Chupaderos (Espiritu Santo), Mexico

Medium octahedrite, Om. Bandwidth 0.65±0.15 mm. ϵ-structure.

Probably group IIIB with 10% Ni, 0.5% P, judging from the structure.

High probability that it is a transported fragment of Chupaderos.

HISTORY

Nothing is known of the history of this iron, not even its original size. The only preserved piece appears to be a 54 g fragment in the Field Museum in Chicago. It was briefly mentioned by Farrington (1916: 259), but before that it had been listed as part of the Ward-Coonley Collection (Ward 1901a: 3). In Ward's later, much larger catalog (1904a) it was omitted both from the collection and from the list of all known meteorites, which may indicate that Ward had come to consider it a fragment of a well known meteorite.

COLLECTION

Chicago (no. 1056, 54 g).

ANALYSIS

No analysis has been performed, but the author would expect from the structural characteristics, about 10% Ni and 0.5% P, with a trace element content characteristic of group IIIB.

DESCRIPTION

The only known specimen was kindly lent to me by Dr. E. Olsen, Field Museum, Chicago. It is a part slice, 5 x 3 x 1 cm, with one polished and etched surface of 10 cm^2. The slight superficial damage is apparently due to hammering and chiseling while trying to separate the specimen from some larger mass. It is corroded very little showing only incipient attack along some near-surface inclusions.

The etched section reveals a beautiful medium Widmanstätten structure with oriented sheen and with straight, long ($\frac{L}{W} \sim 25$) kamacite lamellae with a width of 0.65±0.15 mm. Since the section happens to be almost parallel to the fourth (111) direction, probably because the mechanical chiseling was easiest this way, the fourth set of lamellae show up as a few, irregular, 2-3 mm wide ribbons. The lamellae are bent, and the phosphide inclusions are broken at the surface due to hammering. The kamacitic matrix is of the hatched ϵ-structure associated with shock pressures above 130 k bar. Plessite occupies about 50% by area, partly as comb and net plessite with tiny, concave taenite islands, partly as brown-etching martensite which displays the four directions of the bulk Widmanstätten pattern.

Schreibersite is common as 0.5-4 mm monocrystalline skeleton crystals, and as 40-80 μ grain boundary precipitates. Further, as 3-25 μ vermicular bodies inside the various plessite fields. Rhabdites were not observed, but the subgrain boundaries of the kamacite are decorated with 1-2 μ phosphides.

Troilite occurs in the small section only as 0.3-0.8 mm bodies associated with, or embedded in, schreibersite crystals. The troilite is an aggregate of 10-25 μ anisotropic grains with a few 1-2 μ metallic inclusions. The troilite appears to have been shock melted, since it displays ragged edges against the surrounding kamacite where a little metal has been dissolved. The borderline against the schreibersite is, as usual, smooth, indicating that no reaction takes place easily between troilite and schreibersite upon reheating.

The specimen displays an unusually wide, heat-affected α_2 zone, about 8 mm thick. Rather coarse-grained, micromelted phosphide bodies are found to a depth of about 4 mm. A similar, wide heat-affected zone was observed on specimens of Chupaderos.

Comparison, point for point, of specimens of Chupaderos with Espiritu Santo fails to reveal any structural difference between the two. The slight corrosion and the wide, heat-affected zone are also identical. Furthermore, Espiritu Santo appears to be a detached fragment from some larger mass and to be the only meteorite known from the state of Michoacan. I think, therefore, that it is, in fact, a fragment chiseled off Chupaderos at some early date, transported to Michoacan and then acquired by Ward upon one of his numerous visits to Mexico about the year 1900. It appears, furthermore, that Ward himself had come to a similar conclusion since he omitted the meteorite as a separate entry in his 1904 catalog, at a time when he certainly otherwise worked hard to increase the number of entries, in competition with the collections of Vienna and London.

Cincinnati, Ohio, U.S.A.

39°7′N, 84°30′W; 200 m

Reheated hexahedrite. Structure originally probably as Coahuila.

Group IIA. About 5.4% Ni, 0.2% P.

All specimens in collections have been artificially reheated to 1,000° C.

HISTORY

The iron was found during excavation for a new house in Cincinnati in 1870. The Swiss mineralogist Hosaeus acquired it, and, upon his death, two slices of about 300 g total weight came into the possession of the Geological Museum of Basel (letter from C. Wendler of June 3, 1927, in the Smithsonian Institution). Part of this material was sold to the British Museum (51 g) and the U.S. National Museum (31 g).

COLLECTIONS

Vienna (about 250 g), New York (84 g), Chicago (61 g; 1 g) and Harvard (38 g). Some of these specimens may have been acquired through the same channel. Others came directly from Hosaeus, such as the 28 g specimen in Munich, which was described by Cohen (1905: 51) as a nickel-poor staxite of the Siratik group. The meteorite was

restudied by Perry (1944: plate 10 and 59) and by Henderson & Perry (1958), who concluded that the meteorite had been thoroughly reheated in the atmosphere or before it entered the atmosphere.

DESCRIPTION

From the form and weight of the slices now in collections it appears that the original weight of the mass was between 1 and 2 kg. It is corroded, and some specimens, e.g., Vienna no. 1459 show plane-parallel exterior surfaces and interior cracks which, no doubt, originated from artificial heating and hammering.

An etched section shows a granulated metallic matrix composed of irregular α_2 units, 20-50 μ in diameter. Rhabdites are evenly dispersed; however, they are either partially dissolved by diffusion into the matrix or show fine dendritic solidification, indicating – together with the α_2 structure – temperatures around 1000° C. The hardness of the α_2 phase varies irregularly from 135 to 225, mainly due to varying proportions of phosphorus and nickel in solid solution, supporting the impression of a late reheating which failed to homogenize the material. Due to the small overall size of the meteorite (< 8 cm in diameter) it could be argued that the heating in the atmosphere was sufficient to create this structure since examples are known where small irons have been reheated to the center when passing through the atmosphere, e.g., Föllinge.

Figure 630. Cincinnati (Vienna no. H 1459). Artificially reheated and slightly forged. The interior cracks date from this operation. Deep-etched. Scale bar in centimeters.

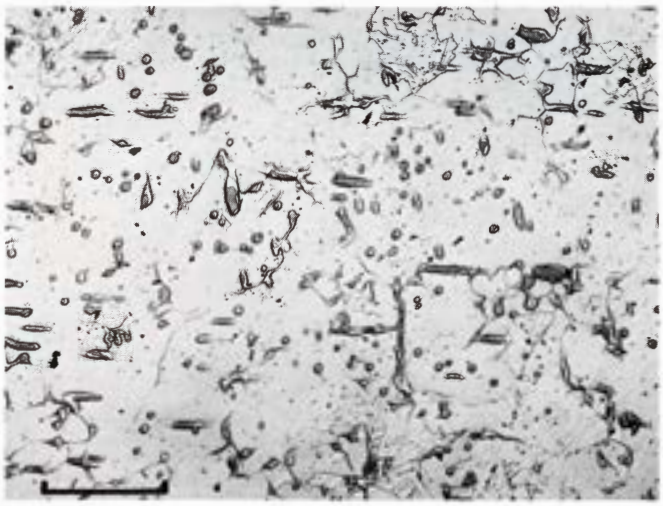

Figure 631. Cincinnati (New York no. 89). Artificial reheating to about 1000° C caused the rhabdites to melt and become partially resorbed in the metal. Etched. Scale bar 200 μ. (Perry 1944: plate 10.)

There is, however, good reason to believe that man reheated the iron thoroughly before Hosaeus got hold of it. One indication is the form of the Vienna specimen as stated above. Another crucial one is that the corrosion products in the cracks have reacted at high temperature with the metal and the minerals to give lacework structures of complex oxides and sulfides. Furthermore, the surface is penetrated by high temperature, intergranular oxidation products as in Burlington, Cacaria, Misteca and others. It is concluded, therefore, that Cincinnati arrived as a normal hexahedrite but was artificially converted to a "nickel-poor ataxite."

Specimen in the U.S. National Museum in Washington:
31 g endpiece (no. 789, 3 x 2 x 1 cm)

Clark County, Kentucky, U.S.A.

38°0′N, 84°10′W

Medium octahedrite, Om. Bandwidth 1.00±0.10 mm. Neumann bands. HV 240±25.

Anomalous. 6.99% Ni, 0.32% Co, 0.19% P, 0.15% Cr, 6.9 ppm Ga, 0.82 ppm Ge, 6.2 ppm Ir.

HISTORY

A mass of 11.3 kg was reported by A.D. Nininger (1939) and Young (1939) as having been recovered in 1937 through the assistance of J.D. Figgins, Director of the Bernheim Museum (now Colorado Museum of Natural History, Denver). It was secured from the finder, a resident

CINCINNATI – SELECTED CHEMICAL ANALYSES

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Sjöström in Cohen 1905	5.43	0.68	0.05		500	0	100					
Henderson & Perry 1958	5.33	0.74	0.20		60							

The cobalt values appear high. Ga and Ge would probably analyze out as a normal hexahedrite.

Figure 632. Clark County (U.S.N.M. no. 2571). A medium octahedrite which is unusual because of its very low cobalt content (0.32%). Deep-etched. Scale bar 30 mm. S.I. neg. 1496A.

of Lexington, in whose possession it had been for many years after having been found in southern Clark County (note in U.S. National Museum). A description of the structure by Nininger appeared with an analysis by Goldberg et al. (1951). The meteorite has repeatedly been included in age determinations, e.g., by Signer & Nier (1962), and it now appears to be one of those meteorites with longest exposure age, viz., 1440±55 million years (Voshage 1967).

Signer & Nier (1962) reported a total of 49 x 10^{-6} cm^3 helium per gram while Bauer (1963) reported 55 x 10^{-6} cm^3/g. Only Deep Springs has been found to contain more helium. Wänke (1960a) examined the distribution of scandium-45 in the meteorite. On the basis of ^{10}Be-^{36}Cl determinations, Chang & Wänke (1969) estimated the terrestrial age to be about 600,000 years.

COLLECTIONS

London (3 kg), Tempe (1.8 kg), Washington (2.1 kg).

DESCRIPTION

From the slices in existence it appears that the meteorite had the form of a somewhat flattened ellipsoid with maximum dimensions about 19 x 19 x 10 cm. It is heavily corroded. Cavernous oxide scales several millimeter thick, adhere locally, and broad limonitic veins penetrate along the {111} planes of the Widmanstätten pattern through the whole mass. Nevertheless, parts of the original melted crust are preserved in some depressions as 0.5 mm thick laminated, dendritic metal (no. 2571). Polished sections continue to corrode rapidly under normal museum conditions.

CLARK COUNTY – SELECTED CHEMICAL ANALYSES

The chemical composition deviates from that of a normal group IIIA medium octahedrite, such as Henbury, in many respects. Cobalt is 40% lower, phosphorus is 100% higher, chromium is extraordinarily high, and the gallium-germanium values are very low. No other iron, except Nelson County, analyzes out like Clark County.

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Goldberg et al. 1951	7.02								7.36			
Cobb 1967	7.27	0.30					96		5.8		7.0	
Smales et al. 1967						1565	80	6.5	6.74	0.65		
Moore et al. 1969	6.88	0.33	0.19	150	600							
Schaudy et al. 1972	6.79								6.92	0.99	6.2	
Crocket 1972											5.3	16

The Widmanstätten pattern is well developed with a bandwidth of 1.0 mm. Plessite and taenite are very limited, and secondary grain growth of the ferritic phase has eliminated large amounts of α-bands and created irregular, lobed new ferrite grains, often several centimeters in diameter. In the interior of these grains, remainders of former plessite fields and of taenite may still be seen as micron-sized lamellae. The event that produced the Neumann bands occurred after the grain growth had stopped because the large grains have continuous and uniform Neumann bands. Near the surface these are selectively attacked by corrosion. The microhardness of the kamacite is 240±25. It drops near the surface to 200±10, because of the heat influx while traversing the atmosphere.

Schreibersite occurs as 25-50 μ grain boundary precipitates and as smaller nodules that visibly have impeded the ferritic grain growth. Rhabdites are not present, but the amount of phosphorus in solid solution in ferrite is very high (Reed 1969) and accounts for nearly all the phosphorus found by the chemical analysis. Troilite occurs as small lenses, typically 3 x 1 mm, with parallel daubreelite lamellae. The troilite has been shock melted and the daubreelite and any schreibersite present were by that occasion brecciated and partially suspended as fragments in the solidifying melt. The nodules have a grain size of 1-10 μ and have developed a lobed, serrated boundary against the metallic matrix. Chromite was not observed and daubreelite is present in far too small an amount to account for the analytical value of 0.15% Cr. If the analysis is not biased by having sampled a daubreelite-rich metal section, the chromium must be present in solid solution in the ferrite and/or as fine chromium carbides. The α-subboundaries are well decorated with precipitates.

