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**Campbellsville, Kentucky, U.S.A.**

 37°20'N, 85°21'W; 250 m
 

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 Medium octahedrite, Om. Bandwidth 1.25±0.20 mm.  $\epsilon$ -structure. HV 295±15.

Group IIIB. 8.61% Ni, 0.52% Co, 0.30% P, 21.7 ppm Ga, 44.4 ppm Ge, 0.08 ppm Ir.

**HISTORY**

A mass of 15.4 kg was plowed up in 1929 on virgin land on the farm of Edgar Cox, Stoner Creek, Taylor County. This is near Campbellsville, which has the coordinates given above. The mass was acquired by the University of Kentucky, where it was described by Young (1939). It was cut and somewhat distributed, and the remaining material was transferred in 1968 as a permanent loan to the U.S. National Museum.

**COLLECTIONS**

Washington (9.5 kg), Harvard (459 g), London (429 g), Miami University (250 g), Tempe (279 g). According to Young (1939) 1.34 kg was, in addition, set in circulation through Ward's Establishment.

**DESCRIPTION**

The mass had the approximate average dimensions of 22 x 15 x 12 cm. Judging from the half piece preserved in Washington, the mass is well rounded due to heavy corrosion that locally opens the surface along Widmanstätten lamellae. The adhering oxide crust is 0.5-5 mm thick, and all flight-sculpturing is removed by corrosion.

Etched sections show a beautiful Widmanstätten structure with somewhat swollen lamellae ( $W \sim 10$ ) of widely varying width. It appears that the broader lamellae (1.5-2.0 mm) are those that have frequent precipitates of schreibersite crystals, while the true Widmanstätten width may be measured on the precipitate-free lamellae as 1.25±0.20 mm. The  $\alpha$ -phase is converted by a shock of medium intensity to the hatched  $\epsilon$ -structure of high hardness, 295±15. The schreibersite inclusions are brecciated and locally sheared 1-5  $\mu$ . Plessite fields occupy roughly 30% by area and are developed as coarse comb

plessite, as poorly resolvable duplex  $\alpha + \gamma$  plessite ("black taenite") or as martensitic plessite, where the brownish-black etching martensite laths are parallel to the bulk Widmanstätten pattern. A typical plessite field will display a tarnished taenite rim (HV 365±15) followed by martensitic transition zones (HV 440±30). Then come indistinct duplex  $\alpha + \gamma$  structures (HV 325±25) and finally well developed  $\alpha + \gamma$  structures with hardnesses similar to those of the adjacent kamacite lamellae.

Schreibersite is rather dominant as 2 x 0.5 mm angular, monocrystalline bodies located centrally in the  $\alpha$ -lamellae. In many instances it could be proven that neighboring units were identically oriented and connected below the surface of the section. Frequently a tiny 10-20  $\mu$  euhedric chromite crystal had served as nucleus for a modest bleb of troilite, and these two minerals had again served as a heterogenous nucleation center for the first schreibersite, precipitating directly from the austenite phase. The schreibersite then grew rather irregularly to form a glove-like structure, e.g., 6 x 4 x 0.5 mm in size. Depending upon the angle of cutting, such a crystal will be seen either as several aligned islands (the fingers) or as a more massive structure (the palm). The plane of the glove-like crystals appears to be parallel to {110} of the taenite, that is, the crystals are, in fact, imperfectly developed Brezina lamellae that could grow only to a small size because of the limited supply of phosphorus. Point counting of the schreibersite, taken

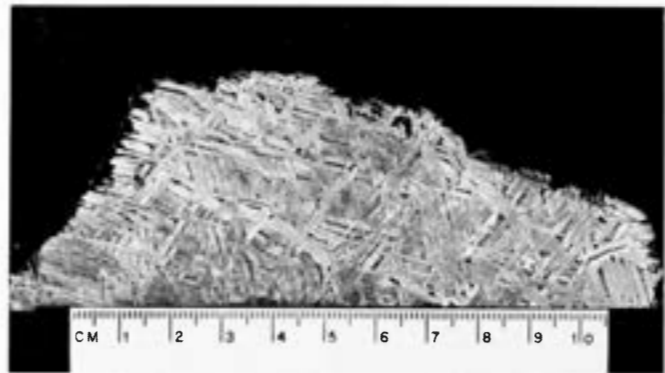


Figure 429. Campbellsville (Tempe no. 351.1). This medium octahedrite is corroded and shows local exfoliation along Widmanstätten lamellae. Deep-etched. Scale bar in cm. (Courtesy C.B. Moore.)

**CAMPBELLSVILLE – SELECTED CHEMICAL ANALYSES**

The original analysis in Young's paper (1939) showed 10.27% Ni and 0.26% Co and reflects the difficulty of correctly asserting the nickel, iron and cobalt content when

the analyst has but little experience with nickel-rich iron alloys. Reed (1969) found the kamacite lamellae to have 7.2% Ni and 0.12% P in solid solution.

References	percentage			ppm								
	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Smales et al. 1967						5.3	123	1.8	23.0	45		
Moore et al. 1969	8.57	0.52	0.28	150	80							
Wasson 1970, pers. comm.	8.65								20.4	43.8	0.09	
Crocket 1972											0.061	

together with Reed's value for the phosphorus in kamacite, leads to an overall estimate of 0.30% P in the meteorite.

Typical rhabdites are not present. It appears, however, that the ferrite matrix is loaded with submicroscopic particles that locally increase in size to become distinguishable as 1-2  $\mu$  angular crystals. They are particularly abundant in zones adjacent to "black taenite" where they apparently have precipitated on slipplanes created in the  $\alpha$ -matrix when the taenite transformed to martensite under volume increase. This feature has previously been discussed for the iron meteorite Thule by Buchwald (1965: plates 9 and 10; 1966: Figure 29).

Subboundaries are common in the ferrite. They are decorated by less than 1  $\mu$  particles, which visibly have impeded the movement of the boundaries. Locally a grain boundary has succeeded in breaking free, having left behind a line of precipitates.

No large troilite inclusions were disclosed on a total of 800 cm<sup>2</sup> sections. However, as mentioned above, small troilite blebs, 10-50  $\mu$  in diameter, are scattered throughout the mass and usually associated with a little chromite.

Campbellsville is a shock-hardened medium octahedrite with significant phosphide content and with  $\epsilon$ -structure. It is closely related to such irons as Aggie Creek, Orange River and Plymouth. All are chemically intermediate between group IIIA and group IIIB.

