upon corrosion, had recemented the schreibersite, troilite and silicate breccias, have decomposed to oxides with 1 μ metalic particles, frequently forming 5-10 μ wide laceworks against the metallic matrix. Locally, the corroded troilite has melted and again solidified to fine-grained Fe-S-O eutectics. High temperature intercrystalline oxidation and minor amounts of sulfide melts have penetrated along the grain boundaries of the high temperature austenite phase. In this way the austenite grain size is revealed to have been 5-15 μ.

These observations indicate that the specimen was subjected to artificial reheating to about 850° C for a short time. Whether the reheating took place while Kendall County was still an entire 20.8 kg mass is unknown. No report to that effect exists. If so, there must have been a rather steep temperature gradient from 850° C at one end to perhaps 600° C at the opposite end, since Neumann bands seem to be preserved in many samples cut from the mass.

Kendall County is an iron which only superficially bears some resemblance to Holland's Store and other meteorites with 5-6% Ni. Its graphite and silicates, and its trace element composition, suggest rather a remote relationship to Campo del Cielo and similar irons of group I. Its texture could probably be the result of mixing of metal-particles with silicate and graphite particles and subsequent compression and sintering at a not too elevated temperature, perhaps about 1100° C. There are no unambiguous indications that the meteorite as we not know it was once a product of a solidifying magma.

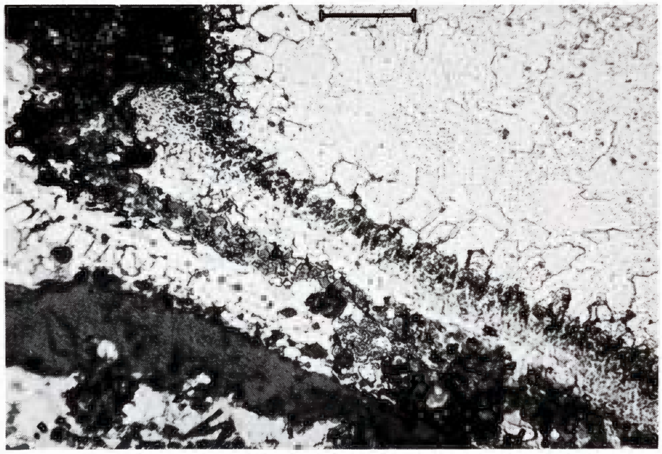

Figure 991. Kendall County. Detail of the altered nodule in Figure 990. An extremely complex high temperature reaction mixture of limonite, kamacite, troilite, schreibersite, graphite and silicates. Etched. Scale bar 40 μ.

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

742 g slice (no. 255)
1,164 g slice (no. 343)
14 g part slice (no. 1657)
123 g part slice (no. 2846)

Kenton County, Kentucky, U.S.A.

38°48′N, 84°34′W; 270m

Medium octahedrite, Om. Bandwidth 0.90±0.10 mm. ϵ-structure. HV 325±15.

Group IIIA. 7.45% Ni, 0.48% Co, 0.08% P, 18.2 ppm Ga, 35.0 ppm Ge, 14 ppm Ir.

Williamstown is a 31 kg fragment of Kenton County.

HISTORY

A mass of 163 kg was found in 1889 by G.W. Cornelius on his farm, located about 13 km south of Independence, in Kenton County. The meteorite was discovered while cleaning a spring situated at the head of a gully; the mass was about 1 m below the surface and interlocked in the roots of an ash tree. It was purchased by Ward's Establishment and briefly described with a picture of the exterior by Preston (1892). In the following years it was extensively cut and distributed through Ward's from whom slices were still available as late as 1940. Brief descriptions were given by Brezina (1896: 284), Klein (1906: 119) and Farrington

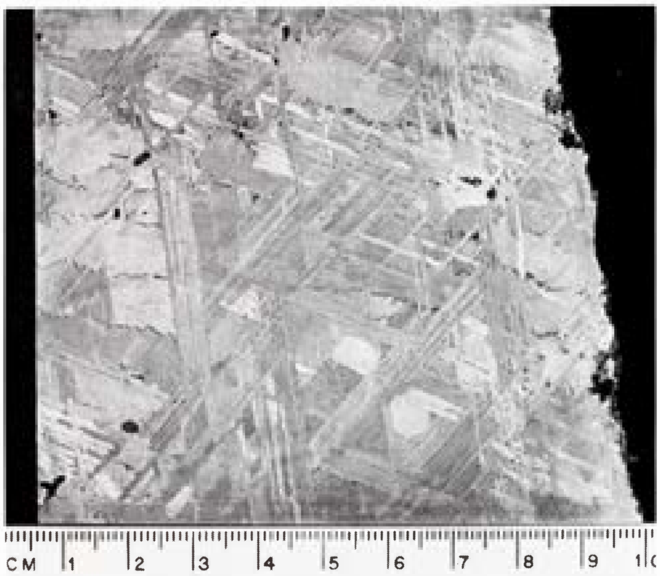

Figure 992. Kenton County (Tempe no. 68a). Shock-hardened medium octahedrite of group IIIA. Section almost parallel to $(111)_\gamma$ so that the fourth set of kamacite lamellae appear as ragged plumes. Deep-etched. Ruler in cm. (Courtesy C.B. Moore.)

KENTON COUNTY – SELECTED CHEMICAL ANALYSES

	percentage			ppm							
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Moore et al. 1969	7.52	0.48	0.08	50	630		170					
Scott et al. 1973	7.38								18.2	35.0	14	

(1902; 1915). Perry (1944) presented three photomicrographs.

COLLECTIONS

Chicago (39.4 kg endpiece and 25 kg slices), New York (9,590 g), Yale (5,670 g), Harvard (3,856 g), Vienna (3,057 g), Washington (2,691 g), London (2,517 g), Budapest (1,485 g), Vatican (1,257 g), Paris (575 g), Sarajevo (521 g), Leningrad (467 g), Tempe (435 g), Calcutta (423 g), Berlin (406 g), Prague (306 g), Bonn (283 g), Sydney (254 g), Tübingen (227 g), Stockholm (221 g), St. Louis (201 g), Ottawa (200 g), Rome (128 g), Ann Arbor (116 g), Dorpat (83 g), Strasbourg (53 g), Kenton County is one of the better distributed iron meteorites.

DESCRIPTION

The exterior shape resembled a nautilus, and the average dimensions were 53 x 36 x 20 cm (Preston 1892). Although Preston stated that it was a "beautiful meteorite . . . entirely free from crust," all the specimens that the present author has seen are coated with a 0.1-3 mm thick crust of terrestrial oxides, and most of the exterior sculpture and local pitting is, no doubt, caused by longtime exposure to corrosion. The fusion crust and the heat-affected α_2 zone have disappeared long ago, and oxidic veinlets penetrate several centimeters inward, particularly along octahedral planes. That it should be an observed fall, as believed by Preston, is out of the question. The terrestrial age probably runs high in the tens of thousands of years. Compare the description of the Williamstown fragment.

Etched sections display a medium Widmanstätten pattern of the somewhat indistinct, contrast-poor type. The straight, long ($\frac{L}{W} \sim 40$) lamellae have a width of 0.90±0.10 mm. In several places a late grain growth of the α-phase has eliminated the straight lamellae boundaries and created equiaxial 5-10 mm alpha grains that appear as irregular blotches, loaded with subgrain boundaries, on an etched surface. Since the cutting by Ward's was deliberately done almost parallel to an octahedral plane, the fourth direction of the kamacite lamellae is seen in numerous sections as 3-6 mm broad ribbons that usually display ragged taenite borders. The kamacite is densely hatched, presumably due to a shock that peaked in the 200 k bar range, and its microhardness is 325±15. The kamacite subgrain boundaries are rich in 0.5-2 μ rhabdite precipitates.

Plessitic areas cover about 40% of the surface. This would expectedly correspond to a rather high total nickel content of the meteorite, but because the plessite is very open-meshed with few and narrow taenite bands, the total nickel content is as low as 7.5%. The comb and net plessite areas are, in fact, almost resorbed. Some of them have an interior which is an intricate network of grain boundaries

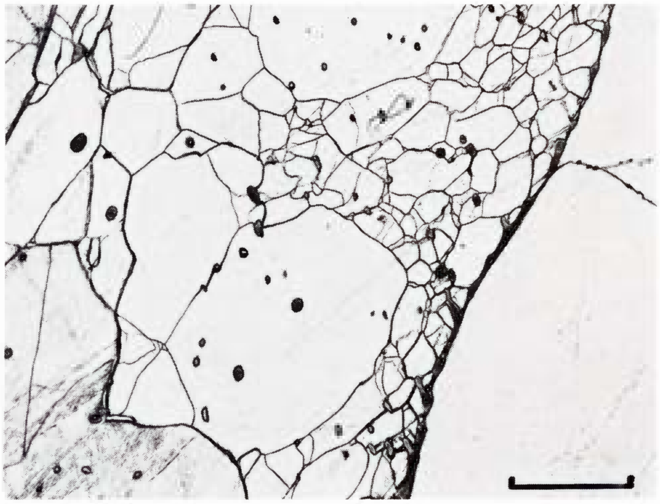

Figure 993. Kenton County. Almost resorbed net plessite field showing kamacite grain growth. Spheroidized taenite particles. Etched. Scale bar 200 μ. (Perry 1950: volume 2.)

Figure 994. Kenton County. Same sample, but more etched. The kamacite matrix shows a distinct shock-hatched ε-structure. Scale bar 20 μ. (Perry 1950: volume 2.)

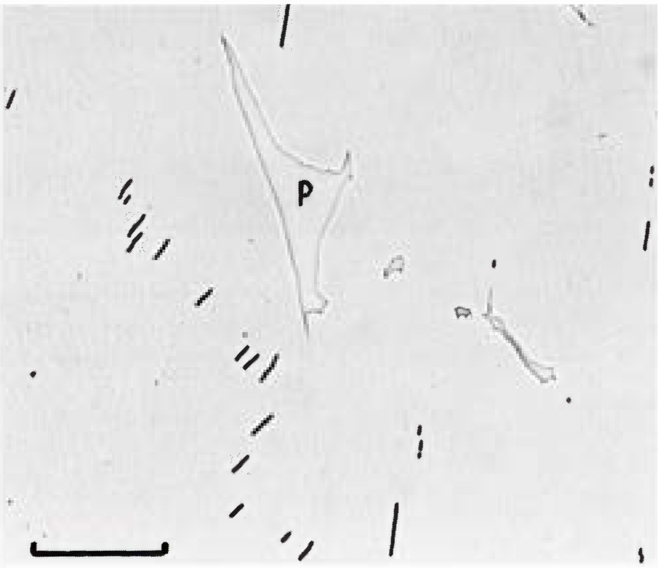

Figure 995. Kenton County (U.S.N.M. no. 597). Match-like carlsbergite platelets in kamacite. Several taenite and plessite (P) fields. Polished. Scale bar 200 μ.

and subgrain boundaries with a few scattered taenite blebs in some junctions. The framing taenite is often discontinuous. A few of the larger taenite wedges have an acicular interior or an interior of poorly resolvable duplex $\alpha + \gamma$ (black taenite). The taenite rims usually become grayish-brownish tarnished upon etching.