Clark County is different from other medium octahedrites of this bandwidth because its ferritic phase is supersaturated with phosphorus and shows extensive grain growth. Chemically and, in part, structurally it is remarkably similar to Nelson County, which apparently was found not very far away.

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

849 g slice (no. 1304, 12 x 9 x 1.1 cm)
1,220 g slice (no. 2571, 19 x 10 x 1 cm; from University of Kentucky) figured by Young (1939: figure 2).

Cleburne, Texas, U.S.A.

32°19′N, 97°25′W

A mass of 6.8 kg, found in 1907, was recognized as meteoritic in 1934 (A.D. Nininger 1937: 449). The main mass is in the possession of O.E. Monnig, Forth Worth, Texas. It is apparently a fine octahedrite, but it was not available for examination in time to be included in this study.

Cleveland, Tennessee, U.S.A.

34°53′N, 84°47′W

Medium octahedrite, Om. Bandwidth 1.00±0.20 mm. Neumann bands. HV 275±20.

Group IIIB. 8.88% Ni, 0.53% Co, 0.40% P, 21.0 ppm Ga, 41.9 ppm Ge, 0.094 ppm Ir.

The 13 pound "Whitfield County" (Hidden 1881) and the 254 pound "Lea Iron" (Genth 1886) will be considered to be genuine "Cleveland" material.

HISTORY

A mass of 254 lbs (115.5 kg) was purchased by Dr. Isaac Lea of Cleveland, Tennessee, in 1867 and described later by Genth (1886). The meager information regarding the circumstances of finding strongly indicate that the Cleveland mass was found only half a mile from the 117 pound Dalton mass which Shepard described (1883b). Shepard quoted a letter from his informer (page 336), "A large mass of iron supposed to be a meteorite was found half a mile from this one (Dalton), about the year

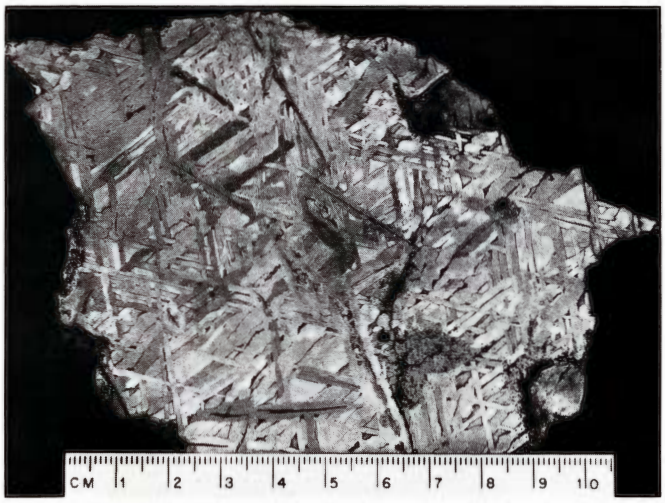

Figure 633. Cleveland (Tempe no. 242a). Troilite nodules, schreibersite skeleton crystals and Reichenbach lamellae in profusion. The Widmanstätten structure looks messy because the numerous inclusions have nucleated swathing kamacite which is usually not parallel to $(111)_\gamma$. Deep-etched. Scale bar in centimeters. (Courtesy C.B. Moore.)

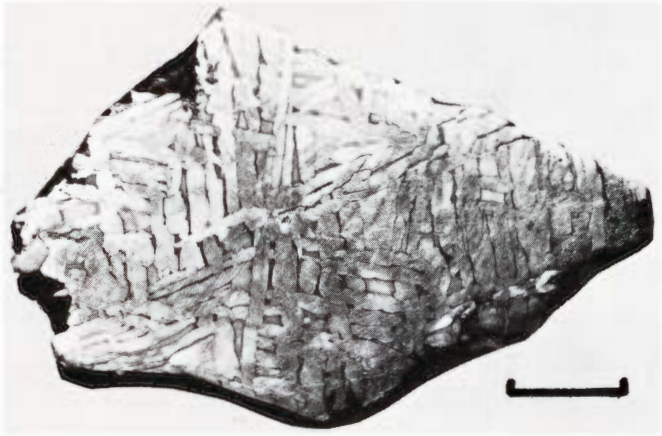

Figure 634. Cleveland (Prague no. 219). This 36 gram slice is erroneously labeled "Dalton" in the Prague collection. It is typical of many slices of the "Whitfield County" mass which are still mislabeled in many collections. Deep-etched. Scale bar 10 mm.

1862. It was sent to Cleveland, Tenn., where it appears to have been lost sight of." The coordinates for Cleveland are thus the same as for Dalton (Shepard mass).

There exists, in addition, a third mass of 13 pounds, found within a few kilometers of the first two, also during farm work, and described by Hidden (1881) as "Whitfield County"; this has traditionally been accepted as a part of the Dalton mass (Hey 1966: 128), or has been considered an independent fall (Merrill 1916b).

In the present investigation the whole question as to the relationship of the various masses was reexamined. It is concluded that the 254 pound Cleveland mass and the 13 pound Whitfield County mass belong together, while the 117 pound Dalton mass constitutes a separate fall.

Excellent photographs of the exterior and of etched sections were presented by Genth (1886) along with his description of the 115 kg mass, the "Lea Iron." Hidden (1881) described the 13 pound mass found in 1877 and gave a woodcut. Apparently most of this material was acquired early by Vienna where Brezina on several occasions gave a few notes (1880a: 351; 1885: 211; 1895: 279). Merrill (1916b) gave a photomacrograph of Whitfield County, while Perry (1944: plate 41 and 44) gave two micrographs of the "Lea Iron." Brett & Henderson (1967) included Cleveland in their study of the Reichenbach lamellae and gave two photomicrographs of these.

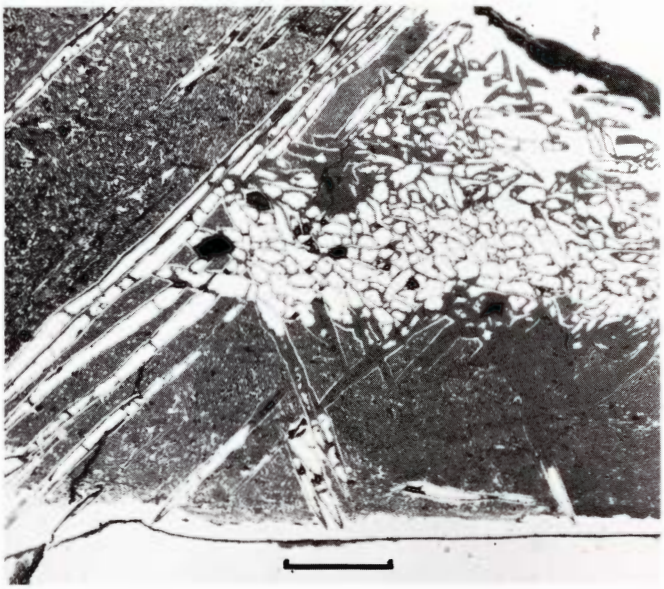

Figure 635. Cleveland (Copenhagen no. 1930, 80). A near-surface section showing selective corrosion of the finely disseminated α-phase of a duplex plessite field. Polished. Scale bar 200 μ.

COLLECTIONS

The main mass of the "Lea Iron" (about 115 kg) was for a long time in The Academy of Science, Philadelphia, but is now apparently lost (R.W. Barringer 1967, pers. comm.). Slices from it (930 g) still exist there. Vienna (1,055 g), Washington (800 g), Chicago (502 g), New York (484 g), Tempe (303 g), Copenhagen (254 g), London (209 g), Ann Arbor (210 g), Ottawa (52 g), Vatican (47 g). These specimens are normally labeled "Cleveland" in collections.

The main part of Whitfield County is in Vienna (about 2.9 kg). Other samples are in Harvard (429 g), Chicago (no. 1119, 123 g), London (no. 53,291, 133 g), Washington (114 g). In my opinion, all these specimens are wrongly listed "Dalton" in present collections, sometimes with the synonyms "Hidden Iron" or "Whitfield Co." added.

DESCRIPTION

The "Lea Iron" was a flattened triangular mass with the maximum dimensions of 45 x 40 x 22 cm and a total weight of 115.5 kg (Genth 1886). Whitfield County was a thin oblong mass, originally of 5.9 kg (13 lbs), but when Hidden saw it (1881) of only 4.4 kg with the dimensions 25 x 12 x 3 cm. It displayed irregular jagged edges which indicate where it broke (or was broken) from the "Lea Iron." Both blocks are corroded and pitted severely with 1-3 mm thick oxides. On sections it is seen that all atmospheric crust and almost all heated α_2 zone have disappeared and that corrosion penetrates to the very center, particularly along octahedral planes, phosphide inclusions and Reichenbach lamellae. Museum specimens continue to corrode rather rapidly.

Figure 636. Cleveland (Copenhagen no. 1930, 80). Plessite field with unresolvable black taenite portions. Decorated slipplanes in the adjacent kamacite. Etched. Scale bar 200 μ.

CLEVELAND – SELECTED CHEMICAL ANAYLSES

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Moore et al. 1969	8.90	0.53	0.40	130	60							
Scott et al. 1973	8.85								21.0	41.9	0.094	

The analyses were performed on the "Lea Iron." No modern analysis on Whitfield County is available.

The following structural descriptions apply to sections from both blocks. The Widmanstätten structure is well developed with somewhat irregular, long ($\frac{L}{W} \sim 20$) lamellae of 1.00 mm average width. Etched structures appear rather messy because swathing kamacite is developed to a significant extent as 1-3 mm wide irregular rims around the numerous schreibersite crystals and Reichenbach lamellae. Neumann bands and deformation bands are common, also in the open-meshed comb plessite. The microhardness of the kamacite lamellae is 275±20, with significant variations mainly due to different degrees of plastic deformation. The hardness decreases to about 200 near the corroded surface. indicating that only two or three millimeters of the exterior surface has been lost by corrosion (hardness curve I, without minimum and left leg). Taenite and plessite fields occupy about 40% by area of the sections and are developed as comb plessite with local patches of black taenite, i.e., a poorly, resolvable $\alpha + \gamma$ mixture, as acicular plessite and as martensite. The immediate surroundings of such triangular 0.5-1 mm dark-etching martensitic blebs display a multitude of slipplanes which are observed upon etching because they are decorated with submicroscopic precipitates, presumably phosphides or carbides. A similar structure was described in Thule, a related meteorite (Buchwald 1965: plates 8-11; 1966: 33). When the austenite inside the field transformed diffusionless to α_2 (or martensite) a considerable strain was induced in the surrounding ferrite, due to the volume increase upon transformation. Dislocations piled up on numerous slipplanes in the kamacite, and in due time these became the site of very small precipitates.

Schreibersite is dominant, e.g., as 10 x 1, 2 x 2, 21 x 2 mm irregular, branched lamellae and skeleton crystals. They are monocrystalline but heavily brecciated and faulted due to some cosmic event. Displacements of long bodies in 5-10 μ successive steps are commonly observed. Schreibersite is further common as 40-80 μ wide grain boundary veinlets and as vermicular or angular 10-50 μ bodies inside the plessite. Rhabdites were not seen.

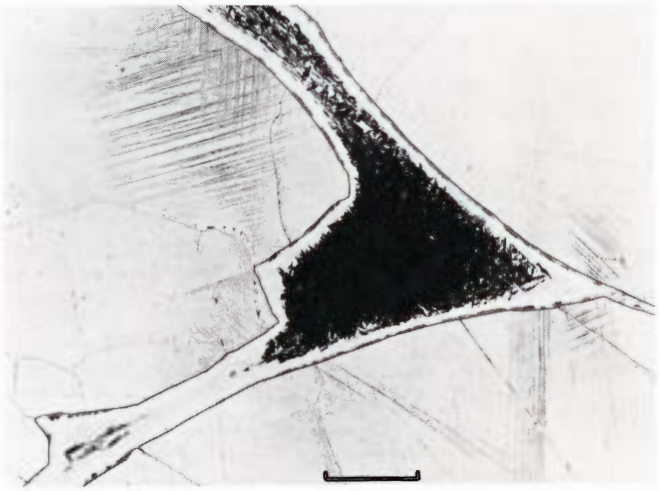

Figure 637. Cleveland (Copenhagen no. 1930, 80). Another plessite field, with cloudy taenite rims and acicular martensite. Decorated slipplanes in kamacite. Etched. Scale bar 200 μ.

Troilite occurs as scattered 1-2 cm nodules some of which are indented by the surrounding metal. They have 0.2-0.4 mm thick, sheared schreibersite rims and are themselves either single crystals or mechanically deformed crystals, displaying irregular, lenticular anisotropic "flames" with poorly defined extinction in crossed nicols.

The Reichenbach lamellae are typically slightly curved, lamellar complex structures with dimensions about 20 x 15 x 0.1 mm. No fresh, unaltered lamellae could be found. The best preserved are composed of parallel lamellae of varying thickness, generally 5-50 μ each, of which the major minerals are chromite, troilite and schreibersite. Locally the troilite and/or the schreibersite will swell to produce a side-positioned "flag" or an end-positioned sack, 0.5 mm in diameter. Terrestrial corrosion products are present in significant amounts.

