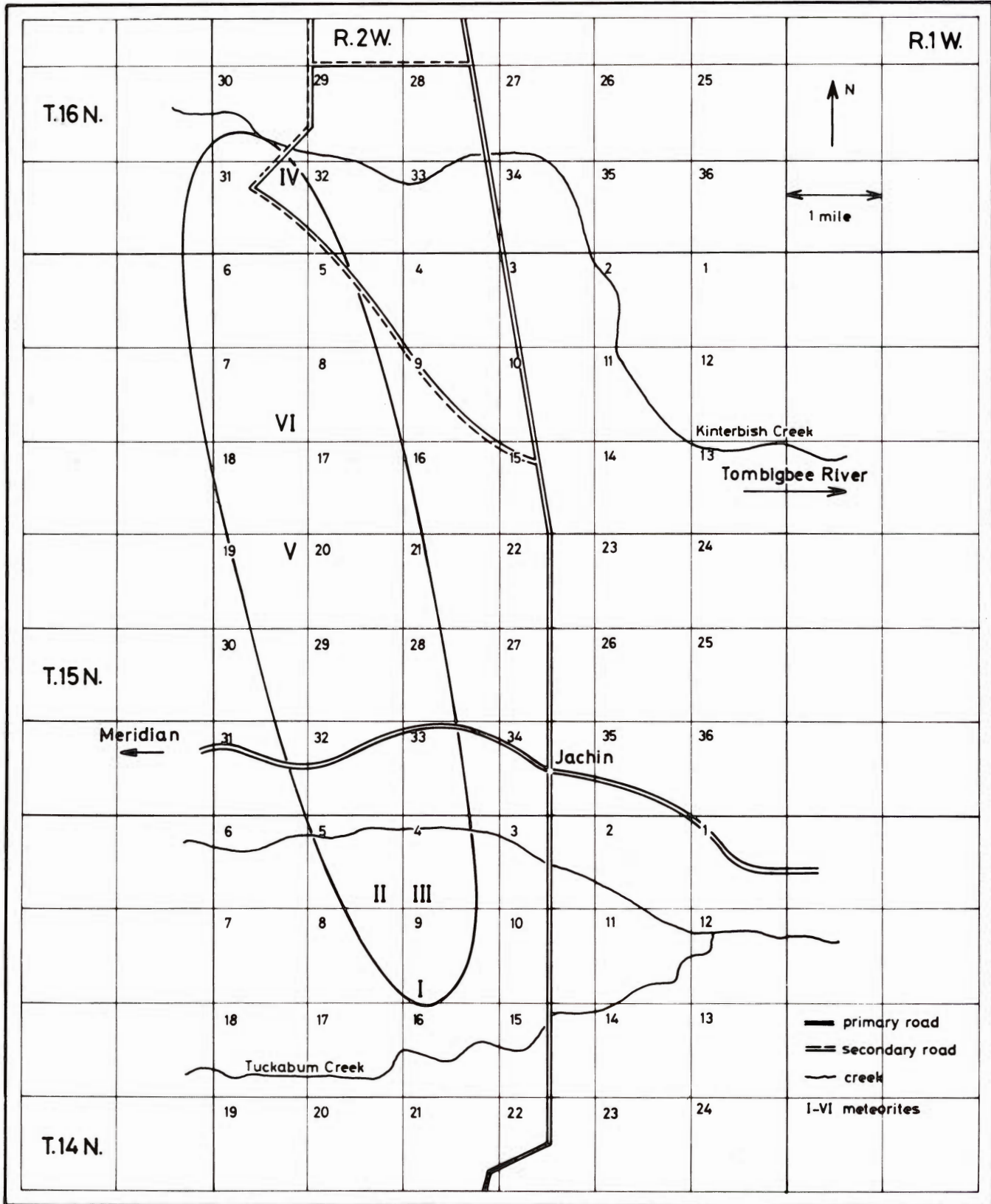
Figure 1769. Tombigbee. A map sketch showing the distribution of the six recovered fragments. Also shown is the characteristic survey grid employed in the United States and repeatedly mentioned in the present handbook. According to Congressional legislation, public land is divided by meridional lines and by parallels of latitude to form land *townships* of approximately 36 square miles. Each township is subdivided into *sections* one mile square and the 36 sections are numbered uniformly, as indicated. A principal meridian (e.g., St. Stephens Meridian in this case) and a standard base line form the initial frame to which all land in the state is referred. A particular Township is numbered after its distance *N*orth or *S*outh of the base line and after its distance (*R*ange) *E*ast or *W*est of the meridian. The Tombigbee fragment No. I was thus found in the southwestern quarter of Section 9 Township 14N, Range 2W.

