



**Figure 1732.** Thule (Copenhagen no. 1955, 186). Another Reichenbach lamella (R-R) with schreibersite precipitates and corrosion products (black). Two plessite fields, the black one surrounded by distorted kamacite with decorated slipplanes. Etched. Scale bar 500  $\mu$ .



**Figure 1733.** Thule (Copenhagen no. 1955, 186). Net plessite with a black taenite wedge surrounded by distorted kamacite, displaying decorated slipplanes. Cloudy taenite edges. Neumann bands pass the entire plessite field. Etched. Scale bar 100  $\mu$ .

environment. One reason is the microfissured assemblage that attracts the ground water by capillary action; another reason is the heterogeneous mineral association. When this formed, it created steep composition gradients in the metallic matrix, thus providing a galvanic element for corrosion. Finally, the presence of shock-melted troilite with particles of dispersed metal also encouraged corrosion.

Thule is a well-preserved medium octahedrite which has been exposed to a severe shock in space. Additional inhomogeneous straining occurred in our atmosphere when it burst. It is a normal member of the resolved chemical group IIIA, and closely related to Trenton, Tamentit, Thunda, Kyancutta and Drum Mountains. It is also related to Cape York, from which it is primarily distinguished by the slight differences in nickel, phosphorus and trace elements; the almost complete absence of carlsbergite, rhabdites and daubreelite; and by its better state of preservation, suggesting a somewhat lower terrestrial age.

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

90 g part slice (no. 2146, 5 x 3.5 x 0.9 cm)  
360 g part slice (no. 4856)

**Thunda, Queensland, Australia**

25°42'S, 143°3'E; 150 m

Medium octahedrite, Om. Bandwidth 1.20±0.15 mm.  $\epsilon$ -structure. HV 305±15.

Group IIIA. 8.24% Ni, 0.51% Co, 0.21% P, 20 ppm Ga, 39 ppm Ge, 2.2 ppm Ir.

**HISTORY**

A mass of 137 pounds (62 kg) was found before 1886 at Thunda, Windorah, in the Diamantina district. It had been lightly covered in the ground and had been known some time by the natives before Liversidge (1886) could obtain it and describe it preliminarily. Half of it was cut and distributed in the following years, while half of it came to the British Museum as late as 1927. Fifty years after the discovery, Spencer (1937b) was able to add more exact information and a sketch map. According to his informer, two masses of iron, the "Old Man" and the "Old Woman," were known to the aborigines on Githa Creek on the Maroo holding. The "Old Woman" was transported about 1881 to the Thunda homestead about 25 km to the north, while the fate of the "Old Man" is unknown. The coordinates above are those of Spencer.

Brezina (1896: 283) and Cohen (1900b: 381) gave good descriptions, while Ward (1904a: plate 3) and Mauroy (1913: figure 24) presented some photomicrographs. In more recent time Perry (1944: plate 35) and Nininger & Nininger (1950: plate 10) have given good photographs of etched sections, showing the  $\epsilon$ -structure and the Reichen-

**THUNDA – SELECTED CHEMICAL ANALYSES**

References	percentage			C	S	Cr	Cu	ppm Zn	Ga	Ge	Ir	Pt
	Ni	Co	P									
Fahrenhorst in Cohen 1900b	8.49	0.56	0.17		200	100	200					
Lovering et al. 1957	8.27	0.51				2.5	145		13	39		
Moore et al. 1969	8.12	0.47	0.25	235	400		165					
Scott et al. 1973	8.08								20.2	38.9	2.2	

bach lamellae. Reed (1965a, b) examined the composition of the various phases; he found a homogeneous kamacite with 7.2% Ni and 0.09% P in solid solution. Jaeger & Lipschutz (1967b) estimated that the  $\epsilon$ -structure was formed by shock in the 400-750 k bar range.

Chackett et al. (1953) examined the helium content. Their values were revised by Hintenberger & Wänke (1964). Vilcek & Wänke (1963) estimated the cosmic ray exposure age to be  $460 \pm 50$  million years, while Voshage (1967) by the  $^{40}\text{K}/^{41}\text{K}$  method found  $680 \pm 60$  million years. Chang & Wänke (1969), however, maintained a value of  $450 \pm 40$  million years by the  $^{36}\text{Ar}/^{10}\text{Be}$  method. These authors also estimated the terrestrial age to be lower than  $10^5$  years, because  $^{36}\text{Cl}$  and  $^{10}\text{Be}$  were found to be present in significant amounts.

#### COLLECTIONS

London (28.6 kg half mass and 7.9 kg slices), Vienna (1,581 g), Chicago (1,551 g), Tempe (642 g), Sydney (610 g), New York (391 g), Oxford (370 g), Budapest (370 g), Paris (222 g), Washington (208 g), Prague (193 g), Yale (168 g), Amherst (113 g), Leningrad (93 g), Calcutta (55 g), Vatican (54 g), Harvard (51 g), Berlin (42 g), Copenhagen (35 g), Sarajevo (32 g), Strasbourg (24 g), Bonn (20 g).

#### DESCRIPTION

The half mass in London measures  $36 \times 26 \times 10$  cm and exhibits a polished and deep-etched surface of  $36 \times 26$  cm (B.M. No. 1927, 1254). The exterior surface displays two different morphologies. About half is covered by normal, rather shallow regmaglypts, 3-5 cm across. The other half is deeply indented by pits and bowls which meet along sharp ridges. A typical bowl is  $10 \times 8$  cm across and 2 cm deep; from the bottom of one of these a hemispherical pit, 45 mm in diameter, penetrates 45 mm into the mass. Some of the bowls and pits display undercut edges which strongly indicate that terrestrial corrosion was the decisive factor in forming the deep sculpture. All surfaces are corroded in a microrelief of densely spaced shallow pits, 1-3 mm across, with sharp edges in between.

It appears that Thunda acquired a normal regmaglypt-covered surface when it penetrated our atmosphere, probably with a few extra-deep cylindrical cavities from the selective ablational burning of troilite nodules. The present violent sculpture with bowls, pits and holes must, on the other hand, be due to terrestrial corrosion. While some parts of the surface remained relatively passive, other parts, particularly those containing shock-melted troilite, corroded selectively and developed the large bowls.

On the passive parts of the surface the heat-affected  $\alpha_2$  zone is irregularly preserved as a 1-2.5 mm wide rim. However, the fusion crust is lost. The  $\alpha_2$  zone is composed of fine-grained, serrated units, 5-25  $\mu$  across. The  $\alpha_2$  grain size is always finest when formed from a shock-hardened  $\epsilon$ -structure. The hardness of the rim zone is  $200 \pm 10$ ; it increases rapidly inwards and, at a depth of 5-10 mm, reaches  $305 \pm 15$ , the hardness of the unaffected interior.

Etched sections display a medium Widmanstätten structure of straight, long ( $\frac{l}{W} \sim 30$ ) kamacite lamellae with a width of  $1.20 \pm 0.15$  mm. The kamacite is very markedly crosshatched and exhibits a considerable variation in contrast from lamella to lamella. The composition and the microhardness of the lamellae are, however, identical within experimental error so the contrast appears to be purely a question of varying orientation and consequent response to etching reagents. Subboundaries are common, locally abundant, and then arranged in subparallel, dense clusters; they are decorated by fine precipitates of phosphides, less than 1  $\mu$  thick.

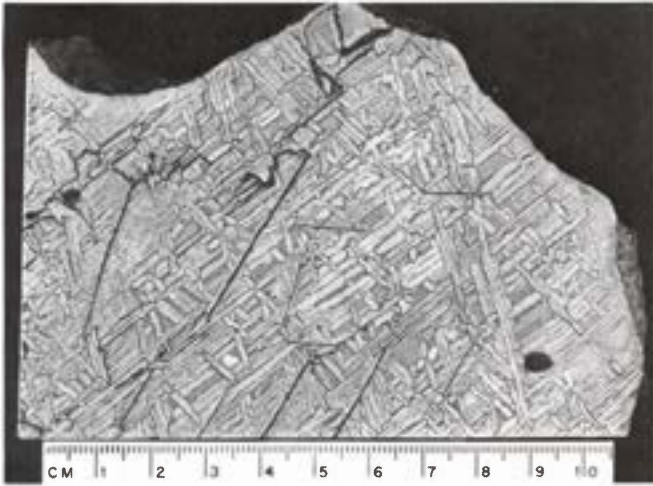
Taenite and plessite cover about 35% by area, as comb and net plessite and as abundant black taenite. A typical field of the latter type will display a tarnished taenite rim (HV  $350 \pm 20$ ) followed by a light-etching martensitic transition zone (HV  $440 \pm 20$ ). The interiors are developed as dark-etching martensite parallel to the bulk Widmanstätten structure, or as fine-grained, almost bainitic structures (HV  $470 \pm 20$ ). Easily resolvable, duplex mixtures of  $\alpha + \gamma$  are not common; but when they occur, they have hardnesses approaching those of the adjacent kamacite lamellae.

Schreibersite occurs as 10-50  $\mu$  wide grain boundary precipitates and as discontinuous, 5-50  $\mu$  thick rims and blebs upon the troilite nodules and the Reichenbach lamellae. Rhabdites are not common.