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

- 240 g slice (no. 903, 9 x 8 x 0.3 cm)
- 7,325 g half mass (no. 2572, 12 x 11 x 10 cm)
- 1,335 g slice (no. 2572, 12 x 11 x 1.3 cm)
- 621 g slice (no. 2572, 12 x 11 x 0.7 cm)

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### Campo del Cielo, Gran Chaco Gualamba, Argentina

27°39'S, 61°44'W; 150 m

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Polycrystalline, coarse octahedrite, Og. Bandwidth 3.0±0.6 mm. Neumann Bands. HV 175-290.

Group I. 6.68% Ni, 0.43% Co, 0.25% P, 87 ppm Ga, 407 ppm Ge, 3.6 ppm Ir.

#### HISTORY

According to the excellent work of Alvarez (1926), the history of this interesting shower of irons goes back to the Spanish exploration in about 1576. At that time, an expedition under the leadership of Captain de Miraval traversed the Gran Chaco Gualamba and brought back a few fragments of a large mass called Meson de Fierro (large table of iron). This was appropriately enough located in a district called Campo del Cielo (Field of the Sky) – an open, brush-covered plain which, although stretching for some hundreds of kilometers, was devoid of stones and water and had a very porous topsoil. Alvarez (1926: 19) stated that the Governor of Santiago del Estero expressly sent Miraval to locate the iron which was known to the Indians and was regarded as having fallen from heaven.

Later expeditions, in 1774, 1776 and 1779, brought back more material. For a time it was considered to be a rich silver ore (1/5 silver, 4/5 iron) and in 1778 a large amount of mercury was dispatched from Almaden, Spain, in order to avoid delay in extracting the silver from the supposed ore (Alvarez: 33). However, a commission of blacksmiths, and the analyst O'Gorman, independently deduced from their results that the mass was absolutely devoid of silver and was an iron of superior quality.

In 1783 Rubin de Celis, a lieutenant of the Royal Spanish Navy, relocated the mass near Otumpa and excavated it from its "clay and ash bed" (Celis 1788). In order to ascertain whether the iron had roots or was part of a metallic vein, as assumed by many early visitors, de Celis dug trenches around the mass and tipped it over. He made a curious remark that the iron was sustained upon two, thin corroded pillars of the same material but roots were not found. He presented two drawings, one from above and one from the side, and estimated the weight to be 14-18 tons (Alvarez: 45f). He concluded that the block originated from some volcanic eruption and found the economic value to be infinitesimal. Unfortunately, he left the iron in the overturned position in the hole, and Celis was the last man to see it. Apparently soil erosion has since covered all traces of everything. Small, detached fragments amounting to 10-15 kg reached several collections, and were discussed by Chladni (1794: 40; 1819: 318, 341) and others. Proust (1799) and Howard (1802) were among the first to determine nickel in meteorites and agreed on finding a quantity of about 10% in Rubin de Celis' Campo del Cielo material. Stromeyer (1824) claimed to have analyzed an olivine crystal isolated from the material but was disbelieved by his contemporaries who thought that he had worked with mislabeled Krasnojarsk material.

Another mass of about 1,000 kg, found in 1803 at Runa Pocito and called Otumpa, was transported via Santiago del Estero to Buenos Aires. Here an attempt was made to forge weapons from it, because there was a shortage of iron in the republic which was at war with Spain at that time. A report of the experiments in the armory by its director, de Luca, is preserved (Alvarez: 158). Two pistols with gun barrels of "Otumpa" iron were presented to President James Monroe of the United States and another to General Manuel Belgrano, but the remainder of the block was presented by the newly founded Argentinean Republic to the British Consul General Sir Woodbine Parish who, in 1826, transferred it to the British Museum where it became the first large meteorite on display.

The two pistols are now on display in the James Monroe Law Office, Museum and Memorial Library in Fredericksburg, Virginia. They constitute a pair of almost identical, short-barrelled, flintlock equestrian pistols with beautiful Spanish style ornamentation. By the kind cooperation of Mr. Lawrence G. Hoes, Keeper of the Museum, I was permitted to examine one of the pistols. A tiny bleb of metal was removed from the flintlock, polished



and examined. The microscopic examination showed the metal to be composed of equiaxial ferrite grains, 50-150  $\mu$  in diameter, with uniformly oriented slag particles, 2-25  $\mu$  across. No meteoritic minerals were present. The electron microprobe study disclosed less than 0.3% Ni. Independently, Daniel J. Milton of the U.S. Geological Survey analyzed the gun barrel by spectroscopy and also found negligible amounts of nickel. The material is thus typically wrought iron with no meteoritic admixture. Perhaps the pistols were originally intended to be produced from meteoritic iron, but the weapon smith may have found his work unsatisfactory and substituted the pistols with normal wrought iron pistols. At any rate, the pistols, formerly in President Monroe's possession and allegedly made from Campo del Cielo meteorites, contain little or probably no meteoritic iron at all.

The material analyzed and discussed in the nineteenth century probably more or less directly originated from the



**Figure 430.** One of a pair of flintlock pistols donated to the U.S. president James Monroe, by the Argentine Republic in about 1816. Although allegedly made of meteoritic iron the present examination found them to be produced from wrought iron. (Photo by courtesy of L.G. Hoes, James Monroe Memorial Foundation, Fredericksburg, Virginia.)



**Figure 431.** Campo del Cielo, labeled Otumpa (Copenhagen no. 2). The sample has, like much of the old Campo del Cielo material, been artificially reheated and partially forged. The indistinct horizontal lines suggest inhomogeneities after partial resorption of rhabdites and taenite.  $\alpha_2$  matrix. Etched. Scale bar 300  $\mu$ .

Rubin de Celis mass, while the Otumpa mass in London was only little cut. The specimens were heat treated, forged and investigated in many ways and then passed on to some other collection without heed to the sometimes rather destructive investigations. That is why the Otumpa or Campo del Cielo iron figured in catalogs as a nickel-poor ataxite for about 150 years, similar to Siratik and Rasgata (see Partsch 1843: 128; Rose 1864a: 51; Brezina 1896: 295; Cohen 1905; Hey 1966: 80). A reinvestigation of two old specimens in Copenhagen (Buchwald 1965; Buchwald & Munck 1965: 53) showed, however, that one specimen was a normal coarse octahedrite similar to Seeläsgen, and that the other was a heated and forged specimen. In the latter, most of the phosphides were resorbed, most of the Widmanstätten structure had disappeared and the matrix was  $\alpha_2$ . Unfortunately, this turned out to be the type specimen with which Cohen (1898a; 1905) had worked, and thus explains part of the long standing confusion about this famous meteorite.

Nagera (1926) described the depressions ("hoyos") in the Campo del Cielo region and concluded that they were of artificial origin, but Spencer (1933) assumed that they were small craters connected with the large irons of which several more were now becoming known (Ducloux 1928). Radice (1959) gave a review of the story and composition of the different masses.