they were unaltered regmaglypts, the large schreibersite crystals could not terminate as they do, flush with the surface or slightly elevated above it. The phosphides would have burned out, leaving narrow grooves as seen on e.g.,

Figure 1770. Tombigbee (Helsinki no. A1574). Typical section showing the prominent winding schreibersite crystals, two of them associated with troilite nodules. Deep-etched. Scale bar 20 mm.

Figure 1771. Tombigbee (Copenhagen no. 1905, 1749). Three large schreibersite crystals in a kamacite matrix. Two shear zones run almost horizontally across the picture. The Neumann bands are distorted. Since the schreibersite crystals are brecciated individual fragments are easily torn out during polishing (black). Etched. Scale bar 2 mm.

TOMBIGBEE – SELECTED CHEMICAL ANALYSES

All published analyses are partial analyses either of kamacite or of isolated phosphides which, from the data below, may be seen to average 4.3% Ni, 0.6% Co, 0.25% P and 12.3% Ni, 0.45% Co, 15.5% P, respectively. From point counting of sections totaling 450 cm^2 I found the schreibersite ribbons to constitute from 9 to 15% by area, averaging 11%. From these data the bulk composition of Tombigbee River may be calculated: 5.1% Ni, 0.58% Co, 1.75% P. The meteorite is thus one of our most nickel-poor, but most phosphorus-rich irons, similar in this and in other respects to La Primitiva and Bellsbank.

(i) On kamacite, remote from the large schreibersite inclusions:

| References | percentage | | | ppm | | | | | | | | |
	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Whitfield in Foote 1899a	4.11	0.40	0.32	1610								
Brezina & Cohen 1904	4.32	0.69	0.20	700	0	0	400					
Henderson & Perry 1958	4.39	0.69										
Smales et al. 1967					8.5	<5	74	<1	38	55		
Reed 1969	4.3		0.25									
Crocket 1972											0.094	0.44
Scott et al. 1973	4.3								38.5	62.5	0.021	

(ii) On swathing kamacite, adjacent to large schreibersite inclusions:

| Reference | percentage | | | ppm | | | | | | | | |
	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Henderson & Perry 1958	3.78	0.58										

(iii) On the large schreibersite inclusions:

