Wiley, Colorado, U.S.A.

38°12′N, 102°47′W; 1,200 m

Plessitic octahedrite, Opl. α-spindles 35±15 μ. Neumann bands. HV 195±10.

Group IIC. 11.59% Ni, 0.67% Co, 0.37% P, 38.8 ppm Ga, 114 ppm Ge, 6.2 ppm Ir.

HISTORY

A mass of 3.5 kg was plowed up by Ed Linville in 1938, 4.5-5 miles northwest of the town of Wiley, Prowers County. It was acquired by Nininger and briefly mentioned on several occasions (A.D. Nininger 1939; Nininger & Nininger 1950: 102, 119). Perry (1944: 65 and plates 19 and 51) gave some typical photomicrographs and classified the iron as a nickel-rich ataxite. Brett & Henderson (1967) presented a photomicrograph of a troilite lamella and Wasson (1969), one of the overall structure. Wasson also noted that Wiley formed a natural member of the new group IIC. Hintenberger et al (1967) determined the occluded noble gases, and Voshage (1967) found by the $^{40}K/^{41}K$ method a cosmic ray exposure age of 740±90 million years. Buchwald (1971d) discussed the gas contents and the structure and presented two photomicrographs.

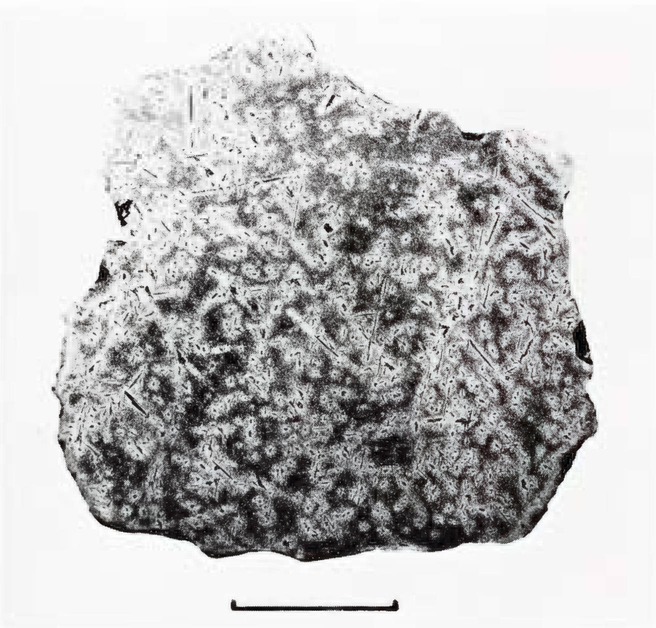

Figure 1935. Wiley (U.S.N.M. no. 1328). A plessitic octahedrite of group IIC. The numerous α-spindles with their phosphide nuclei give a peculiar appearance to this meteorite. Deep-etched. Scale bar 20 mm. (Perry 1950: volume 5.)

COLLECTIONS

London (1,105 g), Tempe (1,054 g), Ann Arbor (324 g), Chicago (285 g), Washington (189 g).

DESCRIPTION

The mass had the average dimensions of 10 x 10 x 9 cm and weighed 3.5 kg. The weathered surface is covered with a 0.5-2 mm thick and surprisingly red oxide crust, perhaps conditioned by the soil in which it was found. Regmaglypts, 10-15 mm across, are visible but altered by weathering. No fusion crust and no heat-affected α_2 zone could be identified, and no altered structures could be detected near the surface. However the microhardness decreases significantly from an interior level of 195±10 to 155±5 at the surface, and this is an indication that only 2-3 mm on the average has been lost by weathering (hardness curve type II, where the left part is removed by corrosion).

Etched sections reveal a structure intermediate between octahedrites and ataxites. It has been suggested that this structure be classified as a plessitic octahedrite and not as an ataxite because octahedral elements are visible to the naked eye (Buchwald & Munck 1965: 14, 70). Ballinoo and Wiley are typical examples, and the whole group IIC is, in fact, plessitic octahedrites. It is characteristic that the

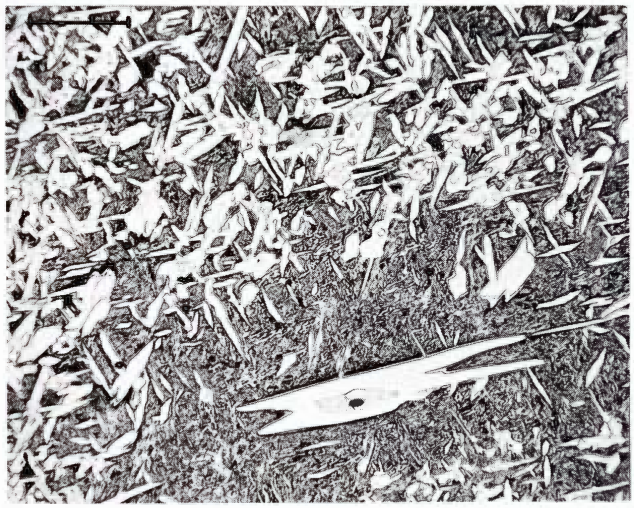

Figure 1936. Wiley (Tempe no. 380.1x). Most, if not all, of the larger schreibersite crystals were nucleated by a phosphate crystal (black). Swathing kamacite developed around them, and later Widmanstätten spindles grew in the matrix. Etched. Scale bar 400 μ.

WILEY – SELECTED CHEMICAL ANALYSES

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Henderson 1941, pers. comm:	11.71	0.60	0.51									
Wasson 1969	11.50								38.8	114	6.2	
Lewis & Moore 1971	11.56	0.73	0.23	50								

α-phase is present as discrete spindles and does not form continuous lamellae.

Wiley was once a single taenite crystal, and when it transformed upon cooling – which occurred, as so often is the case, in successive steps, – it created progressively finer structures, always repeating the same theme. The first generation of pointed kamacite lamellae ($\frac{L}{W} \sim$ 10-20) is visible macroscopically. They have a width ranging from 40-150 μ, and all are apparently nucleated heterogeneously by preexisting schreibersite crystals, 20-100 μ thick, but frequently very long. The kamacite spindles occur with a frequency of one per 3 mm^2 and cover about 5% by area. They may, in fact, all be interpreted as swathing kamacite rims around schreibersite. The kamacite shows subboundaries and a few Neumann bands, and the hardness is 172±8, the lowest hardnesses being associated with the thinnest lamellae because these are poorest in nickel.

The matrix proper is a microscopic, octahedral pattern of straight short ($\frac{L}{W} \sim$ 10) kamacite spindles with a width of 35±15 μ. The spindle-shaped plates are apparently formed by homogeneous nucleation and growth, but there are also a number of irregular kamacite blebs developed around tiny schreibersite bodies. Between the kamacite spindles there is a duplex, easily resolvable $\alpha + \gamma$ mixture, the α-phase of which is subdivided into 1-10 μ wide cells, while the γ-phase forms 1-2 μ grains and vermicular bodies. The hardness of the $\alpha + \gamma$ matrix, integrating over numerous units, is 195±10. The hardness of the taenite-martensite transition zones is 225±10, while that of the kamacite alone is 165±5.

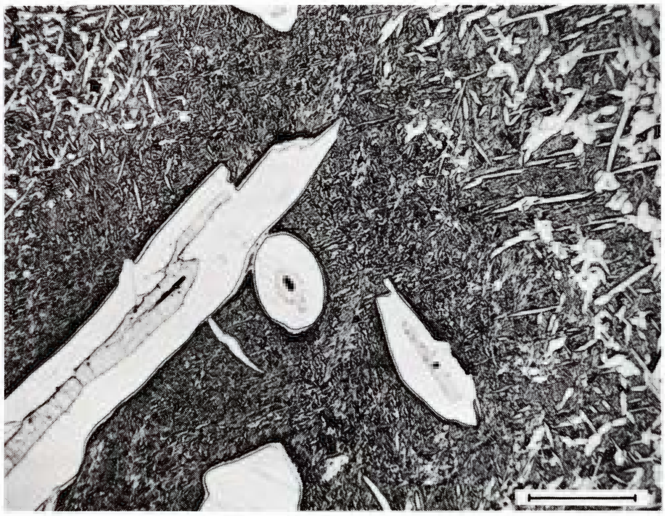

Figure 1937. Wiley (Tempe no. 380.1x). Another view of kamacite grains with schreibersite crystals that were all nucleated by phosphate crystals (black). Compare Figure 192. Etched. Scale bar 400 μ.

Figure 1938. Wiley (Tempe no. 380.1x). Brecciated schreibersite associated with a small troilite crystal. The kamacite shows Neumann bands. Etched. Scale bar 100 μ.