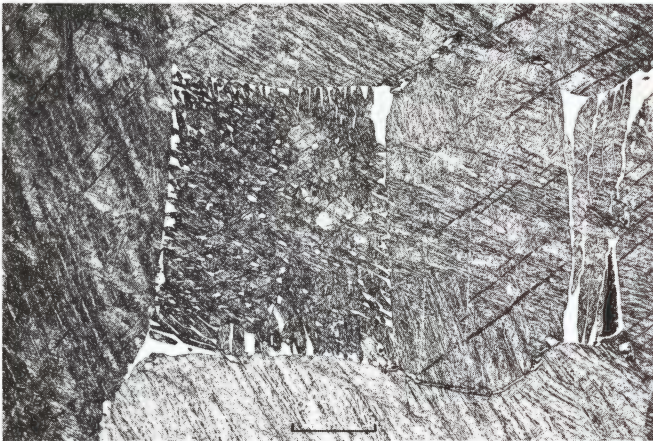
Troilite ranges from 0.5-20 mm in size. On sections totaling 800 cm<sup>2</sup> nine nodules between 10 and 20 mm in diameter were observed. A typical nodule, 1 mm across, is partly monocrystalline, partly shock-melted. The shock-melted parts are located along the phase boundaries against the metal and, to a minor extent, along shear zones in the troilite. The shock-melted material has dissolved some of the adjacent metal and is now solidified to 1-5  $\mu$  aggregates. Daubreelite covers about 5% by area, either as 1-10  $\mu$  wide, parallel lamellae, or — in the shock-melted areas — as shattered fragments.

Thunda is characterized by the abundance of Reichenbach lamellae, occurring with a frequency of about one per 7 cm<sup>2</sup>. They are straight and follow at least five different directions, none of which coincides with the Widmanstätten structure. They range in size from  $70 \times 20 \times 0.05$  mm to  $10 \times 10 \times 0.01$  mm and usually consist of troilite with some later precipitates of schreibersite blebs, locally. Unfortunately, many of the lamellae are severely altered by weathering — evidently because the fissures provided easy access for corrosive terrestrial waters. The swathing kamacite rims are poorly developed, or absent, around both the troilite nodules and the Reichenbach lamellae. Chromite — which was reported in a chemical analysis by Cohen (1900b) — may in fact constitute the backbone of the Reichenbach lamellae, compare e.g. Thule, Kayakent and Cape York.

Thunda is a shock-hardened medium octahedrite which is related to Bagdad, Kayakent, Cumpas and Trenton. It forms a natural member of group IIIA.



**Figure 1734.** Thunda (Tempe no. 121a). A shock-hardened medium octahedrite of group IIIA. Several straight Reichenbach lamellae similar to those of Thule. Two shock-melted troilite nodules (black). Deep-etched. Scale in centimeters. (Courtesy C.B. Moore.)



**Figure 1735.** Thunda (New York no. 167). Two plesite fields in the midst of shock-hatched kamacite lamellae of various shades. Etched. Scale bar 400  $\mu$ . (Perry 1950: volume 5.)

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

- 111 g part slice (no. 456, 4.2 x 4.2 x 0.7 cm)
- 48 g part slice (no. 663, 4 x 3 x 0.4 cm)
- 49 g part slice (no. 3091, 8 x 1 x 0.6 cm)

**Thurlow, Ontario, Canada**

Approximately 44°45'N, 77°35'W

Medium octahedrite, Om. Bandwidth  $0.65 \pm 0.10$  mm. Annealed  $\epsilon$ -structure. HV  $190 \pm 12$ .

Group IIIB. 9.9% Ni, about 0.5% P, 15.9 ppm Ga, 28.0 ppm Ge, 0.017 ppm Ir.

**HISTORY**

A mass of 5.42 kg was plowed up by Mr. E.S. Leslie in May 1888 in the township of Thurlow, Hastings County. Ward's Establishment cut several slices from the meteorite about 1895, but the main mass was returned to the Geological Survey of Canada in Ottawa. The meteorite was distributed by Hoffmann (1897) and Cohen (1905: 377). Brezina & Cohen (1886-1906: plate 34) and Ward (1904a: plate 2) published several photomicrographs of deep-etched sections.

**COLLECTIONS**

Washington (403 g), Chicago (197 g endpiece), London (189 g), New York (136 g), Vienna (about 200 g), Bonn (39 g), Vatican (31 g), Prague (24 g), Paris (2 g). For a long time the main mass was in the Collection of the Geological Survey of Canada, Ottawa, but after the early 1930s there is no trace of its whereabouts (letter of 15 March 1971 to the author from Dr. J.A.V. Douglas).

**DESCRIPTION**

The meteorite is an irregularly-shaped truncated pyramidal mass with the average dimensions of 16 x 13.5 x 10 cm (Hoffmann 1897). It exhibits numerous well developed regmaglypts 10-20 mm in diameter and 5-8 mm deep. The fusion crust is preserved in places, particularly at the bottom of the regmaglypts. Sections through the surface show the fusion crust to be composed of a number of 20-50  $\mu$  thick metallic sheets, each of which is a dendritic-cellular aggregate of metal with phosphide-enriched interdendritic fillings. The number of metallic layers, which evidently were swept into position from adjacent places, ranges from 1-10. The outermost layer is covered by an oxidic fusion crust, about 50  $\mu$  thick, and sometimes irregular oxide layers may be found intercalated between the later metallic layers. Terrestrial corrosion has removed the fusion crust on some parts of the meteorite, but on the whole the specimen is well-preserved.

Etched sections display a medium Widmanstätten structure of straight, long ( $\bar{W} \sim 20$ ) kamacite lamellae with

**THURLOW – SELECTED CHEMICAL ANALYSES**

References	percentage			C	S	Cr	Cu	ppm				Pt
	Ni	Co	P					Zn	Ga	Ge	Ir	
Bürger in Cohen 1905	9.92	1.04	0.25		500							
Wasson & Kimberlin 1967	9.9±0.4								15.9	28.0	0.017	

The old cobalt determination is probably at least 50% too high, while the phosphorus value appears low for a true bulk value.



**Figure 1736.** Thurlow (Vienna no. G8425). A shocked and annealed medium octahedrite of group IIIB. Large skeleton crystals of schreibersite are enveloped in swathing kamacite. At the center of the rosette-shaped schreibersite is a 1 mm troilite nodule. Deep-etched. Scale bar 20 mm.

0.5  $\mu$  across and probably consist of phosphides. The hardness of the kamacite is  $190 \pm 12$ . At the transition to the heat-affected  $\alpha_2$  zone it drops to  $170 \pm 10$ , while the 1-2 mm wide  $\alpha_2$  zone itself exhibits a hardness of  $185 \pm 15$  (hardness curve type 2).

Taenite and plessite occupy about 50% by area. Most fields are repetition patterns of the macroscopic Widmanstätten structure, while ordinary comb and pearlitic plessite are absent. A typical field will display a marked, light taenite rim (HV  $230 \pm 20$ ) followed by a brown-etching martensitic felt (HV  $290 \pm 40$ ). The interior will be an easily resolvable duplex  $\alpha + \gamma$  mixture (HV  $200 \pm 15$ ) with hardnesses only little in excess of the kamacite lamellae. Thus Thurlow, on the whole, exhibits a lower hardness regime than do related meteorites such as, e.g., Smith's Mountain, Knowles and Narraburra.

Schreibersite is common as laths up to  $12 \times 1$  mm (Brezina lamellae) and as rosettes and hieroglyphic shapes, a few millimeters in diameter, developed around the phosphate and troilite inclusions. Schreibersite also occurs as 0.2-0.5 mm wide blebs centrally in some  $\alpha$ -lamellae and as 40-100  $\mu$  wide grain boundary precipitates. A considerable proportion is found as 10-20  $\mu$  thick blebs, arranged in regular garlands 10-20  $\mu$  in front of taenite and plessite fields. Typical rhabdites are absent, but as mentioned above, the kamacite appears to be rich in submicroscopic rhabdite precipitates. The bulk phosphorus content is estimated to be  $0.5 \pm 0.1\%$ .

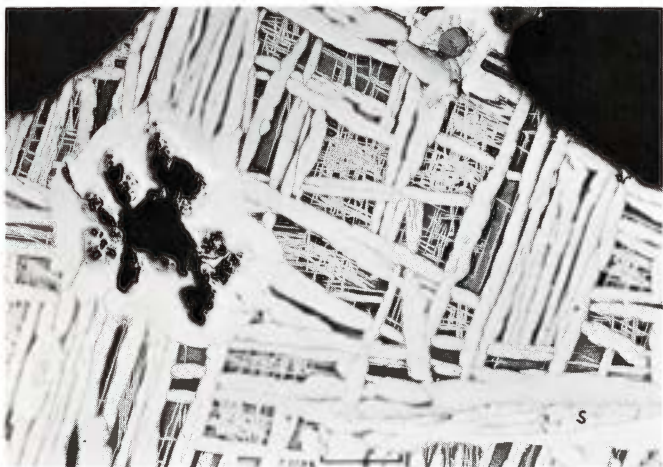
Cohenite and graphite are absent, but phosphates do occur as 1-2 mm softly rounded anisotropic inclusions. The phosphate is grayish-blue in reflected light and displays numerous 2-4  $\mu$  wide twin lamellae. It is brittle and falls out

easily during routine polishing. The phosphates (grafonite or sarcopside) have served as nuclei for the precipitation of troilite and schreibersite which often forms "stars" 5-10 mm in diameter.