Schreibersite is absent as larger units. It does occur as scattered, 3-10 μ wide grain boundary precipitates and as 3-30 μ vermicular bodies substituting for taenite in the plessite interior. Rhabdites are common as 1 μ thick, sharp prisms everywhere in the α-lamellae.

Characteristic are the numerous troilite nodules, scattered across most sections as 1-12 mm nodules and rhombic bodies, often with a 1 mm rim of swathing kamacite. The troilite occurs with a frequency of about 1 per 8 cm^2. It is monocrystalline with well defined, parallel daubreelite lamellae that occupy 10-20% of the volume. The troilite frequently displays lenticular deformation twins in beautiful arrangements, and in places it is faulted and displaced 10-200 μ in massive blocks. The daubreelite is then likewise sheared, but along octahedral cleavage planes, which results in complications along the mutual interfaces. The smaller troilite-daubreelite assemblages may show rhythmic stacking of 1-10 μ thick laminae of troilite and daubreelite, the daubreelite lamellae often projecting 2-10 μ into the metallic matrix relative to the troilite. Subhedral, bluish bodies, 25-50 μ in size, in the alpha phase approach pure chromium sulphide in composition; similar minerals were described by Bunch & Fuchs (1969) as Brezinaite. Because the total phosphorus content is below 0.1% no schreibersite has precipitated upon the troilite nodules, or, at the most, insignificant 3-10 μ blebs and discontinuous rims. The troilite is mildly corroded and converted to pentlandite in 2-5 μ wide veinlets.

Figure 996. Kenton County (U.S.N.M. no. 597). A cluster of oriented carlsbergite platelets on a subboundary in kamacite. Polished. Scale bar 20 μ.

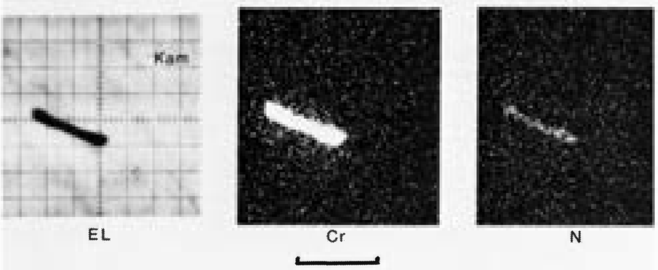

Figure 997. Kenton County (U.S.N.M. no. 597). X-ray scanning pictures of a carlsbergite platelet in situ. Electron picture and CrK$_\alpha$ and NK$_\alpha$ pictures. Scale bar 30 μ.

The hard, platy mineral, mentioned under Cape York and Costilla Peak, occurs here in larger and better defined units than in most meteorites. It is typically 20 x 3 x 0.5 μ, and takes the shape of angular serrated platelets, that may be somewhat distorted; it is situated in the alpha phase and is an oriented precipitate. It has been identified as a chromium nitride and named carlsbergite (Buchwald & Scott 1971).

Kenton County resembles in all structural details Williamstown, which was found about 15 km south of the Kenton iron. Since the chemical composition, as far as it is known, and the state of corrosion are also the same for the two irons, it is impossible to escape the suggestion that they comprise two individual fragments of a meteorite that burst in the atmosphere.

Kenton County also closely resembles Costilla Peak, Henbury, Davis Mountains and Boxhole, in that order, and is a normal group IIIA iron.

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

146 g part slice (no. 206, 4.5 x 4 x 1 cm)
1,381 g part slice (no. 597, 19 x 8 x 1.7 cm)
614 g part slice (no. 686, 11 x 8.5 x 0.8 cm)
104 g part slice (no. 2847, 5.5 x 3 x 0.9 cm)
446 g part slice (no. 2848, 9 x 8 x 0.7 cm)

Kenton County (Williamstown fragment), Kentucky, U.S.A.

38°42'N, 84°32'W; 270 m

Medium octahedrite, Om. Bandwidth 0.90±0.15 mm. ϵ-structure. HV 325±15.

Group IIIA. 7.54% Ni, 0.49% Co, 0.08% P, 18.2 ppm Ga, 32.9 ppm Ge, 15 ppm Ir.

Williamstown is probably a paired fall with Kenton County.

HISTORY

A mass of 30.9 kg (68 pounds) was found in 1892 by A.E. Ashcraft on his farm three miles north of Williamstown in Grant County. The corresponding coordinates are given above. It was acquired by Ward's Establishment and about half of it was cut into sections and marketed after 1908. It was described with a photomacrograph by Howell (1908a). Jaeger & Lipschutz (1967b) noted that the kamacite structure corresponded to the structures produced in Odessa, when exposed to 400-750 k bar shock pressures. Arnold (1961) found the terrestrial age to be as high as 600,000 years which was confirmed by Chang & Wänke (1969). Hintenberger et al. (1967) and Schultz &

Hintenberger (1967) reported on the amount of the various noble gases. Voshage (1967) found by the $^{40}K/^{41}K$ method a cosmic ray exposure age of 650±55 million years. Previously Fisher & Schaeffer (1960) had reported 1,600-2,200 million years, and Signer & Nier (1962) 650±100 million years. These authors also estimated the preatmospheric mass to have been about 2,000 kg. Bauer (1963) estimated the cosmic ray exposure age to be 610 million years. Honda & Arnold (1964) determined the amount of eight different metallic nuclides. References to further work on Williamstown will be found in the quoted literature.

COLLECTIONS

New York (12,725 g midsection and 4,140 g slices), Chicago (1,864 g), Washington (1,158 g), London (838 g), Tempe (625 g), Budapest (520 g), Harvard (359 g), Calcutta (132 g), Vatican (128 g), Ann Arbor (103 g), Yale (80 g), Bonn (43 g), Paris (6 g).

DESCRIPTION

According to Howell (1908a) the flat, rectangular mass resembled a large, double-edged ax with the overall dimensions 40 x 30 x 6.5 cm. The specimens in New York, Tempe and Washington clearly show that the mass is heavily corroded, with 0.1-2 mm thick, laminated, terrestrial oxides, and with superficial, loose octahedral fragments due to a preferential attack along the grain boundaries. At one end several octahedral fragments have been broken off along these weak zones. On sections it is seen that the intercrystalline attack locally proceeds right to the middle of the mass, presumably along narrow fissures created during disruption in the atmosphere. The fusion crust and the heat-affected α_2 zone are long ago removed by the weathering. The terrestrial age is evidently high, but it is only fair to say that the quantitative determinations by Arnold (1961) and Chang & Wänke (1969), which both give about 600,000 years, come as something of a surprise. Their calculations apparently assume that Williamstown was a small mass, little shielded against cosmic radiation. Since it, as shown below, actually is only one minor fragment of a larger mass (about 200 kg survive) the low abundance of ^{36}Cl may be due to an unexpected shielding during irradiation, in addition to ^{36}Cl having decayed during a long terrestrial sojourn. This would presumably lead to a smaller terrestrial age.

Etched sections display a medium Widmanstätten structure of little contrast. The straight, long ($\frac{L}{W} > 30$) kamacite lamellae have a width of 0.90±0.15 mm. In some areas grain growth has wiped out the lamella boundaries and created irregular, granulated kamacite, occupying up to 10 x 6 mm, with no taenite inclusions at all. The kamacite has subboundaries decorated by 1 μ rhabdites, but these are obscured by the superimposed, shock-hardened ϵ-structure, the hardness of which is 325±15. Taenite and plessite cover about 40% by area, mostly in the form of very degenerated comb and net plessite fields. The taenite frames of the fields are discontinuous, and the taenite of the interior is often barely identifiable short ribbons and blebs, 1-5 μ across. Locally, somewhat larger taenite wedges with an

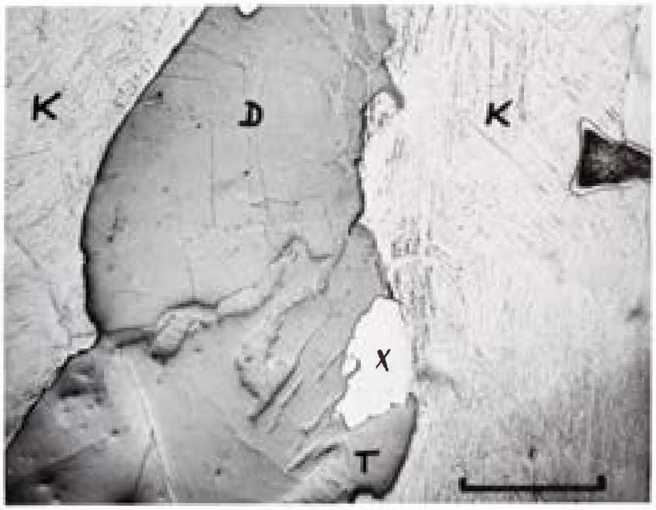

Figure 998. Kenton County. The Williamstown fragment (Tempe no. 161a). Shock-hatched kamacite (K) with a plessite field. Daubreelite-troilite (D-T) inclusion with an unidentified cream-colored phase (X). Etched. Scale bar 500 μ.

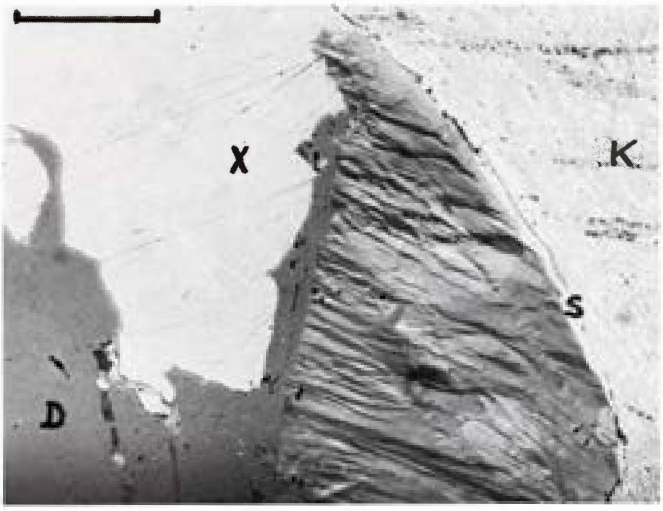

Figure 999. Kenton County. Detail of Figure 998 under slightly crossed polars. The troilite shows undulatory extinction, while daubreelite and the unidentified phase are unaffected. A very narrow schreibersite rim (S) is present. Scale bar 100 μ.

KENTON COUNTY (WILLIAMSTOWN FRAGMENT) – SELECTED CHEMICAL ANALYSES

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Moore et al. 1969	7.57	0.49	0.08	105	360							
Scott et al. 1973	7.50								18.2	32.9	15	

acicular interior occur. These may have the surprisingly high microhardness of 450±25.

Schreibersite is absent as larger bodies but does fill some grain boundaries as 2-5 μ wide precipitates. It is further present in the plessite interior as 2-10 μ thick, irregular blebs. In the kamacite lamellae are tiny rhabdite prisms, about 1 μ in cross section. The analytical value of 0.08% P appears to be a good expression for the bulk phosphorus content of the meteorite.