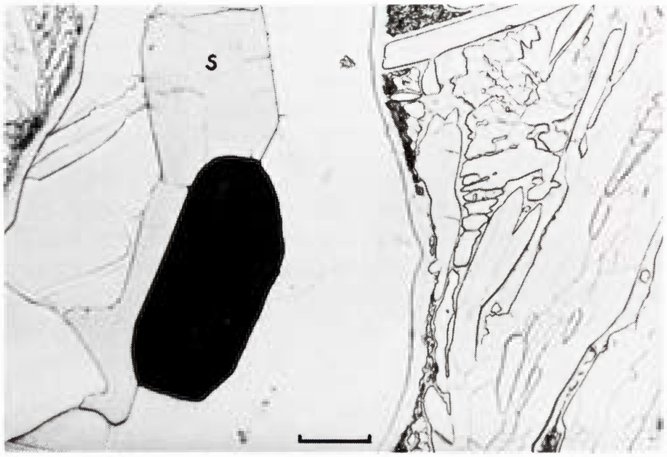

Figure 1939. Wiley (Tempe no. 380.1x). Detail of a phosphate crystal (black) and the associated schreibersite (S). Kamacite with Neumann bands and easily resolved plessitic matrix with numerous subboundaries. Etched. Scale bar 20 μ.

Finally, in 200-500 μ wide zones around the primary kamacite lamellae the matrix is exceedingly fine-grained. It resembles the bulk matrix on a five times reduced scale.

Schreibersite occurs abundantly in all sizes. The largest are lamellar, e.g., 1,000 x 25 or 500 x 100 μ in size, and appear to be arranged as Brezina lamellae in the {110} planes. They precipitated mostly around fine phosphates, before the Widmanstätten pattern formed. They are monocrystalline and only slightly fractured. Smaller schreibersite bodies, 1-25 μ across, are rather evenly distributed, many of them having formed kamacite rims. The presence of iron-phosphide eutectics, mentioned by Perry (1944: plate 19), could not be confirmed and would also not be expected.

Troilite is present as lamellae, 2,000 x 20 or 800 x 100 μ in size, and as discrete blebs, 50-200 μ in size. It is monocrystalline but shows lenticular twins which result from slight plastic deformation. Schreibersite has often precipitated upon the troilite as 10-100 μ discontinuous rims.

A number of rounded or subangular phosphate inclusions, typically 20-100 μ in size and deep gray in reflected light, occur evenly distributed. On the electron microprobe they were found to consist of iron, manganese, phosphorus and oxygen, corresponding to sarcopside or graftonite. They must have been the only foreign material in the high temperature, homogeneous taenite. A beautiful example of the significance of nucleation in the solid state in meteoritic iron is seen in Figures 1936-1937. A 15 μ wide phosphate bleb has served as nucleus for a somewhat larger troilite crystal. The aggregate in turn has nucleated a typical 100 μ wide schreibersite body, and finally the schreibersite nucleated a 100 μ wide rim of swathing kamacite. Within a sphere 1 mm in diameter, no other nuclei were present, and no decomposition occurred here until very late in the cooling period.

Corrosion has formed a 0.5-2 mm thick crust and also attacked the α-phase selectively to less than 1 mm depth, whereby the duplex structure is beautifully brought out.

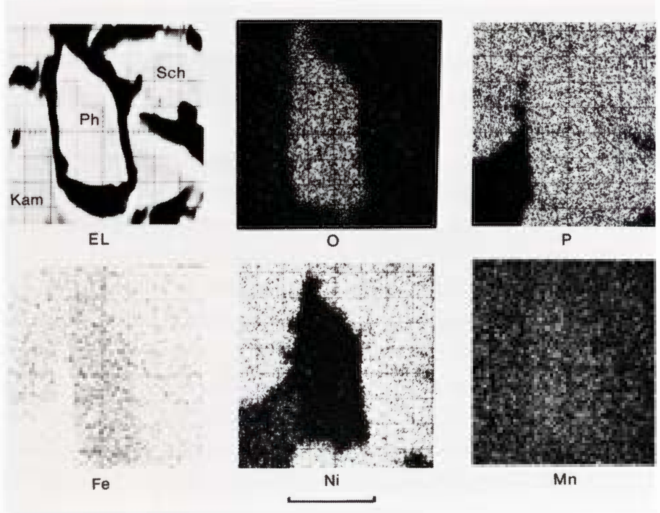

Figure 1940. Wiley (U.S.N.M. no. 1328). X-ray scanning pictures of a phosphate (ph) – schreibersite (sch) – kamacite (kam) intergrowth similar to Figure 1939. K_{α} signals at 15KV of the respective elements. Scale bar 40 μ.

Wiley is a plessitic octahedrite closely related to Ballinoo and similar octahedrites of group IIC. It represents a more primitive stage than Ballinoo, since it is not altered by secondary, cosmic reheating.

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

174 g slice (no. 1328, 6.5 x 6 x 0.6 cm)
15 g part slice (no. 1328, 3 x 2 x 0.5 cm)

Willamette, Oregon, U.S.A.

45°22′N, 122°35′W; about 100 m

Medium octahedrite, Om. Bandwidth 1.05±0.10 mm. Recrystallized and annealed twice in cosmos. HV 153±5.

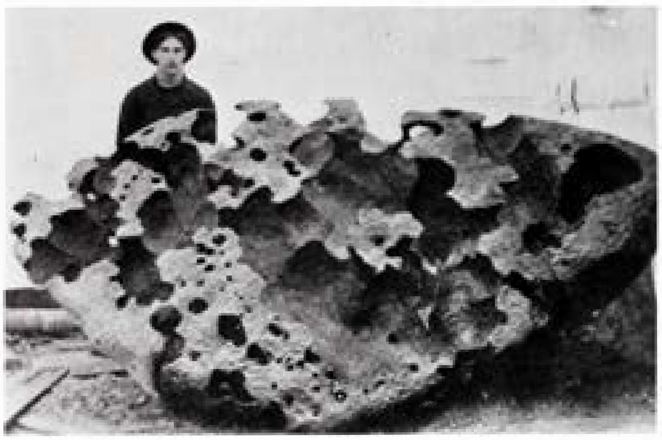

Figure 1941. Willamette. Full view of the lower side of the meteorite. Photographed on the farm of Ellis Hughes. Note the large and small bowl-shaped cavities. (From Ward 1904c: plate 16.)

Group IIIA. 7.62% Ni, 0.45% Co, about 0.14% P, 18 ppm Ga, 38 ppm Ge, 4.3 ppm Ir.

HISTORY

A mass believed to weigh about 4 tons, but later on the railroad scales in Portland shown to weigh 31,107 pounds (14.1 metric tons) (Hovey 1906), was found in 1902 by Ellis Hughes 3 km northwest of the village of Willamette. Willamette is now part of the incorporated city of West Linn, with the coordinates given above. The first scientific mention of the meteorite was made by Kunz (1904), who stated that the mass was found on land belonging to the Oregon Iron and Steel Company, about 2 miles south of Oregon City. According to Reeds (1937: 524) this is incorrect. In a letter to Reeds, dated Sept. 19, 1935, Mr. Strohmeyer, Assistant County Engineer of Clackamas County, stated, "The place is at a point 500 feet south and 600 feet east of the NW corner of the NW¼ of the SE¼ of section 27, Township 2 South, Range 1 East of the Willamette meridian." Reeds placed this site three miles northwest of Oregon City. The following are excerpts from the thorough and vivid description by Ward (1904c), who visited the place while the ownership of the meteorite was still in dispute.

> "This most interesting meteorite, noble in size and wonderful in physical features, was found near the border of Clackamas County, Oregon, in the autumn of 1902. At this point in its course the Willamette River, 80 miles south of its junction with the Columbia, runs between high banks of sedimentary rocks ..... On a hill-side, three miles above the mouth of the streamlet Tualitin, fell, apparently centuries ago, the Willamette siderite, the third largest meteorite in the world. The region is a wild one, covered by a primeval forest of pines and birch, little visited and largely inaccessible. Here, on the spur of a hill in a small level area, lay the great iron mass, lightly buried in soil and the carpet of accumulated vegetable debris. In the valley, half a mile away, there lives with his family, a humble, intelligent Welshman, Mr. Ellis Hughes. He had formerly worked in Australian mines. He had with him in 1902 a prospector named Dale, and together they roamed over the hills seeking minerals. One day a blow on a little rock projecting from the soil showed it to be metal. They dug and found its great dimensions; also that it was iron. It was on land which they learned belonged to a land company. For some months they kept the find a secret, hoping to buy the land on which the mine was located. Some months later they ascertained, in some way, that their supposed iron reef, which they had found to be but ten feet long and a yard or more deep, was a meteorite. They became more secretive than ever, and covered their find most carefully."