In 1962 and following years, joint Argentinean-U.S. expeditions succeeded in locating a large number of meteorites, ranging in size from the 1,998 kg El Taco mass down to minute fragments of oxidized masses (Cassidy et al. 1965; Cassidy 1967; Cassidy 1968). In the 1965 paper is a list of the 10 largest masses, headed by El Toba of 4,210 kg, found in 1923, and now in Buenos Aires. A table based mainly upon Cassidy's information is presented below. The last entry is an enormous fragment partly excavated in Crater No. 10, and preliminarily reported by Cassidy recently (1970). The field work showed that the strewnfield was about 75 km long and very narrow, stretching along a line bearing N<sub>60</sub>°E. From the northeastern part only scattered minor masses were reported; of these most are lost, but in the southwestern part at least 12 craters – or more correctly penetration funnels – created by the impact of the larger masses were discovered. In each hole, 20-100 m in diameter, the main part of the impacting mass was found. Sometimes several masses hitting close to each other had created irregular holes. The distance between the extreme "craters," including those almost destroyed by erosion, is about 20 km; the masses found in connection with these extremes are El Taco of 1,998 kg and El Mocovi of 732 kg. The total recovered weight since 1803 appears to be about 31,000 kg, and this is probably only a small fraction of the total impacting meteorite.

An upright stump of charred wood excavated from one of the holes showed a C-14 age of 5800±200 years, which may be the age of the impact (Cassidy et al. 1965). A more recent C-14 determination on another charcoal sample

The Campo del Cielo individuals

Meteorite name	Mass, kg	Year found	Place of find		Present location
			S. lat.	W. long.	
El Mesón de Fierro	~15,000	Before 1576	Unknown		Probably In situ.
El Toba	4,210	1923	27° 39.5'	61° 46.5'	Museo Bern. Rivadaviva, Buenos Aires
El Taco	1,998	1962	27° 40'	61° 47.5'	U.S.N.M. (on loan)
El Mataco	990	1937	27° 40'	61° 44.5'	Parque Independencia, Rosario, Santa Fé Prov.
Otumpa	~900	1803	Unknown		Brit. Mus., London (634 kg)
El Tonocoté	850	1931	Unknown		Dirección Nacional de Geología y Minería, Buenos Aires
El Mocovi	732	1925	27° 35'	61° 35'	Museo Bern. Rivadaviva
El Abipón, syn. Charata	460	1936	Unknown		Museo Bern. Rivadaviva
El Patio	~350	Before 1960	27° 39'	61° 43.5'	Estancia El Taco, Gancedo, Chaco Province
Unnamed	132	Before 1960	27° 39'	61° 42'	Museo Municipal, Rafaela, Santa Fé Prov.
Unnamed	~100	Before 1960	27° 37'	61° 36'	Estancia Los Guanacos, Gancedo
In Crater No. 10 Gancedo, Gran Chaco, Tucuman and others	~18,000 0.5-5	1969 Numerous small fragments, found on various occasions, and now in various museums			In situ.

showed an age of 3950±90 years (Cassidy 1973, personal communication). The theory (Cassidy et al. 1965) that the impacting mass was only part of a larger mass, in a decaying orbit, which later produced the North Chilean hexahedrites is untenable alone for structural reasons. Campo del Cielo is a coarse octahedrite with 6.7% Ni, while the Chilean masses are true hexahedrites with 5.6% Ni.

The cosmic radiation age was found to be 14±8 million years, which is very low compared to other octahedrites (Nyquist et al. 1967).

Perry (1944) presented several photomicrographs; one of them (plate 48) undoubtedly shows cliftonite, a graphite crystal aggregate, and not troilite as stated in the text. Curvello's (1958: 40) application of the aragonite twinning law in this supposedly troilite crystal is therefore invalid. Park et al. (1966) discussed some millimeter-sized silicate inclusions and showed that they consisted of forsterite, chrome diopside, enstatite and oligoclase, decreasing in frequency in that order, and further identified chromite, graphite, troilite and sphalerite, mostly in complex intergrowths. One of the first publications on dislocations in meteorites by thin-film transmission electron microscopy showed that Campo del Cielo had an immobile dislocation network of high density (Ashbee & Vassamillet 1966). Bunch & Cassidy (1968) discussed the numerous deformation structures and found one fragment in particular with indications of heavy plastic flow and recrystallized kamacite. Clarke & Jarosewich (1969) reported a number of excellent analyses (6.7% Ni), the first to be made since the misleading ones performed generations earlier and showing only 5.1-5.9% Ni (Cohen 1898a; Ducloux 1929). Reed (1965; 1969) found 6.2-6.6% Ni and 670 ppm P in the kamacite.

In 1966, the 1,998 kg El Taco mass was cut in the Max Planck Institut, Mainz. The critical process of making such a large section (about 110 x 40 cm) was carried out under the direction of Professor H. Hintenberger, using a combination of close parallel 1/2 inch drilling holes and sawing. Two slices were prepared.

Nyquist et al (1967), Hintenberger et al (1969) and Schultz et al (1971) determined the rare gases, while Mason (1967) gave a photograph of the newly cut El Taco specimen and discussed the silicate inclusions of iron meteorites in general. Wlotzka & Jarosewich (1969) examined the silicate inclusions in detail. Podosek (1971) presented argon analyses on a silicate inclusion, and

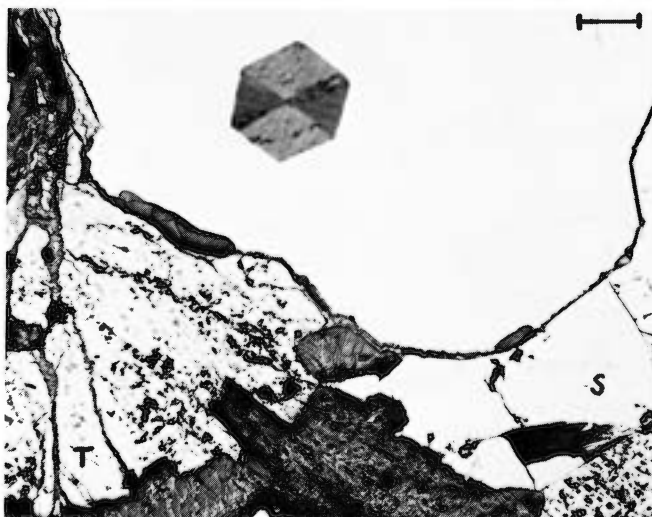


Figure 432. Campo del Cielo (Perry 1944: plate 48). Edge of a troilite (T)-graphite (black) inclusion with a rim of schreibersite (S). In the adjacent kamacite, is a perfect cliftonite crystal. Polished. Scale bar 100 μ.