Troilite is conspicuous as 1-3 mm lenticular inclusions that occur with a frequency of about one per 5 cm^2. Larger inclusions, 12 and 22 mm in diameter, were also observed in one section. Due to the low bulk phosphorus content, only very small schreibersite crystals have been able to grow upon the troilite, generally reaching a width of less than 5 μ and never forming a continuous rim zone. The troilite is monocrystalline but displays numerous lenticular twin lamellae or "sparks" which probably were formed by the shock that created the intensively hatched kamacite matrix. Its hardness is 270±25. Daubreelite is present as 10-500 μ wide massive lamellae in the troilite, covering about 15% by area. Daubreelite-troilite intergrowths are further common as 10-100 μ rounded grains, scattered through the kamacite. Many of the intergrowths are in the form of stacks of parallel, ultrathin (< 1 μ thick) platelets of alternating troilite and daubreelite. Others are relatively poor in troilite.

In the kamacite there are numerous hard platelets, typically 40 x 2 x 1 μ, of the same, oriented carlsbergite as observed in Costilla Peak and Cape York. Locally, the platelets are distorted and sheared, indicating that they were precipitated before the shock-deformation took place.

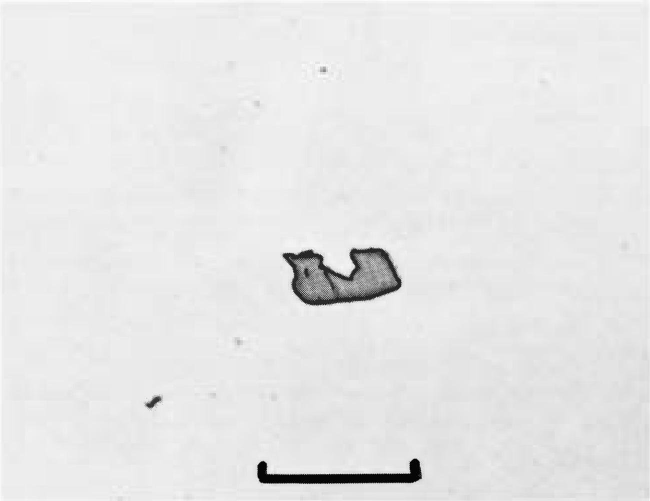

Figure 1000. Kenton County. The Williamstown fragment (Tempe no. 161a). A carlsbergite crystal in kamacite. Polished. Scale bar 30 μ.

The corrosion has attacked the metallic phases more rapidly than the troilite, since in several places this is now seen in slight relief, 0.2-1 mm above the adjacent, metallic surface. Corrosion has selectively converted the grain boundaries and the subboundaries of the plessitic fields to limonite, and it has veined the troilite with cream colored pentlandite.

The structure as discussed above is in every detail identical to that of Kenton County. The chemical composition of the two masses is also the same, and the state of corrosion is the same. The two fragments were found 15 km apart in 1889 and 1892, and both were acquired by Ward's Establishment but were described under different names by two different members of the staff. It is surprising that the striking similarity of the sections of Williamstown and Kenton County was not observed at that time. In the opinion of the present author the two masses are fragments of the same mass which split in the atmosphere and, by a curious coincidence, were found within a few years after having been buried for tens of thousands of years. In future catalogs and treatises it is recommended that they be grouped under one entry, Kenton County, since this is the largest mass and the one first described.

Kenton County and Kenton County (Williamstown) are shock-hardened medium octahedrites that are related to Davis Mountains, Costilla Peak and Henbury. They are at the nickel-poor and phosphorus-poor end of group IIIA.

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

457 g	endpiece (no. 374, 18 x 3 x 2.5 cm)
87 g	part slice (no. 374, 7.5 x 3 x 0.7 cm)
31.5 g	fragments (no. 374, 10.5 g and 21 g)
545 g	slice (no. 377, 30 x (3-6.5) x 0.5 cm)
38 g	slice (no. 3154, 4 x 3 x 0.3 cm)

Kingston, New Mexico, U.S.A.

32°59'N, 107°43'W; 1900 m

Medium octahedrite, Om. Bandwidth 0.80±0.10 mm. Neumann bands. HV 155±10.

Anomalous. 6.96% Ni, 0.48% Co, 0.09% P, 21.2 ppm Ga, 57 ppm Ge, 4 ppm Ir.

The characteristic granulation at one end is due to artificial reheating to about 850° C.

KINGSTON – SELECTED CHEMICAL ANALYSES

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Hovey 1912	6.98	0.51	0.10		140		180					
Smales et al. 1967						44	137	1.9	21.1	55		
Moore et al. 1969	7.01	0.45	0.08	100	360							
Crocket 1972											3.0	17
Scott et al. 1973	6.88								21.3	58.8	5.1	

HISTORY

A mass of 13.0 kg was found in 1891 by a miner who was prospecting for horn silver near the Solitary Mine, about 6 km north of Kingston, in Sierra County. The iron was exposed on the surface of a granite ledge near North Percha Creek. The corresponding coordinates, taken from a modern map 1:62,500, are given above. The mass was purchased in 1910 by the Foote Mineral Company, of Philadelphia, and was cut and distributed by it. It was mentioned in Foote's Catalogue (1912) with a photomacrograph and simultaneously described by Hovey (1912) with an analysis by the firm of Booth, Garrett and Blair and with numerous photographs of the exterior and of etched sections. Chirvinski (1948) examined the troilite inclusions and found a volume percentage of 2.5% FeS corresponding to about 0.57% S in the metoerite as a whole. Hovey (1912) reported lawrencite, but only based upon indirect evidence, the exudation of corrosive droplets. Lawrencite is not present, and the chlorine has, no doubt, been introduced by percolating ground water during a long terrestrial exposure.

COLLECTIONS

Chicago (1,128 g endpiece), New York (1,001 g), Budapest (951 g), Tempe (827 g), Rome (810 g), Harvard (746 g), London (346 g), Philadelphia (341 g), Amherst (333 g), Washington (333 g), Ottawa (320 g), Vatican (274 g), Helsinki (210 g), Tübingen (32 g).

DESCRIPTION

The mass, which was thick lenticular in form, had before cutting the average dimensions 21 x 17 x 7 cm. Two minor fragments of about 150 g had been removed by the finder by chiseling along weathered octahedral planes. All slices in present collections show that the mass is weathered to its very center, particularly following the octahedral traces and especially attacking the surroundings of the numerous troilite nodules and the troilite itself. Near the surface the rhabdites are, in addition, embedded in oxide products, and even the subgrain boundaries of the kamacite are attacked. No fusion crust and no heat-affected rim zone are preserved. Kingston is, no doubt, of very high terrestrial age.

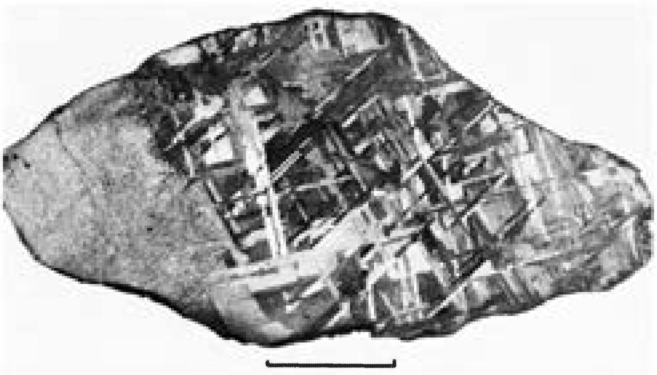

Figure 1001. Kingston (U.S.N.M. no. 539). An anomalous medium octahedrite. The characteristic matte structure at one end appears to be due to artificial reheating. Deep-etched. Scale bar 30 mm. S.I. neg. 33199A.

Etched sections are conspicuous in displaying a beautiful Widmanstätten structure with strong, oriented sheen, which, however, disappears rather abruptly at the blunt end. Hovey (1912), who examined most of the slices cut by Foote, stated that one endpiece was entirely granulated, the opposite endpiece showed significant granulation, while the slices in between showed varying amounts of granulation, as if an interior, normal structure was capped by an anomalous, granulated structure. The matte, granulated structure is very marked on, for example, New York no. 774, USNM no. 539, Tempe no. 189a and on the Ottawa specimen.

The normal structure is that of a medium octahedrite with straight, long ($\frac{L}{W} \sim 25$) lamellae of a width of 0.80±0.10 mm. Locally, grain growth of the α-phase has led to almost equiaxial grains, typically 7 x 5 mm in size. Neumann bands are common, and subgrain boundaries are numerous and often decorated with rather large (1-10 μ) phosphides. The microhardness of the kamacite lamellae is 155±10. The reason for the low hardness may partly be recovery when the mass was heated artificially.

Plessite occupies about 50% by area, or rather occupied, since very little is left. The plessite is almost resorbed, only 10-20 μ wide taenite ribbons and 5-15 μ taenite dents mark the edges of the original framework. The interior is mostly a cellular network of kamacite grains and subgrains with an occasional, still unresorbed, taenite wedge. Locally, a 50 x 50 or 300 x 100 μ acicular plessite island may be found engulfed by growing kamacite.

Schreibersite is only present as 5-10 μ discontinuous rims around the troilite and as a few, 5 μ wide grain boundary precipitates. Rhabdites are, however, common as sharp prisms of a rather uniform size, 1-2 μ across, both in the lamellae and in the former plessite areas. The frequency of the phosphides is in harmony with the chemical analyses.

Troilite is common as 1-10 mm nodules and rods. On 360 cm^2 sections 48 inclusions with a total area of 275 mm^2 were counted, corresponding to about 0.17% S for the mass as a whole. Chirvinskij's estimate (1948) must have been made on a section unusually rich in troilite. The troilite contains numerous daubreelite lamellae, mostly fractured and displaced. Thin troilite veinlets fill the interstices between the daubreelite fragments. The daubreelite occupies 10-20% by area, which, however, does not interfere significantly with the sulphur estimate given above. The troilite is monocrystalline but displays numerous, lenticular deformation twins.

In the alpha phase there are many 25 x 1 μ thin, hard platelets of carlsbergite.

A polished and etched section from the matte structured end of U.S. National Museum No. 539 shows, as expected, that the granulation is due to reheating. The original α-lamellae are decomposed to lobed and serrated, 25-200 μ α_2 grains. The rhabdites are partially resorbed, but not melted, and the few larger schreibersite crystals display a creamcolored, 2 μ wide reaction rim between the phosphide and the terrestrial corrosion products. The troilite nodules are partially melted to eutectics of iron, sulfur and oxygen, and 1-3 μ wide veinlets of such eutectics penetrate the grain boundaries up to 50 μ from the troilite. The daubreelite is recrystallized to a stack of 1-3 μ wide, parallel laminae of two different sulfides. Along the surface and along corroded grain boundaries of the metallic matrix there are 50 μ wide laceworks of Fe-S-O eutectics and of various, unidentified high temperature oxidation products. The structures indicate that the maximum temperature reached was about 850° C, and that this must have been maintained on the order of a few minutes.