Perhaps the interest in the large meteorite would soon have waned had it not been for Mrs. Hughes, who was determined that her husband should move it to his own property, to prevent curiosity seekers from carrying it away in a number of small pieces (Lange 1958). Again let us follow Ward's narrative 1904c):

> "In August of 1903, Mr. Dale in the meantime having left the country, Mr. Hughes conceived the idea of bringing the great iron mass to his house, a distance of nearly three-fourths of a mile. This seemed an almost impossible task, he having only his son of 15 years and a small horse as motor power. But he was an old miner, full of mechanical resources, and also full of pluck and energy. With infinite pains he fashioned a simple capstan with chain to anchor it, and a long braided wire rope to roll up on it, as his horse traveled around it as a winch. Then he fashioned an ingenious car with log body timbers and sections of tree trunks as wheels; also some heavy double-sheaved pulleys. By wearisome blocking-up and leverage he succeeded in capsizing the great mass directly upon the car and lashing it securely. Then he stretched out his hundred-foot hauling wire-rope, attached one end of it to the car and the other to his staked-down capstan, and started his horse going round. ... The great mass moved slowly, for the ground was soft, and, even with boards put under them and constantly changed, the wheels sank deep into the mud. ... At last, after three months of almost incessant toil, the giant meteorite reached Hughes' own land, where it now rests. It was a herculean struggle between man and

Figure 1942. Willamette. South end view, meteorite capsized. When discovered, the blunt apex pointed approximately vertically into the ground and the surface with the cavities was almost level with the surrounding terrain. (From Ward 1904c: plate 15.)

Figure 1943. Willamette. The 14.1 ton meteorite turned upside down on the primitive wheel cart constructed by Hughes and his son (right). Note the hole entirely piercing the base. (From Ward 1904c: plate 14.)

meteorite, and the man conquered. It is unpleasant to have to record what followed.

"The Hughes, father and son, had for these months worked unobserved in the dense forest. . . . But when the great find was announced, people came trooping up the little valley . . . to see the celestial wonder."

They rode the one mile from Oregon City to Willamette on the old electric streetcar, and then walked two miles to the place where Hughes charged 25¢ in admission. Among the curious sightseers was an attorney for the Oregon Iron and Steel Company, and he soon noticed that the newly hewn road led to the property of his employers. It has been reported that the attorney offered Hughes fifty dollars for his meteorite, an offer which was promptly refused. On November 27, 1903, Hughes found himself as defendant against the Oregon Iron and Steel Company for the possession of his prized curiosity (Clackamas County Circuit Court Case No. 7587).

The company based its claim to the meteorite on the premise that it was part of the land on which it was found and had been stolen. Hughes contended it was personal property, an abandoned Indian relic. As witnesses he brought in two Indians who testified that the now extinct Clackamas tribe had used and venerated the meteorite as their "Tomanowos," or visitor from the moon. One Indian was Susap, a 70-year-old Klickitat, who testified that he had seen the meteorite as a child and had been told by Wochimo, Chief of the Clackamas, that the Indians washed their faces in the water collected in the basins of the meteorite, and that their young warriors dipped their arrows in the water before engaging in battle with neighboring tribes. The other Indian, 47-year-old Sol Clark, a Wasco Indian, remembered that the iron mass belonged to the medicine men of the Clackamas tribe, who still used it to support various beliefs until about 1870.

If the jury had accepted the meteorite as an abandoned Indian relic, Hughes would have won the case, since numerous examples were known where the finder, rightly or wrongly, became the owner.

However, the jury announced a verdict in favor of the company who immediately began to make preparations for the removal of the meteorite. Hughes appealed his case to the Oregon State Supreme Court, but before much progress had taken place, a queer incident occurred. The owner of the land which lay between Hughes' property and the hill where the meteorite was found claimed that he was the rightful owner, since the meteorite really had been found on this third party's land. As proof, he showed a hole in the ground from which he said Hughes took the meteorite. It was, however, proved that he had blasted out this hole in order to put in a false claim. He lost his case.

At last, the Supreme Court, on July 17, 1905, sustained the decision of the lower court. Chief Justice Wolverton ruled (47 Supreme Court Reports, p. 313, 81 Pacific, 572; see also Sunday Oregonian for October 23, 1938, where J.H. Pruett reviewed the case): "Meteorites, though not embedded in the earth, are real estate, and consequently belong to the owner of the land on which they are found." Hughes gave up further claim to the noted object. He lived to be an old man, but was very bitter over the court decision; Pruett (1939; 1943) and Lange (1962)

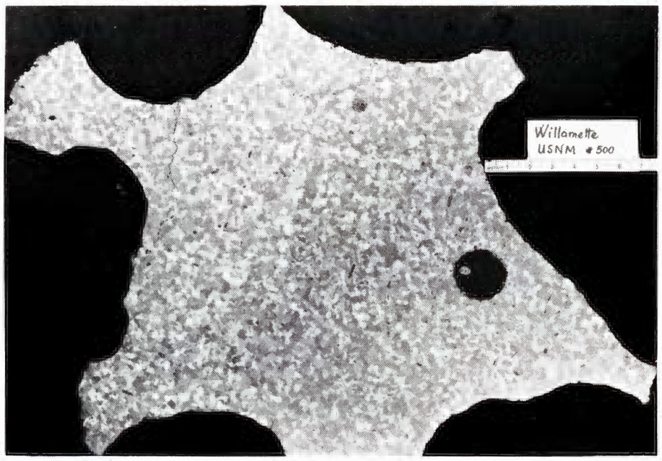

Figure 1944. Willamette (U.S.N.M. no. 500). A 1.9 kg slice with a shock-melted troilite inclusion, inside which is a metal globule (compare Merceditas). The slice was cut through one of the pedestals (page 1316) and, therefore, shows an irregular corroded outline resembling a deer skin. Deep-etched. Scale bar in centimeters.

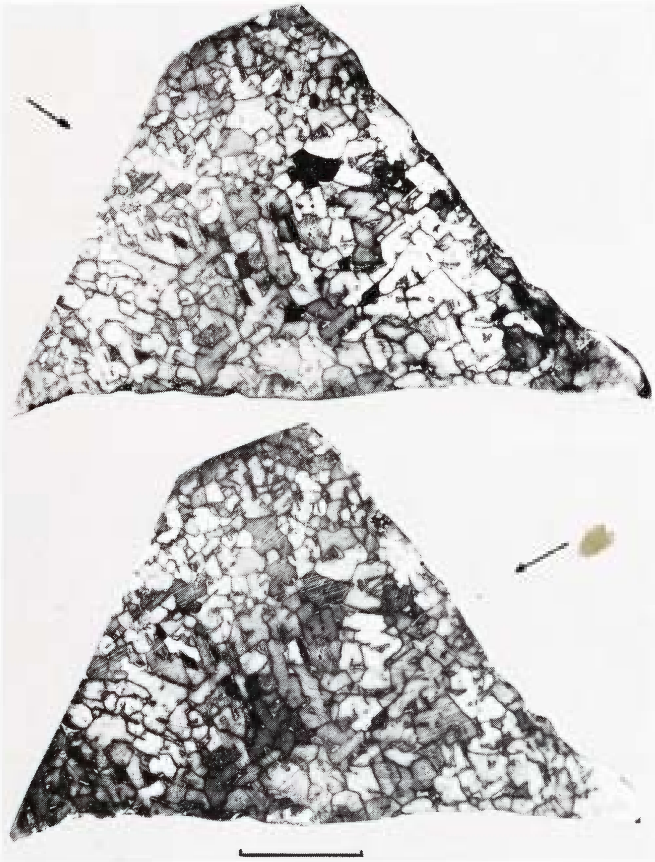

Figure 1945. Willamette (Brit. Mus. no. 86945). A shocked and recrystallized medium octahedrite of group IIIA. While the kamacite grains appear equiaxed in Figure 1944, remnants of the original Widmanstätten structure are distinctly visible in this sample, particularly when the etched slice is viewed with the light coming from different directions (arrows). Scale bar 10 mm.

gave some details and photographs of him; he died and was buried in 1942, across the river from Willamette.

The meteorite was taken by its new owners to the Mines Building at the Lewis and Clark Exposition at Portland. A ceremonious unveiling was carried out in the presence of the governor and other dignitaries, and it was hoped that the meteorite could remain in the state where it was found. Then came, however, a tempting bid, reportedly of $20,600, from Mrs. William E. Dodge II of New York (American Museum Journal 1906: volume 6:61). She presented the mass to the American Museum of Natural History, where it has been exhibited since 1906. When, in 1935, the new Hayden Planetarium was added to the Museum (Reeds 1937: 524), Willamette and the Cape York meteorites were moved in, and the building was, so to speak, constructed around them. Today, it appears that there is not a door large enough to let the Ahnigito and Willamette masses pass.

Very few meteorites have been subject to legal queries and law suits. Five different cases, Forest City, Homestead, Willamette (all U.S.A.), and two French falls were known to Carpenter (1945), who treated the American cases in some detail. Lacroix (1906) reviewed the dispute concerning the stone Saint Christophe-la-Chartreuse which fell in France in 1841. The law concerning the ownership of meteorites varies in different countries. In the U.S.A. there are now at least three court decisions maintaining that a meteorite belongs to the land on which it has fallen and is, therefore, the property of the landowner. One such case involved the Forest City shower of stones, actually seen to fall in 1890. A vivid account of the recovery and dispute of Forest City was given by Winchell (1923). In the Willamette case, the disputed mass was much larger, of iron-nickel metal, and was not an observed fall. The Supreme Court of Oregon decided again that the landowner was the rightful owner of a meteorite. These decisions have been criticized by various parties (e.g., La Paz 1946; Nininger & Nininger 1950: 17) as unfair to the actual finders of meteorites. In practice it appears that the finders have, by private arrangement with the landowner, often obtained their fair share of the market price for any newly discovered meteorite.