Figure 433. Campo del Cielo. The El Taco mass being cut in Mainz. Numerous large angular silicate-troilite-graphite aggregates. Length of slice 110 cm. (Courtesy Professor Hintenberger.) See also Figure 78.

potassium-argon ages calculated by the  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  method. He estimated a K-Ar age of  $4.6 \times 10^9$  years and found evidence of a later heating event  $3.4 \times 10^9$  years ago.

#### COLLECTIONS

The 634 kg Otumpa mass is in London. At least 8 masses ranging from 100 to 4,210 kg are in different museums in Argentina (see the table, page 375). Of the newly excavated material 35 kg is in New York, while 44 kg is in Washington, where two large slices of the El Taco mass are also on display. Of the old and partly man-damaged material, small amounts are in Berlin, Copenhagen, London, Tübingen, Vienna and Canberra.

#### DESCRIPTION

It is not possible to describe all the fragments which are now in many different museums. See the table on page 375. Typical important specimens will, however, be treated in the following passage.

*El Toba*, weighing 4,210 kg, measures 165 x 110 x 100 cm and displays a 32 x 16 cm cut and roughly polished surface. Chiseled in one place is, "Meteorito el Toba. Dada del Dr. Bartolome Vassallo - 1924 -." Chiseled in another place is, "IV - AV," several Roman numerals and an illegible year, evidently an inscription of much older date. The mass is very well-preserved, the caliche deposits

reveal that for a long period it was only partially buried, with 60 cm below and about 40 cm above the soil. The regmaglypts are fine and large; on the sides they are developed as subparallel grooves, indicating the flight direction. They reach sizes of 18 x 10 cm with depths of 1.5 cm. In several places there are secondary fracture surfaces where smaller fragments separated from the mass late in the flight. The secondary surfaces have only small and immature regmaglypts. Everywhere on the top side there are remnants of fusion crust which is only slightly weathered. The details of the sculpture on the under side are hidden beneath caliche deposits. On various occasions visitors have broken or chiseled material from El Toba, leaving scars of, e.g., 20 x 10 cm and 15 x 5 cm. Some of the detached samples are exhibited in the vitrines in Museo Bernardino Rivadavia.

*El Mocovi* weighs 732 kg, measures 72 x 60 x 40 cm and carries, on a 17 x 13 cm roughly polished surface, the chiseled inscription, "Meteorito El Mocovi. Dada del Senor D. Luis E. Zuberbuhler. 1925." It is well-preserved. Most of the regmaglypts are developed as subparallel grooves 4-9 cm wide, or occasionally as pits 2-5 cm across. In numerous places there are holes left by angular troilite aggregates that ablated away in the atmosphere. They attain sizes of 10-25 mm across with depths of 2-10 mm. In two places, measuring 35 x 18 cm and 30 x 20 cm, very rough surfaces indicate where large fragments were torn from El Mocovi at a late stage in flight.

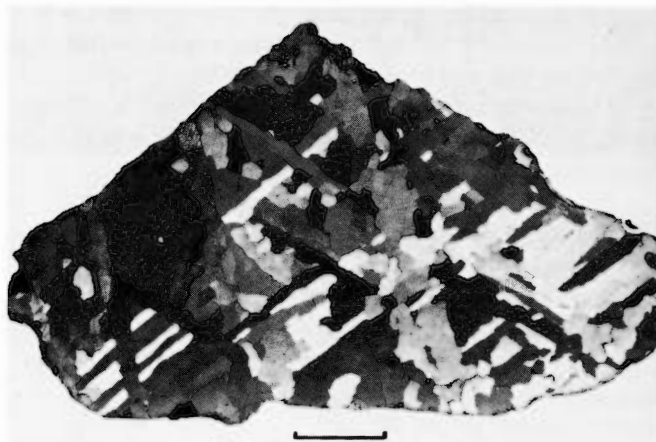


Figure 434. Campo del Cielo (U.S.N.M. no. 2253). Typical coarse octahedrite, exhibiting significant kamacite grain growth. Scale bar 20 mm. S.I. neg. 1494.

#### CAMPO DEL CIELO - SELECTED CHEMICAL ANALYSES

References	percentage			C	S	Cr	Cu	ppm Zn	Ga	Ge	Ir	Pt
	Ni	Co	P									
Smales et al. 1967						12.5	109	28	83	421		
Clarke & Jarosewich 1969*	6.74	0.43	0.25									
Wasson 1970a	6.62								90	392	3.2	
Crocket 1972											3.9	9.7

\*Average of 28 specimens. The range was reported to be 6.65-6.82% Ni, 0.38-0.46% Co and 0.22-0.30% P. The specimens were selected to represent material from the entire strewnfield.



*El Abipon*, or Charata, which weighs 460 kg, is rather pyramidal and measures 70 x 45 x 44 cm. One of the pyramid faces, which is 70 x 35 cm, is almost plane and is covered with shallow, immature regmaglypts, 2-3 cm across. In two places, the rough sculpture indicates late necking and fracturing. One is at an edge and measures 40 x 10 cm. The other is a depression, 12 x 8 x 5 cm, from which a fragment was plucked. The mass is well-preserved and shows fusion crust, albeit slightly weathered.

*Otumpa*, now weighing 634 kg, measures 80 x 50 x 50 cm. It has, just as the above-mentioned, a marked sculpture, but it is also indented in two or three places, thus showing the work of sledge hammers and chisels.

*El Taco*, which weighs 1,998 kg, was rather shield-shaped and measured 120 x 110 x 40 cm before cutting. It is well-preserved and shows regmaglypts on the bottom of which even some slightly weathered fusion crust is present. The regmaglypts of the convex front side of the shield are 4-8 cm across, while those of the slightly concave opposite side are 12-30 cm across and may be further subdivided in 2-6 cm pits. Compare Hraschina, Henbury and Cabin Creek. The *El Taco* mass, as well as the other large masses, evidently had sufficiently long atmospheric flights to develop independently a sculpture characteristic of large single iron meteorites

Several silicate inclusions, e.g., 10 x 9 and 3 x 2.5 cm in size, are on the surface of *El Taco*; they stand in marked contrast to the adjacent metal after the surface had been artificially sandblasted in 1966. Silicates are apparently absent from the surfaces of the other large masses. They also seem to be rare in the interior, judging from the low frequency they are met with on the very few cut sections.

The smaller meteorite fragments are irregular, prismatic or angular, and they usually have coatings, 1 cm thick, of rust and caliche. They have mostly been found by systematic excavations; and since they have been totally

buried and exposed to ground water for a long period, they have absorbed terrestrial chlorides and now continue to corrode and disintegrate in the collections.

