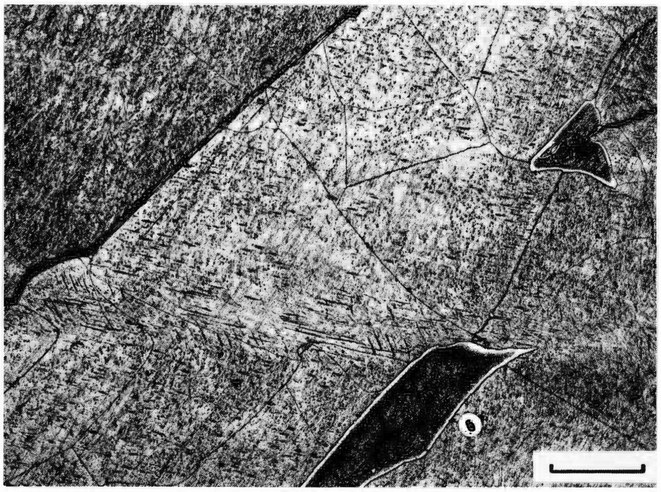

Figure 441. Canyon City (U.S.N.M. no. 468). Shock-hatched ϵ-structure of great hardness. Duplex, almost unresolvable plessite fields. Subboundaries and rhabdites in the kamacite. Etched. Scale bar 400 μ.

($\frac{L}{W} \sim 35$) and with a width of 1.00±0.10 mm. They are, due to shock in the 130-400 k bar range, converted to the hatched ϵ-structure, which shows a hardness of 305±15. The fields, which occupy about 25% by area, are normally open-meshed, almost resorbed comb and net plessite regions. The individual 50-100 μ wide α-grains of the fields are differently orientated, as is evidenced by the various orientations of the ϵ-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±30) followed by an indistinct, martensitic transition zone (HV 420±20) which merges with a poorly resolvable, duplex interior (HV 360±20).

Schreibersite occurs in modest amounts as 5-25 μ wide grain boundary precipitates and 2-20 μ irregular nodules in the plessite interior. Rhabdite prisms 1-2 μ 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 μ 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 μ bluish nodules, some of them with several parallel, 5 μ wide troilite lamellae. Still smaller nodules were found in the comb plessite under such circumstances as to suggest a precipitation from the γ-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±0.5 mm, and sometimes larger variations.

Neumann bands, ϵ-structures, recrystallized and α_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^2 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

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	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	

Figure 442. Canyon Diablo. Meteor Crater facing west. To the right the road leading to the museum on the rim. In background the canyon which has given name to locality. On the horison San Francisco Mountains (3,800 m). Compare Figure 443.

1931), 15,000 tons (Wylie 1943), 5,000,000 tons (Öpik 1936; Rostoker 1953), and 2,600,000 tons (Öpik 1958a). A recent estimate, based upon comparison with nuclear test craters, put the incoming energy equivalent to about 1.7 megatons TNT, which with an assumed velocity of 15km/sec corresponds to a mass of 63,000 tons, or a solid sphere 25 m in diameter (Shoemaker 1963).

The locality had been known to the Indians in precolumbian time, and primitive pit dwellings from the twelfth century have been reported to exist on the outer south slope of the rim. The place was not taboo to the Hopi Indians, and it is quite unlikely that they witnessed the fall (LaPaz 1950; the ruins are marked on the contour map, plate 66, in Merrill 1908). The early pioneers and prospectors in the 1840-1860s knew of the area and the first Canyon Diablo specimen, the 10-pound Ehrenberg mass (see page 401), was brought to the knowledge of science by these people. This was, however, not realized until a century later. In 1871, the locality was called Franklin's Hole by army scouts, and later Coon Mountain or Coon Butte.

The first to describe the meteorites thoroughly was the geologist and mineral dealer, A.E. Foote (1891). He named them Cañon Diablo, after a deep, narrow canyon cutting through the Colorado plateau about 5 km west of the crater and after the post office of the same name at the Santa Fé railway, 17 km northwest of the crater. Foote was unable to explain the existence of the remarkable crater where a careful search had revealed an absence of lava, obsidian and other volcanic products. He made arrangements with the local trading post manager, F.W. Volz, to procure the monopoly on all meteorites recovered during the next year, while under no circumstances could material be sold to his competitor, H.A. Ward.

Because Mother Nature delivered the Canyon Diablo meteorite in the form of conveniently fragmented samples it has been extensively distributed to museums and laboratories all over the World and has been examined in

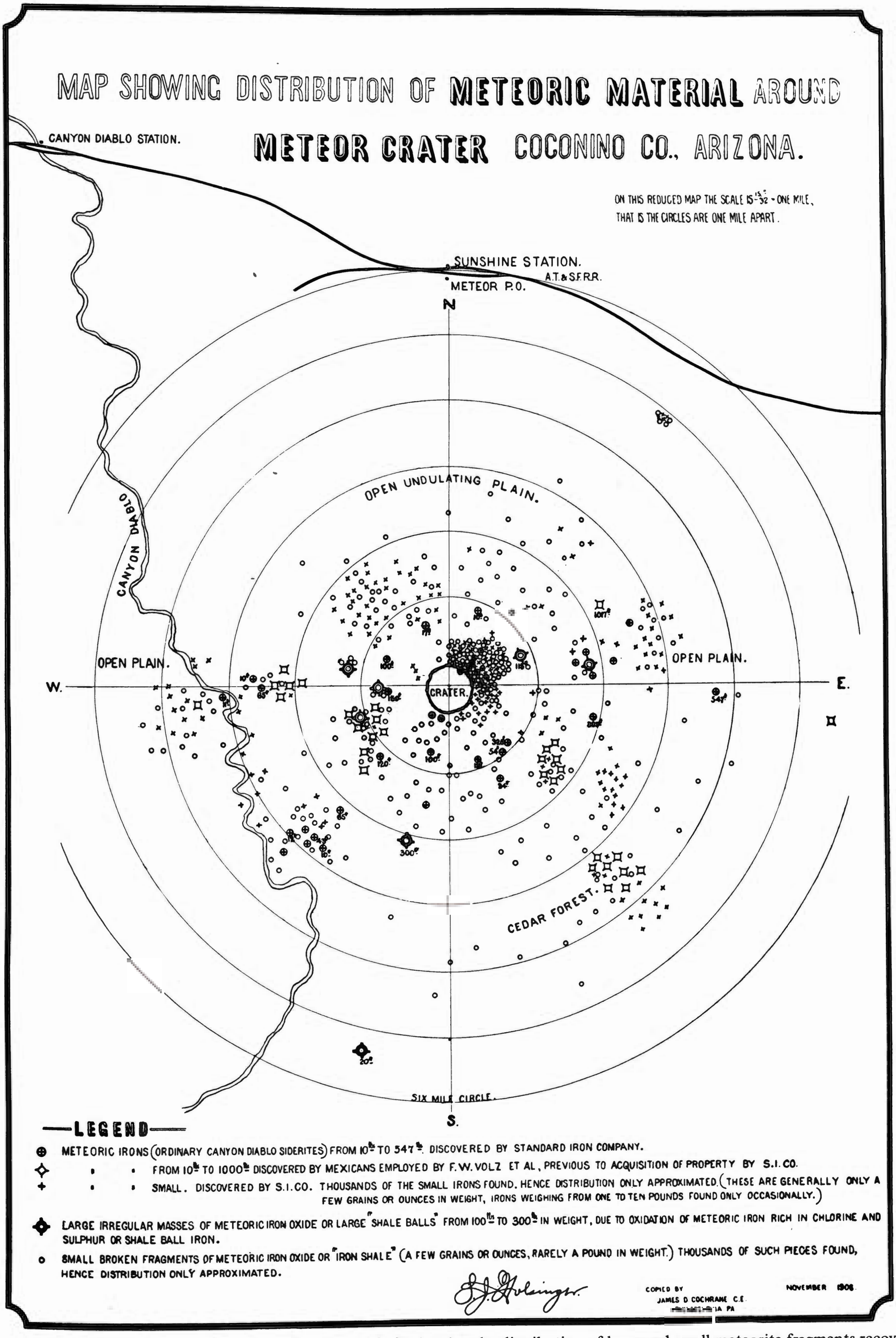

Figure 443. A sketch map by S.J. Holsinger (in Barringer 1909) showing the distribution of large and small meteorite fragments recovered up to that time. Crater in center, the canyon to the West, and one mile between concentric circles.