The troilite is a polycrystalline mosaic of 5-10  $\mu$  units, often arranged in undulatory subparallel bands. Where the troilite is in contact with the kamacite, it is micromelted and has dissolved a small part of the kamacite. The resulting iron-sulfide eutectic has masks, 1-2  $\mu$  across, and a fringed border against the kamacite.

Corrosion penetrates 5-10 mm into the interior, mainly along grain boundaries and brecciated phosphides. The troilite shows incipient alteration to pentlandite. However, the meteorite is in a very good state of preservation.

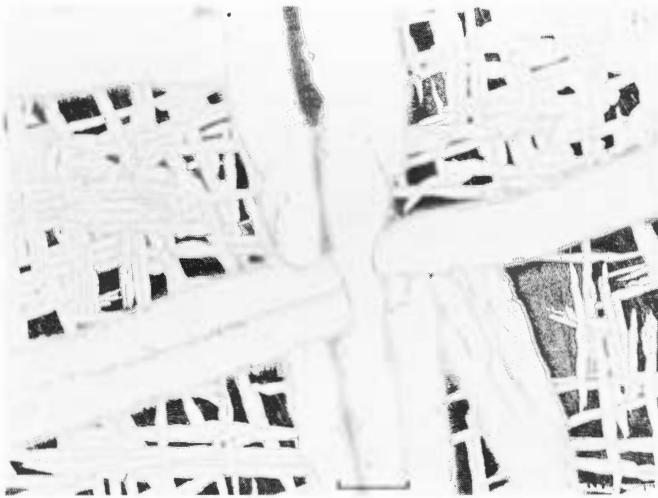
Thurlow is a medium octahedrite of the chemical group IIIB. It is closely related to Knowles, Narraburra, Ilinskaya Stanitsa, Bear Creek and Augustinovka. Thurlow is only a little corroded and exhibits the regmaglypts and the complex fusion crust well.



**Figure 1737.** Thurlow (U.S.N.M. no. 3092). Two schreibersite rosettes with troilite nuclei, the one at left damaged by imperfect polishing. A branching schreibersite crystal below (S). Etched. Scale bar 3 mm.



**Figure 1738.** Thurlow. Detail of Figure 1737. Troilite (T) enveloped in schreibersite (S) and kamacite (K). The morphology is typical for group IIIB. Etched. Scale bar 500  $\mu$ .



**Figure 1739.** Thurlow. Detail of Figure 1737. Acicular plessite fields and fields with bainitic-martensitic interiors. Island-arcs of tiny schreibersite particles. Etched. Scale bar 500  $\mu$ .

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

382 g slice (no. 545, 12 x 6 x 1 cm)  
21 g part slice (no. 3092, 4 x 2.5 x 0.3 cm; previously no. 373 of the Bosch Collection)

### Tieraco Creek, Western Australia

Approximately 26°20'S, 118°20'E; 600 m

Medium octahedrite, Om. Bandwidth 0.52±0.08 mm.

Group IIIB. 10.63% Ni, 0.60% Co, about 0.8% P, 16 ppm Ga, 28 ppm Ge, 0.04 ppm Ir.

#### HISTORY

According to Hodge-Smith & White (1926), and corrigendum by Simpson (1938: 163), a mass of 41.7 kg was found by gold prospectors in the Murchison Gold Field, in the vicinity of Mount Padbury. The original finders, who had discovered the meteorite on the surface of the ground near the head of Tieraco Creek, had taken the mass to town. Disappointed in learning its true nature, they had dumped it in a rubbish heap at Meekatharra. It was rediscovered there in 1922 by J.F. Connelly who donated the mass to the Australian Museum in Sydney.

Hodge-Smith & White (1926) described the meteorite with five photomacrophotographs of the exterior and of deep-etched sections. They discussed, in particular, the unusual

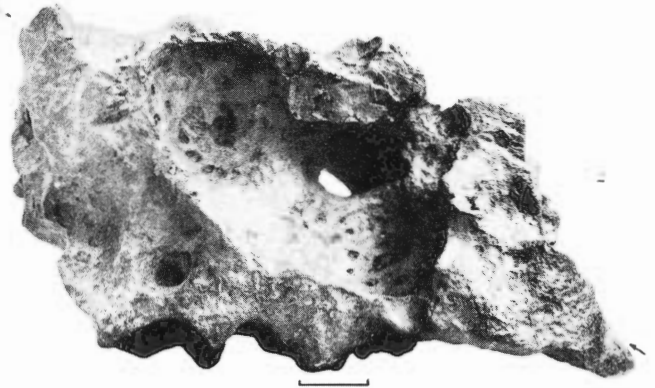
sculpture but also gave a good analysis and a description of large isolated schreibersite crystals. Simpson (1938) added a few observations, and Hodge-Smith (1939: plate 2) presented an additional photograph of the exterior. Wasson & Kimberlin (1967) presented a modern analysis and a photomacrophotograph of an etched section, classifying the meteorite as a high-nickel end member of group IIIB.

#### COLLECTIONS

Harvard (18.16 kg), Sydney (16.47 kg and 178 g slice), Washington (4.04 kg), Canberra (130 g), Chicago (15 g).

#### DESCRIPTION

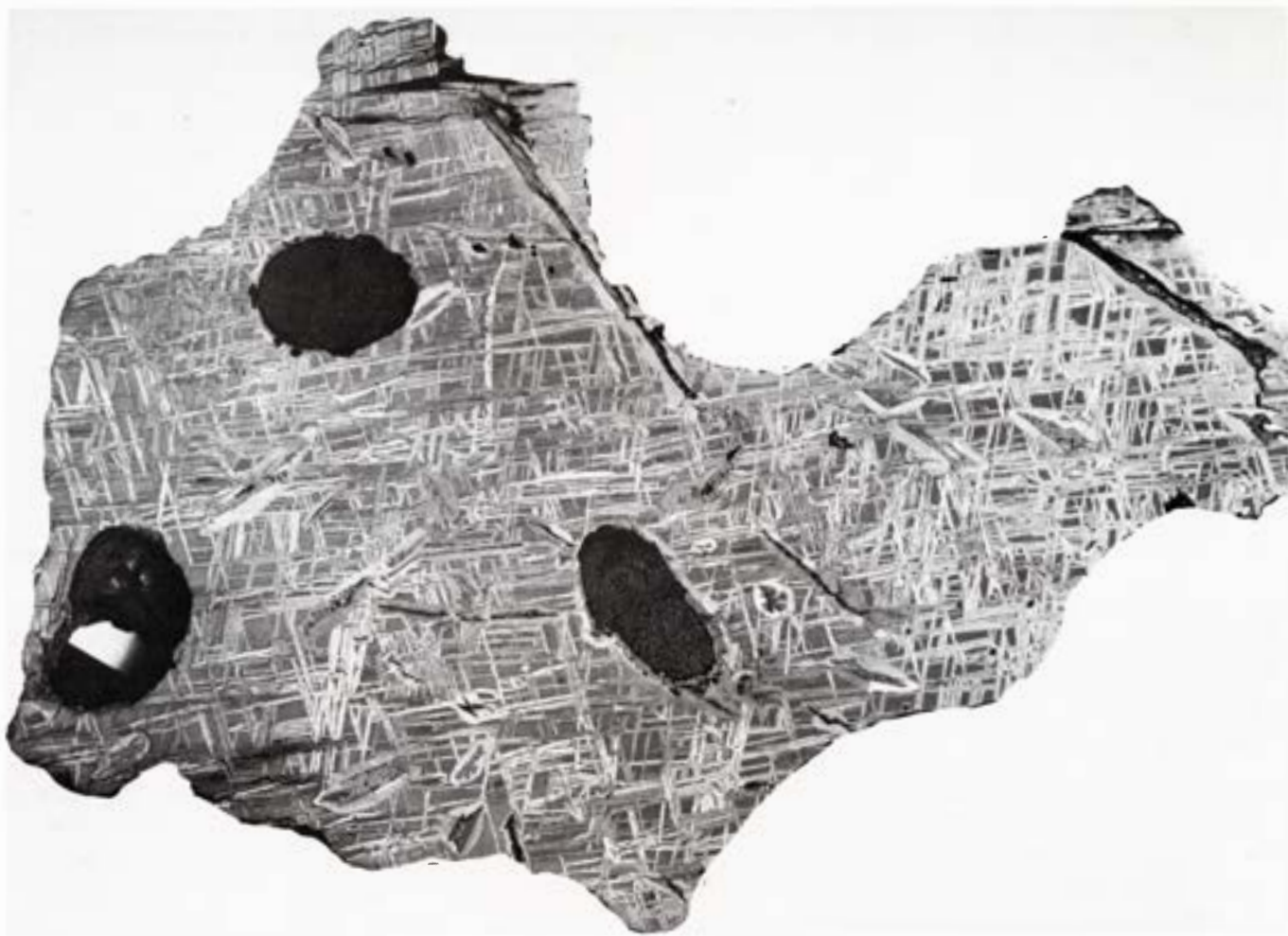
The irregular mass has the average dimensions of 44 x 22 x 12 cm and weighs 41.7 kg. It is deeply indented on all sides by roughly hemispherical pits and bowls. One typical bowl is 9 cm in aperture at the opening and 5 cm deep. Two others are each 12-15 cm across and 7-8 cm deep, and they coalesce to form a large basin. In one place a hole, 25-30 mm in diameter, starts from the bottom of the said basin and completely pierces the mass. Crusts of terrestrial weathering products, 0.1-2 mm thick, cover the mass irregularly. A Widmanstätten grid is naturally etched on part of the surface while small-scale pitting, 2-6 mm across, appears irregularly on all surfaces. No unambiguous regmaglypts from the atmospheric flight were seen, and fusion crust and heat-affected  $\alpha_2$  zones were not detected. It appears that the conspicuous surface morphology is the combined result of flight sculpture and corrosion during a long exposure to a terrestrial environment, and it is



**Figure 1740A.** Tieraco Creek. The main mass before cutting, displaying a large bowl-shaped depression and several other pits. The arrows indicate the plane of sectioning. Scale bar approximately 5 cm. (From Hodge-Smith 1939: plate 2.)

