differential cold working. One mass, Rio Loa, has been significantly reheated, but as shown above, the reheating was artificial. The kamacite decomposition noted in Mejillones is not present in the North Chilean group.

The rhabdite plates are typically 5-15 mm long and 5-40 μ thick; they occur with certainty in the {221} planes of the kamacite and perhaps also in the {100} planes. Tetragonal prisms, 5-25 μ across, have precipitated in the matrix between the plates. The specific conditions around the relatively few schreibersite inclusions were discussed under Puripica. The arrangement of rhabdites in parallel planes as seen in, e.g., Hex River and Uwet, is unknown in the North Chilean group.

Troilite occurs as 1-15 mm nodules and lenses; the smaller they are, the more daubreelite they contain. A significant proportion of the blebs are decomposed into parallel, very thin lamellae of alternating troilite and daubreelite. The troilite has been shock-melted to varying extents and has dissolved part of the adjacent metal or has been injected as fine veinlets into the brecciated and sheared schreibersite and daubreelite. Large monocrystalline troilite nodules are not present.

Graphite is present as loose, almost amorphous aggregates reaching one millimeter in size and leaving cavities upon routine metallographical cutting and polishing. Cohenite and diamonds (?) may be present.

In the kamacite there are numerous precipitates of irregular bodies and fine hard platelets, typically 2 x 1 or 10 x 1 μ in size. They consist of the chromium nitride carlsbergite, identified in Cape York, Schwetz and other irons.

The North Chilean hexahedrites are different in many structural respects from other hexahedrites, notably by the absence of rhabdites in parallel planes and by the absence of recrystallized grains and microprecipitates on the Neumann bands. They are positively characterized by the numerous rhabdite plates in the {221} planes. The hexahedrite which resembles North Chile most is Walker County; this is, in fact, indistinguishable – both in chemical and structural respects.

North Portugal

Approximately 41°N, 8°W

Material thus labeled (see Hey 1966: 347) is almost certainly fragments of the weathered São Julião meteorite.

Northumberland Island. See Cape York

Nova Lima, Minas Gerais, Brazil

A fragment of this name is mentioned by Hey (1966) as a doubtful iron meteorite from Brazil. In March 1973 I had an opportunity to examine the questioned material, incorporated in the Museum of Natural History in Rio de Janeiro. It is a weathered fragment of about 15 g, measuring 4.0 x 1.7 x 1.0 cm, without regmaglypts or other meteoritic characteristics. The polished and etched section reveals a ferritic structure with pockets of dendritic slags. The ferrite displays alternating patches of large grains, 0.5-1 mm across, and small grains, 0.05-0.1 mm across. Along the surface, the ferrite is somewhat carburized, resulting in pearlitic structures with grain boundary cementite. There is, thus, no doubt at all that Nova Lima is a pseudometeorite, being a fragment of a primitive and slightly carburized wrought iron.

Novorybinskoe, Kazakh SSR

51°53′N, 71°15′E

A mass of 3,055 g was found in 1937 and was acquired by the Academy of Sciences, Moscow. It was fully described, with photographs of the exterior and of polished sections, by Zavaritskij and Kvasha (1952: 66) and Zavaritskij (1954: 71), who rightly classified it as a fine octahedrite. The classification by Hey (1966: 348) as a coarse octahedrite cannot be supported.

Figure 1301. Novorybinskoe (Moscow). A weathered fine octahedrite. Scale bar 3 cm. (Courtesy E.L. Krinov.)

It was been assumed that the main mass fell in 1927, but this appears to be incorrect considering the significant terrestrial corrosion present.

From the descriptions quoted above, it may be cautiously deduced that Novorybinskoe is a weathered octahedrite with low phosphorus content (about 0.1%) and with 8.5 to 9.5% Ni. It appears to be a shock-hardened fine octahedrite of group IVA, particularly related to Muonionalusta, Boogaldi and Duchesne.

Nuleri, Central Division, Western Australia

27°50′S, 123°52′E

A mass of 120 g was found in or before 1902, 200 miles east of Mount Sir Samuel. The main mass, which has been described as a medium octahedrite, is in Perth. For further information, see McCall & De Laeter (1965: 47 and plate 8), Hey (1966: 350) and Cleverly & Thomas (1969), who found 7.32% Ni. The structure and chemical composition are similar to the crater-forming irons

Boxhole and Henbury. It is, therefore, suggested that Nuleri be compared to these meteorites to disclose whether it could be a transported fragment.

Nutwood Downs. See Supplement

Nyaung, Myingyan District, Upper Burma

21°12 1/2′N, 94°55′E

The only information available on this meteorite is the following brief note which I quote in its entirety, because the referenced journal is rare in most libraries: "Report from Calcutta Office of the Geological Survey of India ... Metallic Iron. On December 24, 1939, at 7:40 p.m. in U(pper) Burma, Nyaung, Myingyn District, (lat. 21°12 1/2′, long 94°55′), weight 737.65 g." (Mohammed Abdur Rahman Khan, A Preliminary Account of the Collection of Indian Meteorites in the Calcutta Museum. Hyderabad Academy Studies, No. 12, Begumpet, Deccan, March 24, 1950).

The mass thus appears to be in Calcutta but has never been described. Neither has it been confirmed that Nyaung was an observed fall. A full examination seems required.

Oakley, Idaho, U.S.A.

42°20′N, 113°42′W; 2,000 m

Coarse octahedrite, Og. Bandwidth 1.40±0.30 mm. Neumann bands. HV 225±25.

Anomalous, judging from the structure. 7.3% Ni, 0.28% P, 7.2 ppm Ga, 1.1 ppm Ge, 5.3 ppm Ir.

HISTORY

A mass of about 113 kg was found in 1926 10 miles northeast of Oakley, Cassia County. It was lying on the surface of the ground on the west side of Harrison Mountain where it was discovered by two youngsters cutting cedar posts. The meteorite was acquired by the U.S. National Museum and was briefly described by Merrill (1927a), who gave three photographs of the exterior. Revised coordinates and an approximate altitude are given above.

COLLECTIONS

Washington (111.4 kg main mass), Calcutta (14 g).

DESCRIPTION

The mass is a triangular, domed shield with the average dimensions of 58 x 47 x 10 cm. Along one edge the mass tapers irregularly to a 1-5 cm thick wedge, while near its opposite end it attains its maximum thickness of 20 cm. The present weight is 111.4 kg, and as yet nothing has been cut from it. The finders had, however, broken about 1.5 kg from the thinnest part of the edge, leaving a 16 x 2 cm hackly fracture, and 420 g of this material went to the U.S. National Museum with the main mass.

The surface shows three distinct morphologies, each of which is rather well developed and considered worth describing, since they reveal something of the terrestrial weathering mechanism. It is known that the mass was

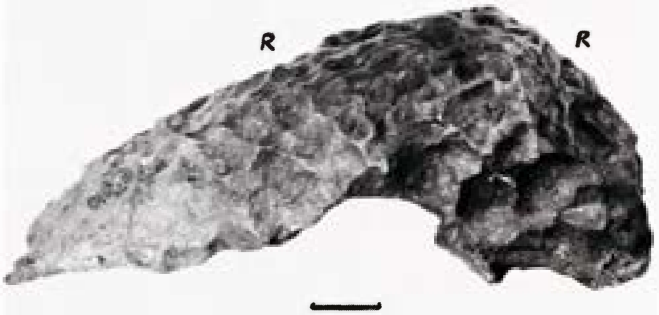

Figure 1302. Oakley (U.S.N.M. no. 780). The main mass is a triangular domed shield. Slightly altered regmaglypts are present at R-R. Scale bar approximately 5 cm. S.I. neg. 18A.

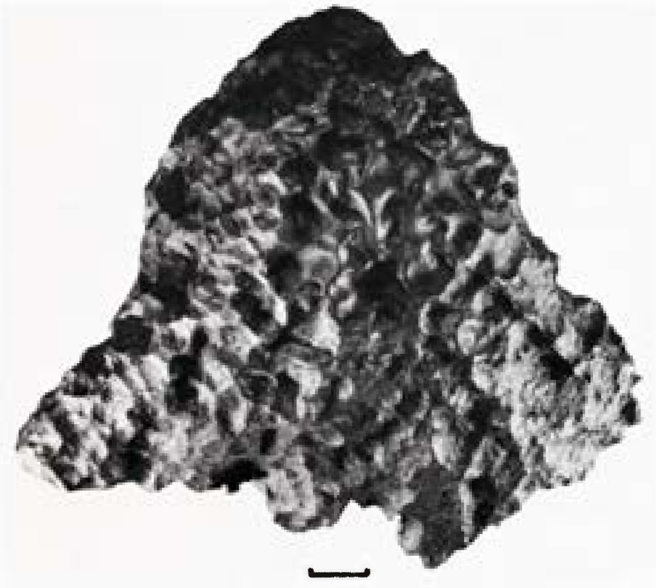

Figure 1303. Oakley (U.S.N.M. no. 780). The main mass from the top side. Central part with little altered regmaglypts. Scale bar approximately 5 cm. S.I. neg. 18F.

OAKLEY – SELECTED CHEMICAL ANALYSES

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Shannon in Merrill 1927a	7.04	0.27	0.28		160		60					
Wasson 1972, pers. comm.	7.32								7.2	1.1	5.3	

found on the surface partly covered with soil; but it is not reported how it was oriented when found. However, it is probably safe to assume that the convex side was uppermost. The crown of this top side, about 25 cm in diameter and 10 cm high, is much less corroded than the skirt of the top side – probably because the crown was the only part that projected above the ground. The crown is covered with typical, angular ablation regmaglypts, 2-4 cm in diameter and 0.5-1 cm deep; and these are separated by rather smoothly rounded ridges. In a majority of the cavities a 0.1-0.4 mm thick fusion crust is preserved, indicating that hardly any material here has been removed through corrosion.

Figure 1304. Oakley (U.S.N.M. no. 780). The opposite side is concave and displays very large shallow regmaglypts. Scale bar approximately 10 cm. S.I. neg. 5464C.

The remaining part of the top side, which was covered by the soil, is considerably corroded. The fusion crust has disappeared and the regmaglypts have been severely altered; the surface is now subdivided into shallow cavities, 3-7 cm across, with sharp ridges in between. Limonitic crusts, 0.5-1 mm, are present; but it is estimated that much more metal has been dissolved from the meteorite than is now bound chemically in the adhering limonite. The remainder must have spalled off or have been dissolved and removed by the ground water.