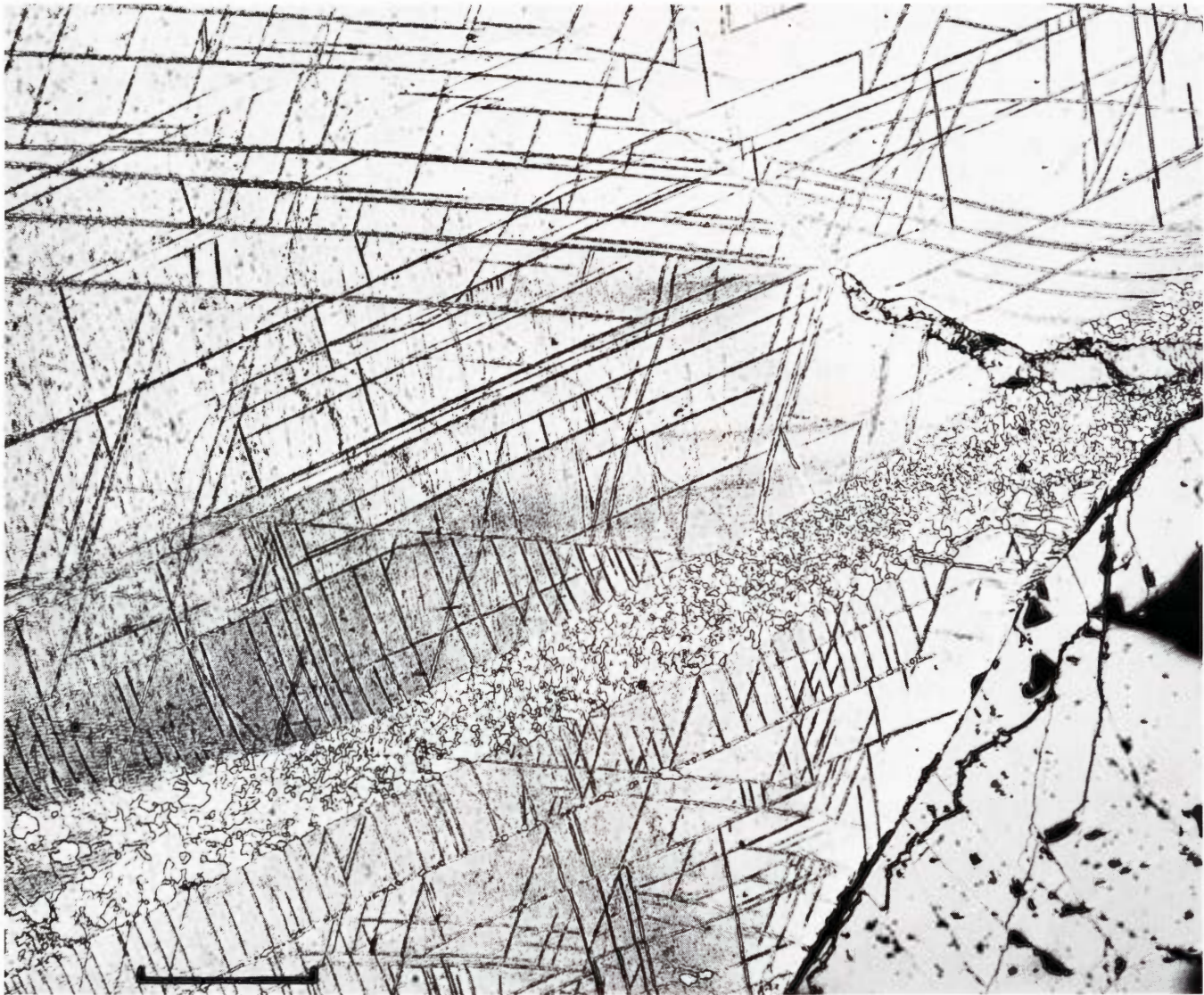| References | percentage | | | ppm | | | | | | | | |
	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Brezina & Cohen 1904	12.58	0.32	15.45									
Henderson & Perry 1958	12.03	0.58	15.59									

Figure 1772. Tombigbee. Detail of Figure 1771 near center. The kamacite is recrystallized within the narrow shear zone and the schreibersite bodies are brecciated. Etched. Scale bar 300 μ.

Grant and Chupaderos. Sections confirm that considerable corrosion has occurred. The Neumann bands near the surface are selectively corroded because they were sensitized by the precipitation of tiny rhabdites. Zones of terrestrial oxides surround the near-surface schreibersite ribbons and the smaller rhabdite plates and prisms.

Since polished and etched sections vary somewhat from mass to mass, I will here discuss the three main types represented by No. 3104 (from mass I), No. 252 (from mass III) and Tucson No. 825 (226 g, from an unidentified mass). The Copenhagen specimen No. 1905, 1749 (255 g) from mass I was also examined and found to be similar to U.S. National Museum No. 3104.