There is no doubt that the reheating is artificial and took place after the meteorite had been considerably attacked by corrosion. Although not recorded in the source literature, it is probable that the finder reheated it in order to test its nature. The peculiar matte structure which has been so puzzling in this particular meteorite is, thus, artificial.

Kingston is structurally rather similar to, e.g., Davis Mountains and Costilla Peak. A close examination reveals, however, significant differences, primarily a narrower bandwidth, a softer matrix and a too high phosphide level for the low-nickel content. This anomalousness is corroborated by the trace element analyses that clearly show Kingston as lying outside group IIIA.

Specimen in the U.S. National Museum in Washington:
333 g slice (no. 539, 16 x 9 x 0.4 cm)

Kirkland, Washington, U.S.A.

42°31′35″N, 122°10′13″W

In my opinion this is a deliberate fraud. However, for the benefit of future workers within Meteoritics, I should like to discuss a little of the "circumstances of fall."

According to Read (1963b), who himself hestitatingly accepted the validity of the fall, two small iron masses fell on January 17, 1955, and penetrated the dome of an amateur astronomer's observatory. The astronomer, Luther L. Hawthorne, a retired toolmaker over 70 years of age, heard a loud report like dynamite exploding and later found that the blast had splintered a window. He soon saw smoke issuing through two fresh holes and other openings in the observatory dome. The fire station was given the alarm, but he succeeded in extinguishing the fire before the arrival of the squad. The fire had started between some reference books, and the cause was a 113 g iron meteorite. Another piece, of 119 g, had hit the observatory clock and stopped it. This piece still had a small bit of the aluminium roofing attached to it.

The local newspapers carried the story immediately, and in 1960 Read examined the case. He confirmed the meteoritic nature of the masses, but due to their handling as curios, the exterior characters, such as fusion crust, etc., were in poor shape. He found that the masses had flown almost parallel through the air at an angle of 63° from the vertical, and he reported and pictured burned white "halos" around the two holes in the aluminium dome. A number of other observations were also reported, the masses were figured, and finally it was concluded that "one must admit that the detailed arrangements necessary to perpetrate a hoax meeting the specifications of this fall would be elaborate to the point of absurdity." Henderson (Meteoritical Bulletin No. 29, 1964), however, pointed out that the specimens were of the Canyon Diablo type, and Hey (1966: 243) consequently labeled the meteorite fall "Very Doubtful."

I have discussed the case with Dr. Henderson and, like him, I am convinced that Kirkland is a deliberate fraud for the following reasons: (i) small meteorites reach the surface of the ground at an angle close to vertical, while the Kirkland angle was reported to be about 63° from the vertical; (ii) holes in aluminium sheet made by falling meteorites would not show evidence of heating; (iii) freshly fallen meteorites have a fusion crust and heat-affected α_2 zones. Moreover, micromelted phosphides would be present in this type of material. The reported handling could not have removed all of these features. However, since they are missing, they must have been removed by corrosion; therefore, the claim of this fall must be abandoned. Several other objections could be raised, but the principal ones are those mentioned, and (iii) alone should suffice to remove any doubt.

It must, therefore, be concluded that two small slugs of the Canyon Diablo meteorite – relatively easily available in the United States – have served to create publicity for an amateur astronomer.

Klamath Falls, Oregon, U.S.A.

Approximately 42°10′N, 121°50′W

According to Mason (1962a: 240) an octahedrite of 13.6 kg was found in 1952 near Klamath Falls, Klamath County. No particulars of this mass have been available until recently when Lange (1970) retraced the meteorite after considerable efforts.

Lange stated that the meteorite was found by Jack J. Halsell while he was building a road from Barkley Spring to Antelope Flat, north of Klamath Falls. The finder took a small fragment to J.D. Howard, an assayer in Klamath Falls; this material was later acquired by Nininger and is now in Tempe (Moore & Lewis 1964: 1033; 6.3 g). The main mass was, however, purchased by the Institute of Meteoritics at Albuquerque where it was cataloged as "Oregon, exact locality unknown, 12.96 kg" (La Paz 1965: 109). The material is as yet undescribed.

Klondike. See Gay Gulch and Skookum Gulch

Knowles, Oklahoma, U.S.A.

36°52′N, 100°13′W

Medium octahedrite, Om. Bandwidth 0.75±0.15 mm. ε-structure. HV 280±20.

Group IIIB. About 9% Ni, 18.5 ppm Ga, 30.7 ppm Ge, 0.02 ppm Ir.

HISTORY

A mass of 162 kg was briefly reported as having been found in 1905 near Knowles, Beaver County (Annual Report of the American Museum of Natural History, New York, for 1909; printed 1910; plate showing exterior shape, opposite page 39). Reeds (1937: 584) stated that the meteorite was found in 1903 and was purchased by the American Museum in 1910. Wiik & Mason (1965) presented an analysis, and Wasson & Kimberlin (1967) presented another analysis and compared Knowles to Thurlow.

COLLECTIONS

New York (main mass of 161 kg and a few slices), Tempe (74 g), Washington (58 g), London (55 g).

DESCRIPTION

The overall dimensions of the rectangular mass are 64 x 35 x 18 cm. The mass is flattened with shallow depressions, 5-6 cm in diameter and about 1 cm deep. From one end about 500 g fragments have been removed by chiseling, otherwise the mass appears to be entire.

The specimens in the U.S. National Museum are small, weathered fragments that have been removed from the main mass by chiseling along octahedral planes. A larger fragment of 73 g (No. 411.1x) was kindly loaned the author by Dr. C.B. Moore, Tempe. Also, this was a fragment chiseled from the main mass, but, except for the deformed surface lamellae, the structure was intact. The fusion crust and the heat-affected rim zone have been removed by terrestrial weathering, and corrosion penetrates to a depth of several centimeters along the phosphides.

Etched sections display a medium octahedrite pattern with a bandwidth of 0.75±0.15 mm. The bands are straight, except where distorted by the chiseling, and contain numerous subgrain boundaries in which a few 0.5 μ rhabdites are situated. The kamacite is transformed to a hatched, contrast-rich ϵ-structure, indicative of shock pressures above 130 k bar. The corresponding microhardness was found to be 280±20 HV. Plessite covers about 40% by area, mostly in the form of a peculiar type, also present in, e.g., Narraburra. The 2-5 mm triangular and rhombohedral fields are crisscrossed by acicular kamacite needles that range in width from 10-50 μ. The interstices are concave, sharply faceted taenite areas, the interiors of which are often decomposed to brown- or black-etching martensitic structures where the individual platelets are parallel to the acicular kamacite needles and to the overall Widmanstätten structure.

Schreibersite occurs as numerous, platy or angular, monocrystalline skeleton crystals, that, at least, reach dimensions of 20 x 8 x 0.5 mm. They are enveloped in 1-1.5 mm wide rims of swathing kamacite which often contain numerous rhabdites. In the sections are seen, locally, irregular, large kamacite areas, e.g., 3 x 5, 6 x 7 and even 10 x 20 mm in size. They are relatively rich in rhabdites, and appear to be rim zones around larger schreibersite crystals, above or below the level of the section, but at a first glance they appear very unusual for an octahedrite with 9% nickel. Further, very characteristic is the way a large amount of phosphides are located in rows of discrete, 5-15 μ thick grains, about 10 μ in front of the receding taenite. This island-arc type is common also in Narraburra, Apoala and others. The rhabdites are commonly 200 x 10 μ rods, but may be branched and polycrystalline. Troilite occurs as scattered 100-500 μ units, subdivided in 5-50 μ grains. The troilite is usually associated with or enveloped by the larger schreibersite bodies. One troilite body was found to be developed around an angular, 200 μ chromite crystal.

All the structural details mentioned above are to be found also in Narraburra. It appears, however, that the chemical analyses – which in themselves vary surprisingly much – are somewhat different for Knowles and Narraburra. Structurally, Knowles is very closely related to Narraburra and other group IIIB meteorites.

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

58 g chiseled, octahedric fragments (no. 1190, 7 pieces)

KNOWLES – SELECTED CHEMICAL ANALYSES

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Wiik & Mason 1965	8.59	0.65										
Wasson & Kimberlin 1967	9.4±0.4								18.5	30.7	0.020	

A new analysis for Ni, Co, P and some trace elements is evidently needed.

Kodaikanal, Madras, India

10°16′N, 77°24′E

Polycrystalline finest octahedrite (Off) with silicate inclusions. Bandwidth 0.1 mm. Neumann bands and plastic deformation. HV 210±30.

Anomalous. 8.09% Ni, about 0.3% P, 20.8 ppm Ga, 65.6 ppm Ge, 5.2 ppm Ir.

Not an observed fall in 1890, as believed by Holland and quoted by numerous modern authors, e.g., Murthy et al. (1969).

HISTORY

A mass of 15.9 kg (35 pounds) was secured in 1898 for the Geological Museum, Calcutta. There was no record of its fall, but eight years before, a large meteor was seen to burst over the Pillar Rocks near Kodaikanal, and it was considered likely that this iron fell at that time. The locality of find was the Palni Hills in the Madura District west of Madras (Holland 1900).

Klein (1904a: 149; 1906: 128) gave a preliminary description. He identified rhombic enstatite, monoclinic augite with twins, and tridymite. He classified Kodaikanal as a fine, brecciated octahedrite with silicate inclusions, a classification which has been maintained by all later authors, e.g., Hey (1966: 246). The tridymite mineral has, however, never been confirmed in Kodaikanal, while it has