Finally, the concave underside shows boldly carved, large regmaglypts. These are in the shape of shallow bowls, 8-20 cm in diameter and 1-2 cm deep, and they have softly rounded ridges in between. Locally, a 2 cm wide and 7 cm long furrow cut obliquely a few centimeters deeper into the metal. All these features were created during the brief flight in the atmosphere, since the fusion crust still covers the surface as a 0.5-1 mm thick, warty or striated crust. Oakley was evidently a highly oriented fall where the thick part of the convex side was the leading edge and the concave side was the rear side.

Oakley resembles Cabin Creek, Hraschina and Murnpeowie a great deal in the flight-sculpturing. In addition, it is interesting because it provides a clear example of how a single meteorite may suffer a differential corrosion attack, depending upon the climatic conditions and the extent to which it has become buried in the soil. While the weathering of the skirt must have required countless centuries, during the same period hardly any attack occurred on the crown and on the underside.

The only etched section which could be prepared is from the sharp edge where the convex and the concave sides meet. It shows Oakley to be a coarse octahedrite with straight, long ($\frac{L}{W} \sim 15$) kamacite lamellae with a width of 1.40±0.30 mm. Late grain growth has wiped out many of the linear Widmanstätten boundaries and locally created large, irregular α-grains, 5-10 mm across. The kamacite shows numerous subboundaries decorated with 0.5-1 μ phosphides, and Neumann bands are also present. The

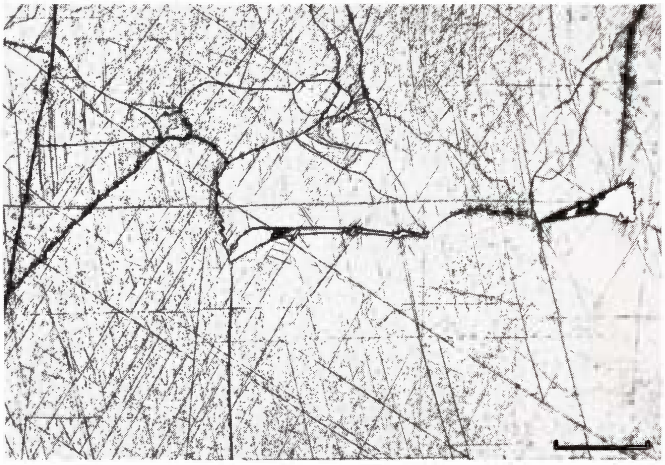

Figure 1305. Oakley (U.S.N.M. no. 780). Part of large irregular kamacite grains with distinct subboundaries. Horizontally a few taenite bodies. Etched. Scale bar 300 μ.

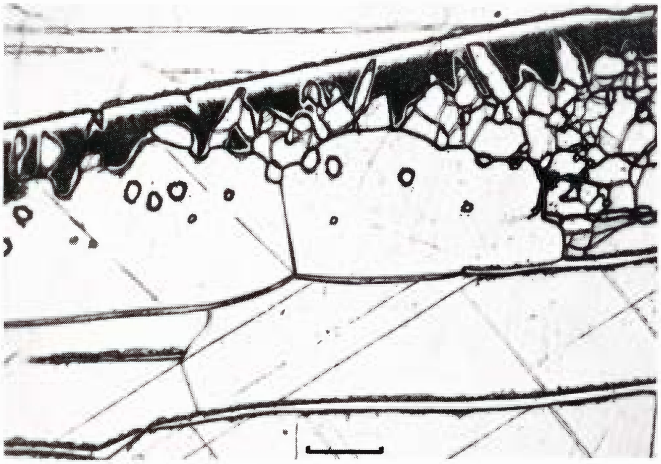

Figure 1306. Oakley (U.S.N.M. no. 780). A degenerated net plessite field. Black denotes an unresolvable martensitic transition zone. White dots are spheroidized γ-particles. Etched. Scale bar 50 μ.

microhardness is 225±25. In several places the kamacite shows slipband systems which by a mild cosmic reheating have become decorated with numerous, very fine precipitates. They are normally less than 0.5 μ across; and indications are that they are phosphides, particularly judging from the way they behave in the heat-affected α_2 zone. Compare for example, Thule, Trenton and Mount Ouray, which show the same precipitates.

Taenite and plessite cover about 15% by area in the form of very degenerated comb and net plessite fields. The framing taenite is discontinuous and the interior is often no more than a tangle of subboundaries with a few 1-5 μ taenite blebs. Locally, larger taenite ribbons show a martensitic interior or have a martensitic transition zone surrounding a poorly resolvable, duplex interior.

Schreibersite is present as 20-80 μ wide grain boundary precipitates and as an occasional 1 x 0.2 mm crystal. It is developed as 50-100 μ wide rim zones around troilite. It is monocrystalline but brecciated. A small amount of 1 μ rhabdites is found in some α-lamellae.

Troilite occurs as irregular nodules, ranging from 50 μ to 5 mm. It is monocrystalline but shows lenticular twins due to plastic deformation. Daubreelite is present as 1-100 μ wide, parallel lamellae covering about 10% by area. The smaller sulfide nodules, 50-100 μ across, are often composed of alternating lamellae of 1 μ daubreelite and troilite.

A small part of the concave surface is preserved on the section. The fusion crust is 1 mm thick and composed of layers of metallic melts, about 50 μ thick, which have solidified rapidly to dendritic-cellular structures. The innermost layers show columnar dendrites, 5-15 μ wide, which have grown perpendicular on the substrate. Farther out, the structure is less regular, and many concentric whirlpool aggregates are present, similar to those described from Jamestown, Arlington and others. The microhardness is 330±20. Under the fusion crust there is a 2 mm thick α_2 zone with a microhardness of 215±10. Micromelted phosphides are present in the exterior 50% of the α_2 zone. The phosphides are clearly seen to have solidified by heat conduction from the cool interior.

Oakley appears to be an anomalous meteorite. The combination of 1.4 mm, only small amounts of taenite, but relatively many phosphides does not seem to correspond to any other iron. A comparison with Toluca, which has a similar bandwidth and amount of phosphides, shows, e.g., that the taenite-plessite amount and morphology are significantly different in the two irons. The modern analysis for main and trace elements showed that Oakley is chemically anomalous, too.

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

111.4 kg main mass (no. 780,.58 x 47 x 10 cm)
15 g fragment, broken from the edge

Obernkirchen, Lower Saxony, Germany
52°16′N, 9°12′E; 350 m

Fine octahedrite, Of. Bandwidth 0.26±0.04 mm. ε; partly recrystallized. HV210±30.

Group IVA. 7.50% Ni, 0.36% Co, 0.02% P, 1.8 ppm Ga, 0.1 ppm Ge, 3.2 ppm Ir.

HISTORY

A mass of about 41 kg was found before 1863 during work in a sandstone quarry on Bückeberg, near Obernkirchen. The coordinates of the present quarry are given above. The iron had apparently been embedded in the moraine sand 4.5 m under the surface but about 3 m above the sandstone banks. When a chemical test showed the mass to be "Swedish iron," the quarry owner lost interest and discarded it, and not until 1863 was its meteoritic nature recognized by Wiepken (1884). Wicke & Wöhler (1863) analyzed and described the mass and gave two wood cuts of

Figure 1307. Obernkirchen (U.S.N.M. no. 1611). A fine octahedrite of group IVA. Within a vertical shear zone the kamacite is recrystallized. Etched. Scale bar 500 μ.

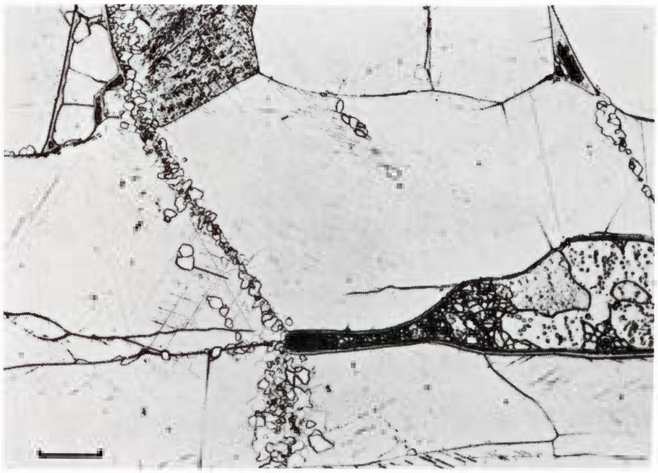

Figure 1308. Obernkirchen. Detail of Figure 1307. To the right, a cellular plessite field. The recrystallized regions stand in contrast to the shock-hatched, but annealed matrix. Etched. Scale bar 100 μ.

the exterior. They regretted that they were unable to purchase the mass from the owner because another party (London) had offered 500 Thaler.

Cohen (1900b: 366; 1905: 363), who described the meteorite under the synonym Bückeberg, reviewed the older literature and also presented a new and better analysis than Wöhler's previous one which had shown much too high a phosphorus content (0.64% instead of 0.02%). Brezina & Cohen (1886-1906: plate 22) presented two photomacrographs with a brief description. Reed (1965b; 1968) analyzed the various phases with the microprobe. He found 7.1-7.2% Ni and 180 ppm P in the kamacite – which is comparable to that of Jamestown and indicates that the kamacite is not saturated with phosphorus.

COLLECTIONS

London (34.7 kg main mass and 68 g fragments), Washington (302 g), Leningrad (286 g), Harvard (284 g), Oslo (218 g), Chicago (184 g), Budapest (180 g), Göttingen (136 g), Belgrad (135 g), Paris (125 g), Oldenburg (92 g), Yale (90 g), Berlin (69 g), Tempe (60 g), Odessa (30 g), Dresden (26 g), Ottawa (21 g), New York (21 g), Vienna (16 g), Copenhagen (16 g), Stockholm (15 g), Bonn (12 g).