Cohenite has been reported from Cleveland, but evidently erroneously. There are, however, indications of carbon dissolved in the taenite rims on, say, the 0.3% C level. Compare Kayakent.

Cleveland is a medium octahedrite related to Thule, Drum Mountains, El Capitan and others, and is distinguished by its high proportion of schreibersite and Reichenbach lamellae. Chemically is is in the transition region between group IIIA and IIIB.

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

Lea Iron	7 g chiseled fragment (no. 191, 2 x 1 x 1 cm, from Lea Collection)
	185 g part slice (no. 608, 7 x 7 x 0.5 cm)
	367 g slice (no. 608, 12 x 8 x 0.5 cm)
	239 g part slice (no. 1000, 7 x 3.5 x 1.7 cm; Shepard Collection no. 99)
Whitfield County	35 g part slice (no. 519, 3 x 2.5 x 0.5 cm)
	79 g slice (no. 520, 5.5 x 4.5 x 0.5 cm)

Clinton, Tennessee, U.S.A.

36°5′N, 84°12′W

According to Nininger & Nininger (1950: 45) a total of 7.7 kg was found before 1950. Due to the weathered nature, no thorough examination has been published, but it is assumed that Clinton was an octahedrite.

Coahuila, Mexico

Approximately 28°30′N, 102°29′W; 1500 m

Hexahedrite, H. Single kamacite crystal. Decorated Neumann bands. HV 180±10.

Group IIA. 5.59% Ni, 0.45% Co, 0.28% P, 57 ppm Ga, 180 ppm Ge, 15 ppm Ir.

Synonyms: Santa Rosa; Sanchez Estate; Saltillo; Couch Iron; Bonanza Iron; Butcher Iron; Lupton's Iron; Fort Duncan; Bolson de Mapimi.

HISTORY

This important shower of over 2,000 kg was known to the local population of Coahuila long before it was reported

Figure 638. Coahuila (U.S.N.M. no. 389). The Sanchez Estate mass. The drill hole, 28 mm in diameter and 45 mm deep, was probably made by the blacksmith when the mass was in use as an anvil. Samples have been removed from both ends and from the top, reducing the original weight of 114 kg to 105 kg. Scale bar approximately 5 cm. S.I. neg. 28940.

by scientific explorers. Most of the smaller transportable masses appear to have been removed at an early date to be used as supplies of iron or as anvils. The 114 kg Sanchez Estate anvil which Lieutenant Couch discovered in Saltillo in 1854 and acquired for the Smithsonian Institution (Smith 1855; Merrill 1916a: 141), is known with certainty to have come from this source. Another mass of about 87 kg, Lupton's Iron, seen in the town of Santa Rosa as late as 1879, may have been removed from the original site with a similar intention (Lupton 1885). It is further known that in 1837 an Indian traded a 10- or 12-pound meteorite in Santa Rosa de Muzquiz (the present name is Muzquiz: 27°53′N, 101°31′W), supposing it to be silver (Smith 1869b), and it is possible that many other small fragments were picked up in due time and transformed into tools. The fact that the meteorite could be readily forged into useful items is proven by an undescribed experiment conducted in The Smithsonian Institution in the 1920s: a fragment was successfully forged into a beautiful and durable knife blade of great perfection (U.S.N.M. No. 740).

Our sampling of the meteorite shower may thus be biased by exhibiting too many large specimens. The individuals, mentioned or recovered on various occasions, are compiled in the table. The total weight is just above 2,000 kg; and perhaps another 1,000 kg of small masses have been disseminated; but we will probably never know.

The first report of the Coahuila hexahedrites came from Smith (1855) who presented a sketch of the anvil discovered at Saltillo. Shepard (1866; 1867b) furnished a sketch map and one of the best descriptions of the locality, which he called Bonanza and estimated to be ninety miles northwest of Santa Rosa. He described a 120 g fragment, chiseled from a large mass, but he probably later acquired about a pound of additional fragments, judging from what was left in his possession and distributed from him. Encouraged by Smith's and Shepard's descriptions Dr. H.B. Butcher in 1867 or 1868 undertook an expedition to the locality. Helped by local guides, he successfully recovered eight individuals, ranging from 290 to 654 pounds, see the table (Smith 1869b; Burkart 1870: 679). The masses, labeled no. 9-13, were never discussed by Smith, but they are nevertheless listed in Huntington's catalog (1888: 58) and are undoubtedly minor individuals from Butcher's expedition. Since the weights before cutting are not stated, I have placed my estimates in parentheses.

The controversial Smithsonian Iron is a small nearly complete individual of about 3.6 kg which was first mentioned by Shepard (1881b) as a mass from an unknown locality. Brezina (1896: 290) and Merrill (1916a: 56), however, identified it as a Coahuila specimen. At the time of writing, the mass could not be found in the Smithsonian Collection and the identification could, therefore, not be confirmed. (See page 1147, where the mass was finally identified as an independent meteorite). The last mass to be secured, Fort Duncan of 44 kg, was found in 1882 in Maverick County, Texas, on the north side of Rio Grande. The fort was situated near Eagle Pass, which is 180 km east of the other masses; the mass appears to have been transported and lost, then rediscovered by Mr. Cusick (Hidden 1886c; Brezina 1886; Fletcher 1890a: 116). Castillo (1889: 9) and Haro (1931: 23) mentioned a 63 kg rounded mass in the School of Engineering, Mexico City, as coming from Santa Rosa, Coahuila. However, it shows Widmanstätten figures and must, therefore, be excluded from the Coahuila shower; see Puente del Zacate.

Having examined the original written information on the Coahuila irons, one is left completely confused as to the

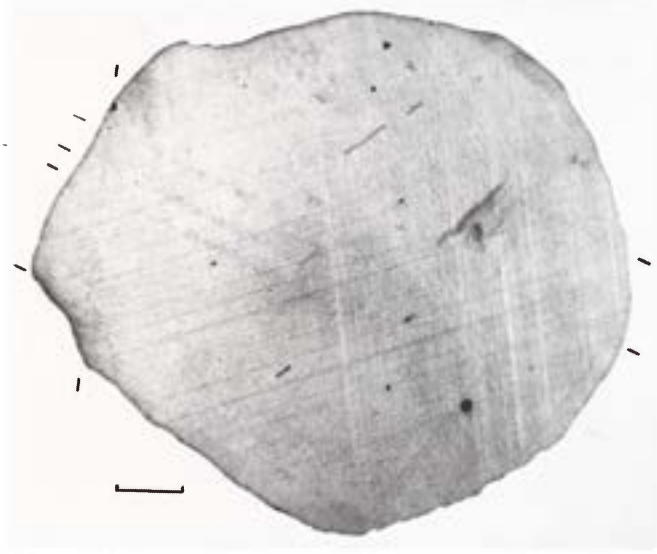

Figure 639. Coahuila (U.S.N.M. no. 389). A 1,237 g slice cut from the left end of the mass shown in Figure 638. Conspicuous troilite blebs (black) and six indistinct parallel planes with phosphide precipitates. Also a vertical plane with 0.2-0.5 mm troilite crystals. Deep-etched. Scale bar 20 mm.

exact locality of the fall. Fletcher (1890a: 113) concluded that the discovery site was near San José de las Piedras (28°42′N, 102°44′W), and his conclusion seems to be well supported. I would nevertheless prefer to rely upon one particular military report quoted by Shepard (1866; 1867b) rather than to average a number of reports of varying quality. Shepard's information came from a party guided by Major E.M. Hamilton that visited the locality in 1865 and partly excavated one of the masses. Comparing Shepard's sketch map with modern maps of the scale of 1:500,000 and utilizing the descriptive text, we can recontruct Hamilton's journey, if we assume that the reported distances are about 50% overestimated, due most likely to the rugged landscape and the psychological pressure from the raiding Apache Indians.

The route described is from Muzquiz 40 km west-northwest to the westernmost of two villages named Nacimiento. Then through the mountains along a winding trail following Cañon Alameda and over the Puerta Santana pass to another valley; this is generally in a westerly, but later in a southwesterly direction; the distance is 30 km on a map but may easily be 45 km due to the winding trails. The valley is then followed for 12 km in a north-northwest direction past a spring, until, after a further 25 km, the trail bends west and another valley is entered. Thence, in a westerly direction past a group of springs (about 15 km) and finally 25 km in a northwesterly direction towards an apparent junction of the mountains. I conclude that the locality of the fall has the coordinates 28°30′N, 102°29′W and constitutes the northwestern sack end of a valley which on some maps bears the name Valle de los Guajes. The distance from Santa Rosa de Muzquiz as the crow flies is 115 km in the direction 217°.

Within an area of approximately 2 x 2 km, partially overgrown with palmetto palms, Hamilton saw twelve large specimens protruding above the ground or situated among limestone blocks in the ravines. A thirteenth small one, of 75 pounds, was taken to Santa Rosa since when it has not been seen. A few years later Butcher evidently recovered eight of the masses seen by Hamilton's party. Whether the remaining masses are still in the area has never been examined, or at least never been reported, and the exact locality remains obscure. The northern part of Coahuila was relatively unexplored in the nineteenth century because the area was a refuge for the warring Apaches. Today there is no particular reason for not relocating the site and perhaps – with modern mine-detecting equipment – discover a few more lightly buried irons.

Reviews of the history and of the numerous disputes in the nineteenth century concerning the identity of the masses, the number of separate falls and the probable location can be found in Burkart (1870), Fletcher (1890a), Wülfing (1897), Cohen (1905) and Farrington (1915: 128, 203).

Table of Coahuila Individuals with Reconstructed Weights and Present Distribution

	References	Weight Originally Pounds	Weight Originally Kg	Presently Kg	Collections
Sanchez Estate	Smith (1855, figure 2)	252	114.4	105.4	Washington no. 389
Bonanza Iron	Shepard (1866; 1867b)	about 1 lb fragment		238 g	Washington no. 974
Unnamed, seen by Hamilton	Shepard (1867b)	75	34		Lost in Santa Rosa
Butcher no. 1	Smith (1869b; 1871; 1876b; 1878) Burkart (1870; 679, 692)	654	297	317.5!	Harvard University
no. 2		580	263	250	Paris, with cut face
no. 3		550	250	249.5	Harvard University
no. 4		450	204	243.5!	London
no. 5		438	198	198	Vienna
no. 6		430	195		Cut and distributed
no. 7		353	160	158.8	Harvard University
no. 8		290	132		Cut and distributed
no. 9	Huntington (1888: 58)		(25)	21.9	Harvard University
no. 10			(23)	22.3	Harvard University
no. 11			(18)	12.7	Harvard University
no. 12			(5)	4.5	Harvard Univeristy
no. 13			(1)	1.0	Harvard University
Indian mass, 1837	Smith (1869b)	10-12	5		Lost in Santa Rosa
Lupton's Iron	Lupton (1885)	estimated 192	87		Seen in Santa Rosa 1879
Fort Duncan	Hidden (1886c)	97 1/4	44		Cut and distributed

The total weight listed here is 2,059 kg. There is considerable uncertainty as to the weight of the largest masses; they are given differently, in Smith's various publications, and as shown above, two now exceed the original weight in their partially cut state.

Cohen, Farrington, Merrill (1916a: 141, plate 17), and in more recent times Perry (1944) and Nininger (1952a: 117, plate 4) considered Sanchez Estate and Fort Duncan distinct falls. This opinion appears, however, to be abandoned by other authorities such as Hey (1966: 109) and it could not be supported by this study. All the masses are identical in macro- and microstructure so it must be assumed that Sanchez Estate (114.5 kg) and Fort Duncan (44 kg) represent samples which have been humanly transported due to the absence of iron in the interior of northern Mexico.

Smith (1876c; 1878) discovered and examined daubreelite in the Butcher masses and predicted that it would be almost universal in meteoric irons. He further (1876c) described the yellowish-brown incrustation products on the surface of the masses. He found the crusts to be aragonite, while modern examination interpret them rather as calcite or caliche deposits. They form readily on the underside of exposed rocks in arid climates, when the soil is rich in limestone deposits. Many meteorites from the southwestern part of the United States, from Mexico and from Chile are partially covered with caliche; the incrustation may help both to estimate the terrestrial age and to identify the underside of the meteorite while it was exposed to the terrestrial environment. Smith (1881) also identified a 17 x 12 mm chromite nodule situated in the metallic matrix, a relatively rare and large occurrence of chromite for an iron meteorite.

Böggild (1927) identified plate-shaped phosphides, only present in hexahedrites, and prismatic normal rhabdites. Owen & Burns (1939) found by X-ray examination a well defined α-structure with a parameter of 2.8625Å. Henderson (1941c, d) reanalyzed the Coahuila iron and supported the nickel determination of 5.6% found by Cohen (1894). Previous analytical work on various Coahuila fragments had indicated that they were from different falls since the nickel values ranged from 2.1-7.4%. It was, however, the analytical methods that were unsatisfactory.