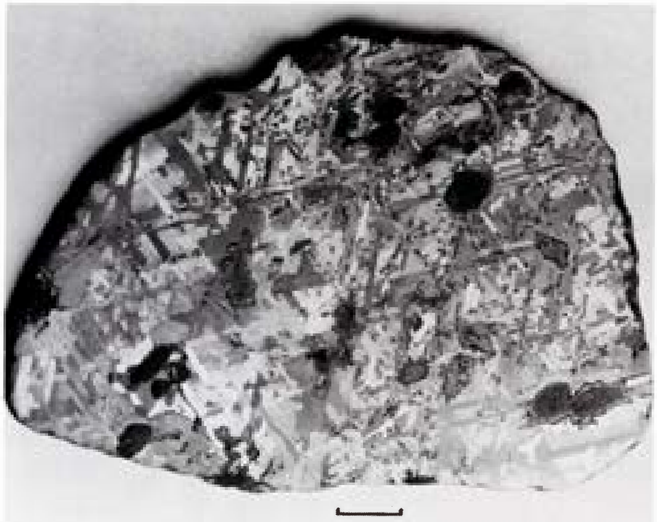

Figure 444. Canyon Diablo. Typical full slice through an unaltered specimen, showing coarse Widmanstätten structure with an oriented sheen. Troilite-graphite-silicate nodules with schreibersite-cohenite rims. Also schreibersite skeleton crystals with cohenite rims and elongated cohenite crystals in Widmanstätten kamacite. Deep-etched. Scale bar 25 mm. S.I. neg. 38866. See also Figure 197.

Figure 445. Canyon Diablo (U.S.N.M. no. 3310). Previously cataloged as Estherville, but erroneously. Large, perhaps oriented troilite-graphite inclusions in an unaltered 57 kg specimen. Deep-etched. Scale bar 50 mm. S.I. neg. 1684.

more detail than any other meteorite. Early descriptions and analyses were presented by Derby (1895), Brezina (1896), Cohen (1900b), Moissan (1904), Merrill & Tassin (1907), Merrill (1908), and Young (1926). Further descriptions were presented by Nininger (1940), Lord (1941), Perry (1944), Nininger (1951), Reed Knox (1954) and Curvello (1958). The recent investigations by Feller-Kniepmeier & Uhlig (1961), Brentnall & Axon (1962), Maringer & Manning (1962), Agrell et al. (1963), El Goresy (1965), Massalski & Park (1966), Heymann et al. (1965), Lipschutz (1965), Walker (1967), Wasson (1967b) and Moore et al. (1967) are of particular value. Radcliffe (1969) pioneered a transmission electron microscopy study of meteorites, by preparing thin metallic films from shocked Canyon Diablo samples.

Professor Koenig stated in Foote's paper (1891) that small diamonds were present, and this was later confirmed from many sides (Mallard & Daubrée 1892; Kunz & Huntington 1893; Huntington 1894; Nininger 1939d).

Figure 446. Canyon Diablo. Typical slice through a small specimen which was reheated during the cratering impact. The kamacite was altered to unequilibrated, polycrystalline aggregates and the meteorite lost its oriented sheen. Deep-etched. Scale bar 10 mm. S.I. neg. M-27.

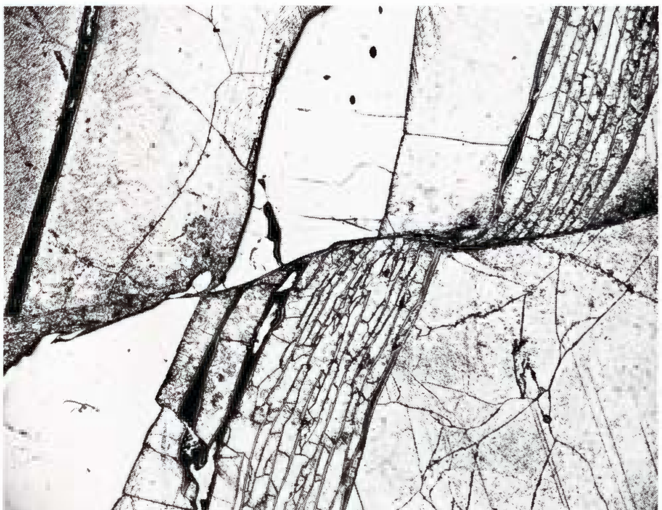

Figure 447. Canyon Diablo. A section through a 100 g slug. A cohenite crystal and the adjacent comb plessite are displaced by heavy shear. Etched. Scale bar 40 μ. (Perry 1944: plate 75.)

Ksanda & Henderson (1939) X-rayed about 50 carbonados 0.1-0.6 mm in diameter and described them as somewhat porous, layered and polycrystalline. Nininger (1952a: 120), when summing up the knowledge gained by cutting Canyon Diablo specimens, stated that the carbonado type diamonds, 0.1-1 mm in diameter, normally occurred in amorphous carbon-graphite-troilite nodules and had been found with a frequency of about 1 per 200 cm^2 cut surface. He also observed (1950a; 1956) that diamonds were only found in fragments recovered from the rim, and furthermore, showed that such meteorites had a reheated, granulated matrix. This observation was confirmed by Lipschutz & Anders (1961) and by Heymann et al. (1966), with one exception. Moore et al. (1967) found no diamonds in 14 meteorites recovered from the plain but did find diamonds in two out of 32 rim specimens which had an accumulated cut surface of 313 cm^2. Since many of the heat-affected specimens contain diamonds, while diamonds have not been found in any of the unaltered fragments, Nininger (1956) suggested that the temperatures indicated were those required to form diamonds from graphite during the passage of shock waves produced in the meteorite upon collision with the Earth. Lipschutz & Anders (1961) and Heymenn et al. (1966) supported this hypothesis, so it is no longer possible to maintain the theory proposed by Urey (1956) that the existence of diamonds in meteorites is proof that the meteorites were formed under high, static pressure.

Frondel & Marvin (1967) showed that many of the carbonados normally accepted as diamonds are, in fact, aggregates of diamond and a hexagonal polymorph of diamond, a new mineral called lonsdaleite. While the aggregates are as large as 0.1-2.2 mm in size, X-ray examination invariably showed them to consist of numerous particles, each only a few hundred Ångströms in size, and without preferred orientation. At the General Electric Company, Bundy (1967) and Hanneman et al. (1967) synthesized the hexagonal diamond by the application of shock to graphite particles. According to them, and using a method patented by Du Pont, the meteoritic diamond-lonsdaleite assemblages were identical to synthetic aggregates produced by shock from graphite particles. The meteoritic aggregates usually contained diamonds and lonsdaleite in the ratio 10:1.

Maringer & Manning (1962) pointed out that the local presence of micromelted sulfide, phosphide and carbide, distant from any atmospheric ablation surface, could also best be explained by attenuation of shock waves to produce local hot spots. If the temperature, as judged by all microstructural evidence, was assumed to be 950° C and of short duration (possibly of the order of a second), it tended to rule out any hope of diamond formation by a diffusion process, while the direct transformation of graphite to diamond (in the presence of nickel-iron as a catalyst) appeared logical.

The cohenite in rim specimens may be micromelted to ledeburitic structures and surrounded by a pearlitic-bainitic rim (Maringer & Manning 1962; Brentnall & Axon 1962; Heymann et al. 1966; Zukas 1969) or it may be polycrystalline, due to lower intensity shock waves which only sufficed to produce recrystallization (Lipschutz & Jaeger 1966; Walker 1967).

The occurrence of silicon carbide as a meteoritic mineral rests solely on Moissan's (1904) identification of it in the insoluble residue from a 53 kg mass. Kunz (1905) named the mineral moissanite in honor of Moissan. Merrill (1930) and Mason (1962a) have, however, pointed out that the mass was cut with a steel band saw which was probably fed with a slurry of carborundum, introduced as an abrasive in 1893. It is probably safe to conclude that Moissan's residue was contaminated by this carborundum abrasive. The alleged mineral has never again been reported by any of the numerous investigators of Canyon Diablo, nor has it been observed in any other meteorite (Mason 1967a).

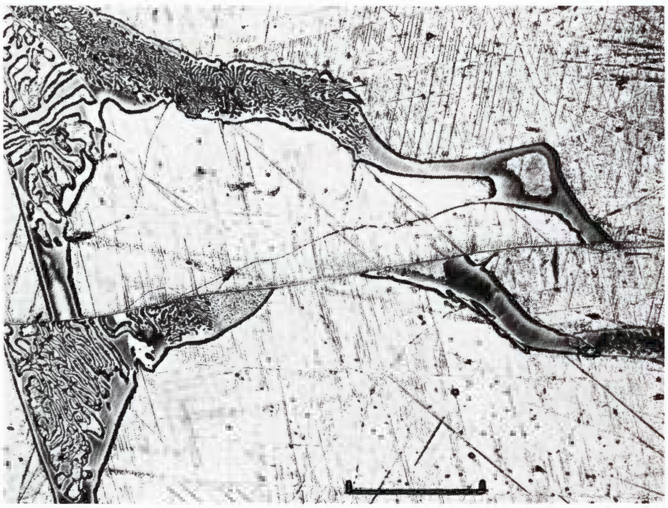

Figure 448. Canyon Diablo. A section through a 100 g slug. Shear-displaced pearlitic plessite field. The shear has here occurred within a very narrow zone, less than 10 μ. Etched. Scale bar 300 μ. (Perry 1944: plate 75.)