DESCRIPTION

The mass is irregular, pyramidal, with a base, four sides and a crest at the top. The approximate height is 25 cm, and the base is about 22 x 20 cm. At one end is a cut face from which most specimens were taken about 1865 when

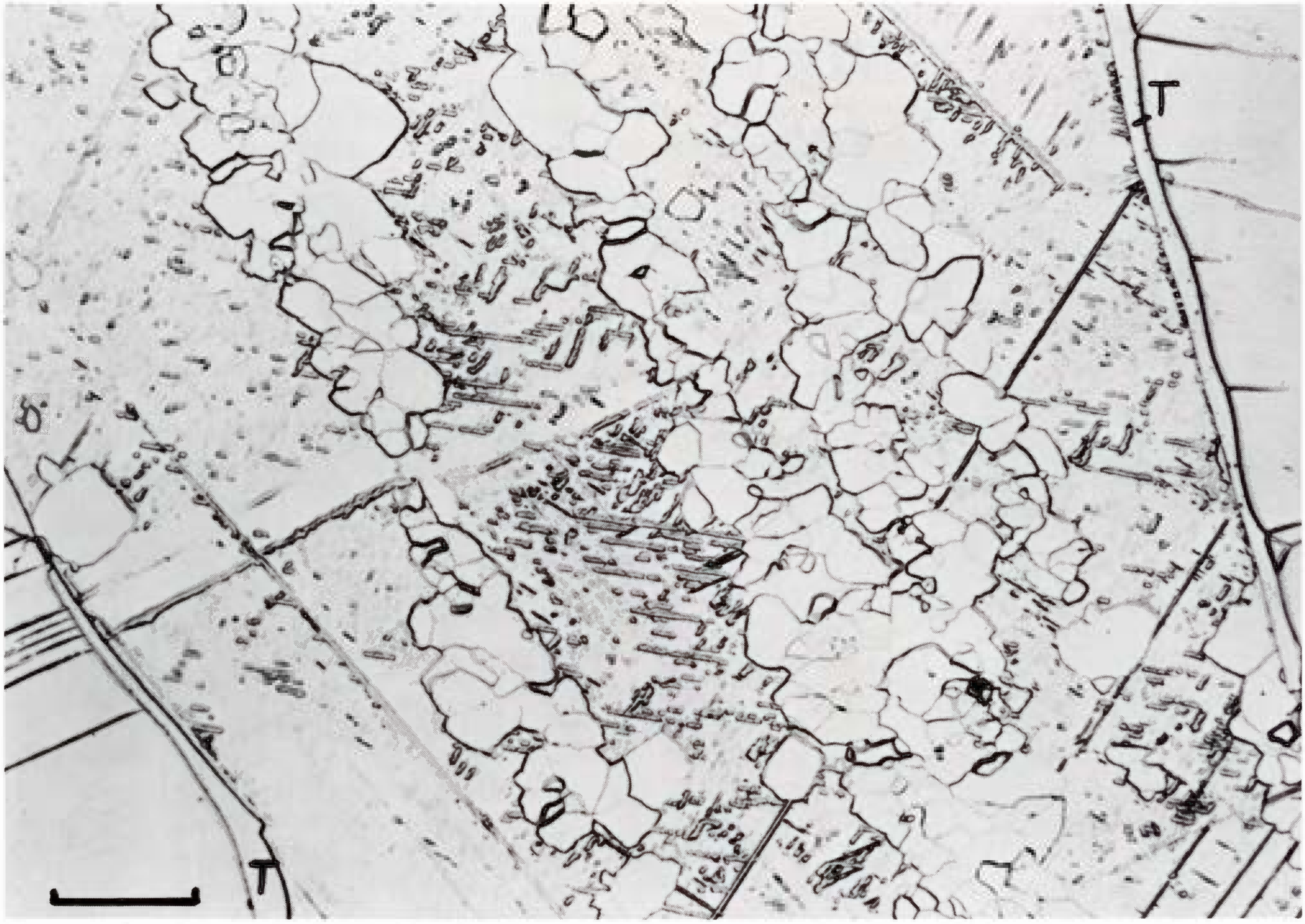

Figure 1309. Obernkirchen. Detail of the dark-etched kamacite lamella at top center in Figure 1307. The kamacite is recrystallized in parallel planes while remnant Neumann bands occur outside. Two annealed taenite lamellae are marked T. Etched. Scale bar 50 μ.

OBERNKIRCHEN – SELECTED CHEMICAL ANALYSES

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Smales et al. 1967					27	355	127	<1	1.70	0.20		
Jarosewich 1968, pers. comm.	7.67	0.36	0.02									
Schaudy et al. 1972	7.33								1.80	0.091	3.21	
Crocket 1972											1.8	7.25

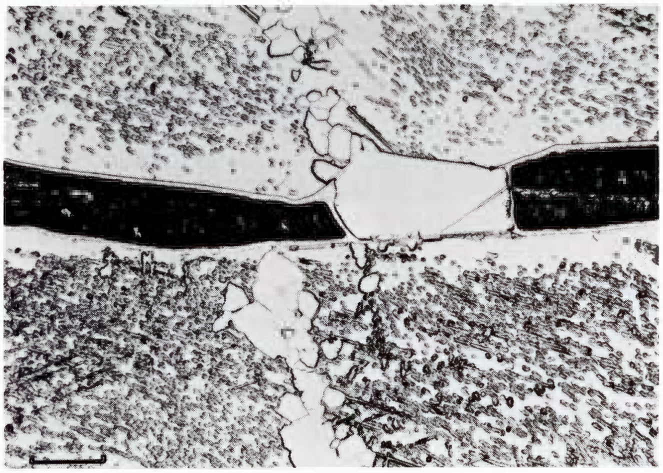

Figure 1310. Obernkirchen (U.S.N.M. no. 1611). Two tempered black plessite fields and a vertical shear zone with recrystallized kamacite. Etched. Scale bar 50 μ.

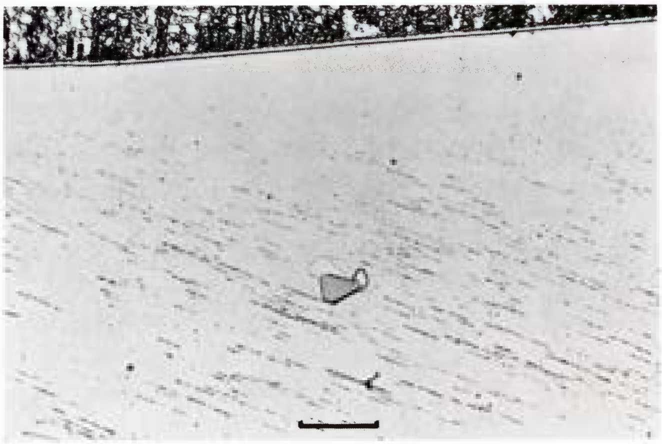

Figure 1311. Obernkirchen. Detail of Figure 1307. A daubreelite or chromite crystal with cubic morphology. Two small recrystallized kamacite grains have started growing around it in an otherwise homogeneously strained kamacite matrix. Etched. Scale bar 50 μ.

the mass was acquired for the British Museum. The mass is severely corroded; in many places it is attacked along the octahedral planes, whereby rhombic and lamellar fragments become detached. Terrestrial oxides cover the surface as a 1-10 mm thick crust, and all indications of fusion crust and heat-affected rim zone are long since removed. Polished, near-surface slices often continue to corrode when used as exhibit specimens. Fahrenhorst (in Cohen 1900b) found 0.02% Cl which was, as usual, interpreted to indicate the presence of lawrencite. It is, however, more likely that Obernkirchen is of considerable terrestrial age and that most of the chlorine has been introduced by circulating ground water.

Etched sections show a fine Widmanstätten structure of straight, long ($\frac{L}{W} \sim 35$) kamacite lamellae with a width of 0.26±0.04 mm. The kamacite displays a mixture of shocked ϵ-structure and recrystallized grains. The hatched ϵ is contrast-rich and shows various shadings in neighboring alpha lamellae. The recrystallized alpha grains are 5-50 μ in diameter and occur singly or clustered, particularly along inclusions and old high angle grain boundaries. A 2-3 mm annular zone around a 10 mm troilite nodule was thus observed to be fully recrystallized, while inclusion-free areas farther away generally showed only 5-10% recrystallization. Heavy shear zones with, e.g., 50 μ relative displacement of taenite and plessite, occur locally. Recrystallization has taken place in the highly deformed alpha phase of the narrow shear zones. The microhardness of the kamacite phase is highly variable; it ranges from 175 to 240 in accordance with the highly variable microstructure.

Plessite covers about 33% by area in the form of open-meshed comb and net plessite, of duplex $\alpha + \gamma$ fields, and of cellular Chinautla plessite. The taenite makes up such a small part of the fields that they mostly appear light-etching and stand in low contrast. The taenite of the duplex $\alpha + \gamma$ fields is 0.5-2 μ in cross section and easily resolvable. Near the surface the fields are heavily corroded, leaving the taenite intact among the terrestrial oxides for a while.

Phosphides were not observed and are probably not present at all, in harmony with the analysis. Cohen (1900b) reported schreibersite but, almost certainly, erroneously.

Troilite occurs as 0.5-10 mm nodules with 10-20% daubreelite lamellae. The larger troilites are partly melted, the smaller wholly melted. The larger ones are composed of shattered monocrystalline blocks 0.1-0.5 mm in size, separated by 1-40 μ wide veinlets of melted polycrystalline sulfide. The included daubreelite lamellae are shattered and displaced but not melted. Tiny veinlets of melted troilite penetrate a short distance into the metallic matrix. The morphology is very similar to that of Huizopa, Jamestown, and La Grange, although no long zigzagging fracture zones were disclosed on the small sections available.

It appears then that Obernkirchen, after an initial cooling period that led to a Gibeon-like structure, was severely shocked whereby the troilite point-melted and the metal recrystallized. Whether we will have to assume two separate shock events – one for the ϵ-structure and one for the recrystallization structure – is not clear. Maybe ϵ was created immediately all over the alloy, followed rapidly by partial recrystallization around favorable nuclei near relaxation heat peak centers.

Obernkirchen is a fine octahedrite closely related to Jamestown, Charlotte, Putnam County and a considerable number of other phosphorus-poor octahedrites with 0.25-0.30 mm bandwidth. Chemically, it belongs to group IVA.

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

152 g part slice (no. 87, 5 x 2.5 x 1.5 cm)
53 g part slice (no. 1101, 4 x 2 x 0.6 cm)
97 g part slice (no. 1611, 2.5 x 2 x 1.5 cm and small sections)

Odessa, Texas, U.S.A.

31°45′21″N, 102°28′43″W; 910 m

Coarse octahedrite, Og. Bandwidth 1.70±0.25 mm. Neumann bands. HV 185±15.

Group I. 7.35% Ni, 0.48% Co, about 0.25% P, 0.5% S, 0.2% C, 75 ppm Ga, 285 ppm Ge, 2 ppm Ir.

HISTORY

In the flat, semi-arid, shrub-covered country 10 miles southwest of the city of Odessa, in Ector County, lie a meteorite crater and a small group of impact holes. The total amount of iron meteorites which has been removed from the area since Barringer (1928) recognized the crater as of meteoritic origin may be estimated to be above 1,000 kg.