#### TIERACO CREEK – SELECTED CHEMICAL ANALYSES

References	percentage			C	S	Cr	Cu	ppm				
	Ni	Co	P					Zn	Ga	Ge	Ir	Pt
Lovering et al. 1957	10.55	0.60				<1	110		13	23		
Wasson & Kimberlin 1967	10.70								16.2	28.0	0.04	
De Laeter 1972									16.4			
Rosman 1972								0.92				



**Figure 1740B.** Tieraco Creek (U.S.N.M. no. 927). A medium octahedrite of group IIIB. Brezina lamella of schreibersite and large nodules of troilite. Deep-etched. Length of specimen 45 cm. S.I. neg. 1349.

interesting to note the similarity to the sculpture of many Youdegin samples. Although these meteorites are different in composition, the Western Australian climate in this desert mountain range evidently produces the most puzzling pitting-corrosion on a large scale. A few meteorites, such as Willamette, display a more pronounced corrosion sculpture.

Etched sections display a medium Widmanstätten structure of straight, long ( $\frac{l}{w} \sim 30$ ) kamacite lamellae with a width of  $0.52 \pm 0.08$  mm. Taenite and plessite cover about 50% by area.

Schreibersite occurs as Brezina lamellae in the  $\{110\}$  planes of the parent taenite crystal. They are typically 25  $\times$  1 mm in size, but are occasionally larger or display branching or cuneiform units. They have nucleated 1-2.5 mm wide rims of swathing kamacite that may be divided into cells and are asymmetrical with respect to the schreibersite lamellae. Schreibersite also occurs as 20-60  $\mu$  wide grain boundary precipitates and as 5-50  $\mu$  blebs inside the plessite fields substituting for  $\gamma$ -particles of similar size. The bulk phosphorus content is estimated to be  $0.8 \pm 0.2\%$ , similar to Augustinovka.

Troilite occurs as rounded nodules 1-3 cm across. They have nucleated 0.5-1 mm wide rims of schreibersite, which again have nucleated 0.5-2 mm wide rims of swathing kamacite. In one of the nodules on a Sydney specimen, Hodge-Smith and White (1926: 67 and plate 4) noted a 1 cm large crystal penetrating a troilite nodule. They assumed it to be schreibersite, but the identification is doubtful; and the inclusion should be reexamined, for example by X-ray methods. It is possible that it is a phosphate similar to those reported by Fuchs (1969) from other group IIIB irons.

Simpson (1938) recorded several inclusions of cohenite, but this seems to have been a misinterpretation of schreibersite. He also attributed the fine octahedral ridges on the surface to differential oxidation of kamacite and taenite during the flight through the air. Considering the extensive corrosion present, I am inclined to interpret the Widmanstätten grid as due to selective corrosion during weathering.

Tieraco Creek is a medium octahedrite closely related to Augustinovka, Narraburra, Thurlow and Chupaderos. It is particularly interesting because of the large bowls which

indicate a corrosion loss by pitting of the order of kilograms.

Specimen in the U.S. National Museum in Washington:  
4,038 g slice (no. 927, 45 x 10 x 1 cm)

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**Tishomingo, Oklahoma, U.S.A.**

34°14'N, 96°40'W

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Martensitic ataxite. Anomalous. Coarse, slightly tempered martensite. HV 425±25.

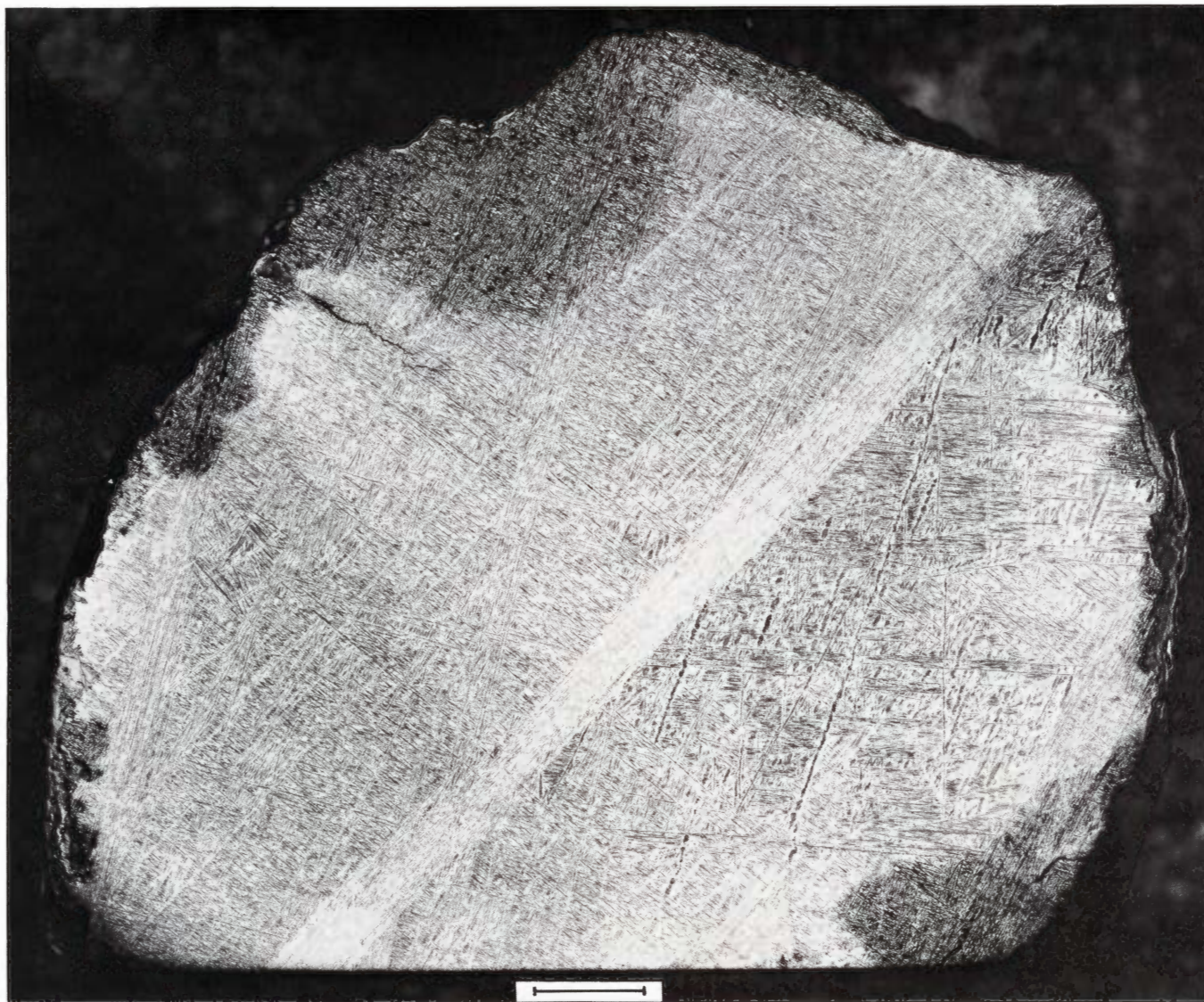
Anomalous. About 32.5% Ni.