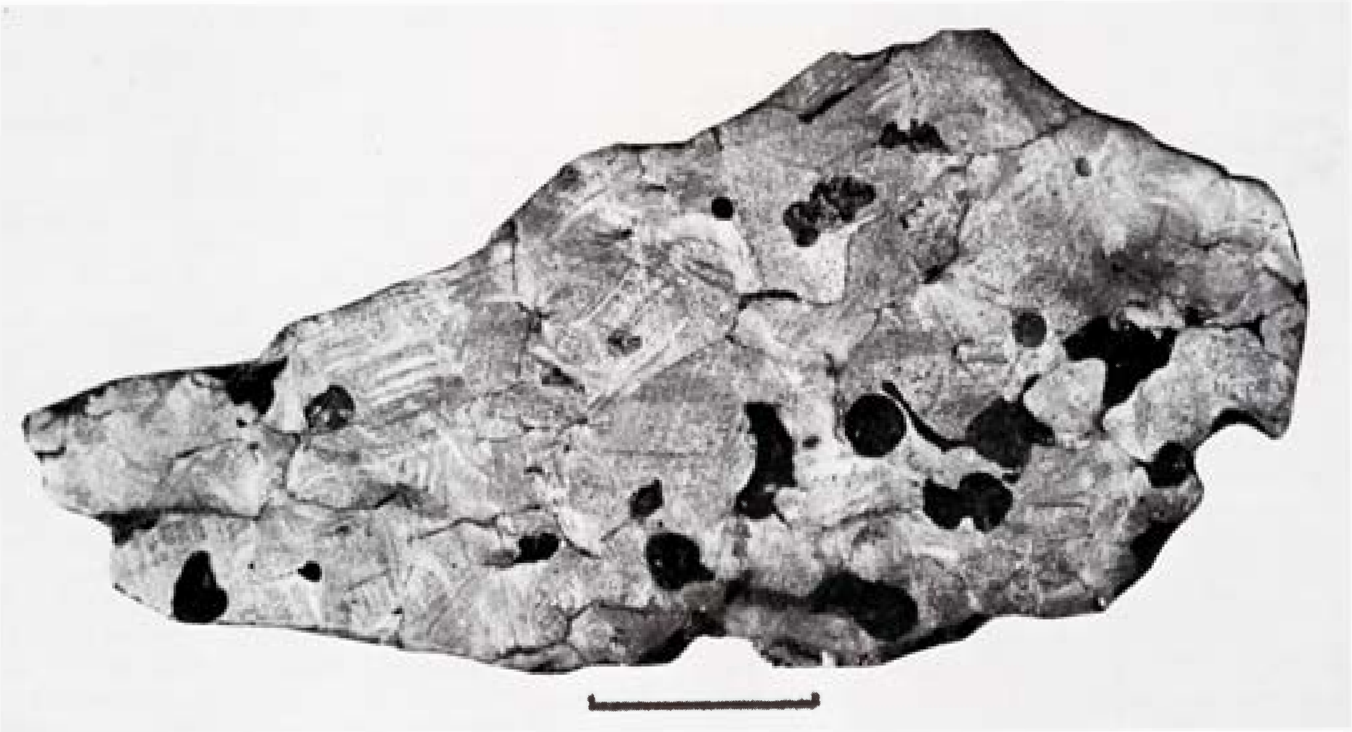

Figure 1002. Kodaikanal (Vienna no. H988). A 4 mm thick full slice showing the polycrystalline austenite matrix. Globular silicates in the grain interiors, vein-like silicates in the grain boundaries. Deep-etched. Scale bar 30 mm.

been identified in the two related meteorites Colomera and Weekeroo Station (Bunch & Olsen 1968).

Berwerth (1906), who examined and photographed a 4 mm thick, 844 g full slice through the mass, described in great detail two silicate types and the deformed metallic matrix. He presented photomicrographs of what was believed to be a new mineral, weinbergerite, but which was later shown to be a slightly weathered mixture of oligoclase and pyroxene (Prior, as quoted by Hey 1966: 246). Berwerth's conception of the deformed metallic matrix, which he felt represented "disturbances in the crystallization process of the iron," is no longer tenable. It must be remembered that Berwerth worked at a time when it was generally accepted that the Widmanstätten structure formed directly as a result of the solidification from a liquid magma (e.g., Brezina, 1895: 17), although other viewpoints were forthcoming just about this time (Rinne 1905; Klein 1906: 49; Fletcher: An Introduction etc., 10th edition 1908: 35 ff.). Mauroy (1913: 28 and plate 3) gave an inappropriate description and a photomacrograph and a later description by Meunier (1915) also proved to be inadequate.

Olsen & Mueller (1964) confirmed most of Berwerth's observations on the silicate minerals. One silicate type consisted of glass up to 8 mm across, the other of an aggregate of glass and several silicates, 3-15 mm across. In the latter case some of the glass was devitrified. X-ray patterns of isolated minerals yielded data corresponding to clinopyroxene, orthopyroxene, and to feldspar mixtures of sodic plagioclase and potassium feldspar, previously unobserved in meteorites. They interpreted the "weinbergerite" of Berwerth as mixtures of feldspar and pyroxene. Additional observations and a correction were published by Bunch & Olsen (1968) along with observations on the related meteorites Colomera and Weekeroo Station.

Buri & Orsini (1966) presented several photomicrographs and electron microscopy replicas of the distorted metallic phases. They concluded, as Olsen & Mueller (1964), that Kodaikanal had been exposed to cosmic secondary alterations. Axon (1968a), examining the metallic phases, visualized a slow structure-forming cooling, followed by mechanical damage, then mild reheating, and, finally, entry through our atmosphere.

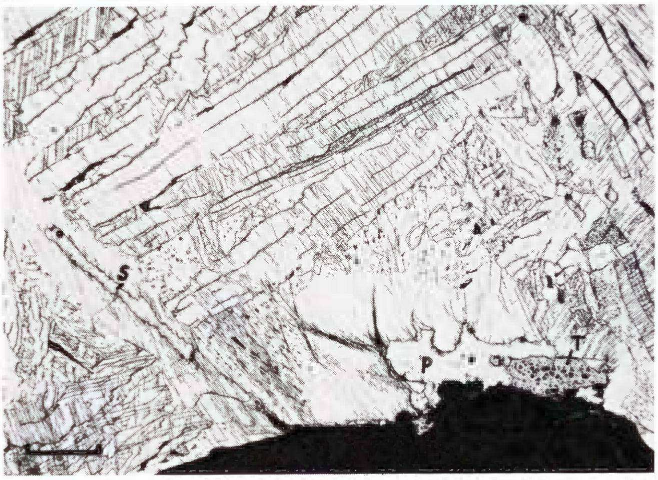

Figure 1003. Kodaikanal (U.S.N.M. no. 2858). To the left an original γ-γ grain boundary with schreibersite (S) and swathing kamacite. Below, a silicate (black) with shock-melted troilite (T) and altered schreibersite (P). Etched. Scale bar 500 μ.

Bence & Burnett (1969) presented an exhaustive study of both the silicates and the metal. They gave sketches of the silicate distribution and photomicrographs of lamellar shock structures in feldspar, strongly resembling the "deformation bands" in shocked plagioclase feldspars from meteorite craters described by Bunch (1969). Excellent photomicrographs illustrated the unusually intense deformation and kneading of the metallic constituents. The minerals previously noted were confirmed and analyzed with the microprobe. A single grain of graphite was noted in the metal. The apatite of Berwerth (1906) and Bunch & Olsen's (1968) whitlockite were shown to be calcium phosphate crystals, 10-100 μ in length, only present as inclusions in the feldspar aggregates. An excess of silica was noted in all feldspars and, to a smaller extent, in the glasses, relative to an ideal feldspar formula. The mineral assemblage and the formation history were discussed in great detail, and reference must be made to this paper in any future examination of Kodaikanal.

The high concentrations of alkalis in the Kodaikanal silicates, already noted by Berwerth, suggested that the silicates would be highly favorable for Rb-Sr studies. Burnett & Wasserburg (1967b) found that not only was Rb highly enriched but also that various samples of the silicates yielded a well defined isochron corresponding to a formation age of 3.81×10^9 years, which is almost 10^9 years after the initial formation period of solid bodies in the solar system. So far, it is the only known meteorite with a Rb-Sr age which is distinctly different from the 4.6×10^9 years of the solar system. Bogard et al. (1968) measured K-Ar ages of 3.53×10^9 years for two samples of Kodaikanal silicate. Bogard et al. (1969) found very low amounts of cosmic ray-produced He, Ne and Ar in the metal phase indicating an exposure age of $(10\text{-}20) \times 10^6$ years which is very short compared to normal octahedrites.

Alexander & Manuel (1968) found extensive losses of the lighter cosmogenic gases (^{3}He, ^{4}He) from the silicates in Kodaikanal. Their results could, after correction for losses, be combined to yield an estimated cosmic ray exposure age of $(7.5\text{-}40) \times 10^6$ years, in reasonable agreement with the above quoted data. They also discussed the behavior of radiogenic ^{129}Xe. Fleischer et al. (1967), in diopside extracts, identified fossil tracks probably of fission origin.

Wasson (1970b) determined the concentrations of Ni, Ga, Ge and Ir in the metal of 19 iron meteorites with silicate inclusions. Kodaikanal was found to correspond closely to Weekeroo Station, Elga, Colomera and Netschaevo in this respect, supporting and developing the conclusions previously arrived at by other authors who had examined the silicates.

COLLECTIONS

Calcutta (8 specimens totaling 3.9 kg), London (2.45 kg endpiece), Vienna (about 1.6 kg), Paris (921 g), Smith Kodaikanal Observatory (500 g), Budapest (312 g, lost in 1956), Washington (282 g), Chicago (264 g), Tempe (160 g), Vatican (148 g), Rome (106 g), Berlin (89 g), Canberra (75 g), Bonn (73 g), Prague (70 g), Minsk (62 g), Strasbourg (61 g). Murthy et al. (1969: 144) briefly described the material in Calcutta. Three samples (Nos. 146 X, Y, Z) with fresh fusion crust and apparently of a coarse octahedral structure (Og) were also discussed without reservation. The descriptions strongly suggest, I think, that these samples are not genuine Kodaikanal material, but possibly come from Samelia or Garhi Yasin. This should be examined as soon as possible, since these meteorites are too valuable to be mixed up and/or lost.

DESCRIPTION

The Kodaikanal mass was not described before it had been extensively cut, apparently about the year 1900. From slices and endpieces known to me, I have tentatively restored the shape of the mass to resemble a flattened lenticular body with the average dimensions 20 x 17 x 13 cm. Somewhat weathered regmaglypts can be indistinctly recognized. The fusion crust has disappeared, but a heat-affected α_2 zone is irregularly preserved as up to 2 mm wide rims. Micromelted phosphides are present in the exterior 40% of the α_2 zone. Thus it may be estimated that

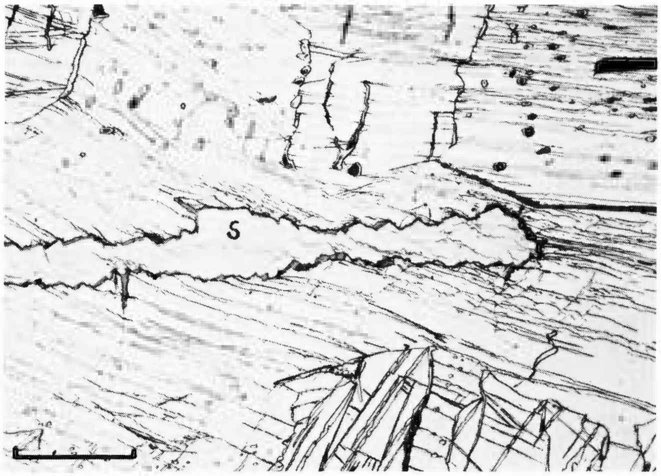

Figure 1004. Kodaikanal. Detail of Figure 1003. Severely deformed matrix with densely spaced Neumann bands, bent taenite lamellae and sheared schreibersite (S). Etched. Scale bar 200 μ.

KODAIKANAL – SELECTED CHEMICAL ANALYSES

	percentage			ppm								
References	**Ni**	**Co**	**P**	**C**	**S**	**Cr**	**Cu**	**Zn**	**Ga**	**Ge**	**Ir**	**Pt**
Nelen in Mason 1967a	7.96											
Wasson 1970b	8.22								20.8	65.6	5.2	

the present exterior shape of Kodaikanal actually reflects the shape of the mass when it landed. Only 0.5-2 mm has been lost to terrestrial exposure, and this only in places. Corrosion penetrates deep into the interior along brecciated schreibersite and silicates and along grain boundaries. Some Neumann bands are selectively attacked, presumably because they were decorated by phosphides less than 0.3 μ across. The troilite is somewhat altered and displays 1-2 μ wide pentlandite veinlets. The state of corrosion excludes the possibility that Kodaikanal was an observed fall in 1890. On the contrary, it has most likely been exposed to terrestrial corrosion for countless generations.