Early mapping and exploratory work around the crater was done by Sellards (1927), Nininger (1934; 1939b) and Monnig & Brown (1935). While Sellards hesitated to conclude that the crater was meteoritic in origin, Barringer, Nininger and Monnig gave many independent proofs. One difficulty was that the flat-lying limestone deposits were literally sprinkled with holes of the same general size as the crater itself, and these could be interpreted as sinkholes – so-called "blow-outs" – due to solution of the limestone. The meteorite crater, however, distinguished itself by having slightly elevated, rock-buttressed rims and by being associated with meteoritic iron and iron-shale. The largest iron found in this first period, when only the surface of the country was searched with electromagnetic devices, weighed 3.7 kg.

Systematic drilling and excavation was initiated about 1939, and the results were presented by Sellards & Evans (1941), Sellards & Barnes (1943), Nininger (1952a: 222) and Evans (1961). Krinov (1966: 9) has reviewed the work and placed Odessa in the proper relationship to other meteor craters. The crater is about 165 m in diameter, its sand-filled bottom is 2 m below the level of the surrounding plain, and the rim is 2 m above the plain. The rim consists

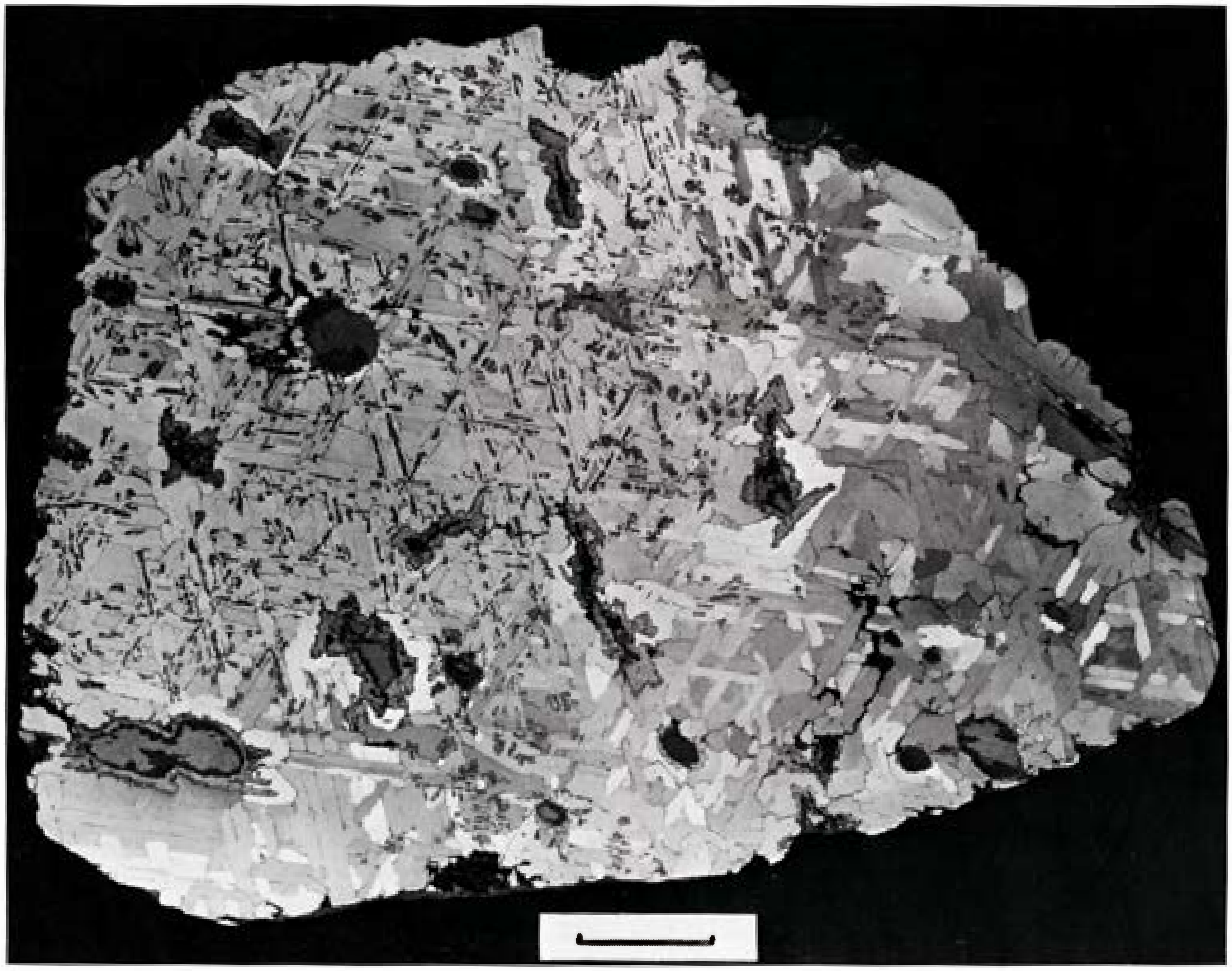

Figure 1312. Odessa (U.S.N.M. no. 1418). Typical coarse octahedrite of group I. Large troilite-graphite-silicate aggregates with irregular jagged rims of schreibersite and cohenite are conspicuous. Deep-etched. Scale bar 20 mm. S.I. neg. 1343. See also Figures 27B, 30, 88, 112, and 139.

of strongly folded and thrust-faulted sequences of limestone with the oldest strata in the "overthrust rim folds" uplifted as much as 15 m (Evans 1961; Roddy 1968). Drillings proved that the crater, immediately after the explosion of the impacting meteorite, was funnel-shaped with a maximum depth of about 30 m. The lower part of the funnel is covered with rock flour (finely pulverized sandstone) and with fallout material composed of brecciated limestone and shale. The upper part has slowly been filled with blowing sand and downwashed silt, and caliche has cemented the deposits together. The important question, whether any large meteorite could be found in the crater, was solved by putting more than 80 closely spaced drill holes – in addition to the 31 exploratory holes – into the crater. All holes passed the fill-in and the rock flour and penetrated into undisturbed bedrock – cretaceous sandstone – without encountering any iron obstacles. The crater-forming mass must, therefore, have disintegrated completely upon impact and has most probably vaporized to a considerable extent.

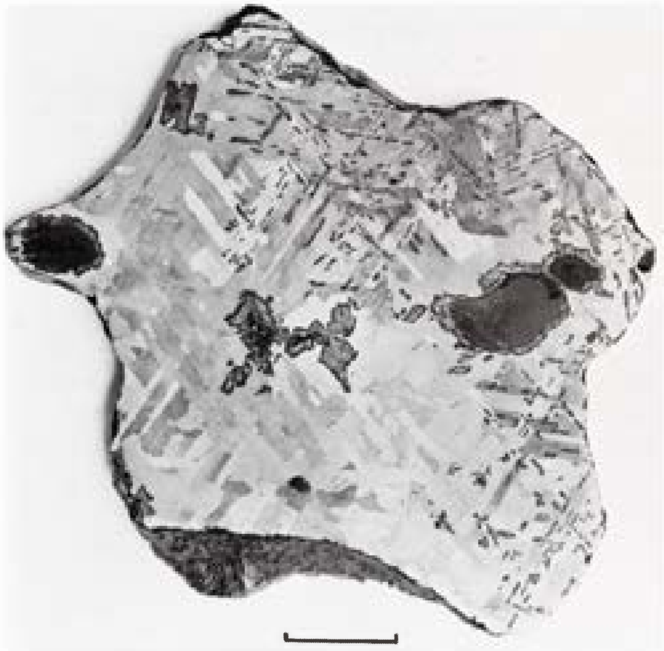

Figure 1313. Odessa (Copenhagen no. 1969, 931). A full slice through another fragment from the crater field. Centrally, skeleton crystals of schreibersite with rims of cohenite. Neumann bands in the kamacite. Deep-etched. Scale bar 30 mm. See also Figures 203, 204, 205, 208, 210, and 214.

Magnetometer surveys led to the discovery of four smaller craters – or rather impact holes – that had been completely leveled with the plain by post-impact sediments. The largest of these holes was thoroughly examined by Sellards and Evans and was estimated to contain a total of six tons of meteoritic fragments. This hole was situated 50 m west of the rim of the main crater and could be reconstructed as a low funnel 24 m in diameter and 6 m deep. Most of the meteoritic debris was at the bottom of the fill-in, in immediate contact with the crushed, calcareous sandstone bedrock. This hole – and the smaller three – are, therefore, best interpreted as impact holes, similar to those of Sikhote-Alin and to the satellite holes of Wabar, Henbury and other craters. Coesite, shishovite and other shock indicators have not been reported from Odessa. The observed facts are best explained if we assume the arrival of one mass which partly split in the lower atmosphere. The fragments continued their flight closely together, and while the largest mass undoubtedly exploded and expelled large amounts of rock debris and overturned the crater rims, the many smaller masses – each less than six tons presumably – made significant impact holes of simply crushed material. As discussed below, the event apparently occurred in the late Pleistocene period, between 10^4 and 10^5 years ago, most probably about 50,000 years ago.

The first iron fragment from the Odessa field was described by Merrill (1922c), who gave a photograph of the etched slice. Lord (1941) compared Odessa and Canyon

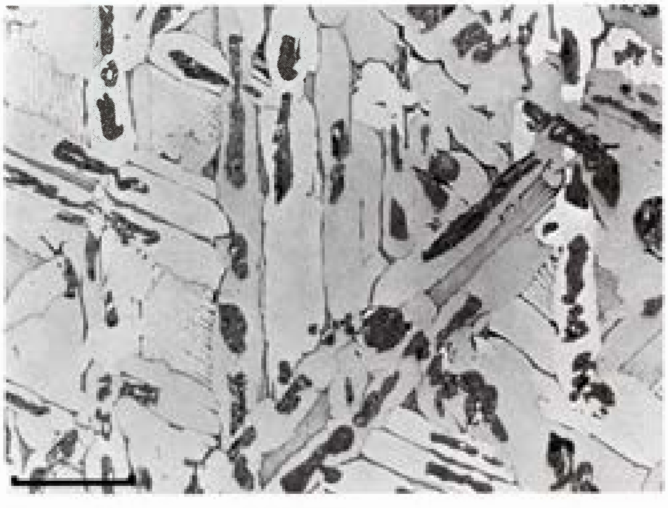

Figure 1314. Odessa. Detail of Figure 1312. Elongated cohenite crystals with "windows" of kamacite, taenite and schreibersite. Various plessite fields. Deep-etched. Scale bar 5 mm. S.I. neg. 1343D.