In the Soviet Union meteorites may not be bought or sold and all meteorites found on its territory are considered property of the State. A reward in money is offered from the Committee on Meteorites as a measure of encouragement (Krinov 1974a). In India meteorites belong to the Government (Murthy et al. 1969: 1); in Scotland they rank as treasure trove and, as such belong to the Crown. In England and Denmark the law is uncertain. It would require a court ruling on the subject of ownership, but there has been no litigation in any of the previous nine cases of meteorites on English territory (Wold Cottage 1795, Launton 1830, Aldsworth 1835, Rowton 1876, Middlesbrough 1881, Appley Bridge 1914, Ashdon 1923, Pontlyfni 1931, Barwell 1965) and two on Danish territory (Mern 1878, Århus 1951). The matter has always been settled privately.

Recently Lord Cranbrook, a trustee of the British Museum, introduced a bill before the House of Lords, proposing that all meteorites which fall in Great Britain should automatically become crown property (Meteorites 1971, Volume 6:125). At the time of writing the outcome of the debate was not yet known.

Ward (1904c) gave a fine description, accompanied by nine excellent photographs of the recovery action in 1903. He discussed at length the intriguing depressions and large basins, which were described as "kettle holes, wash-bowls, and small bath-tubs." He believed the smaller depressions on the apex to be genuine regmaglypts, while the large basins were supposed to be excavated by terrestrial water, heavily charged with carbonic acid. His views were violently attacked by Winchell (1905) who saw no traces of fusion crust or regmaglypts, and believed that the large bowls were due to such ingredients as once filled the openings. These ingredients were supposed to be nonmetallic, stony matter,

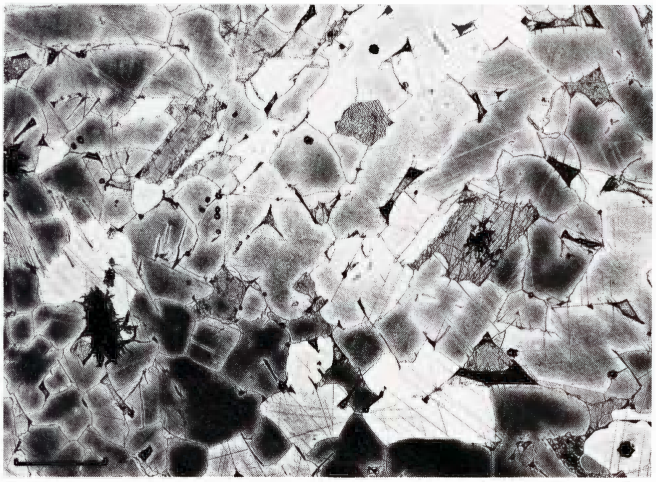

Figure 1946. Willamette. Detail of Figure 1945 (inverted). Recrystallized medium octahedrite. Original taenite and plessite fields still indicate the former Widmanstätten directions. Three black spidery blebs are shock-melted troilite nodules. Etched. Scale bar 3 mm.

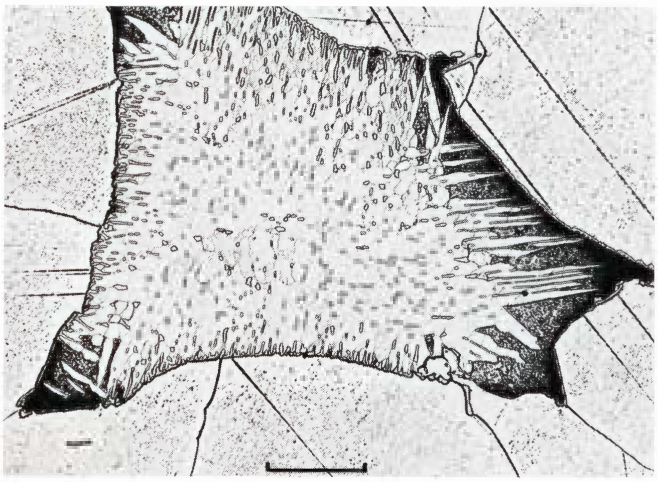

Figure 1947. Willamette (Copenhagen no. 1905, 1735). An altered plessite field, however, still displaying Widmanstätten directions, indicative of one former austenite crystal. Numerous fine precipitates in the adjacent kamacite. Etched. Scale bar 300 μ.

perhaps olivine, perhaps troilite. But he admitted that no trace of such stony matter was to be found at the present time. The dispute has continued on and off, since these early examinations, with contributions by Hovey (1906), Farrington (1915), Reeds (1937: 524), Henderson & Perry (1958: 347), and more indirectly, Krinov (1960a: 249). Henderson & Perry concluded that the present rear side of Willamette, which is about 2 x 3 m in size and exhibits deep craters, might have some topographic similarities to the surface that existed there before the iron entered our atmosphere. This view cannot be supported by the present examination.

Buddhue (1939a; 1957: 124) studied the lamellar oxide-shales from the pit where the meteorite rested. He found, and it was shown to be generally true, that the meteoritic nickel did not enter quantitatively into the terrestrial corrosion products, but could be removed selectively by leaching. Similar conclusions had previously been reached by Nininger (1938) when examining weathered samples of metal from the Brenham pallasite. Morley (1948) reexamined the pit and excavated – from a depth of about one meter – more than 8.5 kg of oxide-shales. For a distance of several feet the ground was found to be rich in nickel, giving a heavy precipitate with dimethylglyoxime reagent. This supports qualitatively the observations by Buddhue and indicates that the mass has been exposed to weathering for a very long time and has thereby lost substantial amounts of material.

Axon et al. (1968) examined in detail the microstructure of Willamette and presented five photomicrographs of shock-altered troilite and taenite. The alteration in Willamette was estimated to approach the completely altered taenite structures of Hammond and Reed City. Jain & Lipschutz (1969), on the other hand, found in their specimen a kamacite phase which apparently had not been exposed to shock pressures above 130 k bar. They tentatively concluded that a mass as large as Willamette might exhibit a large pressure gradient; consequently, the reason for the discrepancies was the distance between the examined samples. Unfortunately, samples have never been cut from Willamette in a systematic way, and samples already distributed cannot be assigned definite positions on the main mass. However, in the discussion below it is proposed that the discrepancy noted by Lipschutz may be eliminated if we accept a two-stage cosmic event, including two shocks and two annealings.

Reed (1969) examined the kamacite phase with the microprobe and found it to contain on the average 7.1% Ni and 0.121% P. The rather high value for phosphorus covered both P in solid solution and P present in almost submicroscopic, densely spaced rhabdites. Axon et al. (1968) showed several microbprobe tracks, indicating a significant decrease from 6.85% Ni in the kamacite interiors, to 5.4% along kamacite-kamacite grain boundaries. The nickel depletion was ascribed to the diffusion of nickel along the boundaries to form phosphide precipitates.

It appears that the only attempt to measure the noble gas content of Willamette was made by Signer & Nier (1962). They found very low amounts of He, Ne and Ar, similar to those of Gibeon, Cape York and Campo del Cielo. Perhaps their sample came from a well-shielded portion, well below the surface of the meteorite. Such samples have been circulated, since it is possible without dividing the whole mass to remove small samples with a hammer and chisel from the corroded basins, 20-45 cm below the surface.

Numerous pictures have been given of the mass and its fascinating sculpture, for example by Ward (1904c), Hovey (1906), Mason (1962a: figures 13 and 14) and Lange (1962). Photomacrographs of etched sections have been given by these authors and, in addition, by Merrill (1916a: plate 36), Nininger & Nininger (1950: plate 13) and Axon et al. (1968). The history and the judicial finesses have been discussed by Winchell (1905), Farrington (1915), Pruett (1939; 1943), Carpenter (1945) and Lange (1958), on whose treatises the present author has freely drawn in this exposition.

Figure 1948. Willamette (Copenhagen no. 1905, 1735). Spheroidized plessite fields with schreibersite (S) at grain boundaries. To the right a shock-melted troilite nodule. Neumann bands are partially annealed out. Etched. Scale bar 300 μ.

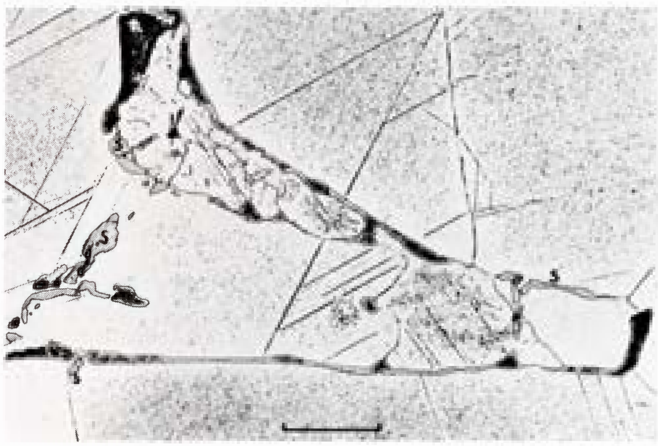

Figure 1949. Willamette (Copenhagen no. 1905, 1735). A former plessite field. Its boundaries are indicated by taenite and schreibersite particles (S), but recrystallizing kamacite has penetrated it in various places. Etched. Scale bar 300 μ.