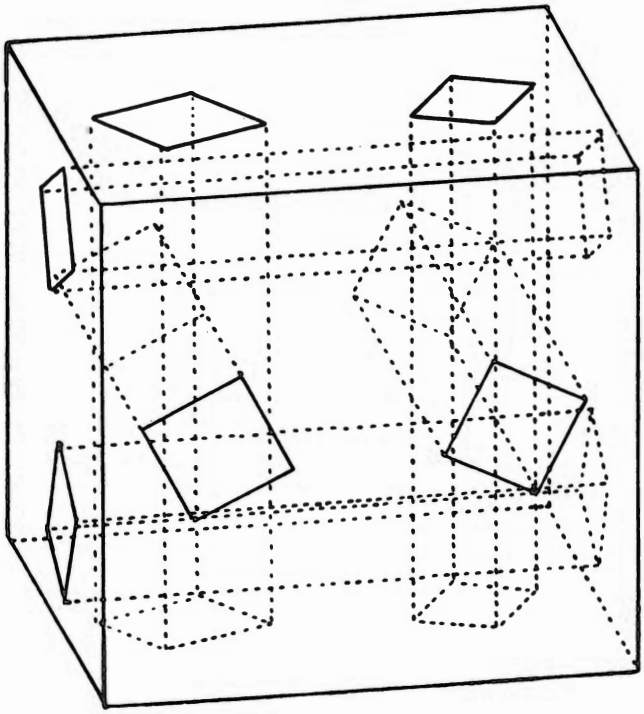

Figure 640. Coahuila. A sketch by Böggild (1927), showing the six possible positions of the rhabdites in kamacite. The prism faces of the tetragonal phosphide crystals are parallel to (210) α of the kamacite.

COAHUILA – SELECTED CHEMICAL ANALYSES

If it is known, I have added the name of the particular fragment analyzed. Coahuila is perhaps now the best analyzed iron meteorite of all. Reed (1969) found the kamacite to have 5.3% Ni and 0.07% P in solid solution, while the schreibersite ranged from 21-30% Ni and the rhabdites from 34-39% Ni (Reed 1965a).

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Cohen 1894, Butcher	5.62	0.60	0.29									
Henderson 1941c, Sanchez Estate	5.59	0.78	0.32									
Goldberg et al. 1951	5.65	0.53							64.5			
Lovering et al. 1957	5.65	0.45				44	122		54	152		
Nichiporuk & Brown 1965											14.8	24.2
Cobb 1967		0.41					138		57		14	
Smales et al. 1967						37	122	<1	51	175		
Wasson & Kimberlin 1967	5.49								57.6	178	16	
Wasson 1969, Sanchez Estate	5.58								60.7	189	15	
Moore et al. 1969, Butcher Iron	5.59	0.43	0.23	100	100		146					
ibid., Sanchez Estate	5.58	0.44	0.26	100	20		152					

Perry (1944) gave a macrograph of Sanchez Estate and micrographs of Fort Duncan. Lovering & Parry (1962) included Coahuila in their thermomagnetic analysis of iron meteorites. Frondel & Klein (1965) described a new mineral, ureyite, a chrome pyroxene, from Coahuila. Buri & Caramazza (1966) examined sections from Coahuila with transmission electron microscopy. Buchwald (1966: 27) used the meteorite as a type member of the hexahedrite group, and Reed (1965a, b; 1969) examined the composition of the various phases with the microprobe.

Paneth (1954) reported upon the helium concentration, and Bauer (1963) presented additional data, determining ^{3}He and ^{4}He separately.

COLLECTIONS

Harvard (820 kg), Paris (260 kg), London (251 kg), Vienna (225 kg), Washington (125 kg), Budapest (17 kg), New York (9.54 kg), Chicago (8.9 kg), Stockholm (7.47 kg), Yale (6.2 kg), Göttingen (2.65 kg), Helsinki (2.4 kg), Berlin (1,570 g), Dresden (1,100 g), Copenhagen (1,058 g), Oslo (864 g), Bonn (749 g), Leningrad (715 g), Ann Arbor (663 g), Prague (652 g), Tempe (544 g), Calcutta (453 g), Rome (390 g), and small pieces in numerous other collections. In Mexico City there appears to be only 250 g (no. 37 of 176 g, mislabeled Rodeo, and no. 57 of 74 g).

DESCRIPTION

The recovered masses are more or less rounded and have been compared with worn boulders. The Sanchez Estate mass in Washington averages 50 x 26 x 20 cm in size; its somewhat elongated shape, terminating in a blunt point, made it eminently suited for an anvil. A cylindrical hole, 28 mm in diameter and 45 mm deep, has been drilled by the blacksmith to suit his purpose. The mass is hammered and exhibits some chisel marks, but it has apparently not been heated artificially. The fusion crust is weathered away and 0.1-1 mm thick crusts of terrestrial oxides cover the surface.

Since the present examination on sections from Butcher's Iron, Bonanza, Bolsom de Mapimi, Fort Duncan and Sanchez Estate failed to reveal any significant differences, the following remarks on the structure are common to all specimens of Coahuila.

Sections have so far not produced any heat-affected rim zones, and no hardness gradient perpendicular to the surface could be established. This suggests significant weathering with losses above 5 mm. To the best of my knowledge none of the irons exhibit fracture faces from atmospheric breakup; this may be due partly to end stage ablation, partly to prolonged weathering. Corrosion has selectively attacked the nickel-depleted zones around the phosphides. Some wide (0.2-1 mm) limonitic fillings follow cracks along the plate-shaped rhabdites; the cracks were probably formed when the meteorite split in the atmosphere. Pentlandite and other corrosion products vein the near-surface troilite nodules.

Etched sections show Coahuila to be a single kamacite crystal, at least as far as sectioning goes. Rhabdites of various sizes are precipitated in crystallographic directions and Neumann bands cross the entire surfaces uniformly. Troilite-daubreelite nodules, 5-15 mm in diameter, are not uniformly distributed, since some sections display 2 or 3 per 100 cm^2, while others are free. Tiny troilite-daubreelite blebs, 0.5-2 mm in diameter, occur with a frequency of about one per 30 cm^2.

Two or three of the Neumann band sets are diffuse and decomposed into short lengths with tangles of subboundaries. They are decorated along both sides with 1-10 μ thick rhabdite prisms. Other Neumann bands, both barallel to the decorated ones and in additional directions, are sharply marked and undecorated. In numerous places the second generation of Neumann bands shear displaces the first decorated generation and several of the larger rhabdite and troilite inclusions. The shear ranges from 5-50 μ, often in

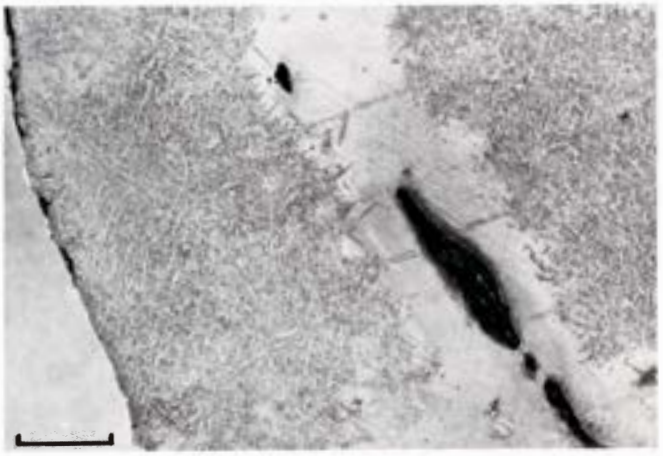

Figure 641. Coahuila (Vienna, no number). Sausage-shaped troilite crystals with interior daubreelite lamellae and narrow rims of schreibersite. Situated in phosphorus-depleted kamacite. Further out, densely spaced phosphide precipitates. Deep-etched. Scale bar 10 mm.

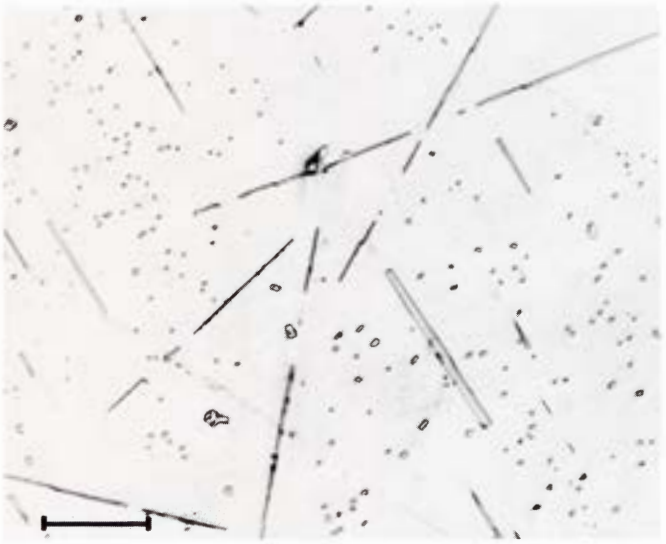

Figure 642. Coahuila (Copenhagen no. 1905, 1747). Profusion of plate-shaped and prismatic rhabdites, many of them displaced by shear. Indistinct Neumann bands. Etched. Scale bar 200 μ.

parallel, successive steps. The microhardness of the kamacite is 180±10. The hardness varies with the orientation of the kamacite single crystal, with the number and size of precipitates and with the nickel content of the particular spot tested. The hardness does not suggest any particular annealing from cosmic or terrestrial sources; the two generations of Neumann bands indicate, however, that two shock events occurred, significantly separated in time, so that precipitation could take place on the first set formed before the next event took place. The second set may be associated with the violent breakup of the meteorite in the atmosphere.

As noted by Böggild (1927), Coahuila contains two kinds of rhabdites. The prismatic ones are most numerous and range from 1-50 μ in thickness. The prisms are orientated in six different positions in the kamacite, their long axes being parallel to the cube axes $<100>\alpha$, and their faces being parallel to 210 α. The plate-shaped rhabdites are less abundant; they usually form extensive, but extremely thin, lamellae which are parallel to 100 α and 221 α. Typical dimensions are 5 x 5 x 0.005 mm, but their thickness may increase to 0.02 mm. Zones 50-200 μ wide on each side of the plates are usually so depleted in phosphorus and nickel that no additional precipitation has taken place. The variation in oriented sheen between dull and bright patches on etched hexahedrite sections is caused largely by the variation in size and number of precipitates; but is also due to the width and perfection of the Neumann bands.

In Hex River and other hexahedrites, parallel planes, rich in rhabdites, occur. They are present in Coahuila, too, and they are perhaps best observed on sections of Fort Duncan and Sanchez Estate where they are seen as shiny, parallel bands 1-5 cm apart. The parallel rhabdite rows are only present in hexahedrites with 2-16 ppm Ir, never in hexahedrites with above 18 ppm. Coahuila thus represents a border case.

Troilite is common as 5-15 mm nodules and as 0.5-10 mm lenticular or elongated bodies, always with inclusions of parallel daubreelite bars that cover 10-15% by area. The troilite is monocrystalline and has a microhardness of 245±10; only in a few cases were minute shock-melted areas noted, mostly near shear zones and phase boundaries. The daubreelite extends as 10-1000 μ wide, incomplete lamellae across the troilite bodies, always parallel to $\{0001\}$ of the hexagonal troilite. Its hardness is 350±25, but it is almost too brittle to measure with a 100 g load. Since the exsolved daubreelite lamellae uniquely identify the orientations of the parent troilite crystals, it is a simple matter to examine large polished sections for any uniform orientation of the troilite crystals with respect to the kamacite lattice. No such correlation was found to exist; the troilites appear to be randomly oriented and, in several cases, two independently oriented troilite crystals were found to join under reentrant angles.

The troilite-daubreelite crystals are enveloped in discontinuous rims of 20-50 μ thick schreibersite (HV 850±25), and interestingly enough, of occasional, narrow cohenite rims. The cohenite rims are 10-50 μ wide and discontinuous, or consist of segments of monocrystalline units. In addition, cohenite is present as 1 x 0.3 mm well developed crystals, precipitated upon substrates of rhabdite plates or prisms. The cohenite has a microhardness of 1090±30, the same as that observed in the cohenite-rich group I irons. Cohenite is uncommon in hexahedrites, but in this study is reported for the first time from Coahuila, Okahandja, Walker County and others, while unmistakable evidence of its former presence is discussed under Hex River, Uwet, Indian Valley, Cedartown and Keen Mountain.

Coahuila is a shower producing hexahedrite of considerable terrestrial age. The early assumption of its fall in 1837 (Smith 1869b) is erroneous. Coahuila is a typical hexahedrite, related particularly to Indian Valley, Calico Rock, Okano and Gressk. Chemically, it is a typical group IIA iron.