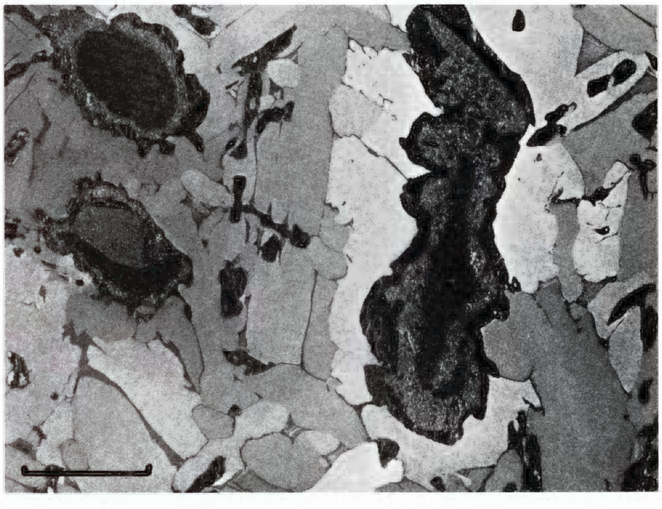

Figure 1315. Odessa. Detail of Figure 1312. Three troilite-graphite nodules with thick schreibersite-cohenite rims. Irregular asymmetric rims of swathing kamacite. Deep-etched. Scale bar 5 mm. S.I. neg. 1343C.

Diablo and gave several photomicrographs. Perry (1944: plate 44) gave a micrograph of a typical plessite field. Nininger & Nininger (1950: plate 18) showed the exterior of one of the largest recovered fragments, a 80 kg mass. Beck & La Paz (1951) examined one of the smaller fragments, weighing 1.3 kg; they reported lawrencite, but this may have been a misinterpretation of chloride implanted by the ground water during a long terrestrial exposure. Buddhue (1957: 116) discussed the oxidation characteristics. Lipschutz & Anders (1961; 1964) discussed the presence of cohenite and argued that, although thermodynamically instable, it might still survive a slow cooling because of nucleating difficulties. Massalski & Park (1962) estimated the cooling rate of Odessa, and more refined estimates were later presented by Wood (1964) and Goldstein (1969). The detailed composition of the metallic phases has, in addition, been studied by Brown & Lipschutz (1965) and Goldstein (1967), while El Goresy (1965) and Marshall & Keil (1965) have given thorough discussions of the complex troilite-graphite-silicate nodules. The identified minerals are olivine (forsterite), enstatite, calcium-rich chromian clinopyroxene, albite and chlorapatite, arranged in order of decreasing frequency. Nininger & Huss (1966) reported a 0.3 x 0.4 mm grain of free copper associated with schreibersite, graphite and terrestrial oxidation products. El Goresy & Ottemann (1966) proposed a new mineral, gentnerite, $Cu_8Fe_3Cr_{11}S_{18}$, which supposedly had formed from daubreelite during terrestrial exposure. The mineral has not yet been accepted (Strunz 1970). Kullerud & El Goresy (1967) found heazlewoodite, daubreelite, sphalerite, awaruite, albite and orthoclase as minor constituents of the troilite nodules. Bunch & Keil (1969) gave the exact composition of the chromite inclusions and also identified ferroan alabandite. Berkey & Fisher (1967) found a significant amount of chlorine, ranging from 1-330 ppm, indicating a thorough penetration of ground water into Odessa. Jaeger & Lipschutz (1967b) used artificially shocked Odessa specimens as standards for estimating the shock-damage of other meteorites. Odessa itself was believed to be mildly shocked only, below 130 k bar. Further experiments of annealing artificially shock-loaded Odessa specimens were described by Jain & Lipschutz (1968). Lipschutz (1967) took X-ray diffractograms of the cohenite and found it to be monocrystalline, unrecrystallized. The compressive yield strength under normal loading rates was found by Knox (1970) to be 33.0 $^{\mathrm{kg}}/_{\mathrm{mm}^2}$ at 0.2% offset. In the papers quoted above, which of course constitute only a part of the extensive literature on Odessa, there are numerous good photomicrographs of the structure and of the nonmetallic minerals.

Figure 1316. Odessa (Tempe no. D91.91). Detail of a troilite-graphite nodule. The graphite occurs as two cliftonitic units and a number of broken fan-shaped units. The troilite is monocrystalline but includes other minerals as minor accessories (dark patch). Crossed polars. Scale bar 20 μ.

Honda et al. (1961) examined the amount of the radioisotopes $^{10}\mathrm{Be}$, $^{26}\mathrm{Al}$, $^{36}\mathrm{Cl}$, $^{40}\mathrm{K}$ and $^{53}\mathrm{Mn}$, while Herr et al. (1961) estimated from the Os/Re ratio an age of 4.0 x 10^9 years for the meteorite. Burnett & Wasserburg (1967a) isolated a portion of the silicate inclusions and measured the $^{87}\mathrm{Rb}/^{87}\mathrm{Sr}$ age to be (4.5±0.3) x 10^9 years. Rancitelli & Fisher (1968) used Odessa as an example to show that $^{40}\mathrm{K}/^{40}\mathrm{Ar}$ ages on iron meteorites may be misleading, due to terrestrial leaching of potassium. Kaiser & Zähringer (1968) found with an improved K-Ar method a formation age of (4.7±0.5) x 10^9 years. They acknowledged and experimentally demonstrated the significant effect of terrestrial leaching upon the loss of potassium from both the metal phase and from schreibersite. They concluded that the K-Ar method should be restricted to carefully selected, unweathered samples from the interior of larger meteorites. The best formation age determinations, no doubt, are based on the Rb-Sr measurements of silicate inclusions.

The terrestrial age, and thus the age of the crater, was estimated by Goel & Kohman (1963) to be greater than 11,000 years from the near-absence of $^{14}\mathrm{C}$. Chang & Wänke (1969), measuring $^{10}\mathrm{Be}/^{36}\mathrm{Cl}$, found that the maximum age was 100,000 years. Quite independent evidence of the age was discussed by Buddhue (1957: 116), who quoted the discovery, by Sellards & Evans, of an extinct horse, Equus conversidens. The bones and teeth had been recovered from a depth of 4m, and Buddhue, making reasonable assumptions of the accumulation rate of the sediments, estimated that the age of the crater was above 50,000 years.

The cosmic ray exposure age was estimated to be 250 million years by Schaeffer & Fisher (1960), while Signer & Nier (1962) and Bauer (1963) found 450±300 million years. Voshage (1967) found 890±70 million years, while Chang & Wänke (1969) found 390±80 million years. Noble gases have been examined by Hintenberger & Wänke (1964), Begemann (1965) and Hintenberger et al. (1967).

COLLECTIONS

University of Texas, Austin (many hundred kilograms), Albuquerque (500 kg), Washington (128 kg), Tempe (85 kg), Adelaide (20 kg), Ann Arbor (17.6 kg), Chicago

(12.9 kg), Los Angeles (8.2 kg), London (3.7 kg), Harvard (3.3 kg), New York (1.37 kg), Moscow (1,150 g), Sydney (1,085 g), Tucson (1,092 g), Copenhagen (620 g), Ottawa (587 g), Amherst (311 g), Canberra (155 g), Calcutta (131 g).

DESCRIPTION

The weight of the individual specimens ranges from 1 g to 135 kg, but the smaller specimens dominate. Nininger (1939b) collected 1,152 fragments on or immediately under the surface, totaling only 1,220 g. Sellards & Evans (1941: 9) recovered from the 24 m impact hole 300 fragments, totaling 225 kg. It appears that the total recovered weight is above 1 ton, of which 500 kg is tabulated in detail by La Paz (1965: 106). In addition, many kilograms of oxidized shale-balls have been recovered. Extrapolations from what has been recovered seem to indicate that at least 10 tons of meteorites were distributed in the impact holes and on the surrounding 5 km^2 of plain. The main mass that produced the crater has disintegrated but was almost certainly larger than 100 tons and more probably about 1,000 tons in size. The volume of the crater is about 0.2 x 10^6 m^3, corresponding to 0.5 x 10^6 ton of expelled rocks.

The typical Odessa specimen is an irregular, angular mass, which has had its original form considerably modified by the long exposure to subsurface corrosion. What is normally described as regmaglypts due to the atmospheric flight is, in fact, usually corrosion pits. They are 1-5 cm in diameter, 1-2 cm deep and separated by sharp ridges. The

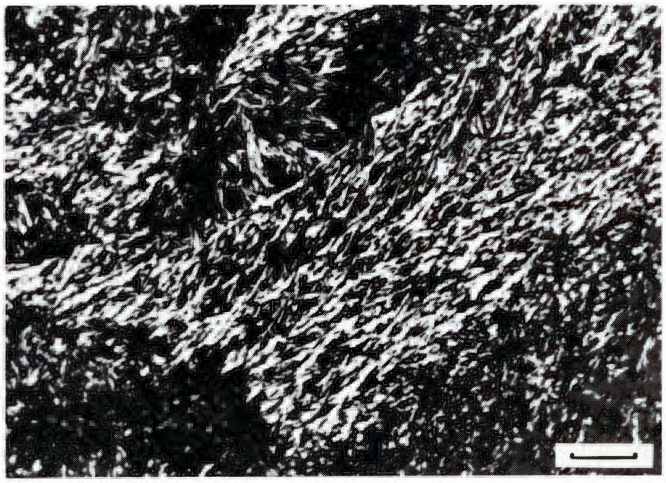

Figure 1317. Odessa (Tempe no. D91.91). Aggregates of acicular graphite crystals in another troilite nodule. Crossed polars. Scale bar 50 μ. See also Figure 165.

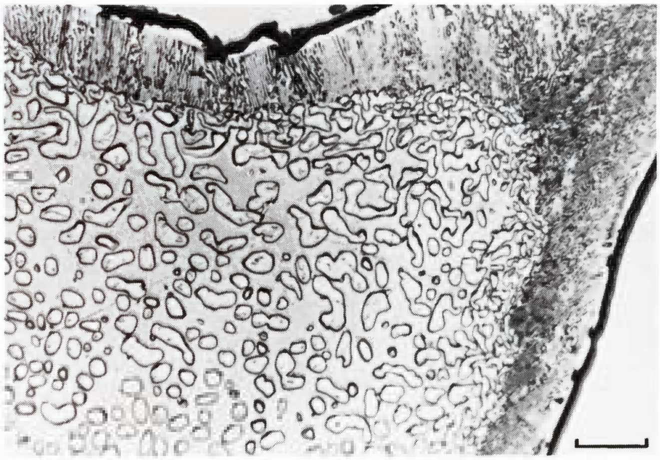

Figure 1318. Odessa (Tempe no. D91.91). Plessite field with pearlitic edge and spheroidized interior. Terrestrial weathering has formed limonite (black) along the $\alpha - \gamma$ interfaces. Etched. Scale bar 20 μ.