The reconstruction of the original body is difficult, but it may be assumed that it was an extended plate about 0.5-1 m thick, rather than a spheroid. Compare Chupaderos. Sections show that the masses were composed of large austenite crystals ranging in size from 5-50 cm. The numerous angular silicate inclusions appear to be concentrated in the grain boundaries along with some troilite and schreibersite. It is not surprising that a tabular mass of this structure should break up into a large number of fragments when decelerating in the atmosphere; most of the smaller individuals found will represent only one austenite crystal or a fragment of a crystal.

The individual, large austenite crystals of which some show twins, transformed upon cooling to a coarse Widmanstätten structure of bulky, short ( $\frac{L}{W} \sim 8$ ) kamacite



Figure 436. Campo del Cielo (U.S.N.M. no. 2253). Section through a mass that was heavily coldworked when the meteorite split in the atmosphere. Wavy sliplines and deformation bands cross the entire specimen. Etched. Scale bar 3 mm. S.I. neg. 1358G.

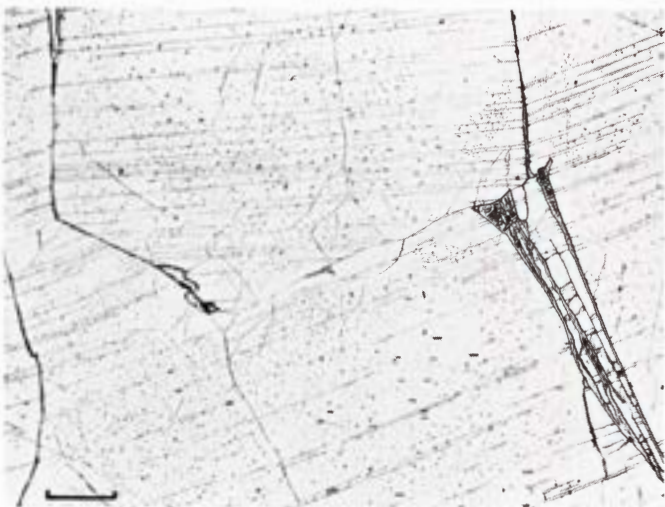


Figure 435. Campo del Cielo (Copenhagen no. 1898.1). A section of the Otumpa mass, showing large kamacite grains with rhabdites and Neumann bands, and a degenerated comb plessite field. Etched. Scale bar 500  $\mu$ .

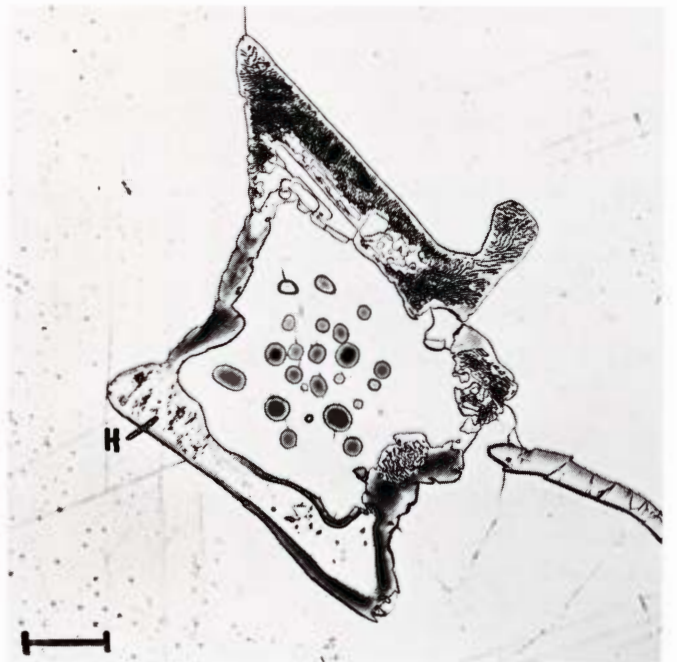


Figure 437. Campo del Cielo (Perry 1944: plate 46). A spheroidized plessite field with rims of pearlitic plessite. Haxonite in lower left part (H). Schreibersite in right grain boundary. Etched. Scale bar 100  $\mu$ .



lamellae with an average width of 3 mm. Later grain growth of the ferrite eliminated many of the straight lamellae and created scalloped, equiaxial grains 5-25 mm across. It is also evident from the sections that, *before* the homogeneous transformation to Widmanstätten lamellae took place in the interior of the austenite grains, a considerable quantity of ferrite had started to grow from many nuclei upon the  $\gamma$  -  $\gamma$  grain boundaries, upon the silicate inclusions, and upon the very few large schreibersite inclusions, forming cellular irregular rims 5-20 mm wide. The resulting structure looks rather confusing to say the least, and the Widmanstätten pattern may pass entirely unrecognized unless large sections are available.

Considering now a single, original austenite grain it is seen that taenite and plessite occur only as minor scattered inclusions, e.g., as 3 x 1 mm degenerated comb plessite, or as still smaller pearlitic and spheroidized fields. The plessite development is thus typical of the carbon-containing group I meteorites, but the area percentage is low – about 1%. Taenite and plessite are apparently never located in the  $\gamma$  -  $\gamma$  boundaries. In a few of the pearlitic or spheroidized plessite fields, minute carbide roses occur, e.g., as 50 x 50  $\mu$  intricate intergrowths of haxonite, kamacite, taenite and schreibersite.

Neumann bands are well developed and profuse. The hardness of the kamacite phase is  $185 \pm 15$ . Near-surface areas of many specimens show severely distorted structures with bent Neumann bands, lenticular deformation bands and brecciated and boudinaged inclusions. In these zones, which are mainly due to the atmospheric disruption, the hardness increases to 240 and above; several cold-worked kamacite areas with the very high hardness of  $280 \pm 20$  were noted. Similar intensive cold deformation occurs in other shower-producing meteorites, too, see, e.g. Gibeon, Sikhote-Alin and Cape York.