Figure 449. Canyon Diablo (Copenhagen no. 17,270). Shock-hardened specimen of 420 g, of transformation stage II. The macrostructure changes from centimeter to centimeter within the same sample. Here, Neumann bands, deformation bands, Neumann bands with "bristles," and recrystallized shear zones (right) alternate. Etched. Scale bar 300 μ.

Canyon Diablo has been included in numerous works on the age of iron meteorites and of cosmic irradiation ages, e.g., by Patterson (1956), Fireman & DeFelice (1960), Fisher & Schaeffer (1960), and Voshage (1967). Heymann (1964) concluded that the so-called Canyon Diablo No. 2 and No. 3 masses (Nininger 1940b; 1950a; 1951) came from the interior of the single main Canyon Diablo mass and were exposed to cosmic ray irradiation for the same length of time (about 540 million years) as the main mass. Lipschutz (1965) showed that both No. 2 and No. 3 exhibited moderate to high shock structures similar to other rim specimens and, therefore, must have been located in the interior of Canyon Diablo at the instant of its explosion. Wasson (1967b), measuring simultaneously Ni, Ga and Ge, came to the same conclusion, and Moore et al. (1967), analyzing a selection of plains and rim specimens, showed that the rim specimens especially showed a significant variation in nickel content large enough to incorporate the No. 2 and No. 3 specimens which are of higher nickel content than the average. In other words, it is now a well established fact that the Canyon Diablo mass varied in composition from 7.0 to 8.2% Ni with accompanying bandwidth variations from about 2.2 to about 1.2 mm, within a few tens of meters.

Meteor Crater has the form of a great bowl with rather steep, locally vertical interior sides and with a floor about 130 m below the surrounding arid plain which is thinly covered with sagebrush and other low shrubs. The rim rises only 40-65 m above the plain, and the diameter of the crater is about 1,200 m. On an aerial photograph it is seen to have a somewhat squarish outline (Zimmerman 1948), apparently due to the nature and composition of the bedrock. What we know of the crater's interior, substructure and immediate surroundings is largely due to Barringer and coworkers. Recently the geological setting and the mechanism of crater formation has been excellently presented by Shoemaker (1963).

Gilbert, who was the first to propose seriously a meteoric origin for the craters *on the Moon*, concluded hesitatingly after a close investigation (1896) that the *Arizona crater* was the result of a violent steam explosion. Gilbert's conclusion or similar geological explanations were accepted in geological works by Barton (1916), Dellenbaugh (1931), Hager (1953) and others. Nevertheless, the postmaster general must have been convinced of the meteoritic theory at an early stage because a post office named Meteor Crater was established before 1906.

The discrediting of the impact idea by leading geologists did not discourage a group headed by the lawyer and mining engineer D.M. Barringer from staking a claim to the crater in 1903 and organizing an exploration company, the Standard Iron Company. Assays of recovered meteorite specimens had yielded an average of 7% nickel and 10 g per ton of platinum metals, and it was, therefore, thought

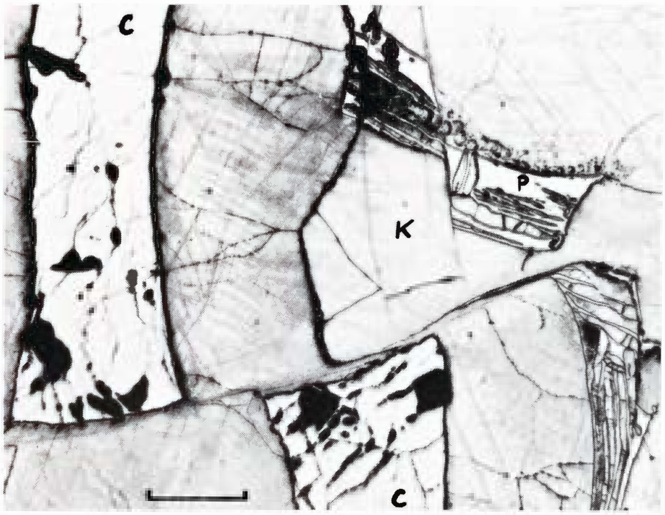

Figure 451. Canyon Diablo. Stage II, as Figure 449. Complex shear in two directions almost perpendicular to each other. Cohenite (C), plessite (P) and shock-hardened kamacite (K). Etched. Scale bar 400 μ.

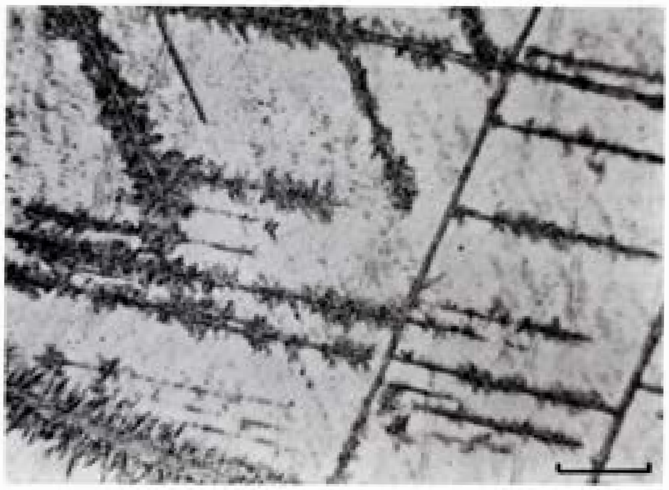

Figure 450. Canyon Diablo. Stage II, as Figure 449. Detail of "Neumann bands with bristles." Etched. Scale bar 40 μ. See also Figure 120.

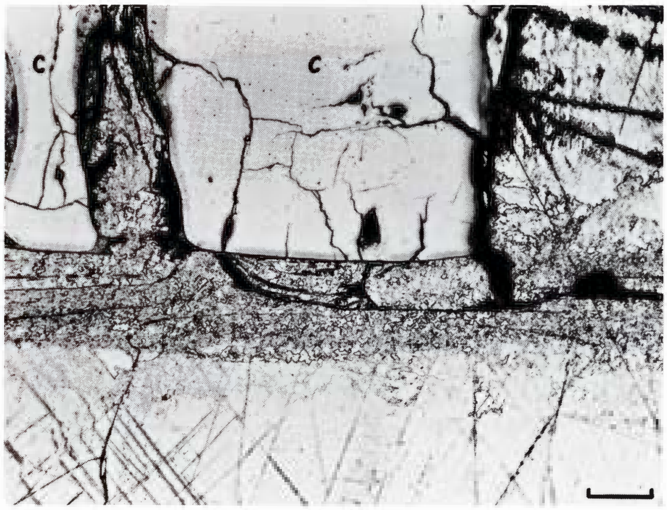

Figure 452. Canyon Diablo. State II as Figure 449. A recrystallized shear zone similar to that of Figure 451, with cohenite above. Etched. Scale bar 100 μ.

profitable to dig and drill the large main mass or cluster that was supposed to be hidden somewhere in the crater. Since there are no deposits of nickel in the U.S.A., the excavation promised to be beneficial and attracted various mining and smelting companies from time to time. Reports by Tilghman (1905) and by Barringer (1905; 1909; 1914; 1924) testify to the will and sacrifices of these groups, and their endeavours command respect. By 1909 a total of 28 drill holes had penetrated the crater floor to a depth of 250 m, and it became clear that the white Coconino sandstone had been crushed by the impact to a "rock flour" of subangular quartz grains which passed the 200 mesh sieve. The underlying Supai sandstone was, however, undisturbed.

It was also shown that part of the Coconino sandstone had been transformed to a vesicular, pumice-like material which occasionally showed glass-like threads. Rogers (1930) described this as a silica-glass, lechatelierite, and concluded, as did Barringer, that it was formed by shock melting of the quartz sand upon the meteoritic impact, in other words was a true impactite somewhat similar to those from Henbury and Wabar. Nininger (1952a; 1956) later collected and examined large numbers of impactites. The metamorphosed sandstone grains were found to be stained by iron oxides, presumably because they had become coated with metal from the iron-nickel vapor. In 14 of the drill holes tiny grains, which gave positive reaction for nickel and phosphorus, were found, and Tilghman (1905: 908 f.) reported that the drilling was often extremely difficult, due to the presence of scattered larger fragments of meteorites. It must have been a tremendous task, with the tools of those days, to penetrate even a small chunk of Canyon Diablo, which is hard, tough, and loaded with cementite and sometimes with diamond.