**HISTORY**

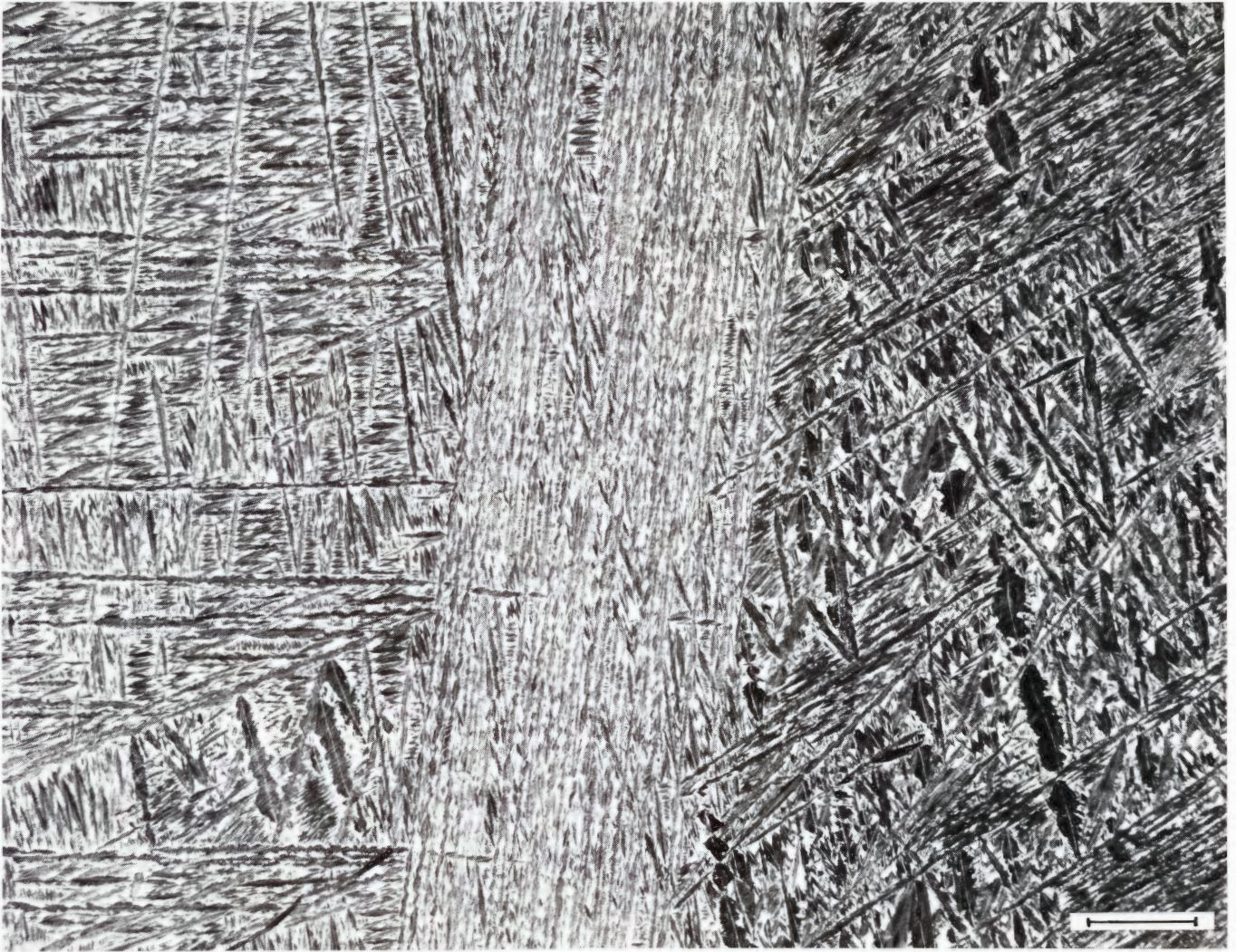
A mass of about 164 kg was discovered in 1965 by a 14-year-old boy, Glenn Orr, when he was bird hunting near Tishomingo, Johnston County. The coordinates above are for the town of Tishomingo.



**Figure 1741.** Tishomingo. The four fragments restored to position in the field where discovered in 1965. The ruler measures 24 inches. S.I. neg. 1470A.



**Figure 1742.** Tishomingo. A part slice showing the anomalous, coarse martensitic structure. An austenite twin crosses the entire section. Terrestrial corrosion penetrates irregularly from the surface (black patches). Etched. Scale bar approximately 4 mm. S.I. neg. 1470C.



**Figure 1743.** Tishomingo. Detail of Figure 1742 showing the central austenite twin. The martensitic plates within the twin are parallel to the twin plane and to one of the directions on either side of the twin. Etched. Scale bar 800  $\mu$ . S.I. neg 1470B.

The mass was protruding from the ground in a granitic pasture. Subsequent efforts to locate additional pieces revealed a 97 kg mass and two fragments of 2.5 kg and 1.08 kg. All the pieces were found in juxtaposition in the same depression, and it appeared that they had once formed one piece which separated upon weathering, possibly along certain preexisting fissure zones from the atmospheric flight (Monnig 1967).

A metallographic examination of polished sections from the smallest sample was reported by Buchheit et al. (1967).

#### COLLECTIONS

The main masses have apparently been retained by the finders. Small samples are on loan to the Smithsonian Institution.

#### ANALYSIS

A partial analysis by Buchheit et al. (1967) yielded 32.5% Ni.

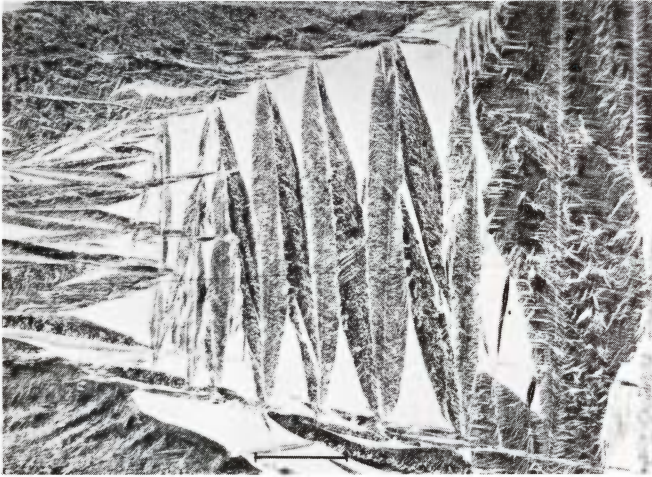
#### DESCRIPTION

The dimensions and shapes of the three larger fragments are unknown. The following is based on an examination of the smallest fragment which was loaned to the Smithsonian Institution in 1968 by Mr. O.E. Monnig, Fort Worth. It is an almost square flat mass with the dimensions of 12 x 10 x 3 cm, and a weight of 1.08 kg. Terrestrial shales form a laminated 0.5-2 mm thick crust over a considerable part of the surfaces. According to Monnig, the piece fits together with at least one of the other fragments, so that corrosion has only slightly altered the overall morphology.

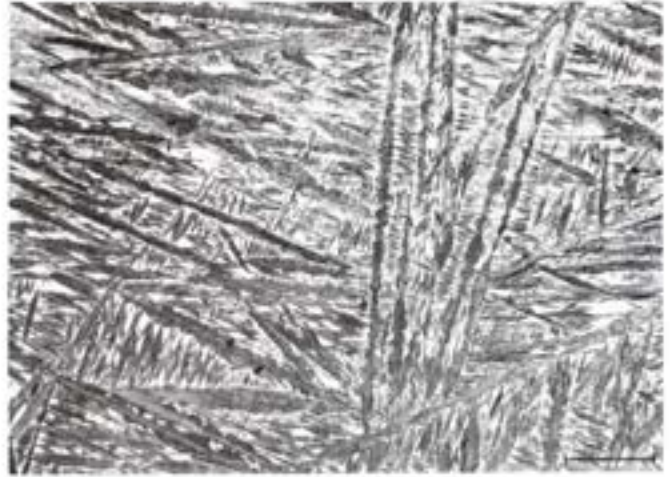
The 1.08 kg piece was cut through the middle and several polished sections were prepared. In a few places the original fusion crust is present as a crust up to 100  $\mu$  thick. It is composed of 5-10 layers of crossbedded metal which is now severely oxidized. Its presence confirms that the present overall size of the fragments is the same as immediately after the fall.

Etched sections display a coarse martensitic structure; a similar structure is unknown in any other meteorite and is





**Figure 1744.** Tishomingo. A group of martensitic plates in retained austenite (white). Etched. Oil immersion. Scale bar 20  $\mu$ .



**Figure 1745.** Tishomingo. Martensite in retained austenite (white). Etched. Scale bar 300  $\mu$ .

also much coarser than in any terrestrial alloy. The martensite forms lenticular platelets which are usually 20-50  $\mu$  wide. In length they range from about 50  $\mu$  to at least 20 mm. However, the longer ones are pinched into segments that are seldom longer than 1-2 mm. Even on the largest section prepared, about 3 x 5 cm in size, all martensite platelets were uniformly arranged, indicating that the parent austenite crystal was at least of that size. In one case an austenite twin, 2 mm wide and 40 mm long, was observed. The martensite platelets all change their directions abruptly when passing the twin boundaries. A majority of those within the band are parallel to the long dimensions of the band, which is presumably parallel to the twin plane (111) $\gamma$ .

The martensitic transformation products constitute about 80% of the volume, while the retained austenite constitutes 20%. The martensite has a hardness of 425 $\pm$ 25. The hardness decreases slightly to 385 $\pm$ 35, in areas where the martensite platelets are small and visibly intercalated with retained taenite. The retained taenite, which forms irregular wedges, 10-50  $\mu$  across, or occasional patches 500  $\mu$  across, is structureless and relatively soft, 250 $\pm$ 10. However, annealed taenite of this composition is at least 100 units softer, so the retained taenite must be cold-worked.

The individual martensite platelets are so coarse that the midrib and the twin striations are distinctly seen in the optical microscope. The twins run obliquely as dense parallel lines across the platelets. Strong anisotropy is observed when using crossed Nicols on an etched section. However the anisotropy seems to be associated with the etching, since no effects were visible on a polished section. The martensite morphology suggests that the transformation is of the acicular type with an irrational habit plane. It was not examined further in this study, but indications are that the habit plane is close to {259}  $\gamma$ , as reported for synthetic Fe-30Ni alloys, with no change in the symmetry of the cubic martensite – but with the martensite being

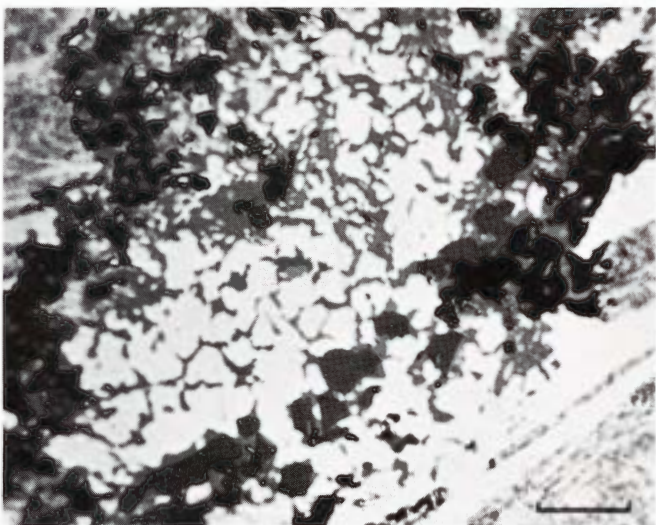


**Figure 1746.** Tishomingo. A daubreelite-troilite aggregate in martensite. The troilite is shock-melted while the daubreelite (D) has survived intact. Etched. Scale bar 100  $\mu$ .

internally twinned (Kelly & Nutting 1961; Owen et al. 1965; Speich & Swann 1965; Dash & Brown 1966; Patterson & Wayman 1966).