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

19	g chiseled fragment of Lupton's Iron (no. 29, 2.5 x 2 x 1 cm)
105.4	kg main mass of Sanchez Estate (no. 389, 50 x 26 x 20 cm, with cuts at both ends of, respectively, 18 x 15 and 20 x 10 cm size)
1,237	g slice (no. 389, 18 x 15 x 0.8 cm, cut from above)
28	g knife, forged in the Smithsonian Institution (no. 740, 18 x 1.3 x 0.1 cm)
11.85	kg endpiece of a Butcher mass (no. 751, 34 x 27 x 4 cm)
238	g part slice, the so-called Bonanza Iron (no. 974, 7 x 5 x 1.5 cm; Shepard Collection no. 27; now subdivided in at least four pieces)
68	g irregular fragment from above (no. 1001, 4 x 3 x 2 cm)
108	g part slice of Fort Duncan (no. 1028, 7 x 3.8 x 0.5 cm)
176	g part slices of Sanchez Estate (no. 1132)
18	g part slice of Fort Duncan (no. 1641, 3 x 2 x 0.7 cm)
66	g part slice of Fort Duncan (no. 2724, 5 x 5 x 0.5 cm)
293	g part slice of a Butcher mass (no. 2725, 6.5 x 4.5 x 1.3 cm)
53	g part slice of Sanchez Estate (no. 2726, 5.5 x 2.5 x 0.6 cm)
101	g part slice of Fort Duncan (no. 3246, 7 x 6 x 0.5 cm)
2,170	g part slice of Coahuila (no. 3297, 10 x 7.5 x 3.6 cm)
30	g part slice of a Butcher mass (no. 3298, 5 x 1.7 x 0.5 cm)
118	g part slice of Fort Duncan (no. 3299, 6 x 6 x 0.6 cm)
321	g various slices of Coahuila (nos. 705, 791, 2727, 3291)

Coldwater, Kansas, U.S.A.

37°16′N, 99°20′W

An almost completely oxidized, limonitic mass of 18.4 kg was found in 1923 and described by Shannon (1927). Buddhue (1939a; 1957) compiled the known analyses and discussed the oxidation products. The original mass was presumably an octahedrite. For further references, see Hey (1966: 112).

Colfax, North Carolina, U.S.A.
35°18′N, 81°44′W

Medium octahedrite, Om. Bandwidth 0.60±0.10 mm. Neumann bands. HV 143±10.

Group I. 10.51% Ni, 0.63% Co, 0.3% P, 55.1 ppm Ga, 155 ppm Ge, 1.5 ppm Ir.

Heated artificially to about 500° C for a short time.

HISTORY

A 2.4 kg iron was found in the spring of 1880 or 1881, immediately after plowing, on the farm of Mrs. E.W. Dedmon, Colfax Township, Rutherford County. It was thrown on a woodpile near the house and was frequently beaten with an axe. Eventually it was recognized as a meteorite by S.W. Cramer of the U.S. Assay Office at Charlotte, and was turned over to Kunz (1890b), who described it with an analysis by Cramer. A 315 g specimen was donated to the U.S. National Museum and was described and analyzed by Eakins (1890).

COLLECTIONS

Chicago (652 g + 123 g), Harvard (743 g), Washington (312 g), New York (237 g), Ottawa (61 g), London (48 g), Amherst (30 g), Vatican (12 g), Uppsala (1 g). These specimens add up to 2,300 g in harmony with the weight stated by Kunz, when allowing for loss by cutting.

DESCRIPTION

The meteorite had the shape of a double gourd with three or four large indentations. The total length was 15 cm, the diameter at the ends was about 7.5 cm and at the constricted middle, about 5 cm. The specimen in U.S. National Museum shows that the mass is heavily corroded with 0.5-1 mm adhering iron oxides. Some of the oxides have, however, the color distinctive of scale formed on iron upon artificial reheating. Heavy hammer blows are also visible; they have caused the mass to open along octahedral cleavage planes.

Etched sections show that the natural fusion crust and the α_2 zone have completely disappeared due to corrsion. The Widmanstätten structure is composed of straight, long ($\frac{L}{W} \sim 20$) lamellae with a width of 0.60 mm. Neumann bands are present, but not very distinctly, in the kamacite. The hardness is unusually low, 143±10, for a group I iron, indicating recovery at 400-500° C. Plessite fields occupy about 40% by area. The plessite is either a rather normal comb plessite with densely spaced lamellae or an acicular martensitic type. Some fields are unusual, displaying carbide roses. Such fields, typically 1 x 1 mm but increasing to 3 x 2 mm in size, display an interior of palmate, scalloped carbide framed by a continuous taenite rim. A zone of varying width between the carbide and the taenite is transformed to spheroidized or pearlitic plessite of the type usually seen in group I meteorites like Canyon Diablo, Odessa and Toluca. The roses are complex aggregates of

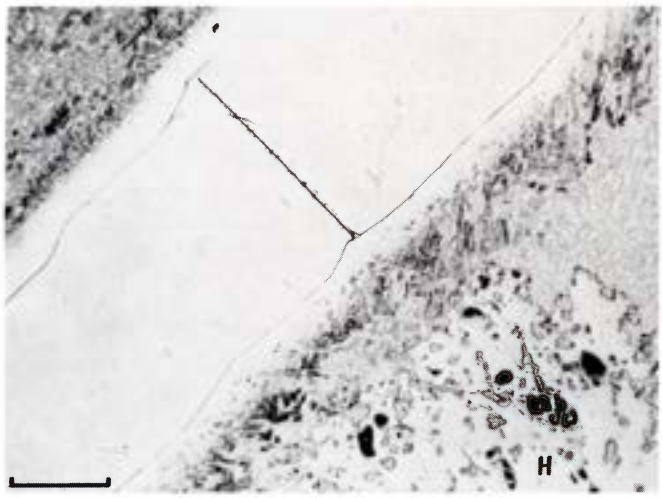

Figure 643. Colfax (U.S.N.M. no. 151). A kamacite lamella with plessite on either side. Below right, a large haxonite crystal (H) in the plessite. Lightly etched. Scale bar 300 μ.

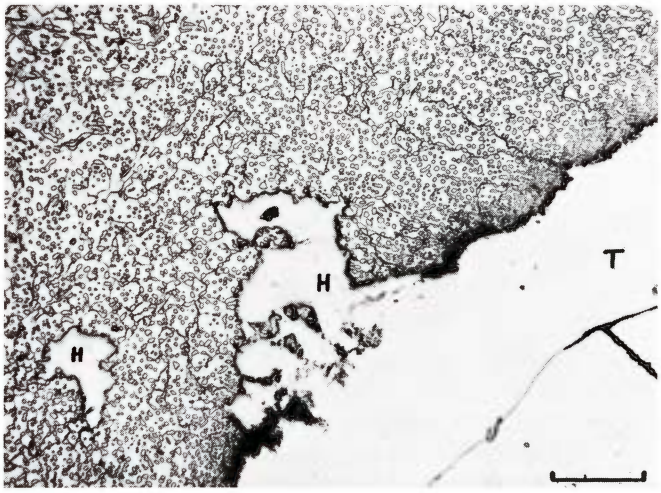

Figure 644. Colfax (U.S.N.M. no. 151). Spheroidized plessite with a clear teanite rim (T), and kamacite with a corroded grain boundary. Irregular, hard haxonite crystals (H) stand in high relief. Etched. Scale bar 100 μ.

COLFAX – SELECTED CHEMICAL ANALYSES

References	percentage Ni	Co	P	ppm C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Cramer, in Kunz 1890b	10.32	0.58	0.19		900		450					
Eakins 1890	10.37	0.68	0.21		800		400					
Smales et al. 1967						43	294	32	57.4	156		
Wasson 1970a	10.84								52.8	153	1.5	
Crocket 1972											1.6	

carbide with built-in grains of taenite, kamacite and schreibersite, usually only 1-3 μ wide; they display hardnesses of 750-1000, decreasing in hardness with increasing number of inclusions. It appears, however, that the carbide, even in its pure state, would not exceed 1000, while the large cohenite crystals in the group I irons normally run above 1050. A microprobe scan showed that the cohenite in Colfax (and in Carlton, Rhine Villa and other irons with carbide roses) is usually rich in nickel, containing ~~on the~~ average 5%. The carbide is evidently identical to the cubic haxonite described by Scott (1971). The adjacent spherodized plessite zones are thoroughly annealed and have hardnesses of 155±5.

Troilite occurs sparingly. One 3 mm nodule was embedded in schreibersite; although it was pretty much altered to pentlandite by corrosion, it was still possible to detect the original monocrystal of troilite and its lenticular pressure twins.

Schreibersite is common as 7 x 1, 8 x 4 or 6 x 0.2 mm hooks and branched lamellae. The larger ones have inclusions of 1-4 mm troilite nodules. Schreibersite is further common as 20-50 μ grain boundary precipitates and as 1-10 μ vermicular inclusions in the plessite. Rhabdites are common in the α-lamellae as 4-10 μ prisms. Based upon point counting of two small sections, it becomes apparent that the analytical P-values (0.2%) do reflect only the microscopic phosphides and the phosphorus in solid solution. The total phosphorus content is estimated to be 0.30±0.05%. Due to slight artificial reheating, the rhabdites are partly resorbed in the matrix, while the larger phosphides show reaction rims against the enveloping terrestrial corrosion products. In near-surface areas the corrosion products have reacted with the metallic matrix and formed 10-50 μ wide zones of lace-like appearance: vermicular metal, 1 μ wide, in an oxide matrix. By comparison with other meteorites, which contain these features and are known to be maltreated, e.g., Burlington and Cacaria, it must be concluded that Colfax has been subjected to a mild reheating to about 500° C for, say, half an hour. The information by Kunz already had a hint in the direction of maltreating.

Although Colfax in its macroscopic appearance resembles Chupaderos and other IIIB meteorites, its detailed plessite morphology and schreibersite-troilite-carbon association clearly indicates a much closer relationship to the carbon-rich group I irons. This is also borne out by Wasson's analytical data, where Colfax may be interpreted as a member of group I, high in nickel and relatively low in gallium and germanium. Furthermore, zinc is high (32 ppm) as in all group I irons, while group IIIB apparently runs below 1 ppm.

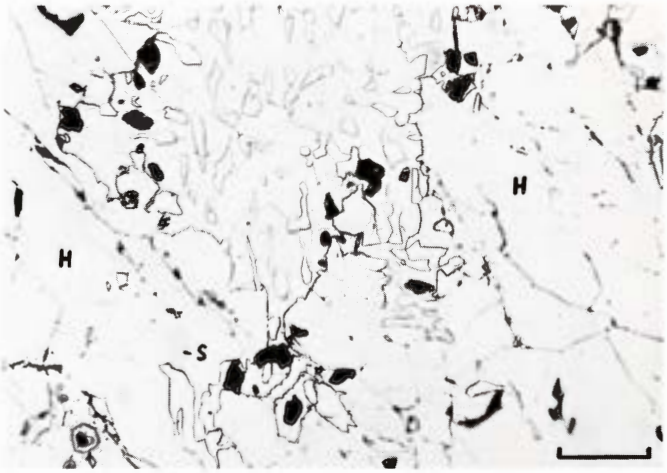

Figure 645. Colfax (U.S.N. no. 151). Plessite with haxonite (H). There are several schreibersite (S) and taenite inclusions in the haxonite. Etched. Scale bar 40 μ.

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

312 g corner piece (no. 151, 5 x 4 x 3 cm)

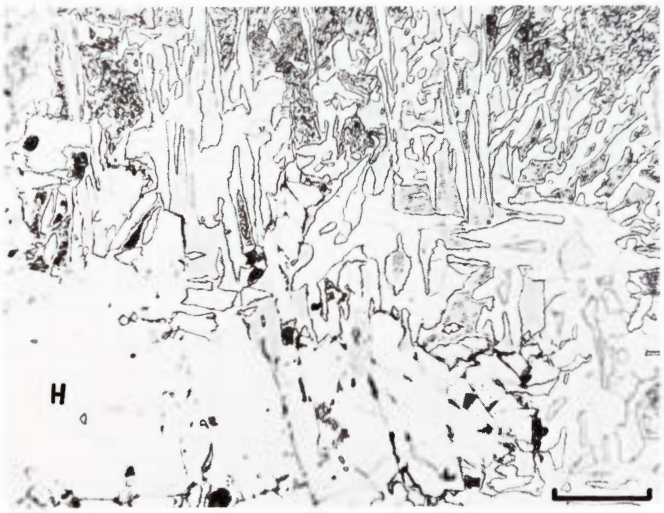

Figure 646. Colfax (U.S.N.M. no. 151). Duplex plessite with cloudy taenite and with a haxonite crystal in the lower left corner. Etched. Scale bar 40 μ.