Schreibersite is uncommon. Apart from 0.1-0.05 mm wide veinlets in the former austenite grain boundaries and scattered 3 x 2 or 1 mm skeleton crystals it may be found

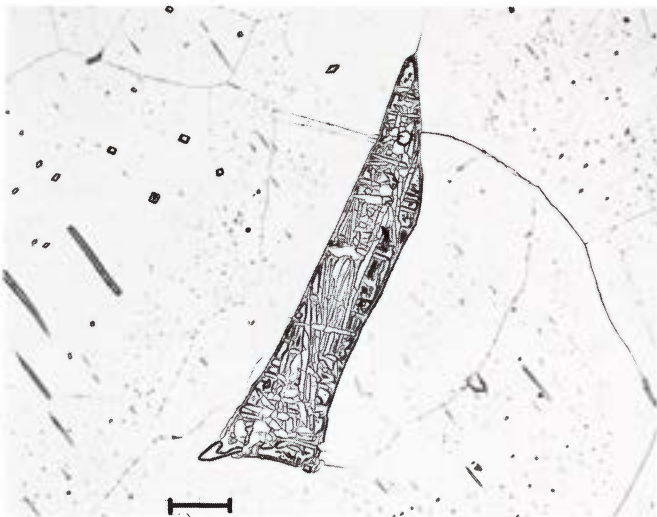


Figure 438. Campo del Cielo (Perry 1944: plate 44). An acicular plessite field. Subboundaries in kamacite and numerous rhabdites. Etched. Scale bar 200  $\mu$ .

as 0.5 mm wide rims around the silicate-troilite-graphite complexes and also as 20-50  $\mu$  wide grain boundary precipitates. Rhabdites 5-20  $\mu$  thick are ubiquitous and often displaced their own thickness along the Neumann bands. Fine phosphide precipitates, 1  $\mu$  across, are common on the numerous subgrain boundaries of the ferrite.

Troilite is not common in the usual nodule form. It does, however, occur in varying amounts together with the silicate-graphite aggregates. These irregular masses occur as black angular inclusions and cover 4-6% by area of polished sections. They are apparently composed of silicates, graphite and troilite in varying amounts, but an estimated average frequency is 1:1:1. The troilite part is normally a polycrystalline aggregate of 5-100  $\mu$  grains of which the finest grains will be situated close to the schreibersite, while the largest are nearest the graphite. In the troilite subangular fragments of sphalerite are dispersed. Graphite occurs as up to 10 mm patches which, in crossed Nicols, display the typical "horsetail" extinction. Numerous 1-5  $\mu$  troilite fragments are dispersed through the graphite. Subhedral crystals, 200-400  $\mu$  across, of olivine, enstatite and oligoclase are embedded irregularly in the graphite. Again 5-25  $\mu$  troilite droplets are found embedded in the silicates. It is most likely that the complex mixtures were produced by preatmospheric shocks that shattered and partially melted a previously more ordered arrangement of the inclusions.

The silicate-graphite-troilite complexes are frequently surrounded by 0.5 mm schreibersite and 0.1-0.2 mm cohenite rims, which are little affected by the shocks. Cohenite is further present as a few isolated 0.5 mm grains with small inclusions of schreibersite, but the typical  $\text{cm}^2$  patches of cohenite crystals centrally in the  $\alpha$ -lamellae were not observed in any section. Cliftonite, i.e., graphite precipitated from solid solution with cubic morphology (Brett & Higgins 1967; Buchwald & Wasson 1968), occurs as scattered 100-200  $\mu$  crystals in ferrite, normally quite close to the silicate-graphite complexes. Chromite and

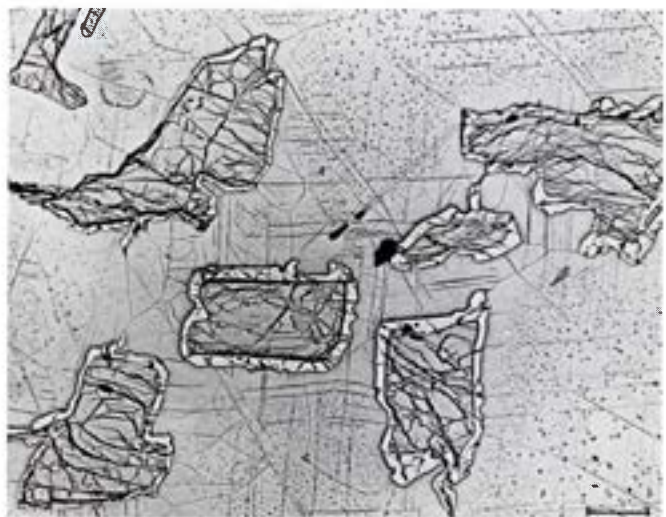


Figure 439. Campo del Cielo (U.S.N.M. no. 2253). A group of schreibersite crystals with rims of cohenite. Scale bar 1 mm. S.I. neg. 1499B.

daubreelite were reported by Bunch & Cassidy (1968) but they are evidently not too common and were not observed in this study.

Campo del Cielo is a polycrystalline, coarse octahedrite with a significant amount of silicate-graphite-troilite inclusions. It has the structure and mineral assemblage typical of the low-nickel end of the group I irons, and it is particularly closely related to Linwood. It is also related to Hope, Sardis, Yardymly and Seeläsgen. The characteristic angular silicate inclusions of El Taco appear to be duplicated only in Linwood and Netschaevo. The latter however, does not resemble Campo del Cielo in its metallic structure and in its chemical composition. Campo del Cielo displays Neumann bands and shock structures from some preatmospheric event. Several structural elements, such as the necking and cold-deformation visible on many specimens, are, however, of much later date and are due to the violent deceleration and breakup in the atmosphere. While many specimens are severely corroded, some, e.g., El Taco, are in a surprisingly good state of preservation, displaying fusion crust over many square centimeters. It appears that the large individuals fell as separate masses, having had sufficiently long trajectories in the atmosphere to develop regmaglypts on a large scale. Similar cases are met with in, e.g., Henbury, Wabar and Sikhote-Alin.

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

- 1.6 kg slices and part slices, mainly labeled "Otumpa" (nos. 783, 1168, 2550, 2983)
- 44 kg on 66 individuals collected 1962 and following years (no. 2253)

**Camp Verde.** See Canyon Diablo (Camp Verde).

**Canton, Georgia, U.S.A.**

34° 11' N, 84° 32' W; 300 m

Medium octahedrite, Om. Bandwidth 1.05±0.15 mm. Acicular kamacite. HV 220±12.

Group IIIA. 7.64% Ni, 0.53% Co, about 0.10% P, 18.6 ppm Ga, 37.2 ppm Ge, 8.6 ppm Ir.

**HISTORY**

A mass of 70 kg was plowed up in 1894 by S.B. May who was clearing new ground about 8 km southwest of Canton, Cherokee County. With the aid of an old ax the

flattened mass was split in two, of which the smaller part was later lost. The larger part, about 3.8 kg, was secured by S.W. McCallie, state geologist, and later exchanged with E.E. Howell, who described it and gave a photomicrograph (1895). Brezina (1895: 353) and Wülfing (1897) assumed, without seeing a piece of Canton, that it belonged to the Losttown mass found 30 years before in the same county. Ward (1900; 1904a), having both meteorites represented in his collection, correctly concluded that they were independent falls. Perry (1944: plate 35) gave a photomicrograph, and Henderson & Furcron (1957) discussed the structure on the basis of several micrographs. Wiik & Mason (1965) gave a new analysis and showed that 877 g slices in New York, previously labeled Losttown, were in fact Canton. Jaeger & Lipschutz (1967b) estimated from Perry's photomicrographs that Canton had been shocked to 130-750 k bar.