Primary Structure Common to samples from masses I and III is the presence of numerous winding schreibersite ribbons in a kamacite matrix. The kamacite shows subboundaries and occasionally high angle grain boundaries, so the material is not a hexahedrite *sensu strictu*. The
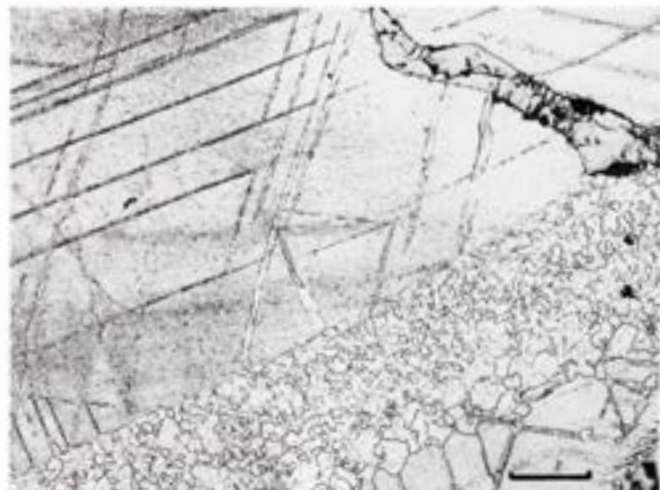
Figure 1773. Tombigbee. Detail of Figure 1772 showing the finely recrystallized kamacite. Brecciated schreibersite in the grain boundary above. Etched. Scale bar 100 μ.

schreibersite covers, on the average, 11% by area; it forms 1-5 mm wide, curved lamellae that appear to be interconnected in space, like rosette graphite in cast iron. A few conspicuous crystallographic facets may be developed on some of the schreibersite ribbons. Several parallel rows of rhabdite plates are to be found in areas remote from the schreibersite. The plates are typically 5 x 4 x 0.005 mm in size and oriented in a few, crystallographic directions. The kamacite matrix between the rows is loaded with rhabdite prisms, 0.5-2 μ across, and the many subboundaries are decorated by 0.5-2 μ thick rhabdites. Neumann bands cross the entire sections but abruptly change directions at the high angle grain boundaries. Quite locally a few troilite nodules appear. They are 5-10 mm in diameter and completely embedded in the voluminous schreibersite.

The Tucson specimen is interesting because it exhibits remnants of a Widmanstätten structure within an area of 6 x 6 cm on the 7 x 8 cm section. The individual kamacite lamellae are 2-6 mm wide and up to 20 mm long, and between them there are a few small taenite and plessite fields. The individual kamacite lamellae each display their set of Neumann bands. Within the 6 x 6 cm area, which evidently was once a single taenite crystal, there are no large schreibersite crystals. Outside, a few of the ribbon variety occur. The bulk chemical composition of the specimen is not known, but it is probably about three times poorer in phosphorus than other "normal" specimens. The presence of taenite and plessite further indicates a relatively high nickel content of perhaps 5.8-6.0%.

It would appear that Tombigbee represents a long-range primary equilibrium, established at about 1000° C, where the major part of the mass was composed of alpha phase, while a minor part was present as gamma grains, about 5 cm in diameter, and small amounts of a phosphorus-rich liquid appeared in the grain boundaries (see Buchwald 1966: 10, 27). Upon complete solidification and continued cooling, much more phosphide precipitated from
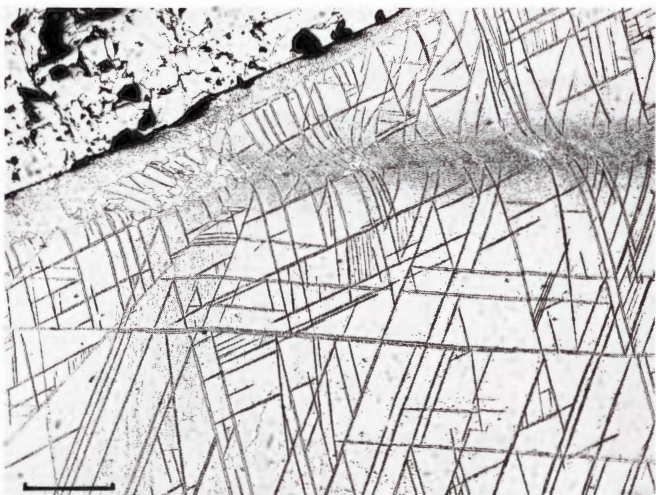
the alpha phase, particularly upon the already existing crystals. Later, phosphides in addition precipitated as parallel rows of rhabdite plates and as finely disseminated prisms in the matrix. The gamma grains, somewhat poorer in phosphorus and richer in nickel, decomposed in a Widmanstätten pattern; but late equilibrium and grain growth almost eliminated the texture. Tombigbee is in my opinion one of the few iron meteorites which was never a homogeneous γ-crystal, but must always have contained a major proportion of α-phase.