ODESSA – SELECTED CHEMICAL ANALYSES

The bulk content of carbon is of considerable interest. Shannon found 0.35%, but noted that it might include some extraneous material. Goel (Dissertation 1962: 89) dissolved four specimens with a total weight of 1,159 g. A total of 2.1 g carbon, combined and graphitic, may be estimated to have been present in these specimens from his data. This corresponds to 0.18% C, a value which is in good agreement with my point counting of large slabs. Nichiporuk & Chodos (1959) examined the composition of the troilite nodules, and Goldstein (1967) traced the distribution of germanium between the various phases. He found that germanium was below the detection level of 40 ppm in schreibersite, troilite and cohenite, while it varied directly with the nickel content of the metal phases. Taenite showed a maximum of 460 ppm, while the kamacite was rather homogeneous with 250±50. Numerous other trace elements have been determined by various authors.

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Shannon in Merrill 1922c	7.25	0.74	0.23	(3500)	300		200					
Goldberg et al. 1951	7.55	0.49							69.3			
Nichiporuk & Brown 1965											1.8	8.5
Wasson 1970a	7.20								74.7	285	2.2	
Lewis & Moore 1971	7.30	0.47	0.17	50								
DeLaeter 1972;									75.3			
Rosman 1972								31				

faces of the small specimens, 0.1-4 kg in size, often meet along sharp edges, and these are usually the result of corrosion pits penetrating from several directions. Contrary to common opinion the troilite nodules, in general, are not removed by corrosion and are not responsible for the cavities seen. The troilite nodules are either flush with the surface or even protrude in high relief, indicating that they are more stable than the iron phase to long-term weathering. The heat-affected α_2 zone is preserved on some specimens, but rarely very well. I noted instances of small individuals (50-150 g) in the Tempe and Washington Collections which showed irregularly preserved 1-2 mm thick α_2 rims with hardnesses of 190±15 (hardness curve type II).

Etched sections display a coarse Widmanstätten structure of straight, long ($\frac{L}{W} \sim 15$) kamacite lamellae with a width of 1.70±0.25 mm. The smaller bandwidth is associated with the cohenite-rich areas. Equiaxial kamacite grains, 5-15 mm across, occur locally as a result of late grain growth. The kamacite has numerous subboundaries, decorated with 1-2 μ phosphides; and Neumann bands are ubiquitous. The microhardness is 185±15. Taenite and plessite cover 5-10% by area with individual comb plessite fields sometimes reaching sizes of 3 x 2 mm. The taenite ribbons have either pearlitic, spheroidized or martensitic interiors. The taenite lamellae of the pearlite range from 0.3-2 μ in width. The martensitic interiors are evidently carbon rich and attain hardnesses of over 500. The untransformed, retained austenite has a microhardness of 320±30. The hardness values must not be taken as exact values, since the detailed nickel and carbon content will affect them appreciably. The relative level does, however, show the significant variation which is believed to be mainly the effect of carbon and nickel.

An interesting manifestation is a few, scattered taenite ribbons which have a deviating structure, corresponding to the carbide roses described under Carlton, Coopertown and others. The taenite border gradually merges with a haxonite interior in which there are numerous short and 1-2 μ wide taenite lamellae. The microhardness of the aggregates is 880±50, and they are usually 0.2 x 1 mm in size.

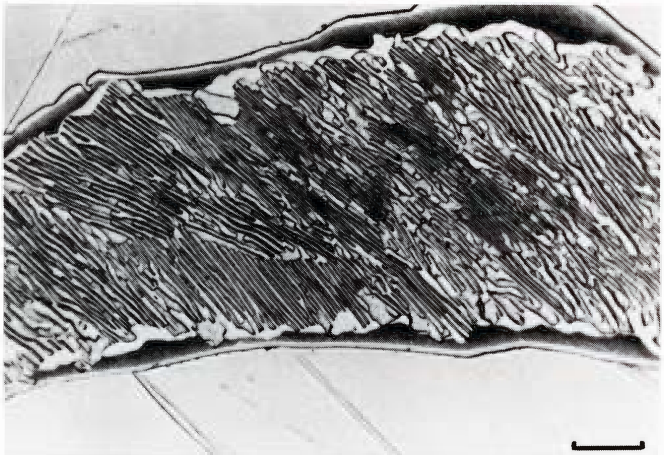

Figure 1319. Odessa (Tempe no. D91.91). Pearlitic plessite. The exterior and interior are high-nickel (~ 35%) homogeneous taenite, while the cloudy patches contain submicroscopic precipitates of α. Compare Figure 109. Etched. Scale bar 20 μ.

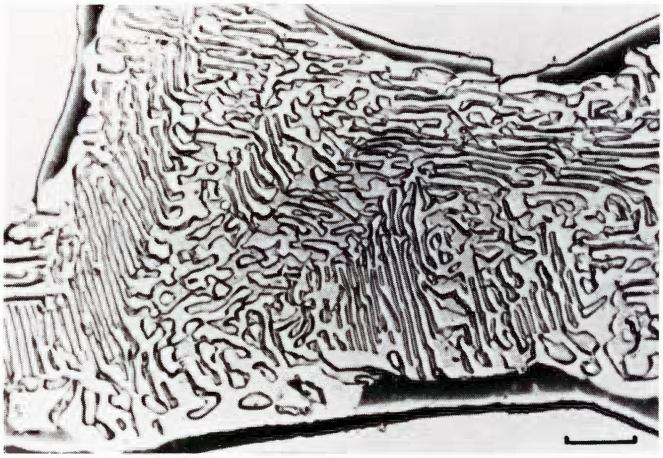

Figure 1320. Odessa (Tempe no. D91.91). Pearlitic plessite in another typical field. Limonite along lower boundary. Etched. Scale bar 20 μ.

Schreibersite is present as up to 30 x 10 x 3 mm laths, but perhaps more common as 5 x 1 mm hooks and hieroglyphs. They are monocrystalline but brecciated – some of this is the result of terrestrial corrosion. Almost all are enveloped in continuous rims of 25-400 μ thick cohenite. The aggregates have nucleated 1.5-3 mm wide rims of swathing kamacite. Schreibersite is further common as 25-100 μ wide grain boundary precipitates and as 5-25 μ blebs inside the plessite fields. Rhabdites are common, but, in general, are smaller than in Canyon Diablo, 1-5 μ across. The bulk phosphorus content is – from point counting – estimated to be 0.25±0.05%.

Complex troilite-graphite nodules and stringers, which occur with a frequency of one per 12 cm^2, are conspicuous. The size of the inclusions is generally 5-10 mm, and the relative amount and mode of mixture of troilite and graphite vary greatly. Also, the amount of silicate inclusions varies from near zero in many globular nodules to dense clusters of 50-500 μ grains in some of the irregular elongated bodies. Pure troilite appears to be absent. The silicate grains, mainly forsterite and pyroxenes, are enveloped in crystalline graphite or in troilite. The graphite shows horsetail extinction or, locally along the edges, is developed as aggregates of 50 μ cliftonite crystals. Individual cliftonite crystals, 50-100 μ across, occur in the troilite, in the kamacite and in the schreibersite. The graphite complex often terminates with a continuous, 50 μ wide fringe of discordant graphite; this border may represent a distinct later stage of graphite precipitation from the metallic matrix. The troilite is monocrystalline and includes only a minor amount of daubreelite (~ 1%) which normally is developed as very short, parallel lamellae. In places the troilite is loaded with fan-shaped or acicular graphite crystals which are frequently arranged in flow textures and may represent disintegrated cliftonite crystals. Terrestrial corrosion has lined the cracks of the troilite with pentlandite. No shock-melted troilite was identified in any section.

The bulk sulphur content was – from point counting – estimated to be 0.5%.

The troilite-graphite-silicate aggregates have served as nuclei for the precipitation from solid solution of schreibersite and cohenite, in that order; and the complete structures are enveloped in 1-2 mm wide rims of swathing kamacite. Lipschutz & Anders (1961: Figure 5) erroneously interpreted a reheated Odessa cohenite as having had substantial amounts of phosphorus in solid solutions. The cohenite usually contains less than 0.1% P in solid solution; it does, however contain discrete blebs, 10-100 μ across, of schreibersite, so the structure shown in the figure is rather the result of the solidification of a liquid formed from a mixture of cohenite and schreibersite crystals.

Cohenite is, in addition, very common as, e.g., 3 x 0.5 mm elongated bodies aligned in the kamacite lamellae and closely associated with taenite and pearlitic plessite. Tiny inclusions of kamacite, taenite and schreibersite are common in the cohenite, but graphite decomposition was not observed. As is usual in group I, large volumes of 15 x 10 x 10 cm^3 may be loaded with cohenite while neighboring volumes of similar size are nearly cohenite-free.

Odessa is corroded, and, unfortunately, many specimens continue to corrode under normal museum conditions. The nickel-depleted zone adjacent to schreibersite and taenite is the first to corrode, and the fine α-phase of the pearlitic plessite also goes early. It appears that a 10-20 μ wide zone, squeezed between the 35% Ni taenite border and the duplex plessite interior, is also sensitive to corrosion. This is the same zone which, on a polished section, etches in bluish-grayish colors – another indication that the zone is reactive. The general overall disintegration is believed to reflect a significant portion of chloride, introduced by the ground water, most critically affecting specimens that have been completely buried.

Odessa is an inclusion-rich coarse octahedrite with a structure typical of the group I irons. It has at various occasions been suggested that it was a paired fall with Canyon Diablo, 900 km west-northwest of Odessa. The structure of the Odessa irons is, however, sufficiently different to be easily distinguishable from Canyon Diablo when due regard is taken of bandwidth, taenite and plessite amount, rhabdite size and nodule size. The main- and trace-element composition is correspondingly different.

So far, shock-altered Odessa specimens of the Canyon Diablo stages II to VII, page 391, have not been identified. All Odessa fragments are remarkably similar in hardness and microstructure and all correspond to Canyon Diablo stage I.