**COLLECTIONS**

New York (877 g), Washington (409 g), London (325 g), Chicago (262 g), Berlin (152 g), Harvard (122 g), Yale (82 g), Strasbourg (32 g).

**DESCRIPTION**

The mass was, according to Howell (1895), of a rough lens shape with one side flattened, but the dimensions were not given. It was heavily coated with iron oxides.

The corner piece (no. 349) in U.S. National Museum is much oxidized and shows well-marked octahedral cleavage due to the corrosion paths along the {111} planes. All traces of flight sculpture and heated rim zone have been removed by corrosion. Troilite nodules that happen to be situated in the surface zone are corroded slightly less than the surroundings and appear locally as rough, protruding knobs.

Etched surfaces display a Widmanstätten pattern of long ( $\bar{w} \sim 300$ , bundled  $\alpha$  lamellae with a width of 1.05±0.15 mm. The kamacite phase shows a very unusual, acicular transformation product which is different from the hatched  $\epsilon$ -structure of most shocked iron meteorites as, e.g., Canyon City. The hardness is rather low, 220±12; perhaps the structure represents an annealed form of a more normal shock structure. The other structural elements do not, however, suggest any appreciable annealing.

Taenite and plessite cover about 25% by area. Most fields are well decomposed to comb and net plessite,

**CANTON – SELECTED CHEMICAL ANALYSES**

References	percentage			ppm								
	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Wiik & Mason 1965	7.69	0.53										
Smales et al. 1967						29	167	2.8	18.6	39		
Wasson 1969, pers. comm.	7.58								18.6	35.4	9.3	
Crocket 1972											7.9	15



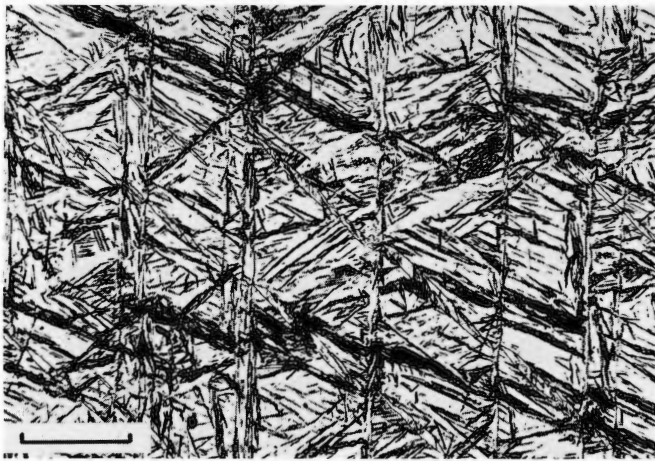


Figure 440. Canton (Perry 1944: plate 35). Canton is a normal medium octahedrite of group IIIA, but its kamacite shows an unusual acicular transformation product. Etched. Scale bar 100  $\mu$ .

repeating the Widmanstätten directions. The taenite rims around the fields are discontinuous, being almost resorbed. Some poorly resolvable black taenite wedges are also present. A typical wedge will exhibit a tarnished taenite rim (HV 310 $\pm$ 15) and an indistinct, martensitic transition zone (HV 360 $\pm$ 20). The dark-etching interiors range in hardness from 365 to 250, the softer parts being associated with clearly resolvable, duplex  $\alpha + \gamma$  mixtures.

Schreibersite is only present in minor amounts, corresponding to about 0.10% P in the mass. It occurs as 10-20  $\mu$  wide, short, monocrystalline veinlets in grain boundaries and as 5-20  $\mu$  irregular bodies inside the comb plessite. Rhabdites are present as 1-2  $\mu$  prisms, not only in the primary  $\alpha$ -lamellae, but also in the ferrite phase of the comb plessite. This is a little unusual, since phosphide precipitating in the plessite fields normally occupies grain boundary positions and shows no crystallographic facets.

Troilite occurs as scattered nodules, 0.5-20 mm in diameter. They only possess a narrow, discontinuous schreibersite rim because the overall content of phosphorus is low. Daubreelite inclusions are present in varying amounts. The smaller troilite-daubreelite bodies are more or less perfect lamellar exsolution structures of numerous parallel bands, often less than 1  $\mu$  wide. Near the surface the troilite is weathered and displays 5  $\mu$  wide pentlandite veins. One troilite nodule, 1.2 mm in diameter, apparently nucleated upon and then enveloped an older, euhedric chromite crystal, 0.8 mm in diameter. The troilite later decomposed so that we now observe troilite and daubreelite in direct contact with chromite. Another lamellar troilite body, 6 x 0.2 mm in size, is an aggregate of 2-10  $\mu$  troilite grains, contains dispersed daubreelite fragments, and displays scalloped edges against the metal. This troilite body evidently micromelted during the shock that produced the acicular structure of the metallic matrix. Several of the troilite nodules have, when they shock melted, squeezed 5-15  $\mu$  wide troilite filaments into the adjacent schreibersite and along the metallic grain

boundaries. These millimeter long veinlets are now severely corroded. Locally, the acicular structure is severely deformed near the troilite.

Graphite reported by Henderson & Furcron (1957), could not be confirmed.

Canton is a medium octahedrite, related to Canyon City, Boxhole and Henbury. Its acicular kamacite is rather unique.

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

409 g corner piece (no. 349, 11 x 4 x 2.5 cm)

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### Canyon City, California, U.S.A.

Approximately 40°51'N, 123°1'W; 1500 m

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Medium octahedrite, Om. Bandwidth 1.00 $\pm$ 0.10 mm.  $\epsilon$ -structure. HV 305 $\pm$ 15.

Group IIIA, 7.72% Ni, 0.10% P, 19.8 ppm Ga, 36.8 ppm Ge, 11 ppm Ir.

#### HISTORY

A mass of 8.5 kg was found about 1875 by John Driver of Canyon City, Trinity County. For a generation it was in the possession of Capt. C.W. Davis, but was tracked down and acquired by H.A. Ward who described it with a macrograph and an analysis (1904b). A preliminary account, based on weathered fragments, had previously been published by Shepard (1885). Ward reported that the meteorite was found on the surface about three miles northeast of Canyon City on the border of a little stream which flows into the Trinity River. The town had already been abandoned in Ward's time, but the site of Canyon City is still marked on modern maps in the scale 1:62,500; the locality of the meteorite has the coordinates given above. Ward cut about half the mass into slices, but the main mass stayed in his collection and came later to Chicago. Nininger & Nininger (1950: plate 5) gave a photomacrograph.