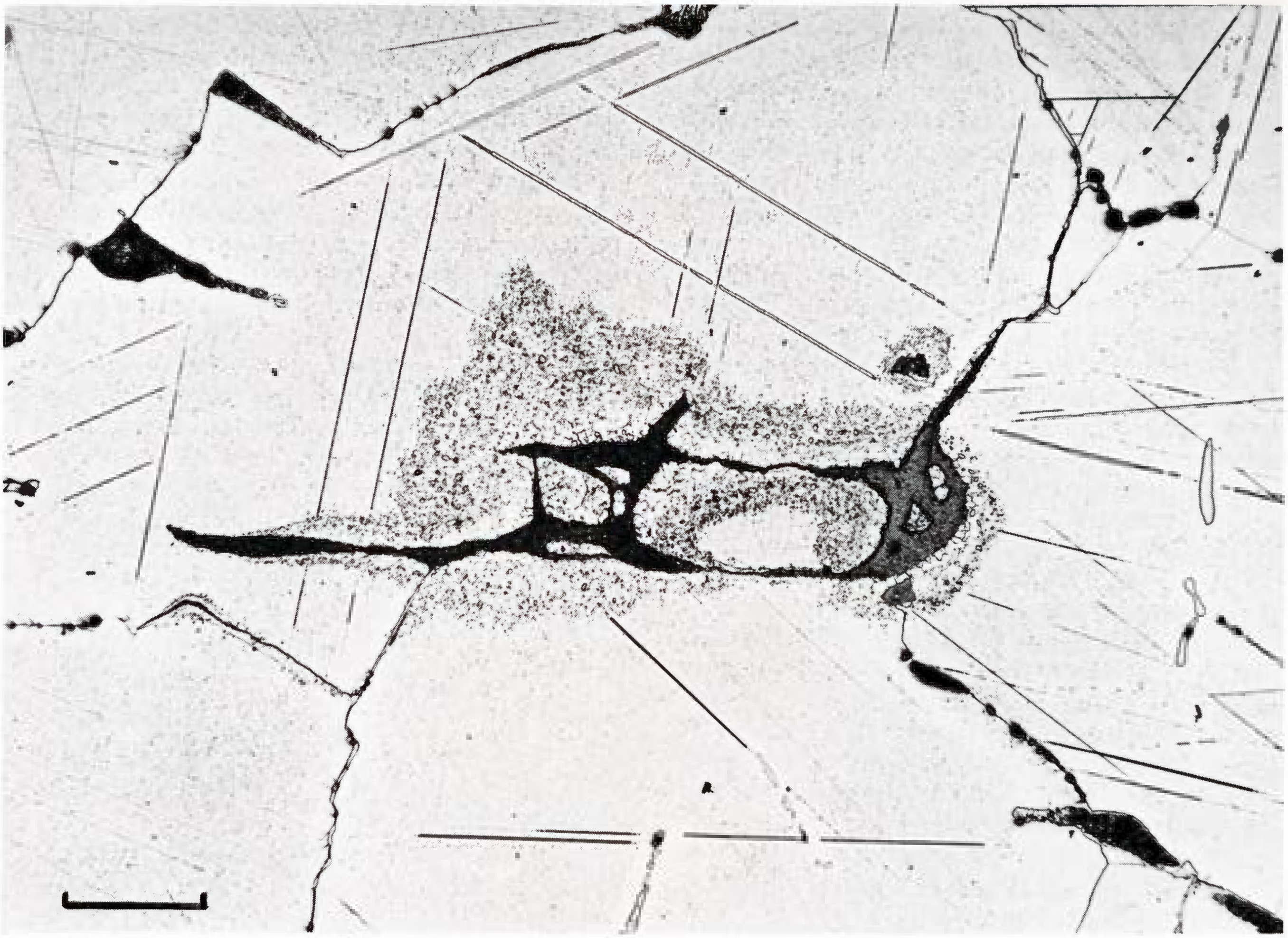

Figure 1950. Willamette (U.S.N.M. no. 333). Several recrystallized kamacite grains that meet at a shock-melted troilite nodule in center. The Neumann bands are annealed and not caused by atmospheric deceleration forces. Etched. Scale bar 500 μ. See also Figure 164.

COLLECTIONS

New York (main mass of 31,107 pounds = 14.1 tons, and 2 kg slices), Washington (2.7 kg), Chicago (2.4 kg), Tempe (1.85 kg), Ottawa (1.59 kg), Budapest (1.1 kg), Berlin (975 g), London (965 g), Prague (693 g), Helsinki (509 g), Ann Arbor (507 g), Los Angeles (389 g), Paris (337 g), Bally (238 g), University of Oregon, Eugene (181 g), Copenhagen (85 g), Vatican (15 g), Vienna (X g). It is known that additional specimens are in existence, mainly in private hands. These apparently were obtained in 1905 by curiosity seekers who tried to satisfy their collecting instinct:

"During the few months that the meteorite rested in front of the Johnson property, the sleep of the Johnson family was often interrupted by souvenier hunters who attempted to break off a specimen with a hammer. Each time the meteorite was struck it rang like a bell, and Mr. Johnson would rush out with gun in hand to drive the prowlers away" (Lange 1958).

Almost all specimens in collections appear to be cross sections of the interior pedestals or bases which are deeply undercut by corrosion and hour-glass in form, tapering from top downwards and from below up. This is why so many specimens exhibit a curious outline resembling the hide of an animal (see, e.g., Merrill 1916a: plate 36). A few samples represent the exterior crowning top of these pedestals.

WILLAMETTE – SELECTED CHEMICAL ANALYSES

Unfortunately, little analytical work has been published on this important meteorite. Whitfield's and Davison's analyses, as quoted in Ward (1904c), appear insufficient in regard to Ni, Co and P.

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Lovering et al. 1957		0.45				51	112		17	29		
Wasson & Kimberlin 1967	7.62								18.3	37.6	4.3	

Several kilograms of oxide-shales are in Albuquerque, Austin, Berlin, Copenhagen, London, New York, Tempe, Washington and at the University of Oregon in Eugene.

DESCRIPTION

The 14 ton mass is presently exhibited in the Hayden Planetarium, New York, in a hall where the light is very insufficient for an examination of the surfaces. The meteorite has a shape like a flattened bell, or somewhat like a compressed Apollo command module. It measures 305 x 200 x 130 cm and rests obliquely on the floor. When found, the apex or nose of the truncated cone was about one meter below ground level while the opposite, oval and rather flat side was almost parallel with the ground (Ward 1904c). It is probable that this was also the position in which the meteorite, in an oriented flight, penetrated the atmosphere. Presumably the mass produced a very deep impact hole and locked itself in position. The many suggestions that the meteorite had been moved from a different place appear to be unfounded.

Considering the external shape of Willamette, the nearest parallel case is that of Morito, the 10 ton Mexican iron, which also has the shape of a compressed cone but of a somewhat smaller size, however. The ratios between the sides and faces are very similar in Willamette and Morito. However, where Morito eminently displays regmaglypts, sinuous rilles and fluted grooves from the atmospheric flight, nothing of the kind can be detected upon Willamette. The fusion crust has spalled off, the heat-affected α_2 zone has disappeared, and it seems that no genuine unaltered regmaglypts are preserved at all. It so happens that the masses have almost identical chemical composition and primary structures, so a comparison between the two masses appears valid.

The truncated nose of Willamette is rather smoothly rounded with few cavities or depressions. It is a blunt cone, 40-50 cm high and 80 cm in diameter covered with 0.1-1 mm thick loosely adhering oxide-shale. No pits, which can be definitely assigned to burned out troilite nodules, are visible on the surface. Morito, on the contrary, displays semiparallel flutings roughly radiating from the apex. Additional pits, 10-20 mm in aperture and 10-35 mm deep, represent the sites of troilite nodules which partly burned out in the atmosphere. It appears that the apex part of Willamette has lost 1-2 cm in thickness by general corrosion. Some of the lost material has been recovered from the pits as oxide-shales, 1-2 cm thick (Morley 1948), and may be studied in various collections, as noted above.

The antiapex, the oval crowning side, which was uppermost when found, measures about 3 x 2 m. It presents a unique sight to the visitor. It is penetrated by an intriguing web of holes, cavities and caverns, some of which perforate the mass. A typical "small" hole is 3 cm in aperture at the surface; further down it swells irregularly to 4-5 cm in diameter, and the rounded bottom is 16 cm below the surface. A typical "kettle-hole" is 65 cm in diameter, significantly undercut, and almost 45 cm deep. The various holes and kettles coalesce and penetrate each other in a labyrinthine way which does not appear to be conditioned by the macrostructure of the mass. Some ten holes penetrate near the skirt or flange of the cone. Ellis Hughes found these holes useful in chaining the large meteorite securely to his crude wagon. Almost all holes are perpendicular to the flat side of the cone which was uppermost and almost horizontal when found.