Tishomingo is a very pure iron-nickel alloy. No carbides, phosphides or silicates were identified at all, and graphite is not present. It is estimated that both the carbon and the phosphorus contents are below 0.05%.

Sulfides are present, however. Scattered through the matrix there are numerous (i.e., about 5-10 per cm<sup>2</sup>) small blebs of what was previously monocrystalline troilite-daubreelite bars and nodules. They are 20-250  $\mu$  across, or occasionally form a straight veinlet 250 x 10  $\mu$  in size. They have been remelted – apparently due to shock reheating – and have dissolved part of the adjacent metal. Upon a very rapid cooling, they developed serrated edges against the metal and an internal microcrystalline eutectic, consisting of iron sulfide and nickel-rich austenite blebs in the 1-5  $\mu$  range. The original daubreelite bars occur as dispersed subangular fragments, 5-10  $\mu$  across, in the eutectic.



**Figure 1747.** Tishomingo. Detail of a shock-melted sulfide nodule like that of Figure 1746. Iron sulfide (gray), metal (white) and angular daubreelite fragments (black). Corrosion and pits (dead black). Etched. Scale bar 10  $\mu$ .

Tishomingo is rich in nickel but is nevertheless easily etched with 2% nital. It is interesting to note that the meteorite is weathered *below* the immediately visible limonitic crust. The internal oxidation has attacked the martensite in a 1-3 mm wide zone and has etched it naturally to a pattern corresponding to what is produced upon etching with nital. Evidently oxygen has been able to diffuse through the bulk of the Fe-Ni alloy to a depth of 1-3 mm and thereby precipitate submicroscopic iron oxides. The hardness of the internally oxidized layer is  $365 \pm 35$ , a decrease of about 60 units relative to the unoxidized interior. Only the strained and disordered martensitic transformation products are attacked, while the retained austenite survives for a long time.

The internal oxidation may appear surprising, since it is unreported (?) in steels. It is, however, quite common in iron meteorites as noted in numerous descriptions in this book. Perhaps the amount of dissolved carbon in the iron meteorites is significantly lower than in technological steels so that any oxygen diffusing into the meteoritic matrix will be available for iron oxide formation, not having been consumed by carbon in solid solution.

Tishomingo is a unique meteorite, unrelated to any other meteorite. Only three others contain more nickel. In its trace-element composition it will probably also be found to be anomalous.

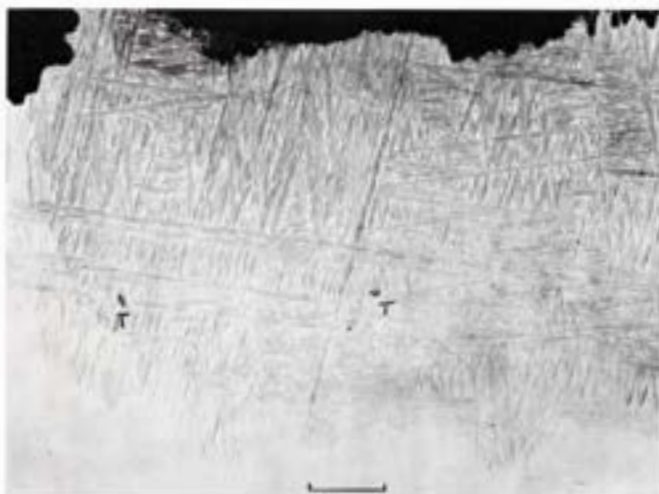
It is the structure, however, that poses the most puzzling problems. It appears that the precursor taenite crystals were large, i.e., above 50 mm in size; but since no large scale sections have been prepared, it is unknown whether Tishomingo was one single crystal or coarsely polycrystalline, as, e.g., Santa Catharina and Twin City.

Tishomingo does not display any structural features which can be referred to  $\gamma$ - $\alpha$  decomposition after the equilibrium Fe-Ni diagram. There are thus no discernible  $\alpha$ -platelets and no swathing  $\alpha$ -rims around heterogeneous

nuclei of troilite. (Or, if they once were there, they are now masked by later alterations.) This is an interesting difference from Twin City (30% Ni) and Santa Catharina (35.3% Ni) and suggests a more rapid primary cooling for Tishomingo.

The cooling may eventually have reached such low temperatures that diffusionless martensitic reactions could occur. According to Kaufman & Cohen (1956) the  $M_s$  temperature for synthetic Fe-32.5% Ni alloys is about 180°K; 80% transformation to martensite might be expected if the temperature ever decreased to about 90°K. It is plausible that a portion of Tishomingo's martensite formed this way but probably not until it had been released from its parent body and circled in space as a small, poorly isolated body.

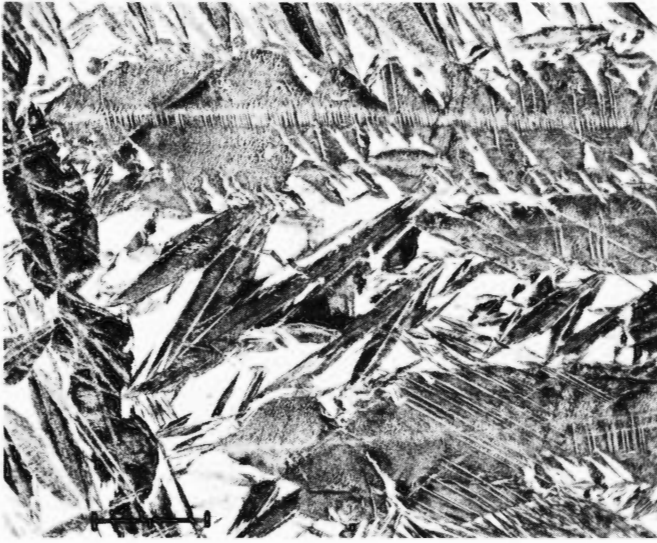
The troilite is present in a micromelted form which is similar to what is present in numerous other meteorites and



**Figure 1748.** Tishomingo. A near-surface section showing how terrestrial weathering has penetrated the massive iron and selectively oxidized it so that the martensitic pattern becomes visible on a polished section. Two dots (T) are shock-melted sulfides. Polished. Scale bar 500  $\mu$ .



**Figure 1749.** Tishomingo. Detail of the martensite plates showing a faulted midrib. Etched. Scale bar 100  $\mu$ .



**Figure 1750.** Tishomingo. Martensite plates occur within this field in a large number of directions. Striations indicate internal twinning. The density of twins is particularly high along the midribs of the plates. Etched. Scale bar 100  $\mu$ .

has been ascribed to shock pressures with associated relaxation heating. The microhardness values, 425 for martensite and – particularly – 250 for retained austenite, indicate hardening from shock deformation, possibly with slight tempering of the martensite. Scheil (1932), McReynolds (1946) and others have shown that plastic strain induces transformation at temperatures well above the martensite start temperature,  $M_s$ . If we accept the fact that the micromelted troilite pools are indicative of intense strain from shock deformation, it must also be considered that part of Tishomingo's martensite can have been formed during the shock. Perhaps future investigations can deduce what relative importance the two possible mechanisms can have played in the case of Tishomingo. Moreover, the problem seems to have general importance for the iron meteorites, since a large number contain martensitic transition zones in the plessite fields, or even wholly martensitic fields. In several cases I have noted martensitic morphologies quite similar to Tishomingo's, albeit on a small scale. So Tishomingo may well be considered only a special case in a general problem.

The final reheating in the Earth's atmosphere was superficial, and the tempering due to the terrestrial climate was very mild. There are no indications of artificial reheating by the discoverer.

**Specimens in the U.S. National Museum in Washington:**  
Polished sections.

### Tlacotepec, Puebla, Mexico

Approximately 18°41'N, 97°39'W

Nickel-rich ataxite, D. Duplex  $\alpha + \gamma$  with a few 30  $\mu$  wide  $\alpha$ -spindles. Oriented sheen in Widmanstätten directions. HV 242±8.

Group IVB. 16.20% Ni, 0.71% Co, 0.05% P, about 0.05% S, 0.20 ppm Ga, 0.03 ppm Ge, 24 ppm Ir.