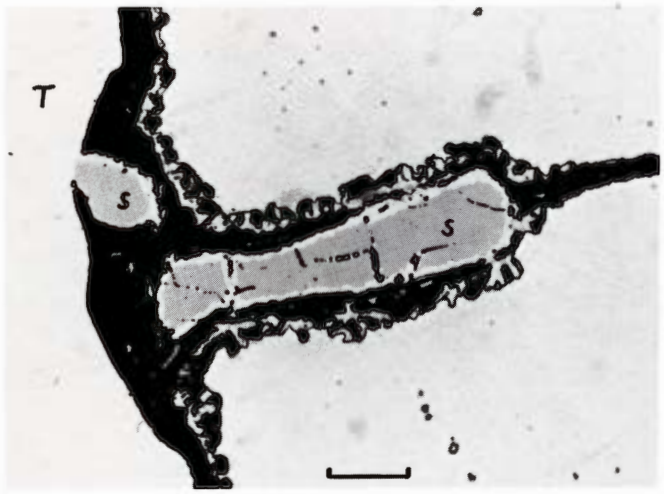

Figure 647. Colfax (U.S.N.M. no. 151). Taenite (T) with two schreibersite crystals (S) in a corroded grain boundary (black). Slight artificial reheating caused a narrow reaction rim between schreibersite and limonite. Etched. Oil immersion. Scale bar 10 μ.

Colomera, Granada, Spain
37°26′N, 3°39′W

Polycrystalline silicate-rich iron. Recrystallized kamacite with Neumann bands. HV 180±6.

Anomalous. 7.86% Ni, about 0.4% P, 28.4 ppm Ga, 74.6 ppm Ge, 7.7 ppm Ir.

HISTORY

A mass of 134 kg was discovered in 1912 by Mr. Ponte in a corral adjacent to his farmhouse, in the village of Colomera, 25 km north of Granada. It was said to have been excavated from a depth of one meter, but in a footnote, doubt was expressed as to whether it had originally fallen here or had been transported and later discarded in the village. Some of the uncertainties are due to the fact that it was acquired by the National Museum in Madrid and was not brought to scientific knowledge until 20 years after its discovery. It was described by Dorronsoro & Martin (1934), who gave an insufficient analysis and four photographs.

In the 1960s the mass was sent to the California Institute of Technology in Pasadena, where four parallel slices were cut through the mass, and minor specimens made available for analytical work, mainly in order to have the important silicates analyzed (Wasserburg et al. 1968). Hintenberger & Wänke (1964) classified Colomera as a pallasite, and Henderson (1965: 36) likewise believed the

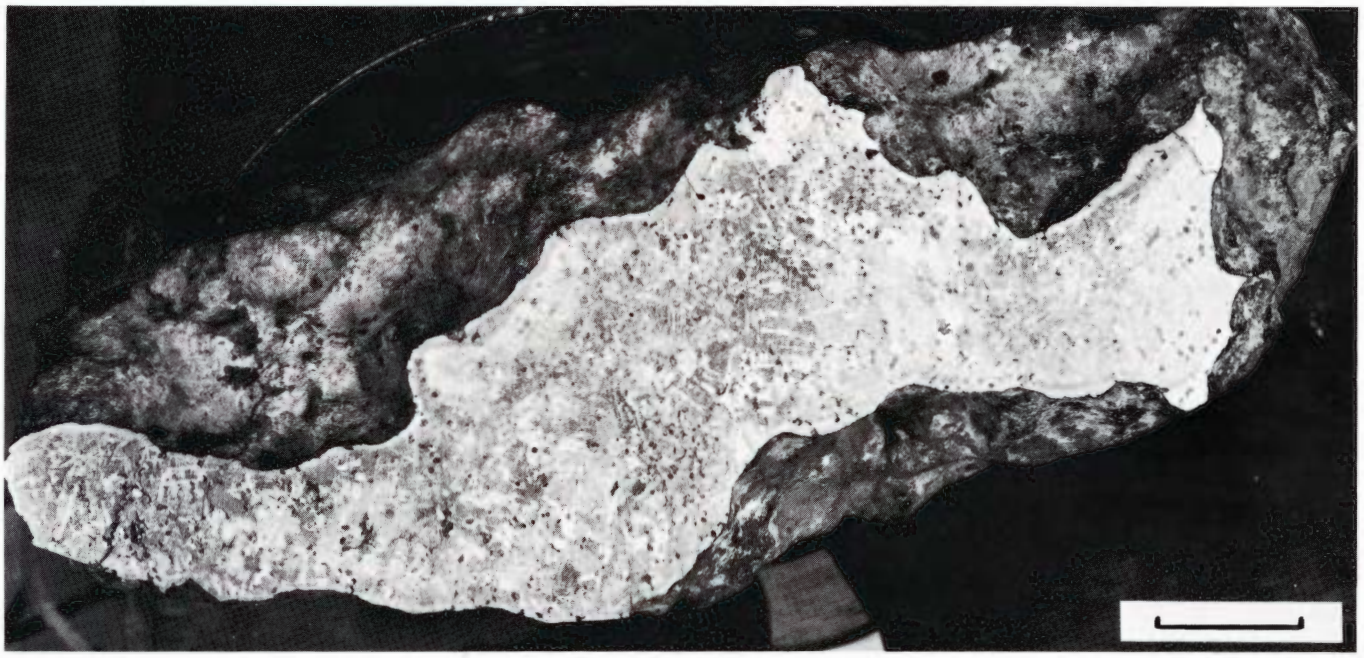

Figure 648. Colomera. Main mass after a few slices have been cut from one end. Regmaglypts and weathered fusion crust are present. Scale bar 50 mm. S.I. neg. M-1294.

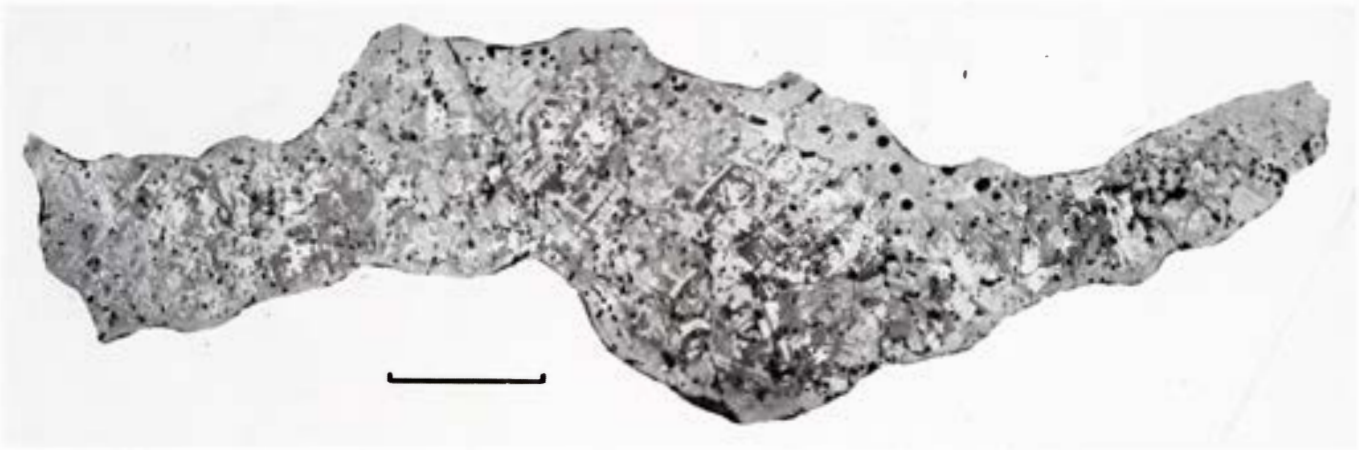

Figure 649. Colomera (U.S.N.M. no. 3396). A slice removed from the mass in Figure 648. Polycrystalline precursor taenite aggregate with silicate inclusions. Etched. Scale bar 50 mm. S.I. neg. M-1316.

included silicates to be olivine, so that a pallasitic classification was proper. Hey (1966), however, classified it as a medium octahedrite with silicate inclusions.

Mason (1967a) derived compositional data on the silicate minerals from refractive index measurements. He found no olivine but stated that the principal silicate was an orthopyroxene close to enstatite in composition. Plagioclase of albitic composition and accessory clinopyroxene close to diopside in composition were detected in minor amounts. Bunch & Olsen (1968) examined the silicates with the microprobe and confirmed the identifications. They also reported glass and devitrified glass of feldspar composition and very small blebs of the rare potassium feldspar.

Wasserburg et al. (1968), when cleaning the surface by "sand blasting" with TiO_2 spherules, discovered that the external surface contained at least four large silicate inclusions. The largest was 11 cm long, 2.5 cm wide and extended in depth more than 1 cm. It consisted of a nearly pure potassium feldspar ($Or_{90}Ab_{10}$) having the structural state of high sanidine. Aggregates or single crystals of green pyroxenes up to 1 cm in size were completely enclosed in the feldspar in a poikilitic texture. A search for similar large crystals in various sections gave a negative result; in the interior, the silicates occurred as small (0.3 cm) drop-like masses. Only a single small zoned olivine crystal was detected. The mean density of the mass was determined to be 7.613±0.048 g/cm^3. Setting the iron-nickel phase to 7.89 and the silicate phase to 3.3 g/cm^3, they estimated the mass to contain from 4.3 to 5.8 volume percent of silicates.

It was concluded "that Colomera was originally formed as a molten iron segregation of rather small mass contained within a silicate matrix. This iron and associated molten silicate were cooled so rapidly that the silicate globules included in the iron were trapped..... This object would therefore not represent a planetary core or the border zone of a core as has been suggested for the pallasites, but rather an incomplete stage in the segregation of metallic iron from iron-silicate mixtures."

Herr et al. (1961) examined the osmium-rhenium ratio. Hintenberger & Wänke (1964) determined the helium and neon content as well as the isotopic composition of the rare gases in the metal phase. The ^3He:^4He ratio was anomalously low; this may perhaps be ascribed to tritium loss during recrystallization. Vilcsek & Wänke (1963) determined ^{36}Cl and ^{39}Ar and estimated a cosmic ray exposure age of 75±5 million years, low in comparison with most iron meteorites. Chang & Wänke (1969) estimated, in a different approach based on ^{36}Ar–^{10}Be measurements, a cosmic age of 90±10 million years. They also inferred a terrestrial age of less than 10^5 years from the fact that the ^{36}Cl isotope with a half life of 300,000 years was found to be present in significant amounts.

Burnett & Wasserburg (1967a, b) extracted five different silicate inclusions and measured strontium and rubidium. The data ranged widely for reasons not understood, and gave ^{87}Rb–^{87}Sr formation ages of (3.8-4.8) x 10^9 years.

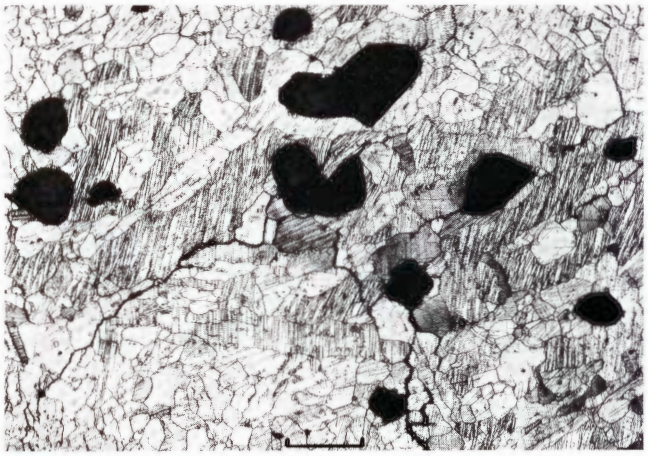

Figure 650. Colomera (U.S.N.M. no. 3396). Indistinct Widmanstätten structure, differently developed in adjacent precursor taenite crystals. Silicate aggregates (black). Etched. Scale bar 3 mm.

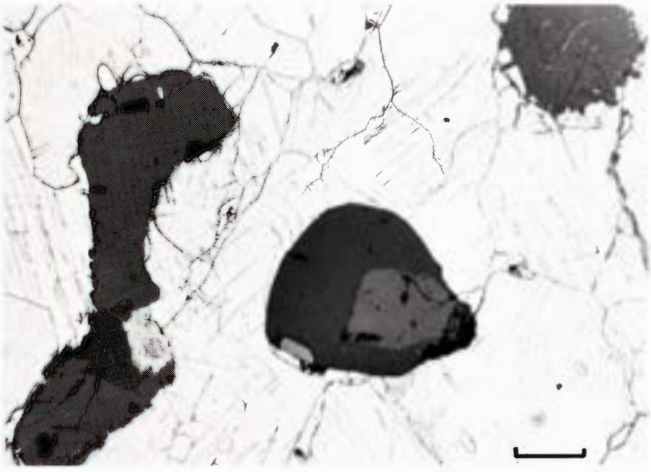

Figure 651. Colomera (U.S.N.M. no. 3396). Silicate aggregates, the one at left with a shock-melted troilite bleb (gray). Recrystallized kamacite with deformed Neumann bands. Etched. Scale bar 500 μ.