Most samples in collections are from the interior of the mass and have been obtained by breaking the "pedestals" that support the undercut crowning surface. It can be observed that at least nine different pedestals have been broken from the mass, and it is estimated that these have yielded some hundred pounds of specimens.

Sections through the triangular or irregular columns that separate the individual basins have not revealed any foreign matter at all – except troilite – and nothing would be expected in an iron so closely related to Morito and Cape York. Moreover, the sections show extremely sharp edges of the type associated with corrosion; they are very different from the ablation-melted edges present on fresh falls like Bogou, Yardymly, Morito and Murnpeowie. No α_2

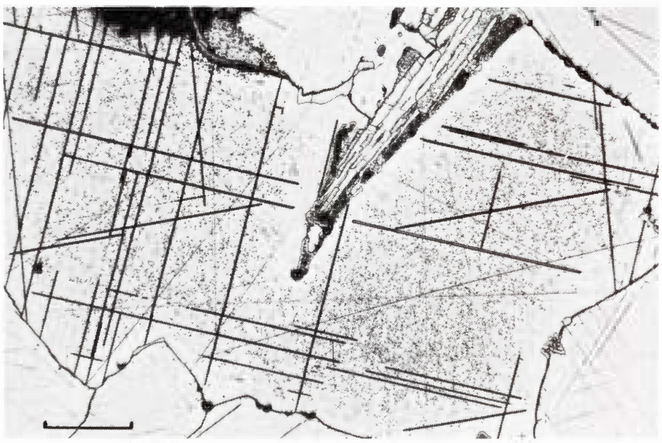

Figure 1951. Willamette (U.S.N.M. no. 333). A near-surface recrystallized kamacite grain cut approximately parallel to $(100)_\alpha$. Four sets of annealed Neumann bands are mutually perpendicular. Etched. Scale bar 400 μ.

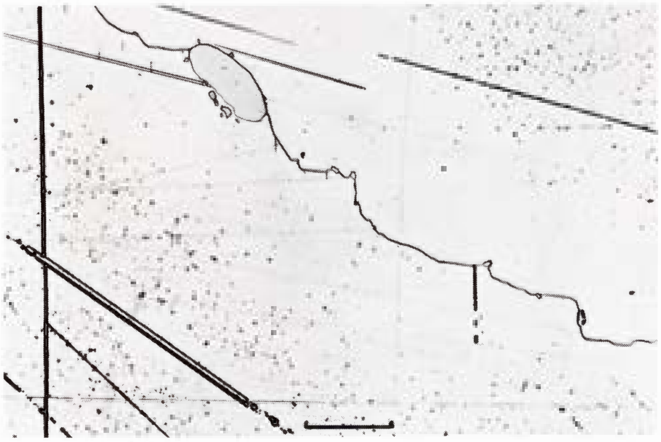

Figure 1952. Willamette (U.S.N.M. no. 333). After recrystallization, grain growth was often impeded by the numerous precipitates that for a while would be able to pin the moving grain boundaries. Note the annealed Neumann bands. Etched. Scale bar 100 μ.

zone or hardness gradient could be detected. Corrosion has selectively dissolved the α-phase of the duplex plessite fields; it also penetrates along α - α grain boundaries and, in particular, along the microcrystalline shock-melted troilite filaments. Thus, on the one hand, the theory held by Winchell (1905) and others, that the large cavities represent holes after silicates or sulfides which were selectively burned out in the atmosphere – or removed by chemical dissolution, – cannot be supported. In that case similar material should be present in the numerous sections made later. Also, examination of typical stony-iron meteorites does not show ablation or weathering of this kind.

On the other hand, the theory held by Henderson & Perry (1958), that the cavities were already there when the mass entered the atmosphere, has no basis either. If this were the case, the interior of the cavities would show softly rounded ridges with fusion crust and heat-affected zones. The cavities would also be expected to serve as reservoirs for ablation melted metal stripped from the nose cone. None of these features are present.

It can, therefore, be assumed that, when Willamette landed in the distant past, it had a shape and sculpture very similar to that of Morito. It must have been deeply furrowed on the cone side with radiating flutings, while the antiapex was a flat, somewhat crowning surface with shallow – but large – depressions. The meteorite must have been significantly more massive then, possibly weighing more than 20 tons.

This leaves us with a mass which by some mysterious process has lost more than six tons since it fell. For this to occur it appears that we have to resort to terrestrial weathering processes, as already suggested by Ward (1904c).

Pitting is a well known corrosion phenomenon on steels and even stainless steels, under certain conditions. Bowl-shaped cavities with sharp edges and undercutting may develop as a result of pitting corrosion which, in the end, may completely penetrate plates, which are a centimeter thick, while the bulk of the plates are relatively slightly affected. Such conditions are perhaps most common when local variations in the oxygen concentration are pronounced. For example, the variation may be caused by differential aeration of the material in direct contact with the steel, either because its composition or its porosity varies from place to place; or perhaps because parts of the surface are covered by debris or oxide-shales while others are not. The loosely covered parts will pass into solution, while the freely exposed surface will act as a cathode and remain protected.

While these processes are known to occur in steels, they are, of course, on a scale much smaller than those observed on Willamette. It appears, however, that given sufficient time and the right conditions of dilute, aerated sulfuric acid from decomposing troilite, the cavities may reach the surprising scale observed on Willamette. The precipitation in that part of Oregon is probably sufficient to have this effect. Portland has an annual rainfall of 930 mm, one half of it falling from November to February.

Most etched sections exhibit a structure rich in recrystallized, equiaxial kamacite grains, 0.5-3 mm across. Typical sections of this type are U.S.N.M. No. 500 of 1,927 g, Chicago No. 592 of 1,487 g, and Copenhagen No. 1905.1745 of 85 g. However, some sections show remnants of an undisputed medium Widmanstätten structure with straight, long ($\frac{L}{W} \sim 25$) kamacite lamellae with a width of 1.05±0.10 mm. Such sections are, e.g., the 981 g slice in Berlin, the 389 g slice in Los Angeles, and the slice privately owned by Harold Johnson, West Linn, Oregon, and pictured by Lange (1962: figure 10). An excellent pair of photomacrographs by Axon et al. (1968) shows how different illumination of the same sample (B.M. No. 86945 of 886 g) can emphasize either the lamellar texture or the recrystallization texture.

When slices of the first type are scrutinized with respect to the orientation of the parent lattice, it will be observed that – even if the recrystallized kamacite grains

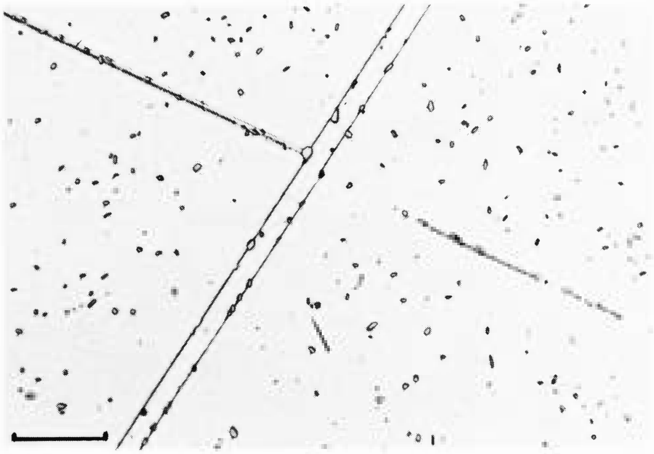

Figure 1953. Willamette (U.S.N.M. no. 333). Detail of annealed Neumann bands which are rich in precipitates, mainly of phosphides. Other phosphides appear in the matrix. Etched. Oil immersion. Scale bar 20 μ.

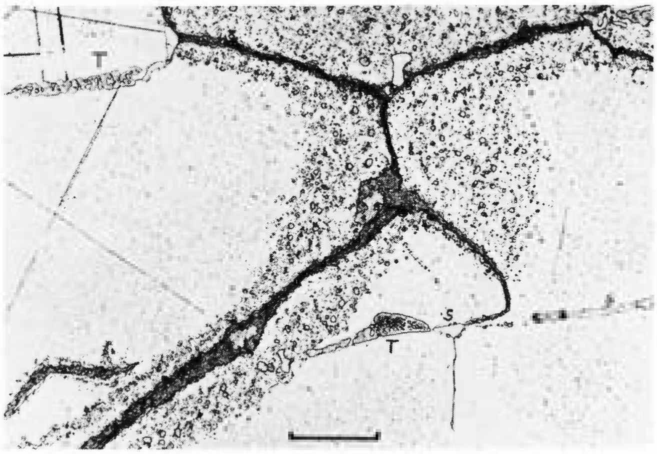

Figure 1954. Willamette (U.S.N.M. no. 333). Filaments of shock-melted material, mainly sulfides, that penetrate along grain boundaries. Annealed and spheroidized taenite lamellae at T. Annealed schreibersite at S. Etched. Scale bar 200 μ.

are randomly situated – the remaining taenite and plessite fields clearly line up in a Widmanstätten array, indicating that the parent material was a normal austenite crystal at least 35 cm in diameter. Whether all of Willamette was one single austenite crystal can only be determined when samples from known positions can be compared in the future.