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

77.0 kg	individual, uncut (no. 2175, 45 x 30 x 15 cm)
20.8 kg	(no. 1376)
13.4 kg	half individual (no. 1418, 20 x 14 x 11 cm)
3.0 kg	individual, uncut (no. 1666, 15 x 13 x 4 cm)
2.28 kg	individual, uncut (no. 1666, 12 x 12 x 3 cm)
2.42 kg	individual, uncut (no. 1666, 14 x 9 x 6 cm)
1.70 kg	individual (no. 829, 8 x 8 x 6 cm)
376 g	slice (no. 639, 8 x 6 x 1.3 cm, the 1922 specimen of Merrill)
153 g	slice, endpiece from no. 829 (no. 1418, 8 x 4 x 1 cm)
6.6 kg	six slices (no. 1418, each about 16 x 12 x 0.9 cm)
2.74 kg	laminated, platy shale (no. 1632, 25 x 18 x 4 cm)
2.00 kg	bread-crust shale-ball (no. 1437, 15 x 10 x 6 cm)
21	individuals, ranging in size from 20 g to 1 kg (nos. 1666, 2115, 2221)
4.30 kg	various fragments, shales and polished sections

Ogallala, Nebraska, U.S.A.

41°10′N, 101°40′W; 1000 m

Coarse octahedrite, Og. Bandwidth 1.60±0.20 mm. Neumann bands. HV 170±10.

Group I. 7.85% Ni, 0.49% Co, 0.16% P, 67 ppm Ga, 266 ppm Ge, 2.6 ppm Ir.

HISTORY

A mass of 3.30 kg was plowed up in 1918 from a field about 5 km northeast of Ogallala, Keith County. In 1930 it was acquired by Nininger who described it thoroughly and presented photographs of the exterior and of an etched slice (1932b). Similar photographs were later reproduced by Nininger & Nininger (1950: plates 10 and 17) and Nininger (1952a: plate 11). Frost (1965a) included Ogallala in his discussion of the bandwidth of octahedrites.

COLLECTIONS

London (1,203 g), Tempe (1,176 g), Washington (118 g), Chicago (48 g), Harvard (17 g).

DESCRIPTION

According to Nininger (1932b), the mass had the form of a very oblique pyramid, roughly quadrangular in cross section and tapering from the basal dimensions of 11.5 x 9.3 cm to 3.2 x 2.2 cm at the opposite end. The total length was 19 cm. The surface is rather evenly covered with angular regmaglypts, usually 1-2 cm in diameter and rarely more than 5 mm deep. It is a complete individual, except for a small piece removed by sawing before it was acquired by Nininger. There is little to support the view, expressed by Nininger, that Ogallala should be the only surviving

OGALLALA – SELECTED CHEMICAL ANALYSES

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Hawley in Nininger 1932b	7.93	0.34	0.16	480	450	310	400					
Moore et al. 1969	7.78	0.49	0.16	150	20		130					
Wasson 1970a	7.85								66.7	266	2.6	

fragment of a larger mass that split in the atmosphere. The surface sculpture seems quite comparable to the surface of many other well-preserved single falls.

Etched sections display a coarse Widmanstätten structure of straight, somewhat swollen ($\frac{L}{W} \sim 12$) kamacite lamellae with a width of 1.60±0.20 mm. The kamacite has numerous subboundaries decorated with 1 μ phosphides, and Neumann bands are common. The microhardness is 170±10. Taenite and plessite cover 5-10% by area. The fields are developed as degenerated comb plessite or as acicular plessite with 2-8 μ wide, pointed kamacite needles in a duplex matrix. Many taenite ribbons and wedges are decomposed to coarse, pearlitic structures with 1-2 μ wide taenite lamellae, or to spheroidized structures with taenite spherules, 5-20 μ in diameter. These forms are typical for cohenite-bearing group I irons.

Schreibersite occurs as scattered skeleton crystals, e.g., 5 x 5 or 5 x 1 mm in size. It is monocrystalline and usually enveloped by a 100-400 μ thick rim of cohenite. Schreibersite is further present as 20-80 μ wide grain boundary precipitates and as 5-10 μ blebs inside the coarser plessite fields. Rhabdites occur in sizes ranging from 1-30 μ, the larger ones being quite common.

The typical, complex group I nodules of silicate-graphite-troilite-schreibersite and cohenite are present, as for example 10 x 5 x 5 mm bodies. It appears that the 50-300 μ silicate grains (olivine and pyroxene) form the nuclei, around which successive shells of graphite, troilite, schreibersite and cohenite are deposited, in that order. The graphite forms 50-200 μ borders or massive 1-2 mm aggregates of cliftonite crystals and of graphite composed of sheaves with "horsetail extinction." In the graphite there are tiny silicate and schreibersite blebs. A few chromite crystals, 50-250 μ in size, occur scattered in the graphite and appear to function as early nuclei in the same way as the silicates. The troilite is only present in minor amounts as 50-500 μ monocrystalline bodies, and only a trivial amount of daubreelite was noted. Irregularly enveloping the mentioned minerals are a 0.5-1 mm thick rim of monocrystalline schreibersite and then a 0.1-0.4 mm thick rim of monocrystalline cohenite. The microhardness of the schreibersite and the cohenite is 900±25 and 1060±40, respectively. Cohenite is almost always 150-200 units harder than the associated schreibersite.

The aggregates and the schreibersite-cohenite crystals have, in turn, nucleated kamacite which now envelops them as a 1.5-4.0 mm wide rim. A few cohenite bodies, typically 2 x 0.3 mm, occur scattered centrally in the kamacite lamellae, adjacent to taenite and plessite. These are, as usual, not enveloped in swathing kamacite, suggesting that they are late precipitates in the kamacite.

Ogallala has a rather well-preserved fusion crust. On sections it appears as 20-150 μ thick, laminated, metallic layers, overlain by a 100 μ crust of fused oxides. Corrosion has, however, converted part of the crust to limonite and another part is spalled off. The dendritic metal has a microhardness of 370±25. Under the fusion crust is a heat-affected α_2 zone ranging from 1-4 mm in thickness. In the exterior 50% of it micromelted phosphides are present, and minute veinlets of phosphide-melts connect the various phosphide bodies. Some fissures extend along these weak zones and have later corroded. The microhardness of the α_2 zone is 190±10; the complete hardness curve perpendicular to the surface is of type II with a minimum of 160±5 at 2 mm depth. Carbon, in addition to being present as free graphite and cohenite, is present in taenite in solid solution. In the heat-affected zone the taenite gradually loses its carbon – and its staining – and is, in turn, surrounded by 10-20 μ wide zones of bainite-martensite, created by the diffusing carbon. Under the metallic fusion crust is a 20 μ thick carburized zone formed by the rapid diffusion of carbon from the fused layers into the solid metal.

Ogallala is a well-preserved iron which structurally possesses all the typical features of group I irons. It is particularly closely related to Bischtübe, Mount Ayliff and Bohumilitz, as is also borne out by the chemical analyses.

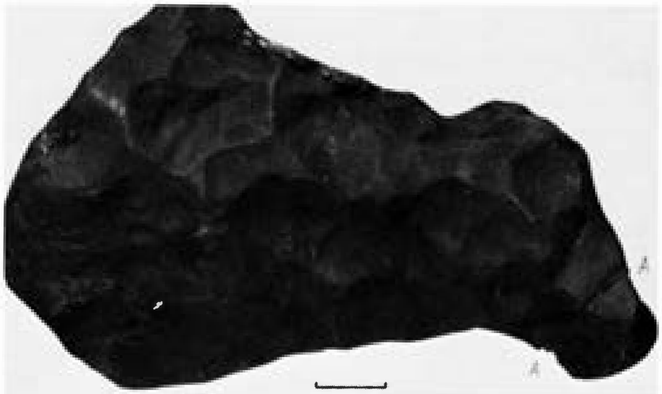

Figure 1321. Ogallala. Main mass showing regmaglypts. At A-A a cut, with samples restored to original position. Scale bar approximately 2 cm. S.I. neg. 26388.

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

118 g slice (no. 919, 7 x 5 x 0.6 cm)

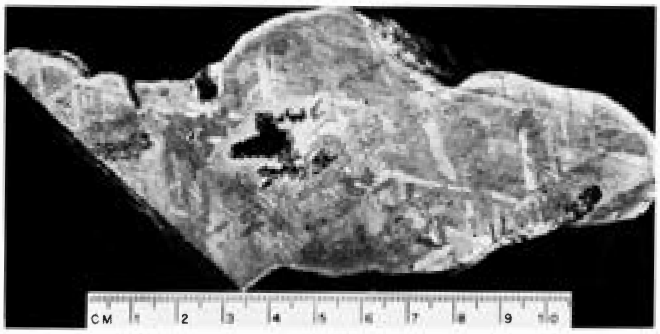

Figure 1322. Ogallala (Tempe no. 90.1x). A coarse octahedrite of group I showing a troilite-silicate-graphite nodule with schreibersite-cohenite rims. The heat-affected rim zone is distinctly visible. Deep-etched. Scale in centimeters. (Courtesy C.B. Moore.)

Oildale, California, U.S.A.

The small mass (50 g) in Albuquerque has an obscure origin (La Paz 1965). According to my study of the material, the size, shape, and internal structure correspond to shocked and reheated fragments of Canyon Diablo stage VI and VII; see page 396. Since this structural development is unique to crater-producing meteorites, I must conclude that Oildale is a transported Canyon Diablo slug.

Okahandja, South West Africa

21°59'S, 16°56'E

Hexahedrite, H. Single crystalline kamacite. Decorated Neumann bands. HV 170-215.

Group IIA. 5.75% Ni, 56 ppm Ga, 185 ppm Ge, 9.2 ppm Ir.

HISTORY

A mass of about 14½ pounds (6.5 kg) was found before 1926 near Okahandja. The material is in the Museum of the Geological Survey, Pretoria. It is undescribed and only recorded as an "iron meteorite" (Hey 1966: 356).

COLLECTIONS

Pretoria (main mass), Heidelberg (450 g).

DESCRIPTION

The shape and dimensions of the main mass are unreported. For the present work a 28 g sample (38 x 12 x 9 mm) was submitted for examination before it was subjected to chemical analysis by Dr. J.T. Wasson.

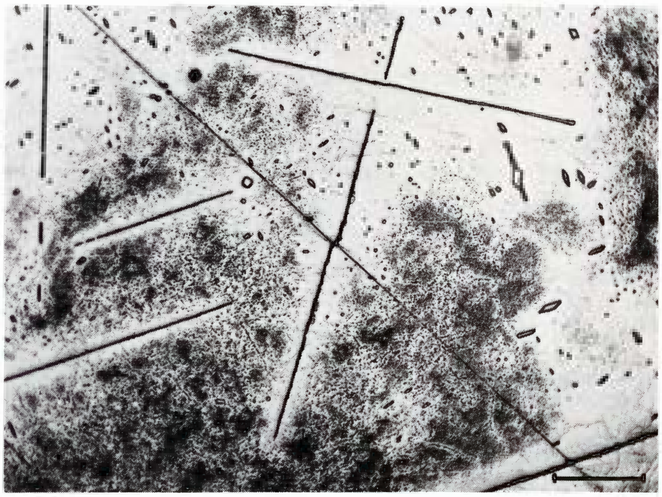

Figure 1323. Okahandja (Heidelberg). Hexahedrite with plate-shaped and prismatic rhabdites. In the dark zones the rhabdites are only about 1 μ across. Etched. Scale bar 300 μ.