Etched sections display a polycrystalline aggregate of parent austenite crystals and silicates. The silicates have been reported to constitute about 15% (Klein 1904a) and 10% (Berwerth 1906) by volume. Various sections in Tempe, Washington, Paris and Vienna, which I have measured, show a range from 7.7 to 15%, and a good average value is 10%. The almost equiaxed metal grains which are partly separated by silicate filaments, partly by 0.03-0.1 mm wide schreibersite veinlets, are on the average 2 cm across, with a probable maximum size of 4 x 3 x 3 cm. Berwerth (1906) counted on the Vienna section (No. H 988 of 92 cm^2) 38 grains, corresponding to an average cross sectional area of 2.4 cm^2.

Each grain is decomposed to a finest octahedral structure, where the kamacite lamellae are 100±30 μ wide. The lamellae are very irregular; sometimes several millimeters long and occurring in bundles, sometimes short, bulky and with ragged boundaries. In many places clusters of almost equiaxial kamacite grains, 100-300 μ across, occur. These are often developed around small schreibersite bodies. The irregular outlines of the lamellae are mainly due to late grain growth of the α phase, occurring after the bulk of the alloy had transformed to a finest Widmanstätten structure. Thereby fine taenite lamellae and spheroids are often found in a confusing array embedded in the kamacite lamellae. On a much coarser scale the same irregular kamacite development may be found in many group I irons, e.g., Bischtübe.

While the interior of the grains are transformed to an Off structure, probably by homogeneous nucleation and growth, the many silicates and γ - γ grain boundaries have acted as heterogeneous nuclei and, at an early date, started α-precipitation. This has led to the formation of somewhat irregular rims of swathing kamacite around most silicates and along the primary grain boundaries and their schreibersite precipitates. The kamacite rims are 0.1-0.3 mm wide and

Figure 1005. Kodaikanal (U.S.N.M. no. 2858). The Widmanstätten structure is imperfectly developed in this meteorite. Distinct plessite fields are rare. Most plessite is of an open-meshed type, like the triangular field in center. Two hardness impressions (black squares). Etched. Scale bar 300 μ.

Kodaikanal. Table II. Silicates.

	Berwerth 1906	Bence & Burnett 1969				Bunch & Olsen 1968
	'Weinbergerite'	Feldspar	Diopside-Augite	Enstatite-Bronzite	Glass 'maskelynite'	Glass fused albite
Na_2O	3.19	8.68	0.51	0.11	5.12	10.6
MgO	4.47	0.16	18.3	30.0	0.17	–
Al_2O_3	9.42	18.3	1.25	0.49	17.2	20.4
SiO_2	42.00	68.0	53.1	56.0	68.5	66.6
K_2O	2.57	3.58	0.0	0.0	7.67	0.72
CaO	3.87	0.22	18.7	1.43	0.09	0.35
TiO_2	0.70	0.52	0.32	0.24	0.51	–
Cr_2O_3	0.98	0.02	1.34	0.50	0.02	–
MnO	trace	0.03	0.33	0.50	0.03	–
FeO	–	(0.5)	5.75	10.5	0.50	0.84
Fe_2O_3	28.75	–	–	–	–	–
P_2O_5	0.88	–	–	–	–	–
H_2O	2.17	–	–	–	–	–
Sum	99.00	100.00	99.7	99.8	99.8	99.51

Data in the first column were obtained by classical wet chemical analysis. All other data are electron microprobe analyses.

often subdivided in cells. Due to late grain growth they have often proceeded outwards over the adjacent Widmanstätten structure.

Bence & Burnett (1969: table 3) discussed the composition of the swathing kamacite, 6.7% Ni, and of the lamellar kamacite 7.3% Ni. They assumed as one alternative, that the swathing kamacite was an early transformation product, nucleated by the silicates. The present structural examination leaves no doubt that the swathing kamacite formed this way, and is not a deformation phenomenon, their second alternative.

The Widmanstätten transformation normally leads to a texture of well defined α-lamellae lying in retained plessite and separated from these fields by distinct and continuous taenite rims. This is not the case for Kodaikanal. While there is a remote similarity to the structure of such irons as Chinautla, Gibeon and Bacubirito the plessite fields proper are entirely lacking in Kodaikanal. Or rather, once present, they have become partially resorbed by annealing and now appear without the continuous taenite rim zones. From what remains it appears that the fields were previously of the comb and net plessite types and of the cellular type so easily recognizable and common to group IVA; see, e.g., Gibeon and Chinautla. Typical fields, e.g., 300 μ across, will show a 1-2 μ wide taenite border and an interior open structured net where taenite spherules 2-20 μ across or lamellae 2-20 μ wide are scattered through the kamacite. The fields may be subdivided into 50-200 μ wide cells, within each of which all taenite particles are uniformly oriented. The hardness of the fields is similar to that of the kamacite.

The taenite lamellae are usually 2-15 μ wide. They stain smoky brown upon etching and, whenever more than 4 μ thick, they display interiors decomposed to martensitic-bainitic or poorly resolvable duplex structures. Many features correspond to the annealed dark-etching taenite structures described in, e.g., Anoka.

Schreibersite is ubiquitous: first, as 30-60 μ thick, more or less continuous rims around the silicates; second, as 30-100 μ wide $\gamma - \gamma$ grain boundary precipitates; and third, as irregular or lamellar 2-50 μ blebs that substitute for taenite everywhere in the comb and net plessite. Rhabdites were not observed. The bulk phosphorus content is estimated to be 0.30±0.05%.

Troilite is only present as minor rims and pockets along the silicate-schreibersite-metal interfaces. The troilite ranges from 50 μ blebs to 100 x 1,000 μ rims.

The metallic structures so far described can be interpreted as the result of a continuous, relatively rapid cooling from about 1000° C to 400° C. The cooling rate must have been considerably higher than the 50° C per 10^6 year, deduced by Goldstein (1969) for Gibeon, which has the same nickel content but a three times larger bandwidth. From curves published by Short & Goldstein (1967) an approximate cooling rate of 500° C per 10^6 year can be

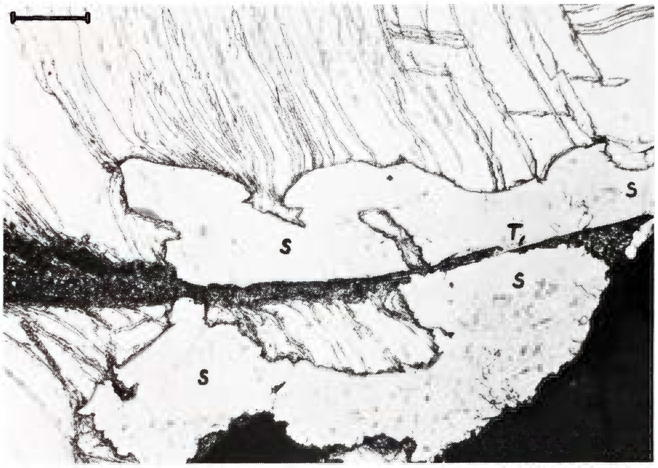

Figure 1007. Kodaikanal. Detail of Figure 1006. The schreibersite crystal (S) is violently sheared and brecciated. In the dark horizontal shear zone the kamacite is partially recrystallized due to frictional reheating. At T, a troilite inclusion is shock-melted and smeared out along the shear zone. Etched. Scale bar 50 μ.

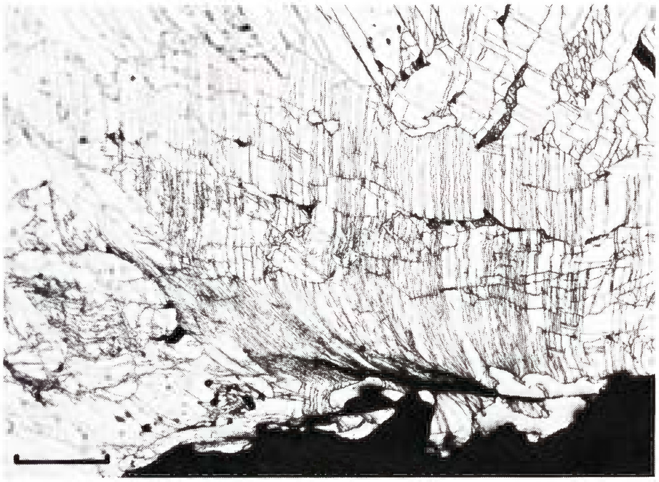

Figure 1006. Kodaikanal (U.S.N.M. no. 2858). Densely spaced Neumann bands in the kamacite. Below, a silicate nodule (black) and shear-deformation in the adjacent matrix. Etched. Scale bar 300 μ.

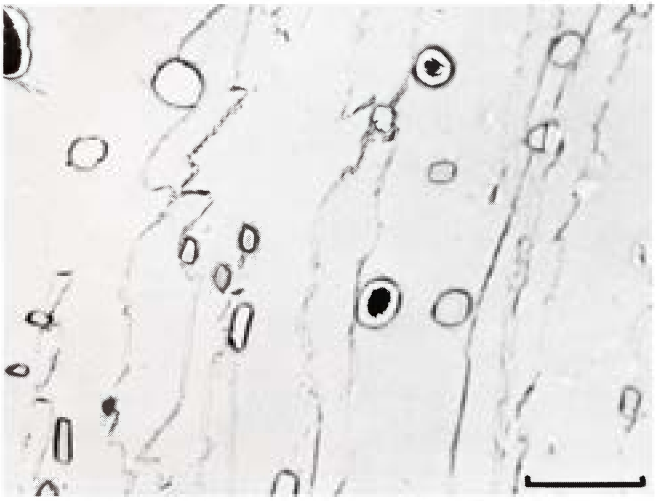

Figure 1008. Kodaikanal (U.S.N.M. no. 2858). Detail of an open-meshed plessite field with spheroidized taenite particles -and deformed Neumann bands. Etched. Oil immersion. Scale bar 20 μ.

estimated. After the primary structure had developed Kodaikanal must have been exposed to some sort of long term annealing whereby the kamacite developed some grain growth, and a large fraction of the plessite fields decomposed. Perhaps the smooth cooling discontinued and a slower cooling prevailed for some time.

A violent event then occurred, profoundly altering the structure. Few iron meteorites display such distortions as those present in Kodaikanal. Some features are otherwise only found in shocked fragments of crater producing meteorites, such as Canyon Diablo and Kaalijärv.