### HISTORY

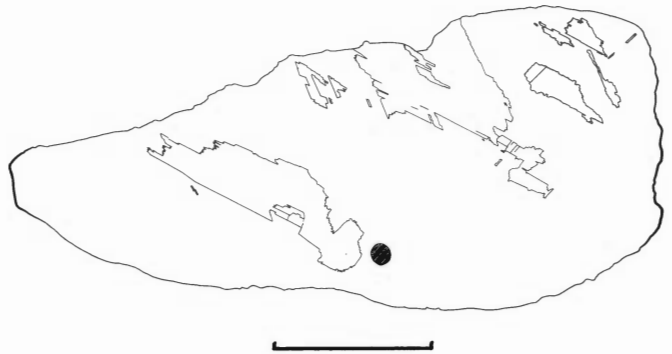
This meteorite was not reported when it was found, but was "discovered" in the Museum of the Institute of Geology, in Mexico City, by Ward (1904a: 25). His information was very insufficient; the sample he saw was estimated to weigh 24 kg and to be an octahedrite from the District of Tecamachalco, State of Puebla. He obtained 40 g of the mass for his own collection. Farrington (1915: 436) and Prior (1923a) could only quote Ward since no more information had become available.

In 1929 when Ninger examined the Mexico collection, he was able to give more detailed information of the weight and nature of the material. The locality was confirmed, but nobody knew about the date of discovery, finder or how the meteorite arrived in Mexico City. Tlacotepec is a village in the state of Puebla, about 70 km southeast of the city of Puebla, on the main road from Puebla to Tehuacan. The corresponding coordinates are given above.

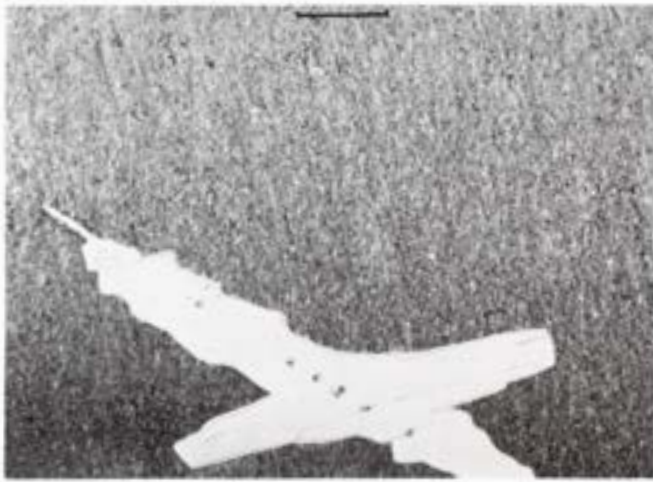
Ninger (1931d) described the meteorite, with an analysis and two photomicrographs. The mass was estimated to weigh 71 kg and to be a coarse octahedrite of an unusual type. It had previously been divided into two halves, one of 34 kg and the other 36.6 kg. Ninger managed to acquire the larger mass by exchange, and this he subdivided and circulated (see, e.g., Ward's Price List No. 342, 1931).

Haro (1931: 79), while reporting on the Mexican meteorites, gave no new information of Tlacotepec. The specimen that remained in Mexico City weighed 32.6 kg and was classified as an octahedrite.

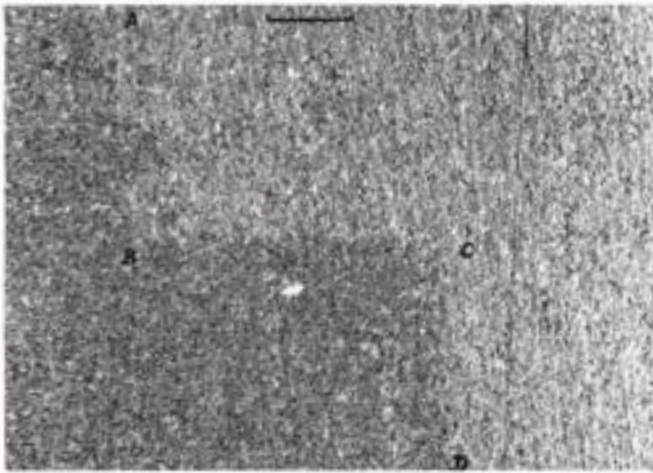
Reeds (1937: 629) also adhered to the classification as a coarse octahedrite. Finally, Perry (1944: plate 23) correctly concluded that Tlacotepec was a nickel-rich ataxite. His two photomicrographs clearly show a fine-grained plessite in which scattered kamacite spindles occur. Reed (1965b) examined the plessite with the microprobe and found an average nickel concentration of 17%, similar to



**Figure 1751.** Tlacotepec (U.S.N.M. no. 872). Sketch of a full slice with a lamellar troilite-daubreelite inclusion. An attempt has been made to delineate areas of different shadings, i.e., different orientation of the  $\alpha - \gamma$  intergrowths. Scale bar 10 cm.



**Figure 1752.** Tlacotepec (Copenhagen no. 1968, 338). Nickel-rich ataxite of group IVB. In the dense matrix several kamacite spindles occur, here developed around a row of tiny sulfide particles. Etched. Scale bar 300  $\mu$ .



**Figure 1753.** Tlacotepec (Copenhagen no. 1968, 238). The boundary between light- and dark-shaded areas is indistinct but proceeds here along ABCD. A kamacite spindle is located between B and C. Etched. Scale bar 300  $\mu$ .

what he found in the closely related Cape of Good Hope ataxite. Nininger & Nininger (1950: plate 10) reproduced the same photomicrograph as was given in 1931. In the meantime the slab which was pictured had been acquired by the U.S. National Museum (No. 872 of 2,400 g).

In retrospect, it is quite interesting to observe how two almost identical nickel-rich ataxites puzzled early investigators because of their extremely fine microstructures:

Iquique was for several generations believed to be a hexahedrite, while Tlacotepec was classified as an octahedrite.

Herr et al. (1961) examined the osmium-rhenium ratios and found a total age of  $4 \times 10^9$  years for Tlacotepec. Bauer (1963) measured the helium isotopes and estimated the cosmic ray exposure age to be 870 million years. Hintenberger et al. (1967a) measured various noble gas isotopes, arriving at helium values slightly different from Bauer's. Voshage (1967) estimated the cosmic ray exposure age to be  $915 \pm 55$  million years on the basis of  $^{41}\text{K}/^{40}\text{K}$  measurements.

#### COLLECTIONS

Mexico (32.6 kg), London (8.3 kg and 140 g), Tempe (7.5 kg), Harvard (3.93 kg), New York (2.78 kg), Washington (2.40 kg), Chicago (2.14 kg), Copenhagen (227 g), Los Angeles (100 g).

#### DESCRIPTION

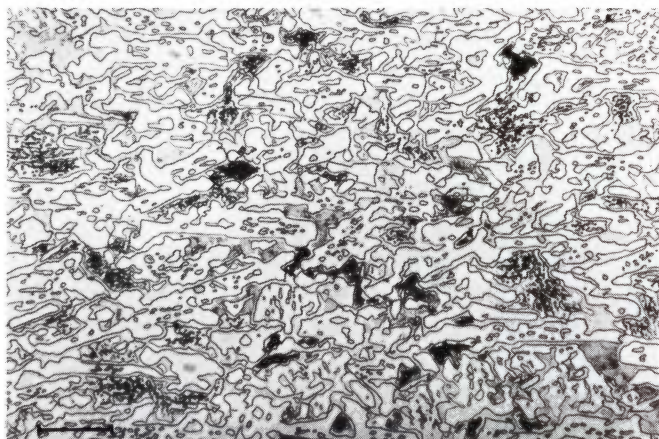
Nininger (1931d) observed that the two masses of 34 and 36.6 kg which he identified as Tlacotepec, fitted together to make a complete individual from which at the most a 200 g sample had been removed. Allowing for loss in the cutting operation the original specimen, thus, must have weighed about 71 kg. The dimensions are unknown, but a reconstruction suggests an elongated pear-shaped mass with a long axis of 45 cm. The heavy end of the pear measured approximately  $22 \times 18$  cm perpendicular to the long axis. Nininger cut the mass lengthwise and produced five slices. Each cut required a cutting time of 150 hours and produced a centimeter-thick slice of about  $40 \times 19$  cm.

The large specimen in Tempe is a truncated endpiece containing a significant portion of the natural surface. It is corroded and covered with oxide shales of 0.1-1 mm thickness. Some indistinct, weathered regmaglypts from the atmospheric flight are present, but no fusion crust could be identified. Part of the surface is covered by evaporites, probably caliche impregnated by iron.

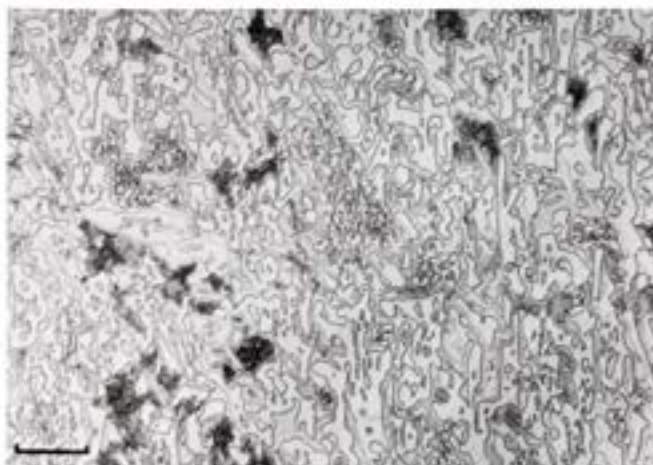
Sections through the mass confirm the corroded nature of the surface. The limonitization has proceeded in a rhythmic way to produce shallow concentric basins of corroded material. The exterior part is completely converted to limonite; then zones follow in which the  $\gamma$ -phase is distinguished as cream-colored particles in a completely converted  $\alpha$ -phase. Next are the zones where the  $\gamma$ -phase is unattacked, and the  $\alpha$ -phase is attacked only along the grain

#### TLACOTEPEC – SELECTED CHEMICAL ANALYSES

References	percentage			ppm								
	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Hawley in Nininger 1931d	16.23	0.68	0.063	500	700	310	900					
Lovering et al. 1957		0.74				168	<30		<2	<1		
Moore et al. 1969	16.56	0.71	0.045	45	40		10					
Schaudy et al. 1972	15.82								0.195	0.031	24	



**Figure 1754.** Tlacotepec. Detail of Figure 1753 left of ABCD. The duplex  $\alpha + \gamma$  structure shows prominent horizontal lineation. Etched. Oil immersion. Scale bar  $10 \mu$ .