The last large scale drilling operation, begun on the south rim about 1920, reached a depth of 412 m in August 1922 when it was announced that the main mass had been struck (Barringer 1924). On this point opinions are still divided, but this much is clear: iron fragments were encountered with increasing frequency as the drill progressed below 300 m before it finally became stuck and was lost. In 1929, D.M. Barringer died, and, at the same time, all shaft and drilling operations were abandoned because of difficulties with ground water and quicksand. At this point, more than $600,000, exclusive of interest, had been spent on the exploration, including over $120,000 of Barringer's personal funds (B. Barringer 1964). Magnetometer and other geophysical methods were then applied (Jakosky et al. 1932; Brereton 1965) leading, however, to contradictory results. Recently, Crowson (1971) has discussed previous results and ideas related to the fate of the impacting main mass. He seems to favor the proposal by Barringer and others that a mass of perhaps one million tons is to be located beneath the crater floor and outlines a method for an exact determination and location of the residual mass. The U.S. Geological Survey (Roddy et al. 1971) had, in 1971, completed 76 rotary drill holes in the rim of the crater to provide a basis for structural mapping.

Surface exploration and mapping has in the meantime continued. The use of mine detectors and similar instruments in the search for lightly buried meteorite fragments has proved very successful (Nininger 1952a: 214). At an early date small samples were found near the crest of the rim and larger ones on the plain beyond the rim (Holsinger's map in Barringer 1909), but Nininger (1951) showed that the large meteorites on the plains were usually associated with small ones, while large meteorites were totally absent on the rim.

Shatter cones have not been discovered in connection with the crater, probably because erosion has not yet

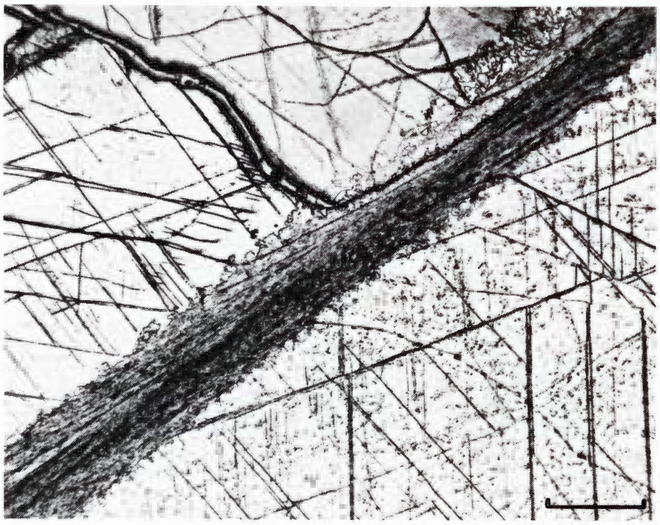

Figure 453. Canyon Diablo. Stage II, as Figure 449. A 200 μ wide shear zone in kamacite within which the displaced grain boundaries and taenite lamellae may still be indistinctly followed. Etched. Scale bar 200 μ.

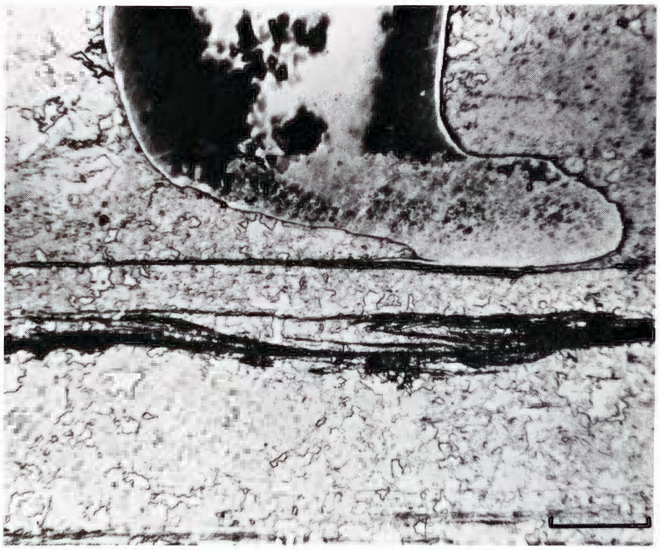

Figure 454. Canyon Diablo. Stage II, as Figure 449. Cloudy taenite (above) adjacent to a shear zone in kamacite (lower part of picture). The taenite has been displaced and significantly reheated in the same way as the kamacite and thereby has lost its cloudy appearance. Melted and smeared troilite occurs within the horizontal dark streaks in the kamacite. Etched. Scale bar 40 μ.

exposed the proper, deep-seated rocks. Coesite, the high pressure polymorph of SiO_2, has, however, been identified as an abundant 5-50 μ mineral in the crushed Coconino sandstone of the crater (Chao et al. 1960). A few years later stishovite (Chao et al. 1962) was also identified but only in minor amounts. Stishovite occurs as submicron particles but was identified by its X-ray powder-diffraction pattern. From the dimensions of the tetragonal cell, the specific gravity was calculated to be 4.28, which is about 45% denser than coesite.

The best estimate of the age of the crater is 20,000 years based on erosion and general geological features. The ground water level has – while the crater has existed – been at least 70 m above what it is now because 20-30 m lake sediments have been identified in the crater (Tilghman 1905).

For fuller history and bibliographical notes the reader is referred to Wülfing (1897), Farrington (1915), Barringer (1905; 1924), Merrill (1908; 1920), Spencer (1933), Boon & Albritton (1936; 1937), Locke (1942), Nininger (1951; 1952a; 1956), Foster (1957), Walton (1959), Shoemaker (1963), B. Barringer (1964), Hey (1966: 83, 552), Krinov (1966a: 78), and Crowson (1971). From these reviews, chronologically listed, the reader may acquire an interesting insight into the history of Meteor Crater and the men and meteorites associated with it.

Meteor Crater is owned by Meteor Crater Enterprises, i.e., the Barringer family, and they have a 199 year lease on the property. A museum has been built on the North rim and over 140,000 tourists are welcomed annually to the Crater after crossing northern Arizona on highway 40 between Flagstaff and Winslow (B. Barringer 1964). The income from Meteor Crater Enterprises is used to investigate the crater, to maintain the museum and to yield support to scientists interested in meteoritics. The present author gratefully acknowledges the financial support made to him in the spring of 1970.

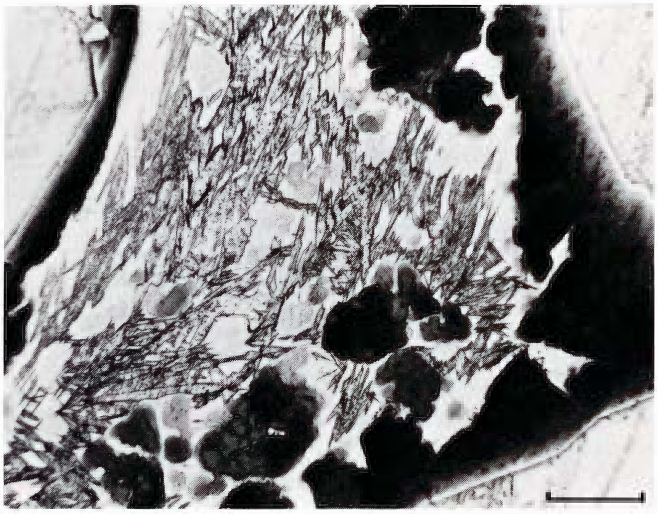

Figure 455. Canyon Diablo. Stage II, as Figure 449. Cloudy taenite and acicular martensite. Etched. Scale bar 40 μ.

COLLECTIONS

Chicago (1,744 kg; maximum 460 kg), Washington (1,675 kg; maximum 452 kg), Meteor Crater Museum (unknown total; maximum 639 kg), Los Angeles (1,196 kg), Tempe (790 kg, maximum 140 kg), New York (593 kg; maximum 493 kg), Denver (five masses, each of about 100 kg), Paris (380 kg mass in Colonel Vésignié's collection; 26 kg in Jardin des Plantes), Amherst (313 kg; maximum 310 kg), Yale (380 kg; maximum 375 kg), Budapest (306 kg; maximum 287 kg), Fred Harvey Indian Building, Albuquerque (283 kg), San Francisco Bay Region (280 kg, see Linsley 1934), Stockholm (225 kg; maximum 193 kg), Vienna (197 kg; maximum 174 kg), London (188 kg; maximum 98.6 kg), Tucson (136 kg mass), Ann Arbor (118 kg mass), Albuquerque (about 100 kg), Hamburg (95.7 kg), Yorktown, Texas (80 kg, see Scherz, (page 406), Harvard (79.9 kg), Prague (69.6 kg), Fort Worth

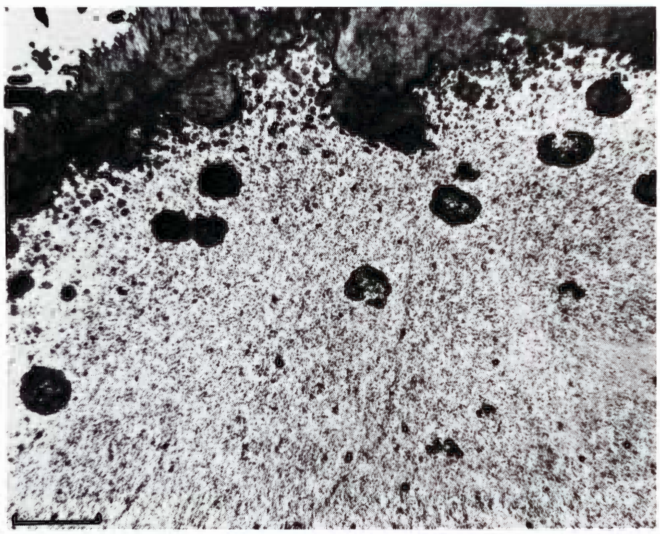

Figure 456. Canyon Diablo. Stage II, as Figure 449. Troilite nodule with graphite rim and several imperfect graphite spherulites. Polished. Scale bar 500 μ.