The typical section shows that the recrystallization has been thorough and that subsequent grain growth has led to large kamacite units, generally larger than the preexisting lamella bandwidth. In this respect Willamette is distinguished from, e.g., Roebourne, Ruff's Mountain and Kokstad – meteorites which it otherwise resembles somewhat. The recrystallized kamacite, therefore, contains remnants of undissolved taenite and plessite, while in other cases a massive plessite field may form the grain boundary of a recrystallized unit. The morphology indicates that Willamette first possessed a normal Widmanstätten structure, whereupon a significant heat input – possibly the reheating associated with a violent cosmic shock – thoroughly recrystallized the material.

The individual kamacite grains are rich in Neumann bands. Thus, after the recrystallization and grain growth was completed, Willamette was again exposed to a shock event but, this time, of a smaller magnitude. The fact that all Neumann bands appear partially annealed proves that this second shock event had no connection with the impact with the atmosphere and finally the ground. The Neumann bands are hacked up in short sections and are decorated along both sides with fine phosphide precipitates, 0.5-1 μ across. They frequently stop before reaching grain boundaries and their two sides are straight, not serrated as in fresh Neumann bands. The kamacite itself is polygonized and shows an intricate network of linear cells, normally only 5-20 μ thick. It appears, then, that the second shock event was followed by a general, slight reheating which was insufficient to bring about more grain growth but sufficient to modify the Neumann bands and the kamacite substructure. The microhardness of the kamacite is 153±5, indicative of well-annealed material.

Taenite and plessite cover about 10% by area, mainly as degenerated, annealed fields. No martensitic or bainitic transition zones are present. The taenite lamellae and the taenite rims around plessite fields become cloudy-brownish on etching; in places they show very ragged borders or are even decomposed to spheroidized particles, 5-20 μ across. In other places they are beset with kamacite windows 0.5-5 μ across. The variation in the taenite morphology often occurs within the same section – even within the same plessite field. The microhardness of the taenite is very low, 159±5, clearly due to annealing. The plessite interiors are also annealed and partly spheroidized – again suggestive of annealing. While two stages of annealing may be distinguished in the kamacite, there is no immediate way of deducing more than one annealing event from the taenite structure. The spheroidization was, however, almost certainly simultaneous with the kamacite recrystallization. Since the postulated second shock event – responsible for the Neumann band formation – must have work-hardened the taenite to perhaps 300 HV, it follows that the second annealing, which decorated the Neumann bands and polygonized the kamacite, also softened the taenite to 159 HV.

Schreibersite is common as 10-50 μ wide, elongated bodies, which were originally precipitated in the grain boundaries of the Widmanstätten structure, but which – after the recrystallization – may now also be found inside the kamacite grains. Irregular particles, 5-30 μ wide, are common inside the plessite fields. No large skeleton crystals were observed. All schreibersite is monocrystalline but often surrounded by minute beads of taenite and phosphide. The beads are 1-5 μ across and are clearly a result of annealing, probably from the first stage. No rhabdites proper were observed, but the kamacite is rich in almost submicroscopic phosphides, generally less than 0.6 μ across.

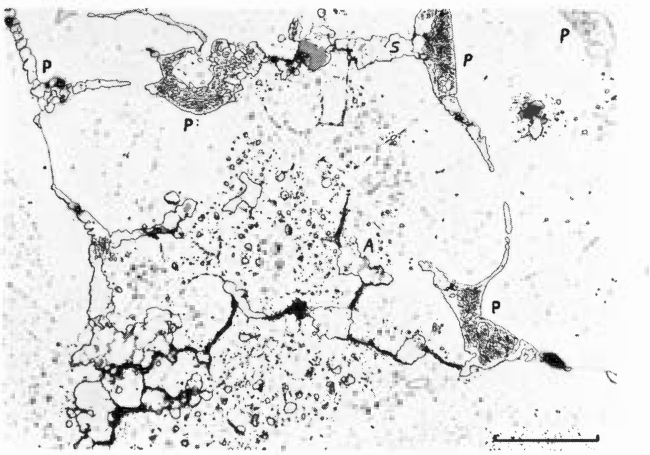

Figure 1955. Willamette (U.S.N.M. no. 333). A complex shock melt with troilite, daubreelite, taenite and schreibersite particles in an unequilibrated kamacite matrix. Along the periphery brecciated schreibersite (S) and spheroidized plessite (P). For detail at A, see Figure 1957. Scale bar 200 μ.

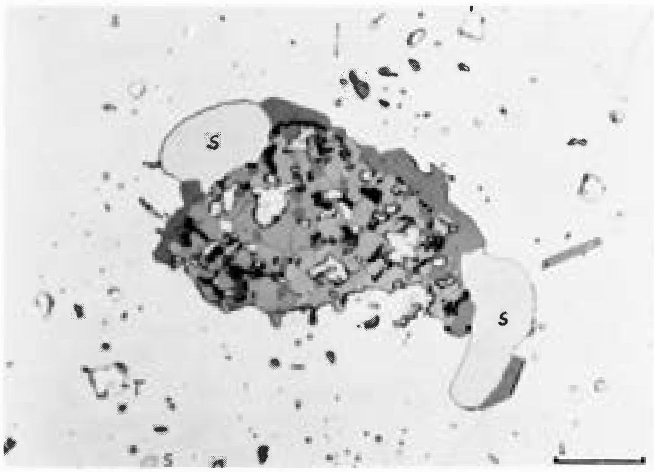

Figure 1956. Willamette (U.S.N.M. no. 333). Remnants of a shock-melted and dispersed troilite nodule. Polycrystalline troilite (light gray), angular-irregular daubreelite particles (dark gray), taenite (T) and schreibersite (S). Etched. Oil immersion. Scale bar 20 μ.

The bulk phosphorus content is estimated to be 0.14±0.02%.

Troilite is present as large nodules, 1-3 cm across, and as smaller lenticular-to-lamellar bodies. The spider shape of many troilite bodies is a distinctive mark of Willamette. All troilite types are shock-melted and subsequently somewhat annealed and recrystallized.

A typical troilite lens is 3 x 0.5 mm in cross section and provided with thongs and spiky protuberances. It is a shock-melted composite of relatively coarse (2-10 μ) troilite grains with a little dispersed daubreelite, taenite and phosphide particles. It is surrounded by a 50-300 μ wide cloudy kamacite zone which is rich in diffuse daubreelite and phosphide particles. Neumann bands normally cut through this zone.

The spidery troilite appears to be shock-altered transformation stages of the original lenticular and lamellar shapes. From a central more massive portion, 50-100 μ across, numerous stringers radiate, often several millimeters in various directions and each spidery filament is itself enveloped in a sheath of cloudy kamacite. Sometimes several filaments coalesce and again separate, or they swell and pinch in a very unusual way. Occasionally the filaments radiate through the kamacite and cut through preexisting plessite fields. They may also follow the preexisting Widmanstätten boundaries for a while.

When the kamacite recrystallized, it often nucleated around the distorted shock-melted troilite. Thereby the zone immediately around the troilite – presumably originally a fine-grained kamacite-sulphide-phosphide intergrowth from eutectic solidification – converted to a monocrystalline kamacite which is cloudy because of the presence of foreign precipitates. Also, the final position of the recrystallized kamacite grain boundaries has often been determined by the presence of the troilite filaments. To a casual observer it may appear that the troilite filaments have protruded along these recrystallized kamacite grain boundaries, but it is probably the other way round.

Silicates, carbides and graphite were not detected during the examination.

CONCLUSION

While the chemical composition of Willamette is straightforward and places it well inside the chemical group IIIA, the structure is complicated and seems to require a series of events for its formation.

Stage one would be the primary slow cooling period, after which Willamette would exhibit a medium Widmanstätten structure with occasional nodules and lenses of troilite, very similar to what may be observed in Cape York and Morito.

Stage two would require a significant shock and subsequent reheating. Whether the reheating was caused by the shock and immediately followed it is unknown. In this stage the troilite shock-melted and penetrated the kamacite and plessite fields in numerous directions. The kamacite recrystallized and started grain growth until individual units met along plessite fields, troilite filaments and neighboring kamacite grains. The taenite spheroidized, and the phosphides detached small particles of phosphide and taenite. The troilite recrystallized, and its border zones of metal with dispersed particles also recrystallized. As some specimens show, the recrystallization of the kamacite did not develop uniformly through the whole mass. However, the kamacite probably polygonized and annealed everywhere. In this respect Willamette is not unique, since much smaller meteorites, such as Holland's Store and Kokstad, show various developments of recrystallized and polygonized parts.

Stage three would require a shock of less intensity than the first shock. It was sufficient to create Neumann bands in all recrystallized kamacite. An associated (?) reheating annealed and polygonized the kamacite and decorated the Neumann bands. Phosphorus in solid solution in the kamacite precipitated as almost submicroscopic particles. Taenite softened by annealing.