Neumann bands in rich contrast are extremely plentiful in the kamacite and so densely spaced that neighbor bands almost overlap. Where they cut narrow taenite lamellae, these are often shear-displaced in 1-2 μ steps. Bundles of sliplines crisscross the structure, run together along silicate-metal interfaces and grain boundaries, then divide and fan out a few millimeters farther away. Where the distortion is most intense, along silicate-metal, troilite-metal, and schreibersite-metal interfaces, there are displacements of 0.1-0.5 mm. The kamacite in the slip zone has been sufficiently deformed and reheated by friction to recrystallize to 1-10 μ new units. The largest recrystallized kamacite grains are found in pockets within the silicate material, cut off from the metallic matrix by the distortion and thus thermally well insulated.

Troilite in the slip zone has either melted completely or recrystallized to 5-10-μ equiaxial grains, and schreibersite has recrystallized or melted. Troilite and schreibersite together have formed composite melts which have been injected for millimeters into the fissures of adjacent silicate aggregates. Here the melts have solidified to extremely fine grained (< 0.5 μ), somewhat branching eutectics. It appears that the silicates themselves were not remolten on this occasion, but became fissured, slightly deformed and shear-displaced through the adjacent plastic metal. Perhaps the dense grid of deformation bands in the feldspars, noted by Bence & Burnett (1969: figure 4) formed at the same event.

The taenite and the plessite were, of course, deformed simultaneously and now show folding, bending and shearing. The kamacite has a hardness range of 179 to 244 while the duplex plessite fields are 10-30 units harder than the adjacent kamacite. The highest hardnesses normally occur where the structure is visibly most distorted. However, where recrystallization and annealing are also present, the hardness drops back again to about 200. In these slightly annealed areas the bent Neumann bands and the sliplines have become decorated by very small precipitates, less than 0.3 μ across, and probably of phosphides.

The deformation features discussed above seem to require shock with associated attenuated peak temperatures for their formation. Gravitational or thermal stresses acting on a slower time scale can be ruled out.

The ten volume percent of silicate occurs as irregular drop-like nodules, grain boundary filaments and almost spherical inclusions. More than 50% of all inclusions consist of alkali feldspars, the rest being clinopyroxene and orthopyroxene in varying proportions. Accessory minerals are calcium phosphate, rutile, chromite (Bence & Burnett 1969), and olivine (Bunch & Olsen 1968). The typical millimeter-sized inclusion consists, according to these authors, of flamboyant X-ray antiperthite with inclusions of euhedral or anhedral crystals of green calcium-pyroxene up to 0.5 mm in size. Colorless orthopyroxene often mantles the clinopyroxene or occurs as euhedral crystals up to 0.2 mm in size. While the feldspar antiperthite is optically unresolvable, the clinopyroxene displays pronounced polysynthetic twinning parallel to (001). As noted above, some feldspar crystals show a densely spaced lamellar structure suggestive of intense shock damage. The clinopyroxenes, and to a minor extent, the orthopyroxenes are fractured and offset. The chromite crystals, 10-80 μ across, normally situated in the silicate near the interface with metal, may also be brecciated and shear-displaced.

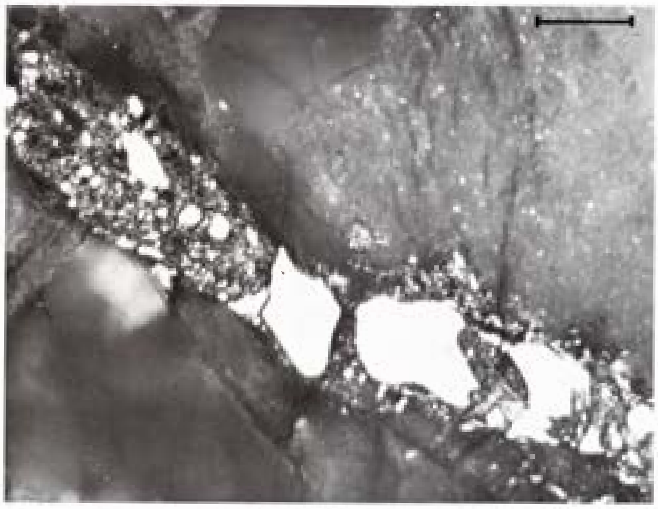

Figure 1009. Kodaikanal (U.S.N.M. no. 2858). A vein of shock-melted troilite-schreibersite-metal (white) runs diagonally across a silicate grain (gray). Polished. Oil immersion. Scale bar 20 μ.

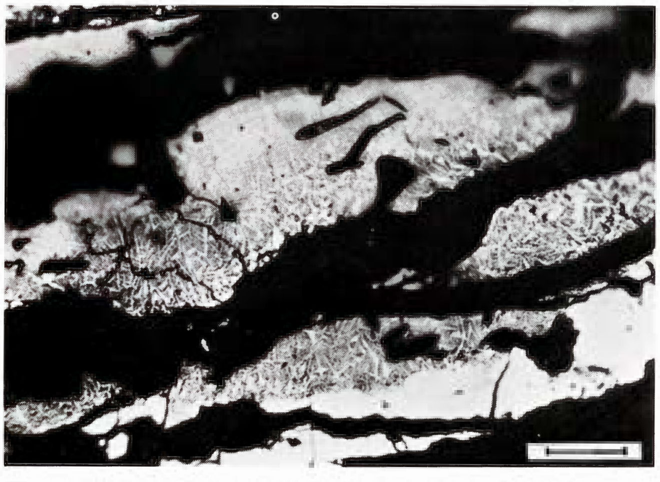

Figure 1010. Kodaikanal (U.S.N.M. no. 2858). Partially shock-melted and rapidly solidified schreibersite in a shear zone, which is now invaded by terrestrial limonite (black). Etched. Oil immersion. Scale bar 10 μ.

Small quantities of glass are present. An analysis is reported in Table II, under 'maskelynite.' It is feldspathic in character but has excess silica relative to the ideal feldspar formula. Bunch & Olsen (1968), who analyzed an almost similar glass, termed it potassium maskelynite to distinguish it from fused glass and indicate the significant potassium content relative to normal maskelynite produced from plagioclase (Tschermak 1872c). The potassic maskelynite is clear and isotropic and retains cleavage traces, planes of inclusions, and grain boundaries of preexisting crystalline feldspar. Milton & De Carli (1963) produced maskelynite in shock-loading experiments and defined it in more precise terms as a shock-formed isotropic phase, produced by solid state transformation and retaining the external features of the parent crystalline feldspar.

Bunch & Olsen (1968), in addition, recognized a second type of inclusion, their (ii). This consists of highly granulated partially fused chromium diopside grains in a matrix that consists of completely fused albite glass, now partially devitrified, fused potassium feldspar glass, and shock-transformed potassic maskelynite. The composition of the relatively low-melting, fused, albite glass is quoted in Table II, but it may vary considerably and contain appreciably more K_2O.

The intriguing macro- and microstructures of Kodaikanal present numerous problems. A tentative explanation is presented in the following. It mainly deviates from prior discussions by assuming an initial mechanical mixture of the metal and the silicates without melting of the metal. In this model, the unusually alkali-rich but simultaneously Ca- and Mg-rich silicates may have been derived as grains from separate sources or different regions within a single differentiated source. The metal would be mixed in as separate grains from a different source.

Upon compression and reheating to peak temperatures of about 1200° C, the silicates would partially melt, the metal would sinter to a compact mass and grain growth would occur to inch-sized crystals while the metal was in a completely austenitic state. Silicate nodules which became engulfed by growing austenite grains would assume near-spherical shapes, while the rest would retain irregular shapes or appear as filamentary grain boundary fillings. The date when this occurred may perhaps be 3.8×10^9 years ago, since Burnett & Wasserburg's determination (1967b) requires that the silicate fraction then became physically separated from a parent material which had a considerably lower Rb/Sr ratio.

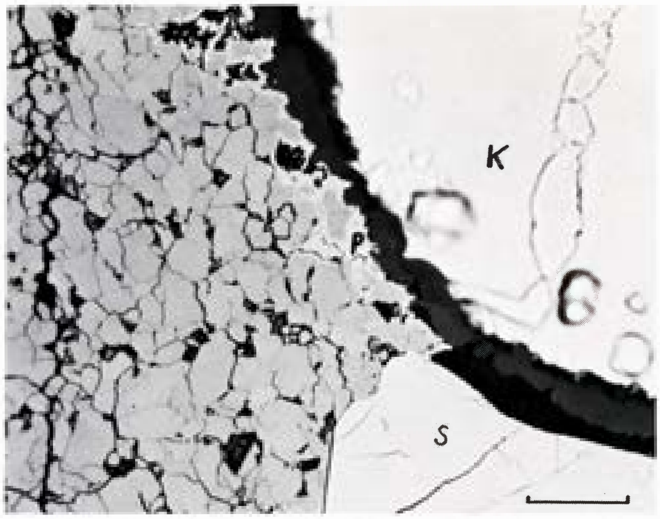

Figure 1011. Kodaikanal (U.S.N.M. no. 2858). Recrystallized troilite to the left, schreibersite (S) and kamacite (K). Terrestrial corrosion has attacked along interfaces (black) and also started to convert troilite to pentlandite (P). Polished. Oil immersion. Scale bar 20 μ.

Subsequent rather rapid cooling allowed (i) precipitation of significant schreibersite rims upon the silicates and upon the γ - γ grain boundaries, (ii) formation of 0.2-0.3 mm wide rims of swathing kamacite upon the same, (iii) glassy metastable states to survive in many silicate aggregates after having initially been heated to complete fusion.

During further cooling, possibly at a somewhat lower rate, through the region 700-400° C, (iv) the formation of a finest Widmanstätten pattern took place, and (v) most albite glass devitrified into masses of cryptocrystalline feldspar and crystallites.

A period of equilibration, or possibly slight reheating to 500° C followed. This was insufficient to erase the Widmanstätten structure, but accomplished (vi) grain growth of the kamacite and, further, (vii) resorption and spheroidization of the taenite.

A violent shock followed. The bulk of the metal responded by (viii) Neumann band formation, while the (ix) silicates became brecciated and shear-displaced. And (x) the feldspar achieved planar features or (xi) transformed in the solid state to 'maskelynite.' Since the troilite and schreibersite around the silicates often appear undamaged and certainly are not dispersed through the silicates, it appears unlikely that the silicates melted on this occasion. Because of the heterogeneous silicate-metal material, as opposed to most iron meteorites, the shear zones followed unusual paths, concentrating along γ - γ grain boundaries and silicate metal boundaries. Thereby, (xii) relative displacements along these boundaries followed with (xiii) shearing and (xiv) micromelting of the associated troilite and schreibersite bodies as a result. And (xv) some of the micromelts were injected into the brecciated silicates where they immediately solidified to ultrafine aggregates. The residual heat from internal friction made some diffusion in the metal possible. Thereby, (xvi) the most cold-worked kamacite recrystallized to 1-10 μ grains, and (xvii) sliplines and bent Neumann bands adjacent to these regions became the seat of almost submicroscopic precipitates of, presumably, phosphides. The taenite (xviii) annealed somewhat. If we assume that this sequence of events was the result of a violent shock that released Kodaikanal from its original parent body, the mass was from now on exposed to cosmic radiation. Alexander & Manuel (1968) and Bogard et al. (1969) dated this event to about 20×10^6 years ago.