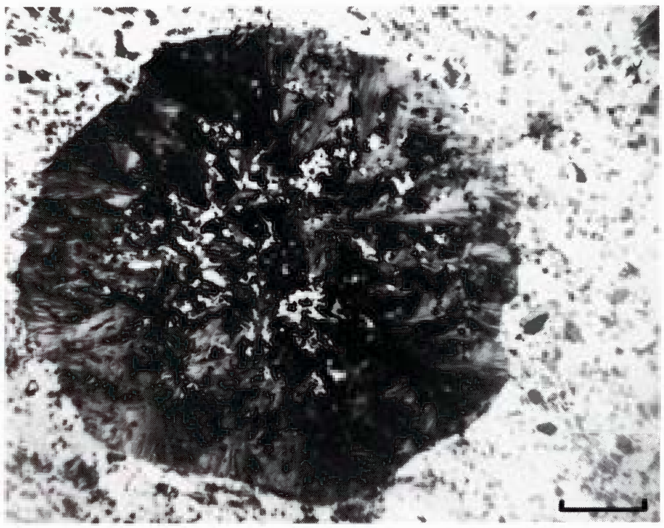

Figure 457. Canyon Diablo. Stage II, detail of Figure 456. One large and several small graphite spherulites in recrystallized troilite. Slightly crossed polars. Scale bar 50 μ.

(50 kg), Leningrad (33.6 kg), Bonn (24.7 kg), Bally (20.6 kg), Tübingen (17.9 kg), Göttingen (13.6 kg), Copenhagen (11.4 kg), Rome (11 kg), Moscow (10 kg), Dresden (9.5 kg), Canberra (5.6 kg), Milano (4.9 kg), Vatican (4.8 kg), Oslo (3.5 kg), Ottawa (3.3 kg), Uppsala (2.0 kg), Berlin (1.7 kg), Strasbourg (1.3 kg). Specimens are also to be found in numerous other collections, both public and private, all over the world. In the American Southwest, large and small masses are particularly often seen, e.g., in the Museum of Northern Arizona at Flagstaff, South Rim of Grand Canyon National Park, and many other National Parks and National Monuments. Additional transported masses are listed separately at the end of Canyon Diablo, (page 398). No other meteorite has been so well distributed. A 212.8 kg mass formerly in Philadelphia (Gordon 1933) is now lost, apparently stolen (R.W. Barringer 1962).

The cumulative weight of the samples in public collections listed above is about 11.5 tons.

Figure 458. Canyon Diablo (Yale no. P400). A 375 kg mass displaying several cavities and holes. The surface of the meteorite is very well preserved, displaying regmaglypts and weathered fusion crust. The ruler, which is inserted under the "bridge," measures 15 cm.

DESCRIPTION

The largest recovered single specimen weighs 639 kg and has the maximum dimensions of 90 x 70 x 35 cm. It was found in 1911 about 2.5 km north-northeast of the crater rim, and is now exhibited in the museum on the north rim (Barringer 1914: 559; Foster 1957: figure on page 13). A mass of 248 kg was discovered before 1909 6 km east of the crater rim (Barringer 1919: map and figure on plate 18). Another large mass, of 460 kg, was discovered before 1909 3.5 km east-northeast of the crater rim and purchased by the Field Museum in Chicago. Other large masses recovered from the plain at distances of 2-8 km from the crater rim are the 493 kg specimen in New York (no. 2235, 67 x 55 x 35 cm), the 375 kg specimen in Yale (no. P400, 55 x 50 x 40 cm), the 310 kg specimen in Amherst (no. 627, 55 x 45 x 30 cm), the 136 kg specimen in Tucson (no. 7639, 45 x 45 x 28 cm), and the three large masses in Washington (no. 198 of 338 kg; no. 210 of 435 kg; and no. 857 of 452 kg). Additional large specimens are mentioned above under collections, and still others are

CANYON DIABLO – SELECTED CHEMICAL ANALYSES

The two sets of analyses by Moore et al. are averages of tests made on 14 plains and 32 rim specimens. The analyses indicate a slight difference between the plains and rim population. The total range in nickel content is surprisingly large, from a minimum of 6.37% Ni to a maximum of 9.13% Ni. The rim population, in particular, displays this large range. Unfortunately, no bandwidth measurements were reported for the analyzed samples. In selecting the most suitable average nickel value for the Canyon Diablo material, I have followed Moore et al. (1967) who, on the basis of numerous analyses, chose 7.10% Ni. The cobalt values of Moore et al. are systematically lower than previous values which is consistent with Moore's cobalt values on most other iron meteorites. This seems to reflect a superior analytical technique in separating Fe, Ni and Co. See also the many analyses reported under transported masses, originally assumed to be independent meteorites, such as Ashfork, Bloody Basin etc.

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Whitfield in Merrill 1916a	7.33	0.51	0.26	1380	90		150					
Goldberg et al. 1951	7.18	0.50							76			
Lovering et al. 1957		0.49				7.4	157		74	283		
Smales et al. 1967					13	9.4	125	29	79.7	322		
Moore et al. 1967, plain specimens	7.10	0.40										
Moore et al. 1967, rim specimens	7.40	0.39										
Wasson 1970a	6.98								81.8	324	1.9	
Crocket 1972											2.0	8.0
De Laeter 1972												
Rosman 1972								49	8.47			

in the possession of private collectors or have been extensively sectioned.

Common to most of these large masses, group I below, is the rounded subangular shape and the presence of regmaglypts. In diameter the regmaglypts are about one-tenth of the size of the mass and correspond closely to the regmaglypts on normal single falls. In some cases, an anterior domed surface with small regmaglypts and a posterior rather flat surface with large shallow regmaglypts may be identified, indicating oriented stabilized flight. Terrestrial corrosion has often modified the surface morphology. However, on, e.g., Yale no. P400, and Washington no. 198 and no. 210, large parts of the surface are quite unaltered and fusion crusts may even be detected locally. Cylindrical holes 2-6 cm in diameter indicate where troilite nodules burned out, and straight "chisel scars," 10 x 1 mm in size, indicate where schreibersite lamellae burned out. Normal 2 mm wide heat-affected α_2 zones are disclosed upon cutting.

These large masses seem to have had independent long flights through the atmosphere. They are believed to have separated from the incoming main mass at an early stage, and, thus, to be rather unaffected by the impacting crater event. They may, however, still have been in the last part of their fall when the explosion wave from the impact roared outwards and passed them. This event may have slightly influenced their path and their surface morphology.

The explanation by Krinov (1966a: 108) and others that these lightly shocked, almost unaltered, blocks should be the inner unweathered parts of originally much larger masses is in complete opposition to the facts which clearly indicate that virtually nothing is lost due to corrosion.

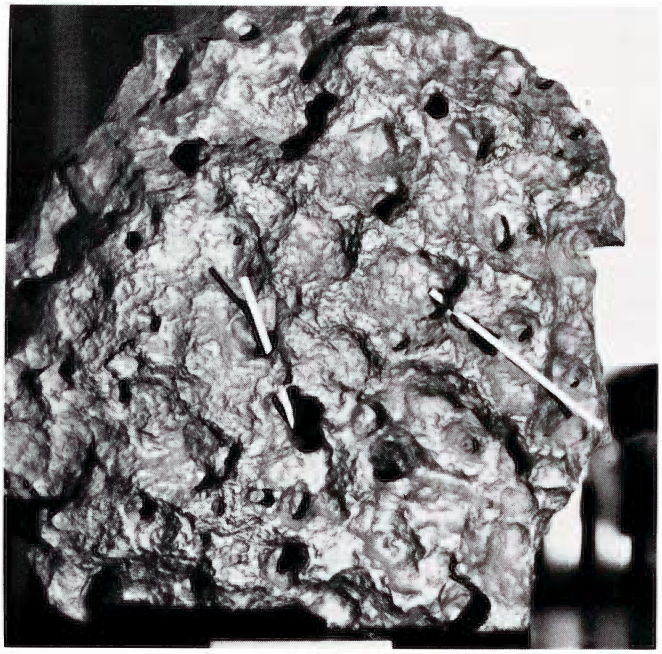

Figure 459. Canyon Diablo (U.S.N.M. no. 857). A 452 kg mass in the Smithsonian Collection, with holes and cavities. The ruler to the right measures 20 cm. S.I. neg. 41402B.