#### COLLECTION

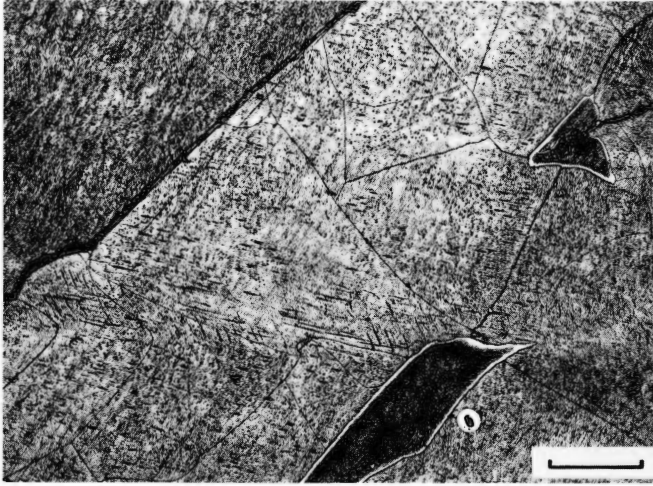
Chicago (4,240 g and 382 g slice), New York (803 g), London (589 g), Tempe (425 g), Berlin (356 g), Harvard (320 g) Washington (280 g), Amherst (218 g), Calcutta (76 g), Ann Arbor (74 g), Yale (45 g), Vatican (17 g).

#### DESCRIPTION

The almost square, flattened mass had the overall dimensions of 21 x 19 x 6 cm. One surface is slightly convex, the other slightly concave, but the flaking off of scales from terrestrial oxidation has obliterated any trace of thumbmarks or other atmospheric sculpturing (Ward 1904b). The limonitic, adhering scales are 3 mm thick in places, and the oxidation also penetrates right through the mass along {111} grain boundaries. The heated  $\alpha_2$  zone is lost.

Etched surfaces display a typical Widmanstätten structure with subdued oriented sheen, caused by the  $\epsilon$ -transformation structure. The lamellae are straight, long





**Figure 441.** Canyon City (U.S.N.M. no. 468). Shock-hatched  $\epsilon$ -structure of great hardness. Duplex, almost unresolvable plessite fields. Subboundaries and rhabdites in the kamacite. Etched. Scale bar 400  $\mu$ .

( $\frac{L}{W} \sim 35$ ) and with a width of  $1.00 \pm 0.10$  mm. They are, due to shock in the 130-400 k bar range, converted to the hatched  $\epsilon$ -structure, which shows a hardness of  $305 \pm 15$ . The fields, which occupy about 25% by area, are normally open-meshed, almost resorbed comb and net plessite regions. The individual 50-100  $\mu$  wide  $\alpha$ -grains of the fields are differently orientated, as is evidenced by the various orientations of the  $\epsilon$ -structure in them. The plessite fields have discontinuous taenite rims. Some acicular plessite is present. A typical field will have a narrow taenite rim (HV  $370 \pm 30$ ) followed by an indistinct, martensitic transition zone (HV  $420 \pm 20$ ) which merges with a poorly resolvable, duplex interior (HV  $360 \pm 20$ ).

Schreibersite occurs in modest amounts as 5-25  $\mu$  wide grain boundary precipitates and 2-20  $\mu$  irregular nodules in the plessite interior. Rhabdite prisms 1-2  $\mu$  thick are common in the kamacite lamellae and particularly conspicuous where selective corrosion has attacked their immediate surroundings.

Lenticular troilite bodies, typically 2 x 0.4 mm, were observed scattered over the surfaces. In a few cases they were sheathed in 10  $\mu$  schreibersite, but the overall phosphorus content is too low to produce a wide seam. "Troilite filled fissures," reported by Ward, are terrestrial oxidation products. Daubreelite is rather common as 50-100  $\mu$  bluish nodules, some of them with several parallel, 5  $\mu$  wide troilite lamellae. Still smaller nodules were found in the comb plessite under such circumstances as to suggest a precipitation from the  $\gamma$ -phase.

Canyon City is a medium octahedrite with shock structures closely resembling Boxhole and Henbury.

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

268 g corner piece (no. 468, 5.5 x 5 x 1.5 cm)  
15 g oxidized fragments (nos. 37, 1165)

**Canyon Diablo, Arizona, U.S.A.**

35°3'N, 111°2'W; 1750 m

Coarse octahedrite, Og. Bandwidth  $2.0 \pm 0.5$  mm, and sometimes larger variations.

Neumann bands,  $\epsilon$ -structures, recrystallized and  $\alpha_2$  structures. HV 145 - 370.

Group I. 7.10% Ni, 0.46% Co, 0.26% P, about 1.0% C, about 1.0% S, 80 ppm Ga, 320 ppm Ge, 1.9 ppm Ir.

**HISTORY**

Probably more than 20,000 fragments ranging from 50 g to 639 kg have been recovered since 1891 in Coconino County from a roughly circular region 15 km in diameter, in the center of which Meteor Crater is situated. In addition, numerous small metallic fragments and numerous heavily weathered chips, flakes and shale balls have been collected. Several large and small irons, individually named, have been found up to many hundred km from the crater and are believed to be transported fragments (see Ashfork, Bloody Basin, Camp Verde, Ehrenberg, Fair Oaks, Helt Township, Houck, Moab, Pulaski County, Rifle, Schertz, Wickenburg, at the end of Canyon Diablo). Also Albuquerque, Las Vegas, Oildale, and Palisades Park appear to belong to this category. The 90 g fragments labeled Monument Rock by Nininger & Nininger (1950: 131 and Plate 15) and Hey (1966: 314), have also been checked by the author and were found to be Canyon Diablo material.

As can be seen on page 389, the cumulative weight of masses in public collections is 11.5 tons. The total weight of all recovered metallic specimens has been estimated to be 30 tons (Nininger 1949), which seems a plausible estimate based on what is in public collections and what is known about the activities of the early collectors. The cumulative weight of all recognizable meteoritic material, based upon soil sampling of weathered, but strongly magnetic fine-grained debris from a 200 km<sup>2</sup> area around the crater, has been estimated at 8,000 tons (corrected for oxygen) (Rinehart 1958). Estimates of the total mass of the meteorite calculated from the size of the crater will, of course, be highly dependent upon the velocity with which it is assumed to have hit the Earth. Of this we know very little, so it is not surprising that figures vary: 400,000 tons (Magie 1910), between 5,000 and 3,000,000 tons (Moulton

**CANYON CITY – SELECTED CHEMICAL ANALYSES**

References	percentage			C	S	Cr	Cu	ppm				
	Ni	Co	P					Zn	Ga	Ge	Ir	Pt
Davison in Ward 1904b	7.85	0.17	0.10									
Scott et al. 1973	7.58								19.8	36.8	11	