Finally, the meteorite penetrated our atmosphere and lost an unknown amount by ablation. The fusion crust and part of the α_2 zone were lost by long exposure to a terrestrial environment, and corrosion penetrated deep into the mass along fissures, especially along the schreibersite loaded grain boundaries that originated in the remote shock event discussed above.

While the metallic structure of Kodaikanal is much more fine grained than in Weekeroo Station and Colomera and must be the result of a much higher primary cooling rate, the chemical composition and the silicates correspond surprisingly well to these irons. Other related meteorites, based upon composition more than structure, are Elga, Netschaevo, Arlington, and Barranca Blanca. The reasons for these similarities in chemistry, but differences in structure, are obscure.

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

88 g part slice	(no. 317)
88 g part slice	(no. 1553)
72 g part slice	(no. 2857)
32 g part slice	(no. 2858)

Kofa, Arizona, U.S.A.

Approximately 33°20'N, 114°W; 1,000 m

Plessitic octahedrite, Opl. Spindle-width 35±15 μ. Neumann bands. HV 265±10.

Anomalous. 18.3% Ni, about 0.15% P, 4.8 ppm Ga, 8.6 ppm Ge, 0.1 ppm Ir.

HISTORY

A mass of 490 g was briefly reported as an undescribed octahedrite from Kofa, Yuma County (Mason 1962a: 228). Dr. Edward Olsen, of the Field Museum of Natural History, kindly informed me that the mass had been purchased about 1917 from a mineral dealer, Lazard Kahn, in New York, but that details of the circumstances of finding had never been provided. In a preliminary fluorescence analysis Olsen found about 19% Ni and classified Kofa as a nickel-rich ataxite. The coordinates above are for the Kofa Mountains, a small range in Yuma County.

COLLECTION

The entire mass is in Chicago.

DESCRIPTION

The small mass is a complete monolith of flat, lenticular shape with the average dimensions 8 x 7 x 2 cm. It is evidently an oriented meteorite, exhibiting a slightly convex front side and a flat or slightly convex rear side. Along the edge between the two sides the metal is visibly ablated away, creating a rather sharp transitional crust. Sections perpendicular to the surface reveal that the phosphides are micromelted to a depth of 0.6-1.0 mm under the convex front side but to double that depth under the rear side, indicating a significantly greater ablation rate on the front side. The α_2 phase is present in the kamacite spindles to double the depth of the melted phosphides, but the identification of the α_2 requires a perfect polished section.

The mass is slightly weathered and pockmarked on all sides by 1-2 mm pits, which are 0.5-1 mm deep. A paper-thin, red-brown crust of terrestrial oxides cover most of the surface. It is rather unusual by its microcracking in a polygonized pattern with 0.2-0.4 mm cells. In spite of the weathering, the metallic fusion crust is preserved in several places as a 0.1-0.2 mm layered, dendritic deposit. It is rich in interdendritic phosphides and has a hardness of 300±15. Terrestrial oxides, 0.1-1 mm thick, cover other parts of the meteorite which, on the average, has lost only 0.5 mm by terrestrial corrosion.

Etched sections display little structure to the naked eye except for the presence of scattered schreibersite inclusions which attain sizes of 5 x 0.5 mm. A hand lens discloses that the structure is composed of numerous kamacite spindles in a plessitic matrix. The kamacite phase constitutes 5-10% of the area, and forms (i) short $(\frac{L}{W} \sim 10)$ spindles with a width of 35±15 μ and (ii) irregular blebs around the schreibersite crystals. The spindles are arranged in the octahedral directions and form an incipient Widmanstätten pattern, similar to what is observed in Freda, Wedderburn and Tawallah Valley. The α-spindles of the interior show Neumann bands and subboundaries and have a hardness of 175±5.

The other half part of the α-phase is developed as swathing kamacite around the schreibersite inclusions. These show a wide range in sizes, from 5 μ to 5 x 0.5 mm, but most common are blebs, 25-50 μ across. These occur with a frequency of 5 per mm^2 and have 10-100 μ wide rims of swathing kamacite. The schreibersite is monocrystalline and only little brecciated and shows no indication of cosmic annealing. The bulk phosphorus content is estimated to be 0.15-0.20%.

The plessitic matrix may perhaps best be described as a bainitic-martensitic structure which is unresolvable under an optical microscope. It exhibits bulk striations parallel to the Widmanstätten structure in the same way as synthetic Fe-Ni-P alloys on the 20% Ni level, which have been annealed for several hundred hours at 350° C. Its hardness

KOFA – SELECTED CHEMICAL ANALYSES

	percentage			ppm								
Reference	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Wasson & Schaudy 1971	18.27								4.79	8.61	0.098	

is 265±10, a hardness which – due to cosmic cold-work – is slightly higher than that of an experimental alloy of the same structure annealed 96 days at 350° C (Buchwald 1966: 18-19).

As is the case with Freda and Wedderburn, the hardness of the matrix drops smoothly and appreciably in the heat alteration zone to a minimum of 220±5. In all three cases we have very small meteorites with a steep temperature gradient; below about 5 mm depths no significant hardness change or diffusion has taken place.

Kofa is a small meteorite, which is rather well-preserved and locally even retains its fusion crust. In many respects it is structurally related to Föllinge, Freda and Wedderburn, but its detailed Ni-Ga-Ge-Ir composition and structure put it somewhat apart from these irons. In its structural details and in its chemical composition, Kofa is particularly closely related to Gay Gulch and Garden Head, two other plessitic octahedrites. Wasson & Schaudy (1971) reached a similar conclusion.

Kokomo, Indiana, U.S.A.

40°25′N, 86°2′W; 250 m

Ataxite, D. A few 20 μ wide α-spindles. Oriented sheen in millimeter-centimeter wide, parallel bands. HV 178±7.

Group IVB. 15.82% Ni, 0.08% P, 0.193 ppm Ga, 0.031 ppm Ge, 31 ppm Ir.

HISTORY

The original reports of this iron came independently from two authors, E.T. Cox (1873) and J.L. Smith (1874). As already noted by Cohen (1889a: 150; 1905: 149) and Farrington (1915: 261) the reports differ in several important particulars as to the year of find, the weight, the circumstances of finding and the structure. While the last problem can be solved today the first three are open to interpretation. I combine here from both sources those data which in my opinion are correct, leaving the least internal conflicts. A mass of 1.85 kg (4 pounds, 1.5 ounces) was found by E. Freeman in 1862 while he was excavating a ditch on his farm. The mass was embedded in clay at a depth of about 60 cm, and the place was seven miles southeast of Kokomo, in Howard County. The mass was taken to the blacksmith who broke two chisels in his attempt at cutting a specimen free.

The mass went through several hands before it was described by Cox (1873) and Smith (1874). In the years immediately following, small specimens were distributed, particularly to European collections, while the largest known section remained in Smith's collection and in 1883 was purchased by the Harvard University (Huntington 1888: 37, 82). Wülfing (1897: 184) believed that originally there was two pieces found, weighing 4 and 1.85 kg, respectively, but this is a misinterpretation of the original

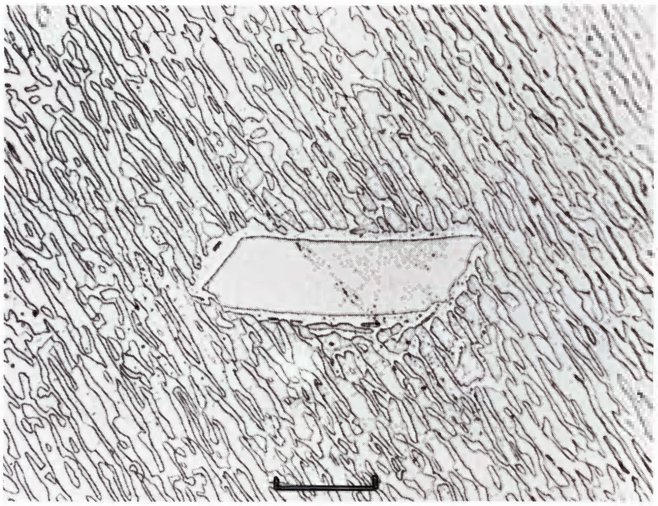

Figure 1012. Kokomo (Copenhagen no. 1876, 2245). This ataxite shows fine α-spindles (center) in an easily resolvable α + γ matrix. See also Figure 73. Etched. Scale bar 30 μ.

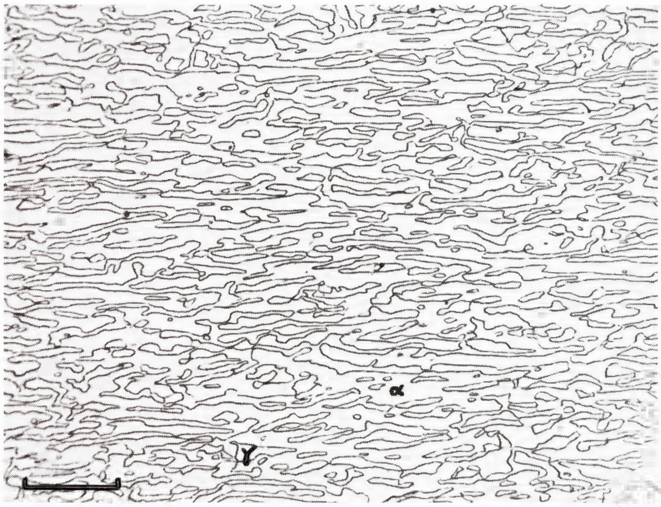

Figure 1013. Kokomo (Copenhagen no. 1876, 2245). The α + γ matrix displays oriented intergrowth. There are indistinct subboundaries in the α-phase. Etched. Scale bar 30 μ.

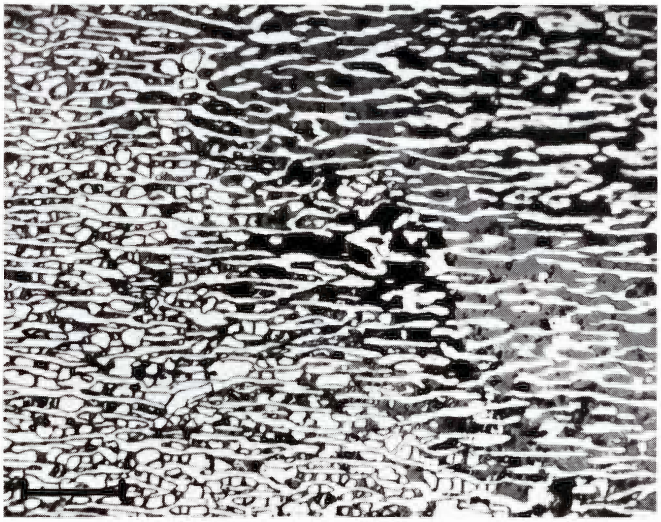

Figure 1014. Kokomo (Copenhagen no. 1876, 2245). Near-surface section showing invading corrosion. Nearest the surface (right) all kamacite is converted to limonite (black); farther in, there is an active, chloride containing zone, in which only part of the kamacite is converted. Polished. Scale bar 30 μ.