In the following, typical Canyon Diablo specimens will be examined. The described samples range in weight from 50 g to 452 kg and are believed to be reasonably representative of the variation in morphology, structure, composition and impact history. The primary cosmic structure is common to all samples; and since this structure is believed to be best exhibited in the large masses from the plain, these are described first. The alterations will then be treated with examples of smaller masses and the so-called slugs which are believed to be surviving fragments from the explosion.

I. Original unshocked material. Usually large masses, 5-500 kg in size, recovered from the plain. The group

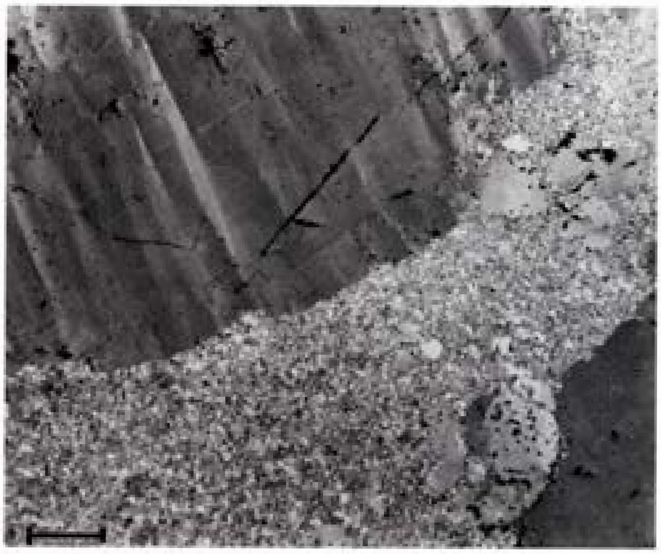

Figure 460. Canyon Diablo (U.S.N.M. no. 1530). Shock-annealed, stage III. Detail of a large troilite nodule. The parts on right and left show deformation and undulatory extinction. These blocks are separated by fine-grained, melted sulfides. Polished. Slightly crossed polars. Scale bar 100 μ.

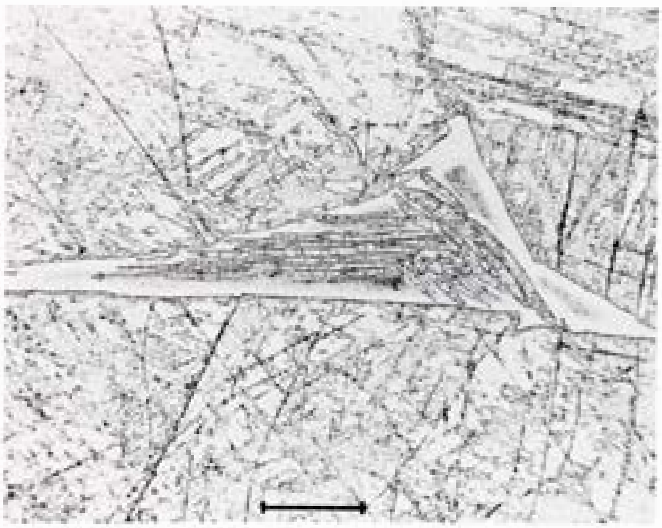

Figure 461. Canyon Diablo (Tempe & Copenhagen no. 34.4040). Shock-annealed, stage IV. Recrystallized to unequilibrated, serrated kamacite grains. Previous Neumann bands are distinct. Tempered comb plessite. Etched. Scale bar 300 μ.

corresponds to the lightly shocked category of Heymann et al. (1966). Within this category are the following examples in the Smithsonian Institution: no. 857 (452 kg), no. 210 (435 kg), no. 198 (338 kg), no. 3310 (57 kg), and numerous large sections through various masses. In many instances the recovered massive meteorites display caliche crusts. The caliche has usually formed on the slightly buried underside, while the topside may be clean and only little altered by corrosion.

Etched sections display a coarse Widmanstätten structure of straight, somewhat bulky ($\frac{L}{W} \sim 10$) kamacite lamellae with a width of 2.0±0.5 mm. Locally, late grain growth has caused the formation of almost equiaxial kamacite grains 5-15 mm across. The kamacite nucleated early and grew to rims of swathing kamacite, 2-10 mm wide, around troilite aggregates and schreibersite skeleton crystals. It is rich in subboundaries decorated with 0.5-2 μ phosphide precipitates, and the oriented sheen is very well developed. Neumann bands occur in profusion; they are straight, and they are indistinctly decorated along both sides with less than 0.5 μ phosphides. The decorated and, thus, slightly annealed Neumann bands, seem to be a preatmospheric feature because the "fossil" remains may be found in the heat-affected α_2 rim zones. The hardness of the kamacite is 190±20. This is somewhat above the hardness of fully annealed material (145) and suggests slight cold working, possibly associated with the atmospheric breakup.

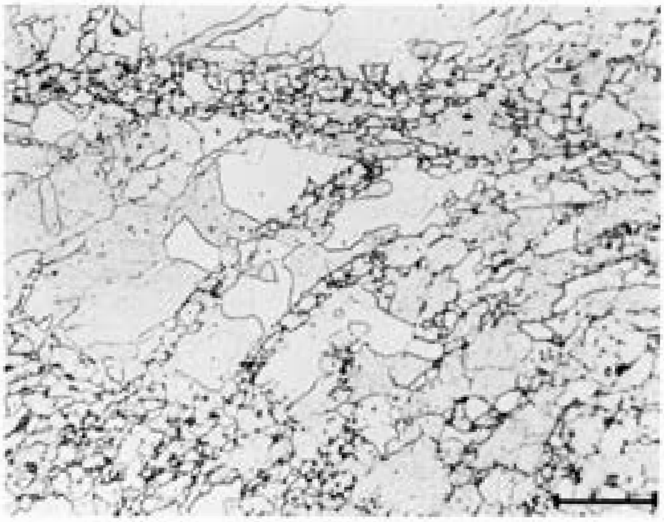

Figure 462. Canyon Diablo. Stage IV, as Figure 461. Detail of recrystallized kamacite with indications of previous bent Neumann bands. Etched. Oil immersion. Scale bar 20 μ.

A search was made for indications of polycrystallinity in the original parent body. The result was negative; no large sections showed high temperature austenite boundaries. The original grain size must thus be estimated to have been at least 50 cm.

Taenite and plessite cover 1-4% by area, as comb plessite, pearlitic and spheroidized plessite, and as acicular varieties with retained austenite. The taenite lamellae and the taenite rims of plessite fields are cloudy, stained in brownish-blue colors and relatively hard, 300±50. There is, as usual, a very narrow, 1-2 μ wide, exterior yellow taenite zone, which is apparently homogeneous, high-nickel (possibly 45%) taenite. The wider taenite lamellae are usually decomposed to pearlitic structures with 0.5-2 μ wide γ-lamellae (HV 210±30) or to spherulitic plessite with 5-20 μ spheroidized γ-particles in kamacite. The acicular fields display martensitic transformation products and 2-10 μ wide pointed kamacite spindles.

Schreibersite occurs as cuneiform or lamellar skeleton crystals that can attain sizes of 60 x 30 x 1 mm or 5 x 4 mm, but usually they are 20 x 1, 3 x 2 mm, etc. Schreibersite also forms continuous, but irregular, 0.5-2 mm wide rims around all troilite aggregates. The schreibersite is monocrystalline but brecciated and often shear-displaced in 5-20 μ steps. Its hardness is 925±50. Schreibersite is also common as 20-100 μ wide grain boundary veinlets and as 5-50 μ particles inside some plessite fields. Rhabdites, 1-25 μ across, occasionally as

Seven Stages of Shock-Transformation in Canyon Diablo

Classification	Kamacite HV (100 g)	Kamacite Structure	Taenite HV (50 g)	Troilite	Cohenite Structures	Schreibersite	Estimated residual Bulk Temperature
"Unshocked" I	170-210	Np	250-350	M, (U), (E)	M	M	< 400° C
Shock-hardened II	250-370	ε, Nb	360-440	M,U,E	M	M	< 400° C
	200-250	N					
	170-210	r					
Shock-annealed III	145-210	Np,r	200-280	M,U,E	M	M	~ 500° C
Shock-annealed IV	145-210	R,Np	160-200	E	M	M	> 600° C
Shock-annealed V	150-165	α_2	148-190	(E)	R,D	M,T	> 750° C
Shock-annealed VI	150-170	α_2	150-170	(E)	R,D	R,T	> 900° C
Shock-melted VII	155-175	α_2	n.d.	(E)	E	E	> 1050° C

Symbols: Np – Neumann bands with < 1 μ precipitates; ε – hatched shock-hardened kamacite; Nb – Neumann bands with bristles, probably of fine martensite; N – normal Neumann bands; r – recrystallized along shear zones; R – wholly recrystallized; α_2 – diffusionless transformation from γ to α_2; M – monocrystalline; U – undulatory extinction; E – eutectics; D – diffusion of carbon has produced black halos around cohenite; T – thorns around schreibersite.

much as 50 μ across, are common, particularly in samples which contain little cohenite. The bulk phosphorus content is estimated to be 0.25±0.05%, in harmony with the wet chemical analyses.