**Figure 1755.** Tlacotepec. Detail of Figure 1753 right of ABCD. The duplex  $\alpha + \gamma$  structure shows prominent vertical striation. Otherwise the size and density of  $\alpha$  and  $\gamma$  particles are identical to that in Figure 1754. Etched. Oil immersion. Scale bar  $10 \mu$ .

boundaries. And, finally, the unaltered interior is reached. The concentric basins may be anywhere from 1 to 10 mm deep. However, little has actually been lost from the meteorite. Microhardness traverses perpendicular to the surface show a significant decrease from interior values of

240 to about 200 in the near surface layers. This suggests that the annealed zone from the atmospheric penetration is still preserved, which again indicates that on the average only 2-3 mm has been lost by weathering. The concentric

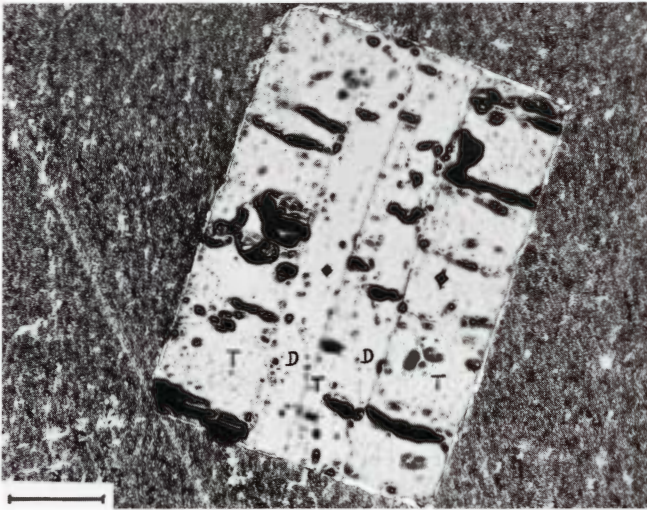


**Figure 1756.** Tlacotepec (Copenhagen no. 1968, 338). Corroded near-surface area. The surface shows sharp contrasts due to the uncorroded taenite being white and the corroded kamacite black. Compare Figure 95. Polished. Oil immersion. Scale bar  $20 \mu$ .

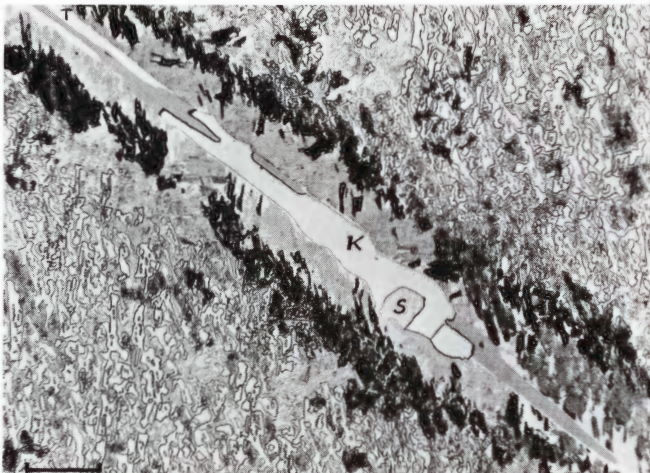
shale development is typical for the nickel-rich ataxites; compare, e.g., Cape of Good Hope.

Etched sections show Tlacotepec to be an ataxite. Light and dark zones alternate, as frequently observed in group IVB irons meteorites, as, e.g., Cape of Good Hope, Hoba and Kokomo. The individual zones are bordered by straight, somewhat indistinct lines, which together apparently form a Widmanstätten pattern. The width of the zones varies appreciably, from 1 mm to at least 10 cm. There are three or possibly four different shadings when viewed in reflected light. The uniformity of the pattern proves that Tlacotepec was once a single austenite crystal like the other IVB irons.

High magnification reveals a plessitic structure of densely interwoven  $\alpha$  and  $\gamma$  phase. Both the  $\alpha$ - and the  $\gamma$ -phases are continuous. The  $\alpha$ -phase is  $0.5\text{--}2\ \mu$  wide, while the  $\gamma$ -phase is  $0.2\text{--}1\ \mu$  wide. Whenever the  $\gamma$ -phase increases above  $1\ \mu$  in width, the interior is decomposed to a



**Figure 1757.** Tlacotepec (Copenhagen no. 1968, 338). Troilite (T) regularly intergrown with daubreelite lamellae (D). The black pits are due to imperfect polishing. Etched. Scale bar  $200\ \mu$ .



**Figure 1758.** Tlacotepec (Copenhagen no. 1968, 338). A narrow troilite-daubreelite lamella runs diagonally across the field. In center schreibersite (S) and kamacite (K). Cream-colored taenite (T). Bainitic transition zones to the duplex matrix. Etched. Scale bar  $20\ \mu$ .

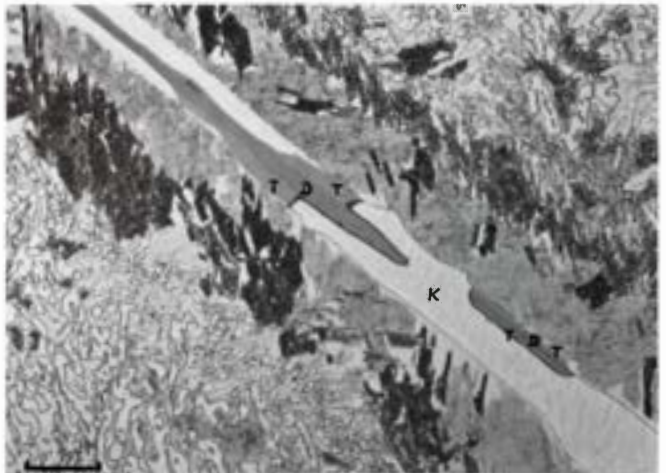
submicroscopic, duplex structure. Some details of the structure are particularly well observed in the corroded surface zones.

Comparison of the duplex structures on either side of a bright-dark borderline reveals that the only difference between the two sides is a slight change of orientation. The linear elements of the  $\alpha$ - $\gamma$  structure shift their positions when the border is passed. Microhardness measurements with 100 g load did not reveal any difference in hardness between the zones. The Vickers impression was about  $28\ \mu$  in diagonal, so a large number of  $\alpha+\gamma$  units were incorporated in each measurement. The hardness was found to be  $242\pm 8$ .

Occasionally a few kamacite spindles may be observed. They are  $30\pm 15\ \mu$  wide and up to  $500\ \mu$  long. They occur with a frequency of 10 per  $\text{cm}^2$ , but are often found in clusters. Apparently they have all grown from minute nuclei either of a sulfide or a phosphide. In one case, a straight row of troilite-daubreelite particles each  $10\text{--}15\ \mu$  across, had nucleated five or six parallel kamacite spindles which had grown until they met the neighboring spindles. No Neumann bands were observed.

Schreibersite is rare, the largest particle seen being  $10 \times 10\ \mu$ . This was nucleated by a troilite-daubreelite particle. Otherwise, only minute  $1\text{--}5\ \mu$  particles occur occasionally in the interphase between the  $\alpha$ -spindles and the duplex matrix. This tallies well with the low bulk phosphorus content reported in wet chemical analyses.

Troilite occurs as an occasional nodule,  $1\text{--}2\ \text{cm}$  across, and as millimeter-sized particles of box- or plate-shape. Even a  $2\ \text{mm}$  particle with hexagonal cross section was observed. On the average the smaller particles occur with a frequency of one per  $15\ \text{cm}^2$ . The large nodules are rarer than one per  $500\ \text{cm}^2$ . The troilite is monocrystalline and undamaged. Its microhardness is  $260\pm 15$ . A number of parallel daubreelite lamellae are usually found inside the troilite; their hardness is  $400\pm 30$ . Some of the smaller sulfide particles are composed of alternating lamellae of



**Figure 1759.** Tlacotepec. Detail of Figure 1758 showing troilite (T), daubreelite (D), kamacite (K) and taenite (white envelope above left). Martensitic-bainitic transition zones to the duplex matrix. Etched. Oil immersion. Scale bar  $10\ \mu$ .

troilite and daubreelite, each 1-5  $\mu$  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  $\mu$  in cross section. They are enveloped in 1-2  $\mu$  wide cream-colored austenite, bordered on either side by 10-15  $\mu$  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)

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**Toluca, Mexico**

19°27'N, 99°35'W; 2700 m

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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.