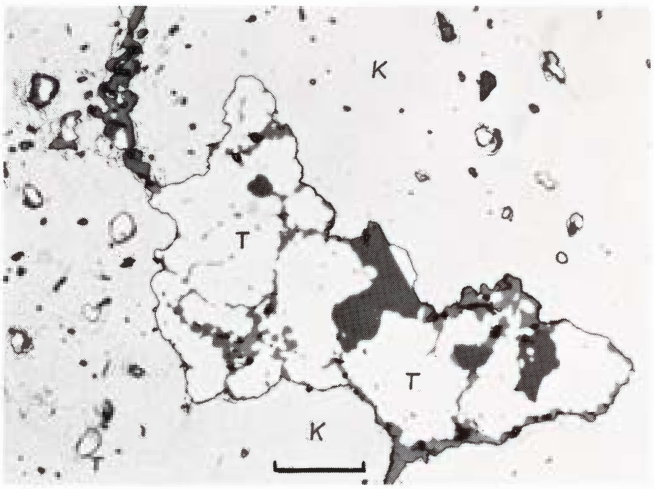

Figure 1957. Willamette. Detail of Figure 1955 at A. Kamacite (K) with dispersed taenite (T), daubreelite (dark) and troilite (light gray). Etched. Oil immersion. Scale bar 20 μ.

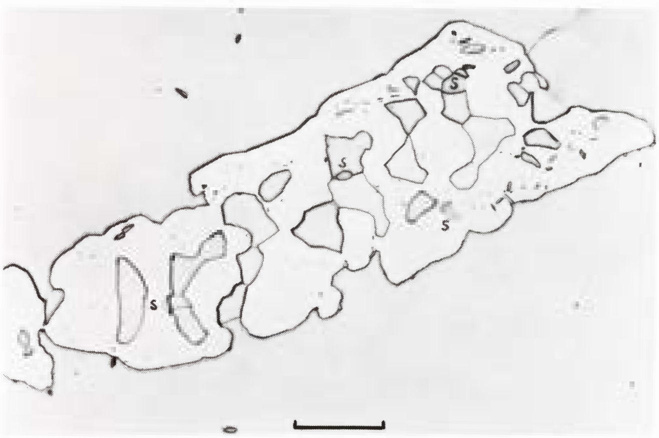

Figure 1958. Willamette (U.S.N.M. no. 333). An annealed and spheroidized taenite lamella. It is rather homogeneous, without cloudy edges. Instead, numerous small and large kamacite precipitates occur inside. A few schreibersite particles (S) appear gray. Etched. Oil immersion. Scale bar 20 μ.

Stage four would be the penetration of the atmosphere. However, no remnants of the associated sculpturing are to be seen today. The fusion crust and heat-affected α_2 zones are all removed by weathering. Immediately after its landing, the external shape of Willamette may have resembled that of Morito rather closely.

Stage five is the final long-term exposure in the humid Oregon valley forest during which the deep cavities, partially penetrating and generally perpendicular to the topside of the mass, were formed. While no large-scale texture, such as silicate inclusions, can be considered responsible for the curious corrosion progress, it is possible that the very distinct troilite filaments have aided in the weathering. These lanes of fine-grained troilite, kamacite and taenite would probably provide easy diffusion paths studded with electrochemical cells and with dilute sulfuric acid from decomposed troilite, where the kamacite phase would provide the anodic areas and dissolve first. The final product, the deeply carved Willamette mass, must, however, be seen to be believed. A famous photograph by Ward (1904: plate 16) shows the fantastic sculpturing with a relief sufficiently large and deep to hide two children. Probably tens of thousands of years were required to bring about the amount of corrosion observed.

In summarizing, it may be stated that Willamette is a shock-altered medium octahedrite of the resolved chemical group IIIA. Its closest relatives are such irons as Cape York, Morito and Casas Grandes. Its shock history and resulting structure is unique but somewhat duplicated by the structures noted in Roebourne, Kokstad, Joel's Iron and Bingera, to name a few. Its terrestrial story, both with regard to corrosion features and law suits, is also unique.

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

397 g part slice (no. 333, 7 x 3 x 0.8 cm)
1,927 g part slice (no. 500, 31 x 19 x 0.6 cm; figured by Merrill 1916a: plate 36)
154 g on three part slices (nos. 1476, 2128, 3153)
242 g part slice (no. 3153)

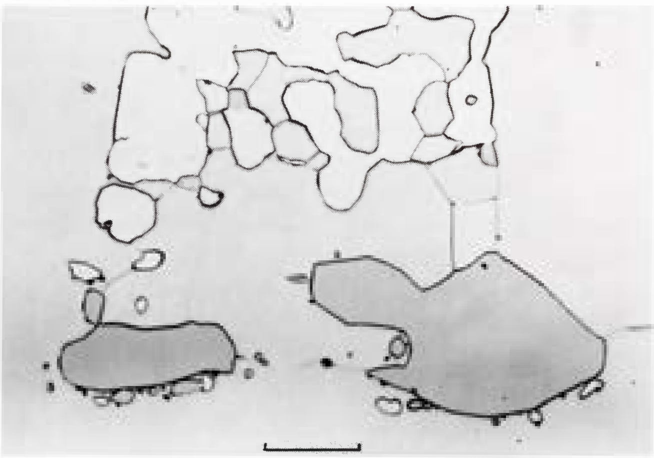

Figure 1959. Willamette (U.S.N.M. no. 333). The end of a similar taenite lamella and two adjacent annealed schreibersite crystals. Surplus nickel has been rejected in the form of minute taenite and phosphide particles along the periphery and they are all well spheroidized. Etched. Oil immersion. Scale bar 20 μ. See also Figure 225.

Williamstown. See Kenton County (Williamstown)

Willow Creek, Wyoming, U.S.A.

43°26′N, 106°46′W; about 1,800 m

Coarse octahedrite, Og. Bandwidth 1.40±0.25 mm. Partly recrystallized. HV 152±6.

Group IIIE. 8.76% Ni, about 0.35% P, 16.9 ppm Ga, 36.4 ppm Ge, 0.05 ppm Ir.

HISTORY

A mass of 112.5 pounds (51 kg) was found by John Forbes of Arminto, Wyoming, near Willow Creek, Natrona County, about 1914. For a long time it was in the possession of the Forbes family, but in 1934 the meteorite

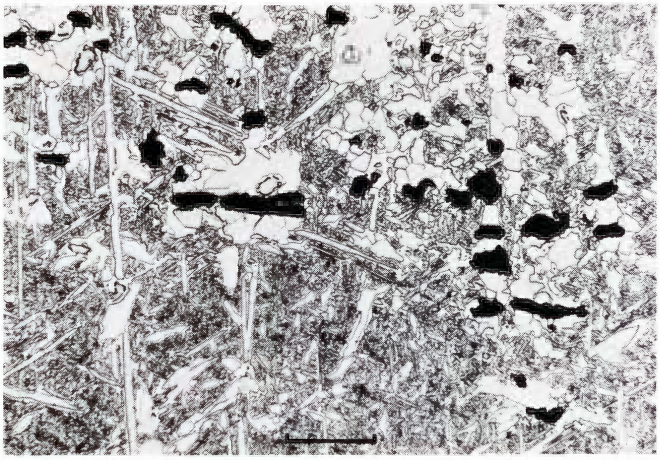

Figure 1960. Willow Creek (U.S.N.M. no. 900). Characteristic of this meteorite are the graphite flakes that occur inside several plessite fields. Compare Figures 145 and 146. Etched. Scale bar 40 μ.

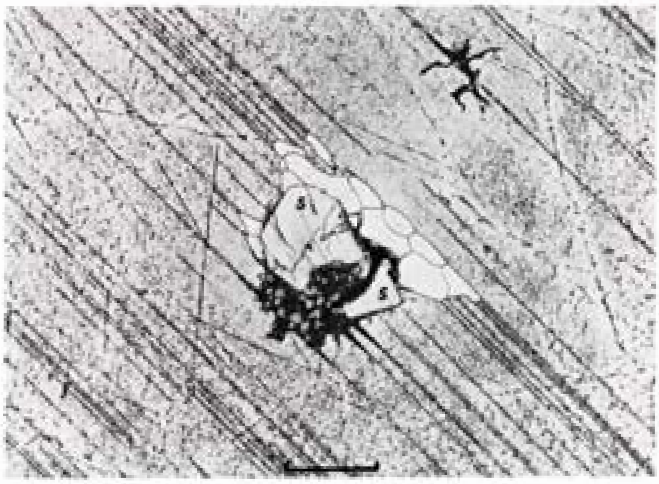

Figure 1961. Willow Creek (U.S.N.M. no. 900). Another characteristic of this meteorite is the shock-melted troilite nodules and the patches of recrystallized kamacite. One troilite nodule is transformed to a spidery shape, as in Willamette. Schreibersite (S) is brecciated. Etched. Scale bar 200 μ.