Troilite occurs as 2-50 mm nodules or as 40 x 10 mm lenticular bodies, elongated in one direction. The troilite is either pure, or it contains varying proportions of graphite, daubreelite, chromite, sphalerite, ureyite (Frondel & Marvin 1967) and silicates. El Goresy (1965) and Bunch & Keil (1969) made a thorough study of these and also reported some accessory minerals, such as rutile, chalcopyrrhotite and mackinawite. Olsen & Fuchs (1968) reported a new mineral, krinovite, $NaMg_2CrSi_3O_{10}$. During the present study other accessory minerals were also noted, but not identified.

Point counting of several large sections totaling 1,620 cm^2 showed an average of 8.5% by volume of troilite-graphite aggregates. About half is troilite corresponding to a bulk sulfur weight percentage of 0.9-1% for the whole meteorite. The amount of troilite and other minerals is best estimated from sections cut through large unaltered masses. The small fragments are anomalously poor in minerals, presumably because the fractures caused by impact followed the minerals, so that these became preferentially lost in the process.

A typical undamaged nodule will exhibit a monocrystalline troilite nucleus, 20 mm wide and surrounded by a 5 mm annular mixed zone of graphite and troilite, and an exterior 1 mm wide rim of almost pure coarsely crystalline graphite. Some of the graphite occurs as distinct cliftonitic units, 30-100 μ across. Parallel daubreelite bars, 1-100 μ wide, are exsolved parallel to (0001) of the troilite. The whole aggregate has served as a nucleating substrate for the precipitation of schreibersite, cohenite and kamacite. It appears that the troilite nodules of some samples are only little damaged, displaying monocrystalline units with undulatory extinction, while in other samples it is shock melted to varying degrees. It is likely that an examination of several nodules from the larger masses will show a systematic variation.

Cohenite is common, both as 50-300 μ wide rims around the troilite-schreibersite nodules and the schreibersite skeleton crystals, and as rounded 3 x 0.5 mm crystals precipitated in the Widmanstätten kamacite lamellae. Here cohenite is usually closely associated – and often in contact – with taenite and plessite fields which are in the process of being resorbed. The cohenite is monocrystalline, hard (1080±50), and displays the usual 5-200 μ windows of kamacite, taenite and schreibersite. In some samples, about one out of five, the decomposition to ferrite and graphite has begun. This must have been a preatmospheric reaction that probably occurred in space in cracked near-surface parts of the meteorite. Various characteristics in the microstructure indicate that it originated before the impact.

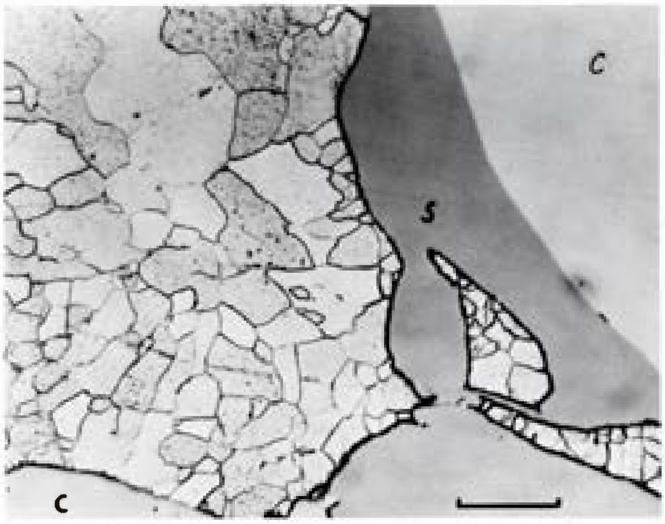

Figure 464. Canyon Diablo. Stage IV, as Figure 461. Cohenite (C) with rim precipitates of schreibersite (S) and recrystallized kamacite. Etched. Oil immersion. Scale bar 20 μ.

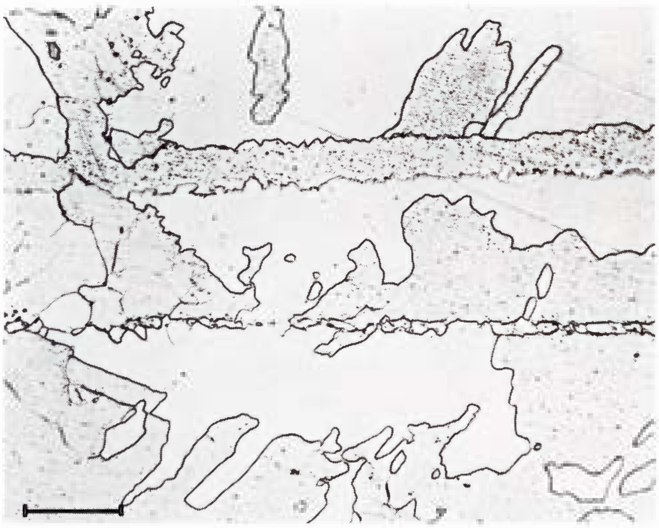

Figure 463. Canyon Diablo. Stage IV, as Figure 461. Two horizontal Neumann bands and irregular recrystallization. Etched. Oil immersion. Scale bar 20 μ.

Figure 465. Canyon Diablo. Stage IV, as Figure 461. Retained austenite (white) with tempered martensite platelets. Etched. Oil immersion. Scale bar 20 μ.

Haxonite, newly established as a mineral by Scott (1971), occurs in many of the duplex plessite fields. It is a face-centered cubic carbide $(Fe,Ni,Co)_{23}C_6$ with a = 10.546±0.003 Å. Its powder pattern is closely related to the X-ray pattern of the artificial carbides $Mn_{23}C_6$ and $Cr_{23}C_6$ known from tool steels and stainless steels. On polished sections it has a creamy white shade, midway between the colors of kamacite and schreibersite, and it strongly resembles cohenite. It is, however, easily distinguished under crossed Nicols because it is isotropic as opposed to cohenite (and schreibersite). It stands out in high relief above the surrounding kamacite and taenite because of its hardness, 900±100, which, however, is significantly lower than that of cohenite. According to Scott, typical haxonite crystals in Canyon Diablo, precipitated within 2 x 1 mm duplex plessite fields, contained 89.2±0.2% Fe, 4.98±0.09% Ni, 0.19±0.03% Co, and – by difference – 5.6% C. The haxonite precipitates of Canyon Diablo are typical for a large number of other haxonite occurrences in group I irons, such a Bahjoi, Bendegó, Bischtübe, Bogou, Goose Lake, Odessa, Seymour, Toluca and Youndegin, and in other irons such as Carbo, Carlton, Edmonton (Ky), Mbosi, Murnpeowie, Rhine Valley, Silver Bell and Lime Creek.

Chromite occurs locally, either free in the kamacite or as inclusions in the troilite aggregates, as 50-500μ subangular crystals.

Silicates are present in Canyon Diablo but not to the extent known in, e.g., Odessa, Toluca and Campo del Cielo. They consist of spongy intergrowths of plagioclase, olivine and pyroxenes which usually attain sizes of 50 μ-1 mm and are normally to be found in the troilite-graphite nodules. Where the troilite nodules are shock melted, the silicates are sheared and dispersed through the eutectics; maskelynite, i.e., plagioclase glass, is apparently present in the fissures of the plagioclase. The silicates of Canyon Diablo have been studied very little. Because of the lack of a thorough discussion of Canyon Diablo material, the reader is referred to the paper by Marshall & Keil (1965) which deals with Odessa – in my opinion a very similar case.

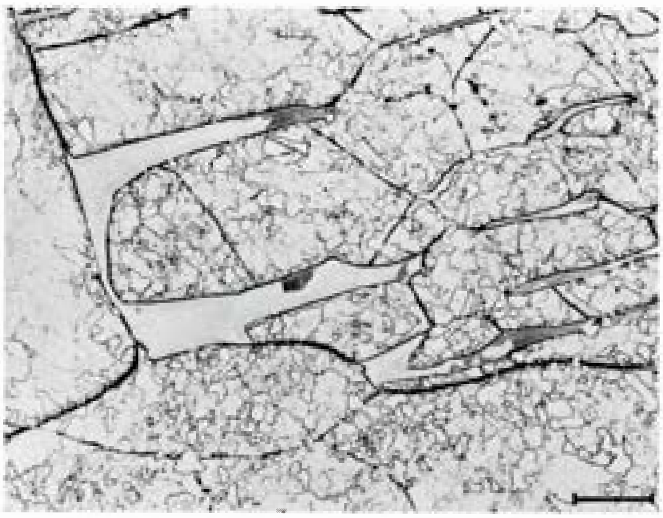

Figure 466. Canyon Diablo (Tempe & Copenhagen no. 34.4045). Shock-annealed stage V. A diamond was identified in this sample. The kamacite displays unequilibrated α_2 structures, and the cloudy taenite has given way to a yellow mosaic pattern. Compare Figure 114. Etched. Scale bar 100 μ.