Secondary Structures   Mass I has Neumann bands which extend uninterruptedly across the sections. The phosphides are brecciated and frequently displaced 5-250 μ
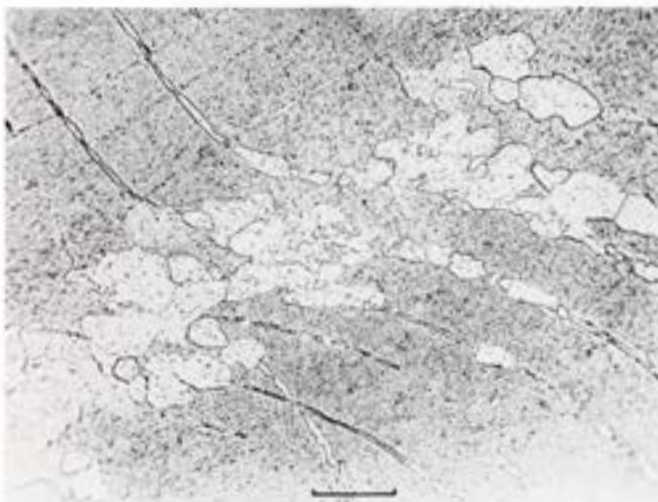

Figure 1775. Tombigbee (Copenhagen no. 1905, 1749). Detail of a partially recrystallized shear zone with dragged Neumann bands. Etched. Scale bar 50 μ.

Figure 1774. Tombigbee. Detail of right part of Figure 1771. Two shear zones, one adjacent to the schreibersite (above), one progressing almost horizontally. The Neumann bands are dragged along. Etched. Scale bar 300 μ.

Figure 1776. Tombigbee (Tucson no. 825). An unusual sample showing remnant coarse Widmanstätten structure in the left side. Taenite and plessite are also indistinctly seen. To the right, a schreibersite skeleton crystal. Deep-etched. Scale in centimeters.

along successive, parallel shear zones. The shear zones continue through the kamacite as 50-500 μ wide zones of cold-worked metal, visible to the naked eye as diffuse streaks. The microhardness of the kamacite matrix (4.3% Ni, 0.25% P) is 170±10, but it decreases to 138±3 in the Ni-P-depleted zones around the schreibersite.

In some of the shear zones, the frictional heat from the deformation was sufficient to recrystallize the strained metal within the shear zone. Such zones, 50-200 μ wide and several centimeters long, extend through many sections displaying aggregates of 5-30 μ kamacite grains. The microhardness is 140-180, similar to the unrecrystallized material; the large range is mainly due to varying amounts of nickel and phosphorus in solid solution in the kamacite and not to different degrees of recrystallization.

The schreibersite has a microhardness of 890±30. In addition to the phosphides already discussed a number of very small blebs appear, 0.5-1 μ across, and these decorate both sides of several Neumann band systems. This small-scale segregation has been sufficient to create a chemical potential along the Neumann bands and thus render them susceptible to terrestrial corrosion, as noted above.

Troilite is present in the microsections as 10-400 μ blebs associated with the large schreibersite crystals. The troilite is shock-melted and solidified to 1-3 μ aggregates in which tiny fragments of the adjacent schreibersite are dispersed. The troilite nodules display ragged edges against the metal because some of the rimming metal has been dissolved and afterwards exsolved within the troilite, and equilibrium was never attained.