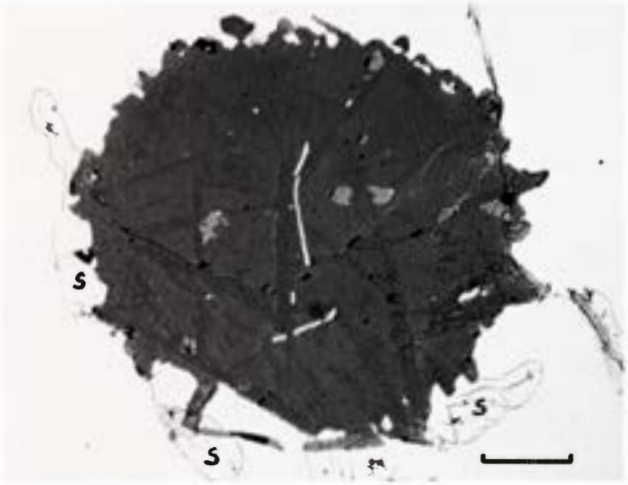

Figure 652. Colomera. Detail of Figure 651, upper right. Three different silicates, one of them bar-shaped, appear to be present within one nodule. White indicates metal. Schreibersite rims (S). Polished. Reflected light. Scale bar 200 μ.

COLLECTIONS

Madrid (main mass), Washington (3.2 kg).

DESCRIPTION

The mass is irregularly lens-shaped with the average dimensions of 52 x 42 x 16 cm. It is very well preserved, exhibiting distinct sculpturing from the atmospheric flight on all sides. Shallow regmaglypts, 2-5 cm across and 1 cm deep, cover most of the surface. In several places are large bowl-shaped depressions, for example 12 cm across and 5 cm deep, and these, too, are subdivided by normal regmaglypts. Fusion crusts, up to 0.5 mm thick but somewhat weathered, may be identified in several places. The mass, as it was found, was, therefore, a complete individual from which virtually nothing has been lost by terrestrial weathering. How this can harmonize with the alleged burial under 1 m of soil in a long populated area, is hard to understand.

In certain places the surface is hammered and scarred by chisel marks, but the damage is superficial and not associated with reheating or forging. It probably dates from the time when the finder detached fragments and submitted them for analysis to various parties, as reported by Dorronsoro & Martin (1934).

Etched sections display an anomalous polycrystalline texture. Large austenite grains, ranging from 5 to 80 mm in size, are separated by grain boundaries rich in filamentary, or occasionally peanut-shaped silicates. The silicates of the grain interiors are on the contrary drop-like globules. An examination of the three parallel slabs, each 5 mm thick and about 40 x 10 cm in size, which have recently been ground and polished in the Smithsonian Institution, Division of Meteorites, confirms that the volume percentage of silicates is on the average close to 5%.

The austenite grains are randomly oriented and slightly irregular in shape due to the pinning by silicates. There are no flow structures as in Tucson. Many grains display distinct twinning parallel to the $(111)_\gamma$ planes. The largest grain with twinning is 8 x 5 cm in cross section. The twins are growth twins, not deformation twins. They must date from the initial formation of the meteorite parent body and must be cogenetic with the silicates.

Each austenite grain has, upon cooling, formed a very imperfect Widmanstätten pattern. The bandwidth may cautiously be expressed as 0.7±0.2 mm ($\frac{L}{W} \sim 10$), but the kamacite lamellae are highly irregular and badly defined. They frequently contain small taenite blebs which fact clearly violates the normal definition of kamacite lamellae. The entire metal phase most of all resembles the coarse comb and net plessite fields found in group IVA irons, such as Gibeon and Chinautla. Within each original austenite (taenite) grain of centimeter-size, the decomposition has occurred according to the normal crystallographic laws, and the retained blebs and lamellae of taenite are aligned in a Widmanstätten pattern. However, the taenite is evenly spaced in a grid, and no plessite proper occurs. The taenite forms 10-50 μ wide, short lamellae or 10-100 μ thick rounded blebs. The taenite interior stains cloudy gray upon

Table 1. Metal Phase

COLOMERA – SELECTED CHEMICAL ANALYSES

Reference	percentage Ni	Co	P	ppm C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Wasson 1970b	7.86								28.4	74.6	7.7	

Table 2. Silicate minerals, from Wasserburg, et al. (1968). LSI, i.e. large surface-inclusion. Glob, i.e., globular inclusion

Phase	Feldspar (LSI) K	Na	Chromian clino-pyrox-ene (LSI)	Olivine (LSI)	Ca-poor pyroxene LSI	Glob	Glass (Glob)	SiO_2 (LSI, Glob)
SiO_2	65.1	67.8	53.6	36.4	54.5	55.6	72.0	99.0
TiO_2	0.05	0.0	0.91	0.07	0.27	0.34	0.41	0.11
Al_2O_3	18.2	20.0	0.63	0.0	0.11	0.90	16.9	0.77
Cr_2O_3	0.0	0.0	1.67	0.0	0.40	0.34	0.0	0.0
FeO	0.13	0.23	7.13	26.7	16.3	11.0	0.11	0.0
MgO	0.0	0.0	15.9	35.6	26.5	30.1	0.09	0.0
MnO			0.60	1.12	1.37	1.13		
CaO	0.12	0.75	18.9	0.07	1.21	0.67	0.47	0.0
Na_2O	1.15	11.2	1.07	0.05	0.14	0.09	8.22	0.33
K_2O	15.0	0.46	0.0	0.0	0.0	0.0	0.97	0.0
Totals	99.8	100.4	100.4	100.0	100.5	100.2	99.2	100.2

etching. A clear yellow 1-2 μ wide rim forms a surprisingly straight border around the gray interior. With an oil immersion objective it appears that the gray interior is of a submicroscopic duplex nature, in which indistinct, decorated sliplines may be observed. The hardness is extremely high, but variable: 300-600. Microprobe analysis revealed about 40% Ni - 60% Fe in the taenite blebs, while P, Cu, Zn and S were absent. The reason for the high hardness is possibly plastic deformation plus carbon and/or nitrogen, but these elements could not be resolved on the probe.

The kamacite is recrystallized to 0.5-2 mm grains with well equilibrated grain boundaries. Conspicuous, often very broad (25 μ), Neumann bands occur within each recrystallized unit. The bands are decorated with precipitates less than 0.4 μ across. Around the spherical glass inclusions the Neumann bands are distorted, perhaps because the plagioclase-glass transformation occurred at a cosmic shock event. The α-phase has a hardness of 180±6.

Schreibersite occurs as 20-100 μ wide discontinuous rims on many silicates and upon troilite. A large number of subangular 50-300 μ schreibersite blebs occur, scattered through the metal, but mainly located on grain boundaries or substituting for taenite in the comb and net plessite. The straight twin boundaries of preexisting austenite grains are sometimes decorated by large numbers of schreibersite grains. A 28 mm long boundary was thus beset with 92 particles ranging in size from 20 to 50 μ. Rhabdites proper were not observed. The bulk phosphorus content may be estimated to be 0.4±0.1%.

Troilite is not abundant and does not occur as typical large nodules. It appears rather as 0.1-1 mm blebs, attached to some of the silicate aggregates. It is also present as 10-500 μ inclusions in the silicates. All troilite is shock melted. When in contact with metal this has been partly dissolved; the troilite now displays serrated edges against the metal, and the melts have solidified to fine-grained (1-2 μ) mixtures of sulfide and metal. The melts have been sufficiently mobile to penetrate as 1-10 μ wide veinlets through adjacent brecciated silicates. Terrestrial weathering has to some extent blurred the picture because the

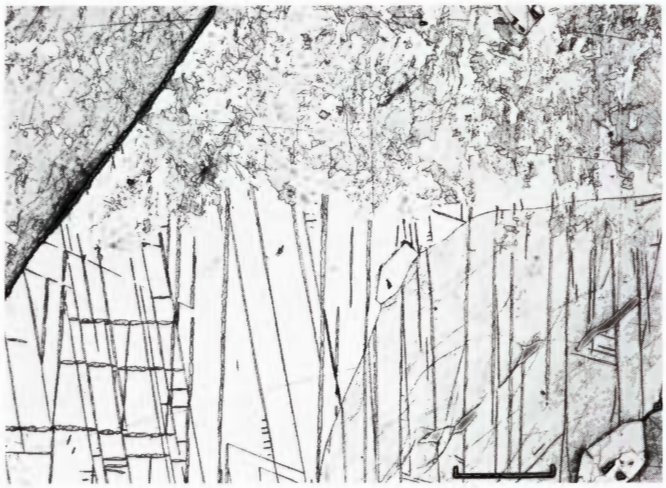

Figure 653. Colomera (U.S.N.M. no. 3396). In the heat-affected α_2 zone (above) the Neumann bands have disappeared. Etched. Scale bar 300 μ.

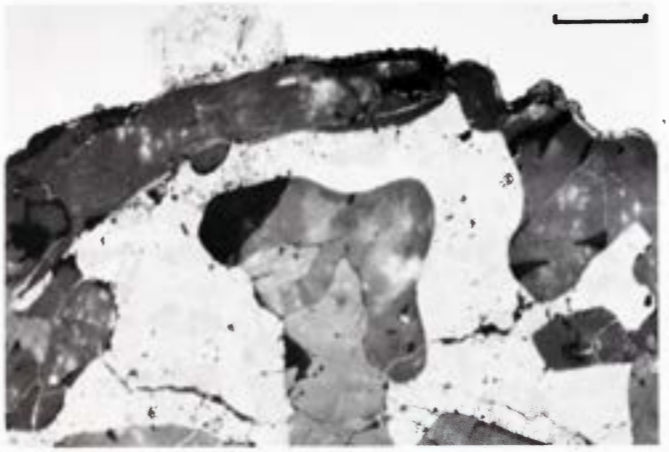

Figure 655. Colomera (U.S.N.M. no. 3396). Troilite-silicate intergrowth. The troilite (gray) is shock-altered to polycrystalline aggregates. Polished. Slightly crossed polars. Scale bar 100 μ.

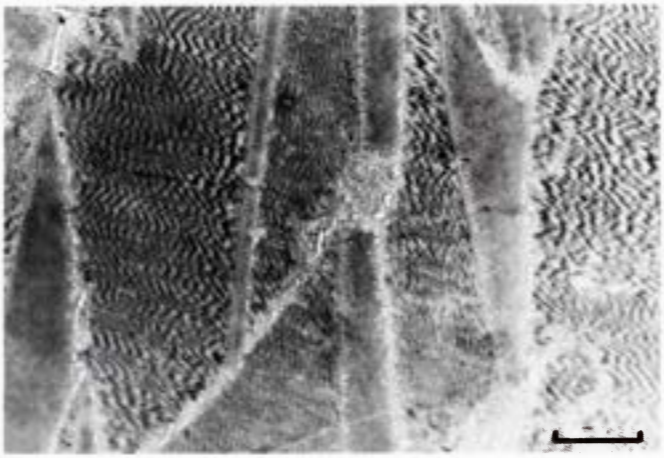

Figure 654. Colomera (U.S.N.M. no. 3396). Melted schreibersite crystal from zone A of the heat-affected surface zone. Compare Figures 45-51. Etched. Oil immersion. Scale bar 10 μ.

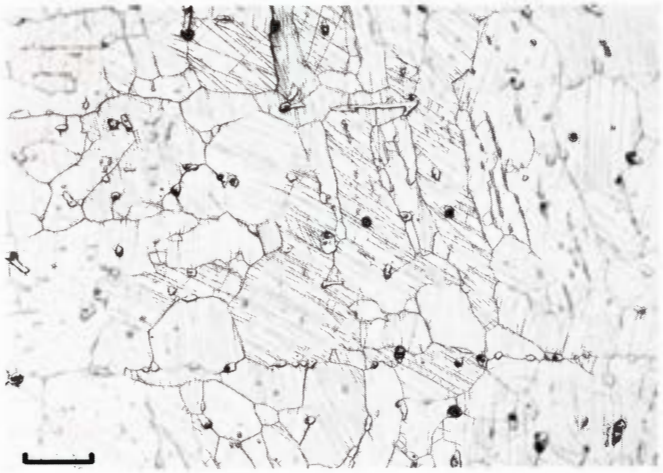

Figure 656. Colomera (U.S.N.M. no. 3396). Recrystallized kamacite with indications of previous Widmanstätten morphology. Below, a horizontal line of phosphides which perhaps were precipitated on a former taenite twin boundary. Etched. Scale bar 1 mm.

fine-grained sulfide-metal mixtures are very sensitive to corrosion. The troilite which was completely embedded in silicate and could not react with metal, solidified to polycrystalline aggregates. Daubreelite, carlsbergite, graphite and carbides were not detected.