Many of the large masses are so well-preserved that regmaglypts and heat-affected α_2 zones are still preserved. For example, the 1.5-2.5 mm wide α_2 zone on no. 198 shows the usual ragged α_2 crystallites (HV 200±15), and micromelted phosphides are present in the exterior half. At this particular place the meteorite has lost less than 0.5 mm by exposure to the terrestrial environment. In the recovered transition zone the hardness drops to 160±10 (hardness curve type II). Locally there are near-surface indications of violent cold-deformation, with tearing of the brittle inclusions and distortion of the metallic matrix. It appears that these zones, which are cold-worked to excessive hardnesses of 250±15, indicate where the fracture took place by complex shear forces during the atmospheric flight. The damage is quite superficial as opposed to the damage on the smaller fragments discussed below. Number 3310 is so well-preserved that it passed for an Estherville specimen for three generations. (The Estherville mesosiderite fell in 1897.) The specimen was for a long time a part of the University of Minnesota collection, and it was not until it was transferred to the Smithsonian Institution in 1967 that it attracted the curiosity of Roy S. Clarke, jr., because of its high specific gravity which was unexpected for a mesosiderite. Cutting revealed it to be a typical Canyon Diablo mass! (Figure 445.)

The shock structures in this type of material, i.e., the decorated Neumann bands and the brecciated minerals, are believed to date back to cosmic events, long before the impact in Arizona.

The large masses have preserved the original cosmic primary structure quite well. Canyon Diablo is closely related to many other coarse octahedrites with silicate inclusions, such as Odessa, Cranbourne, Smithville, Jenny's Creek, and, among recent falls, Bogou. Other recent falls of group I, Mazapil, Bahjoi and Yardymly, differ in one or more respects from Canyon Diablo.

II. Shock-hardened masses. Usually 50 g-1,000 g weight, coming from either the plain or the rim. The samples examined here were from the Arizona State University Collection, and from Copenhagen (no. 17270; 420 g). These samples are typical and correspond to numbers 2,3,5,20,35 and 54C, of Heymann et al. (1966), i.e., their moderately shocked category. They apparently also correspond to samples examined with the microprobe by Axon & Boustead (1967) who found no diffusion across kamacite-taenite interfaces.

First of all, it should be noted that these specimens vary surprisingly in character from centimeter to centimeter within the same polished and etched section. The kamacite displays normal Neumann bands (HV 200-250) which grade into Neumann bands with "bristles" (HV 240-300), which again are substituted by hatched ϵ-structures and dirtybrown-etching kamacite (HV 275-370). Lenticular deformation bands occur locally, and severe shear zones, 2-250 μ wide, cross the entire specimens. The taenite and plessite fields may be abruptly shear-displaced at least 1 mm along these shear zones. Incipient recrystallization to serrated 5-50 μ α-grains (HV 170-210) has occurred in the most cold-worked shear zones. The kamacite may show severe cold working (HV 350), without any indications of annealing, 100 or 200 μ on either side.

Schreibersite and cohenite are brecciated but monocrystalline, and there are no reaction zones around them. The originally monocrystalline troilite is slightly altered; it is divided into millimeter-sized passive monocrystalline blocks, slightly rotated, and separated by polycrystalline, recrystallized troilite grains, 5-50 μ across. The included graphite and cliftonite are sheared, and individual fans and flakes are twisted and bent.

While the bulk of the troilite is only slightly altered, troilite is often present in the shear zones. Here it forms 10-100 μ wide "lubricants" of micromelted spongy material with minute fragments of the walls embedded.

The changes are clearly due to shock waves of brief duration. The high contrast between adjacent parts of the sections suggests shock wave attenuation and steep pressure gradients. The effects are clearly observed around troilite nodules and other large mineral inclusions such as changes in microhardness and etching characteristics of the kamacite. Heymann et al. (1966: figure 6) presented a photomacrograph of a section, in which there had been an unusual pressure gradient, displaying hatched ϵ-structures at one end and recrystallized kamacite at the opposite end, 8 cm distant. Perhaps the peak pressure was 600 k bar at one end and 800 k bar at the other, suggesting pressure gradients of 25 k bar per cm.

III. Shock-annealed masses. Usually 0.5-100 kg, either from the plain or from the rim. U.S.N.M. no. 1530 (15.4 kg), no. 394 (32.8 kg) and no. 676 (about 40 kg). Specimen no. 1530 was discovered in 1947 5 km east-northeast of the crater rim, in Section 16, Township 19 North, Range 13 East. It was partly exposed on the surface under sage brush. There was a considerable amount of oxide under and around it and much of it scaled off on removal of the mass (original label). It measures 18 x 16 x 16 cm and displays large shallow cavities on the buried surface, 3-6 cm across, while the opposite surfaces are pock-marked by numerous densely spaced pits, 1-2 mm across. The outlines of six troilite nodules, each 1-5 cm across, are clearly suggested on the surface due to their different rate of oxidation. Their presence is also revealed with a pocket magnet, because the nodules are less magnetic than the metallic part of the meteorite. Fusion crusts and heat-affected α_2 zones have been lost by weathering.

These masses deviate only slightly from group I. They have a somewhat lower hardness of kamacite (145-210), and locally incipient recrystallization to 5-50 μ grains has occurred. The taenite is slightly annealed (HV 200-280), and the troilite shows mixtures of monocrystalline passive blocks and eutectics. It is estimated that these samples have been slightly reheated to 400° or 500° C, in association with the cratering event, but unless one examines good sections very carefully, there is little to distinguish them from group I above.

IV. Shock-annealed to recrystallization. Specimens usually smaller than 5 kg. Corresponds to some of the moderately shocked samples of Heymann et al. (1966). Type example Tempe no. 34.4040 (about 500 g) from the rim (Moore et al. 1967). The structures can also occur in plains specimens. The sample measures 8 x 6 x 2.5 cm and is highly irregular, rather wedge-shaped with sharp edges. It is weathered and irregularly covered with 0.1-1 mm thick limonitic crusts. Fusion crusts and heat-affected zones of the usual kind were probably never present.

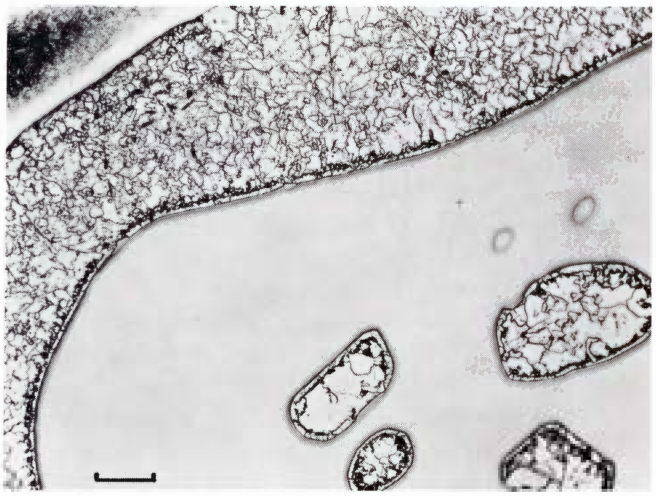

Figure 467. Canyon Diablo. Stage V, as Figure 466. Cohenite with four kamacite and two taenite inclusions. Along the cohenite-kamacite interfaces indistinct reaction zones occur. Etched. Scale bar 100 μ. See also Figures 136 and 138.

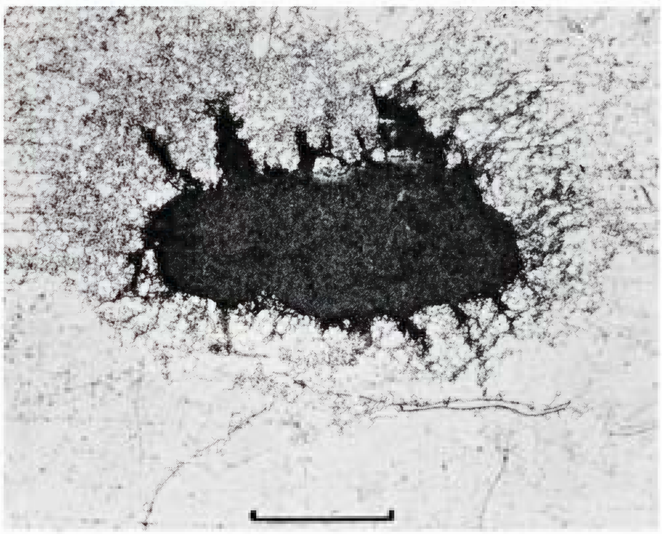

Figure 468. Canyon Diablo. Stage V as Figure 467. A small troilite lens has been shock melted. Filaments of melted material penetrate through adjacent kamacite, which is itself transformed to unequilibrated α_2 grains. Etched. Scale bar 200 μ.