Judging from the sections available, mass III is significantly more recrystallized than mass I. About 50% by area of the etched surfaces exhibit recrystallized material. The new grains are well-equilibrated and often elongated after preexisting Neumann band directions. The grains are usually 200-500 μ across and thus much larger than in I.

Very fine-grained material, 10-50 μ, occurs in the most severely deformed shear zones, while the best developed equixial units, up to 1.5 mm across, occur in the nickel- and phosphorus-depleted rim zones around the large phosphides. Still, the hardness range is as before, 135-180, varying with the precise Fe-Ni-P composition. The more nickel and phosphorus in solid solution, the harder the kamacite (100 g Vickers).

The previous Neumann bands may still be seen indistinctly, presumably because of the presence of tiny precipitates along them. But, in addition, a large number of new Neumann bands are present, differently oriented from grain to grain. These new bands formed when the meteorite was violently decelerated in the atmosphere and burst into numerous fragments.

It was stated above that the masses were corroded. Nevertheless, it is possible to identify both fusion crusts and heat-affected α_2 zones on some specimens. On the Copenhagen sample (No. 1905, 1749) a 150 μ thick laminated fusion crust was detected at the bottom of a shallow regmaglypt. It was weathered and converted to various limonitic products, but no more than could be interpreted as a "fossil" replacement of all the known structures in a fusion crust. Below the crust was a 1-1.5 mm wide heat-affected α_2 zone with micromelted phosphides in the exterior half. The hardness was 170±15, again reflecting the variation in nickel and phosphorus content. In the recovered transition zone between α_2 and α, the hardness decreased to 140±5 (hardness curve type II).

Foote (1899a) expressly stated that parts of mass VI were forged and that, among other things, a horseshoe nail was made from it. I have not had an opportunity to examine this material, but it is expected that specimens from this mass will show α_2 structures throughout from the artificial reheating. Since undamaged specimens only rarely

Figure 1777. Tombigbee (U.S.N.M. no. 252). Entirely recrystallized kamacite with a chipped schreibersite crystal. A late generation of Neumann bands penetrates all the recrystallized grains, probably dating from atmospheric breakup. Etched. Scale bar 200 μ. (Perry 1944: plate 5.) See also Figure 221.
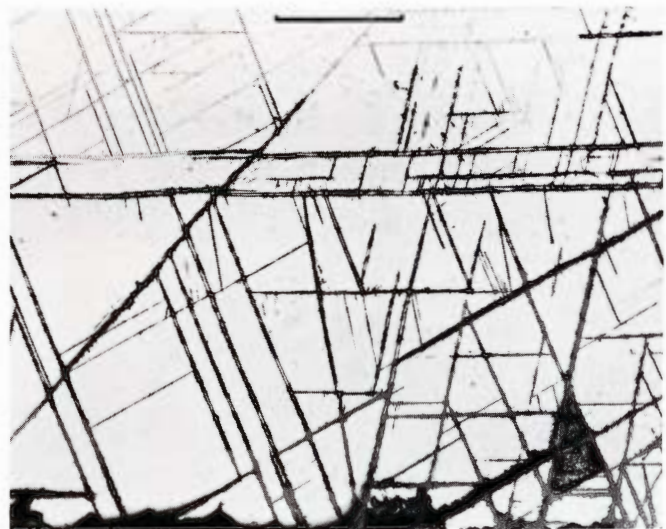

Figure 1778. Tombigbee (Copenhagen no. 1905, 1749). Near-surface section with a corrosion attack that selectively follows the Neumann bands. While Neumann bands per se would not be particularly exposed to corrosion, the annealed Neumann bands have become sensitized by the precipitation of almost submicroscopic phosphide (and γ-) particles. Etched. Scale bar 200 μ.

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) ⎫ all from mass III
140 g part slice (no. 252, 10 x 7 x 0.25 cm) ⎬ Plate III in
95 g various slices (nos. 252, 1679) ⎭ 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

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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 coor-

dinates 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

Reference	percentage			ppm								
	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					