The rounded or vermicular silicate inclusions in Colomera are smaller on the average than those in either Weekeroo Station or Kodaikanal. Most nodules are 0.5-4 mm in diameter, and typical grain boundary bodies of peanut shape are 2.5 x 0.5 mm in size. Silicates smaller than 0.5 mm are rare, and there are no finely disseminated silicates in the metal. As noted above, Wasserburg et al. (1968) identified large potassium feldspar phenocrysts in the surface, but sections have revealed none in the interior. Colomera is thus a rare example in iron meteorites of bulk differences between the (present) exterior and the interior. Since a significant but unknown thickness of the meteorite was lost by ablation in the atmosphere, it is not known what its surface looked like when it circled in space. For example, whether a more massive silicate wrapping existed around the metal.

The silicate textures are complex. At some time, some nodules apparently consisted of two almost immiscible silicate melts, separated by a hemispherical meniscus. One of the melts solidified to a glass, which later devitrified and separated 10-50 μ wide euhedral crystals. The other melt solidified with fine inclusions of the first glass to produce a eutectic-like structure or a structure with flow lines. Chromite crystals, 100-200 μ across, situated at the silicate-metal interface have been brecciated and dispersed in the silicate melts, and this is sometimes true also of schreibersite and troilite. The primary metal-silicate textures were evidently fully developed when the remelting of the silicates and troilite took place. This was possibly the result of a shock event.

A heat-affected α_2 zone runs almost continuously around all exposed sections, indicating that very little has been lost by corrosion. The zone is about 2 mm wide and exhibits micromelted phosphides and sulfides in its exterior

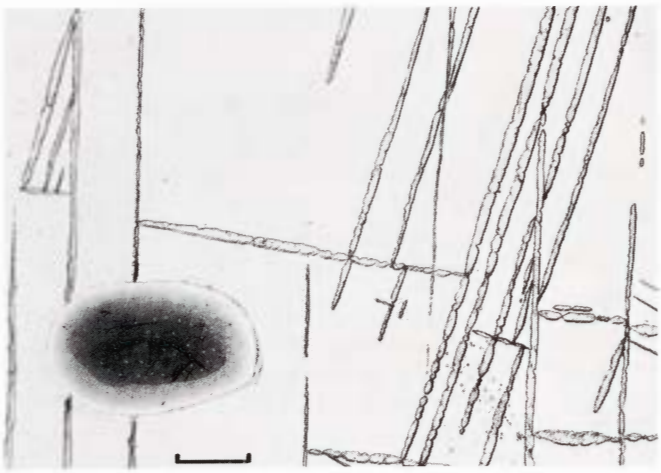

Figure 657. Colomera (U.S.N.M. no. 3396). Neumann bands in a recrystallized kamacite grain. Below, an anomalous, very hard taenite globule with zoning. Etched. Scale bar 50 μ.

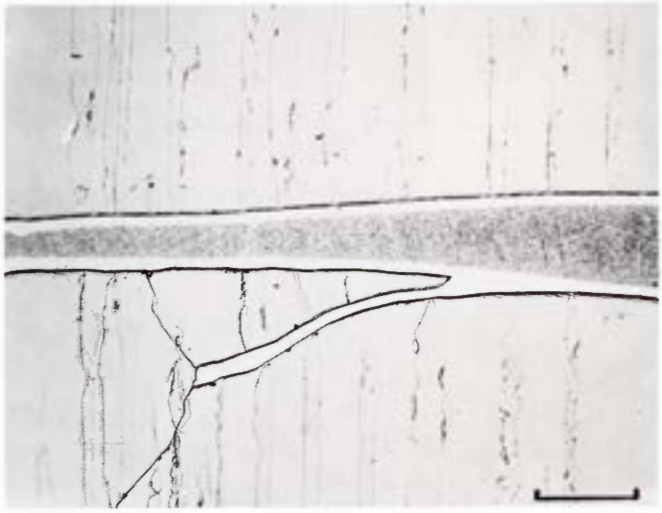

Figure 658. Colomera (U.S.N.M. no. 3396). Annealed taenite lamella and Neumann bands with minute precipitated particles. Etched. Oil immersion. Scale bar 20 μ.

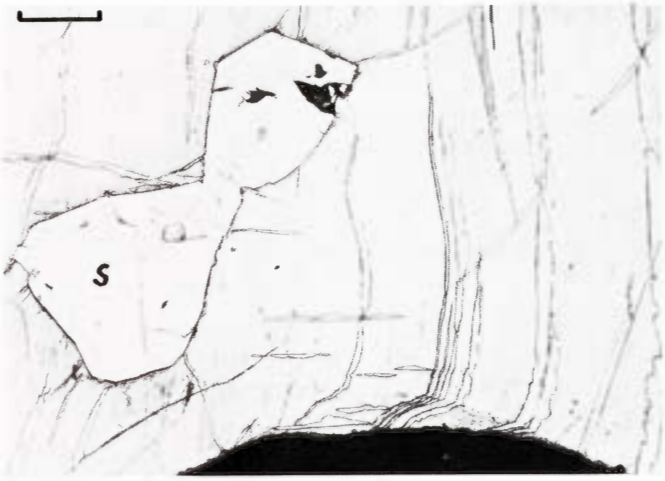

Figure 659. Colomera (U.S.N.M. no. 3396). Violently deformed Neumann bands around a silicate globule (black). Fissured schreibersite crystal (S). Etched. Scale bar 50 μ.

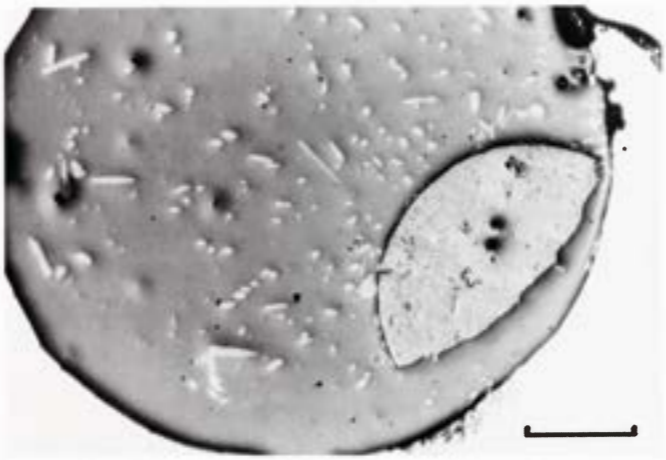

Figure 660. Colomera (U.S.N.M. no. 3396). A spherical silicate glass with a crescent-shaped glass inclusion and many small crystallites (white spindles). Polished. Reflected light. Scale bar 300 μ.

part. Complex melts of phosphides and sulfides, somewhat altered by corrosion, also occur. The α_2 phase consists of serrated unequilibrated grains, 10-150 μ across, with a hardness of 200±15 (hardness curve type II). Surprisingly enough, the Neumann bands apparently survive in the α_2 phase. High magnification reveals, however, that it is only the fine precipitates, previously exsolved in the bands, that are retained, while the bands themselves of course disappeared on the rapid transformation $\alpha \rightarrow \gamma \rightarrow \alpha_2$.

Colomera is an anomalous meteorite, an iron-with-silicate inclusions. If it were not for the detailed trace element analyses and the minute examinations of the silicates, it would be difficult to point to related iron meteorites. As it is, it appears that Colomera belongs to the rather heterogeneous group, comprising Elga, Kodaikanal and Weekeroo Station, and possibly some others, too, such as Arlington and Barranca Blanca, in which silicates have not been detected.

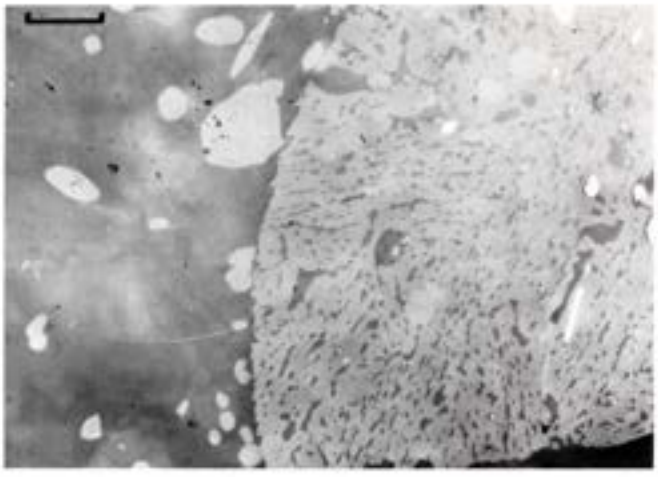

Figure 661. Colomera. Detail of the crescent-shaped inclusion in Figure 660. Polished. Scale bar 50 μ.

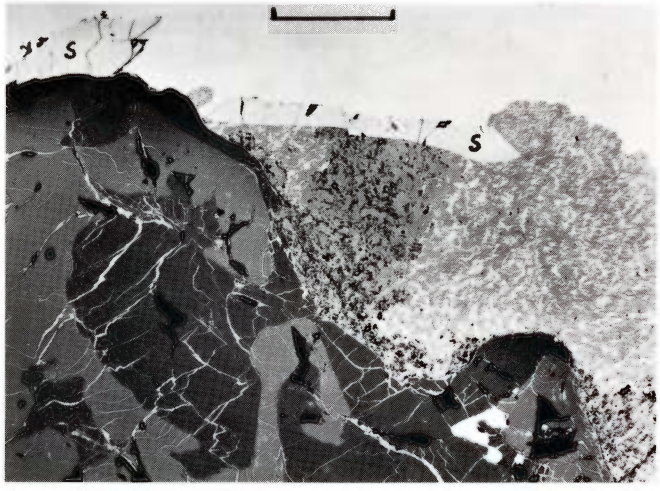

Figure 662. Colomera (U.S.N.M. no. 3396). Shock-melted troilite (right) with metal particles. Shear-displaced schreibersite (S) and altered silicates (gray, black). Polished. Scale bar 200 μ.

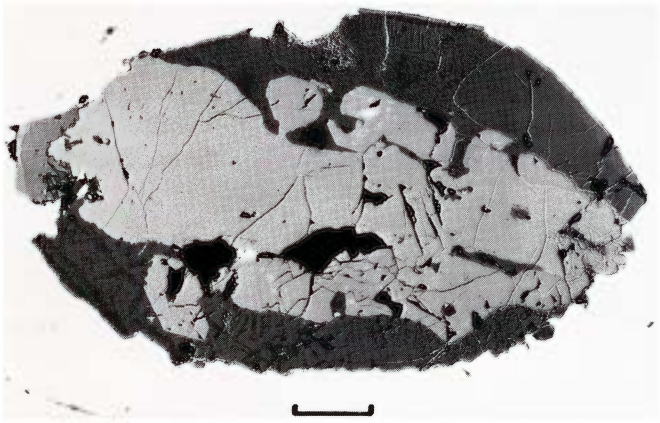

Figure 663. Colomera (U.S.N.M. no. 3396). Massive silicate nucleus surrounded by silicate glass with bar-shaped silicates. Polished. Scale bar 200 μ.

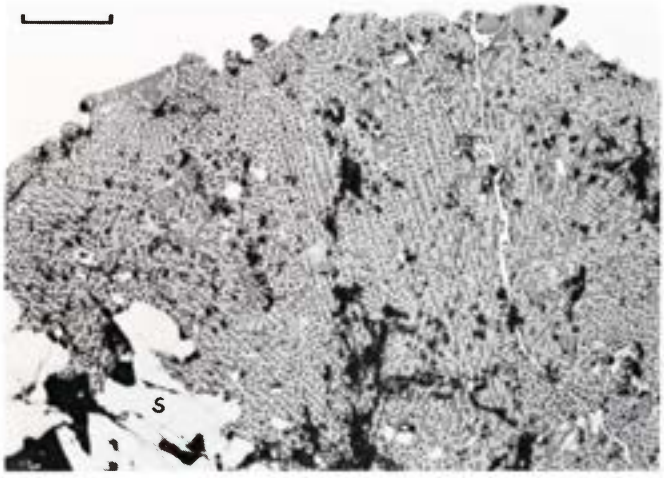

Figure 664. Colomera (U.S.N.M. no. 3396). This particular silicate nodule was located only 1 mm under the surface in the heat-affected α_2 zone. Its dendritic structure seems, however, to be preatmospheric. Schreibersite (S). Polished. Reflected light. Scale bar 100 μ.

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

133 g part slices (no. 1514)
1,224 g slice (no. 3396, 40 x 10 x 0.5 cm)
1,200 g slice (no. 3396, 40 x 10 x 0.5 cm)
781 g slice (no. 3396, 40 x 10 x 0.5 cm)

Comanche, Texas, U.S.A.

32°1′N, 98°42′W; 400m

Coarse octahedrite, Og. Bandwidth 1.50±0.30 mm. Neumann bands. HV 170±15.

Group I. 8.1% Ni, about 0.25% P, 73.9 ppm Ga, 269 ppm Ge, 2.2 ppm Ir.

HISTORY

A mass of 19.7 kg was listed as an octahedrite by Leonard (1956a: 8, 46). The main mass is still in private possession, but, through the kind cooperation of Mr. O.E. Monnig, a 550 g specimen was acquired by the U.S. National Museum in 1964. According to information supplied by Mr. Monnig in letters to the Museum (Decem-