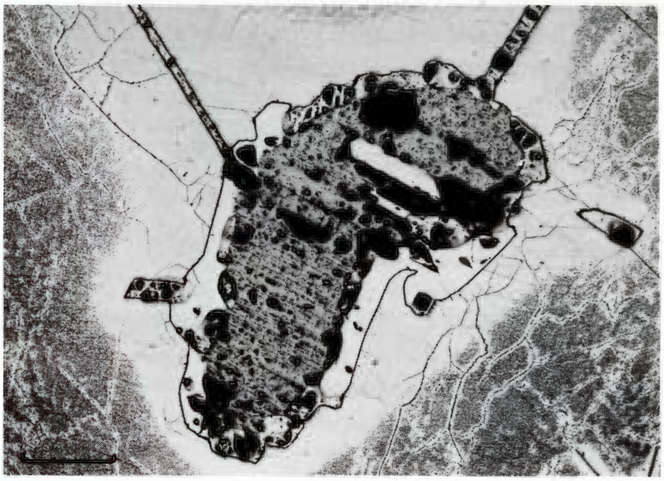

Figure 1324. Okahandja (Heidelberg). Troilite-daubreelite nodule of parallel platelets. Surrounded by cohenite (white, with few defects) and schreibersite (white, severely damaged and torn by polishing). Two rhabdite platelets grow out from the schreibersite rim. Etched. Scale bar 300 μ.

The sample contains the original surface which is only slightly weathered. The fusion crust is lost, but the heat-affected α_2 zone is fully preserved as a 2.5 mm wide rim. From the appearance, it is estimated that the main mass must be very well preserved, having lost, on the average, less than 0.2 mm by terrestrial corrosion.

The heat-affected α_2 zone displays, in its exterior half, micromelted phosphides. These are rapidly solidified with primary dendrites and fine eutectics; many have coalesced to larger units, or are connected by 1 μ wide zigzagging melts following the high temperature grain boundaries. The microhardness of the α_2 zone is 210±5, rather hard, presumably due to a significant proportion of phosphorus in solid solution in the distorted α_2 phase (hardness curve type IV).

The cohenite in the α_2 zone is decomposed to a confusing polycrystalline mosaic of 5-25 μ units, which are usually fan-shaped and reminiscent of the graphite particles so commonly found in the troilite nodules of group I irons. Due to the brief period of reheating, only small quantities of carbon diffused out from the cohenite into the surrounding iron. Upon cooling, the 10-20 μ wide austenite zone, which was now rich in carbon, transformed diffusionless to dark-etching martensitic-bainitic structures, with hardnesses of 290±30 – well above the remaining α_2.

While the younger generation of Neumann bands disappears entirely in the α_2 zone, the older generation apparently persists. High magnification reveals, however,

OKAHANDJA – SELECTED CHEMICAL ANALYSES

	percentage			ppm								
Reference	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Wasson 1972, pers. comm.	5.75								56	185	9.2	

that the bands are eliminated; but the fine precipitates remain, and thus mark the former positions of the bands.

Okahandja is a hexahedrite. Upon being etched the surface becomes cloudy and stained in irregular patches. The clear areas usually show large rhabdites in a pure kamacite matrix, while the matte regions display a few large rhabdites and a kamacite matrix densely crowded with 0.5-1.5 μ rhabdite particles. Subboundaries are numerous and conspicuous because they are copiously decorated with 1 μ phosphide particles. Neumann bands cross the entire section in numerous directions. The bands are 5-10 μ wide in clear kamacite but only about 1 μ wide in kamacite loaded with 1 μ rhabdite precipitates; these evidently restrict the size of the twins formed by mechanical deformation. It appears that the dislocations responsible for the formation of the mechanical twins are severely hindered in their movements by the densely spaced small particles.

An older generation of Neumann bands follows at least three directions and are decorated along both long sides with angular 1-5 μ rhabdite particles. The bands are annealed to straight segments or they are entirely annealed out, leaving only a large number of 5-30 μ cells which are elongated according to the previous band directions. Thus, 1-5 μ rhabdite crystals are often found in long, straight rows, apparently without reason. A close inspection reveals that they have been nucleated along former band-sides, and that these later disappeared by annealing.

Phosphides are very common, both as platelets and as prisms. The rhabdite platelets are rather uniformly distributed and not arranged in rows, as in, e.g., Uwet. They are typically 8 mm x 50 μ, 2 mm x 20 μ, 0.5 mm x 3 μ and oriented in numerous directions. The many platelets that radiate from the troilite nodules – evidently nucleated by the rimming schreibersite – are conspicuous. The rhabdite plates are usually enveloped in 50-100 μ wide zones of clear kamacite which is depleted in phosphorus and nickel.

The rhabdite prisms are 5-15 μ across and occur uniformly distributed between the plates. In addition, a very large number of 0.5-1 μ phosphide particles occur in patches across the sections. Finally, there is a rather unusual variety of polycrystalline, irregular phosphides. These are rounded, subangular or with reentrant angles, 10-60 μ across, and are composed of 5-25 μ units that meet along irregular interfaces. They are best observed on a polished section under crossed Nicols. Some of them are intergrown with cohenite of similar sizes. The cohenite is harder, more ductile and shows stronger anisotropy. In the α_2 zone the cohenite stands out in contrast because it is enveloped by a black martensite halo.

Troilite-daubreelite nodules occur as 0.05-2 mm aggregates. Larger nodules will probably be found when entire sections are studied. The nodules are composed of alternating lamellae of 1-60 μ wide troilite and daubreelite. The small nodules have a larger proportion of daubreelite. The troilite is slightly damaged and recrystallized to 5-100 μ units, while the daubreelite lamellae appear undamaged. Quite locally, minute patches of shock-melted fine-grained troilite occur, particularly along interfaces.

The aggregates have served as nuclei for the precipitation, first, of 20-30 μ schreibersite and then discontinuous 50-100 μ wide rims of cohenite. The cohenite is not decomposed except in the α_2 zone as noted above. One of the troilite nodules burned out in the atmosphere, but the cohenite has survived as a decomposed rim because it is more refractory than troilite.

Okahandja is severely deformed as the result of a cosmic event. All phosphides are brecciated and sheared. The plates are often twisted and individual fragments are shear-displaced 5-100 μ relative to each other. The hardness of the adjacent sheared kamacite is correspondingly high, 200±15. In other, less violently deformed parts of the meteorite the hardness is lower, 175±6. Locally, cubic cleavage fractures occur as millimeter-long, 2-10 μ wide fissures now recemented by terrestrial oxides.

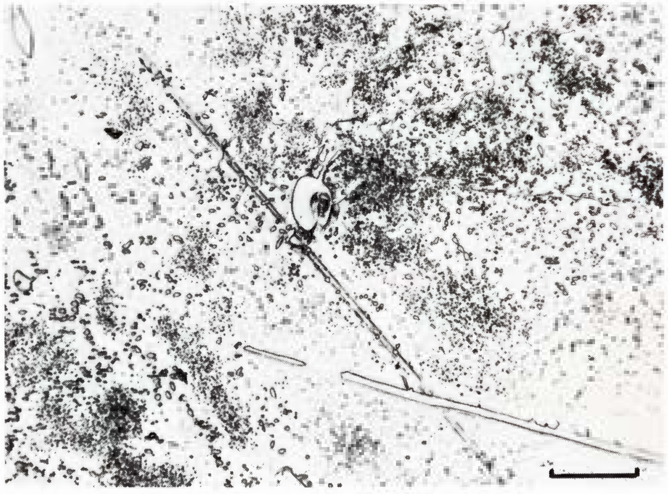

Figure 1325. Okahandja (Heidelberg). The exterior A-part of the heat-affected α_2 zone. Large and small phosphides are fused and partly resorbed in the metal. Etched. Scale bar 50 μ.

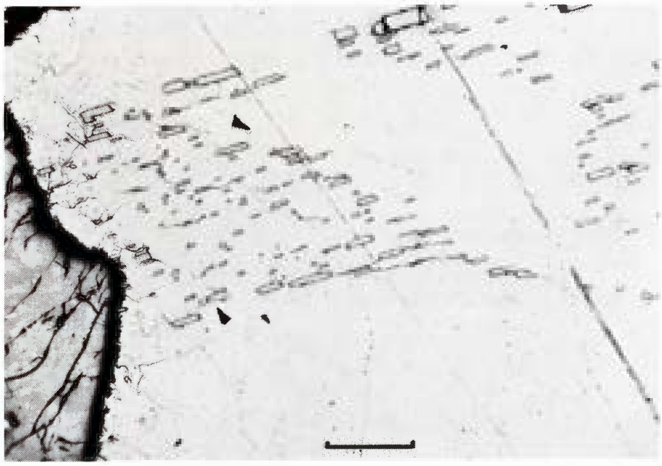

Figure 1326. Okahandja (Heidelberg). From the heat-affected α_2 zone. A carbide crystal (extreme left) is altered to a polycrystalline anisotropic aggregate. Carbon which diffused outwards into the metal caused a narrow bainite zone to form (black). Original Neumann bands and rhabdite crystals are also seen. Etched. Slightly crossed polars. Scale bar 50 μ.

Okahandja is related to Coahuila, North Chile and Keen Mountain, and it is a member of group IIA. Okahandja apparently has had a complicated cosmic history involving slow cooling for the primary structure, followed by plastic deformation and Neumann band-producing shock events. Some of the internal cubic cleavage fissures and the cracks along phosphides must have been open microcavities for countless millions of years in space.

Okano, Hyogo Province, Honshu, Japan

35°5'N, 135°12'E

Hexahedrite, H. Single crystal larger than 10 cm. Neumann bands. HV 170±10.

Group IIA. 5.40% Ni, 0.42% Co, 0.23% P, 60 ppm Ga, 180 ppm Ge, 11 ppm Ir.

HISTORY

A mass of 4.74 kg was observed to fall on April 7, 1904, at 6:35 a.m. near the village of Okano. This is near Sasayama and 40 km north of Kobe. A noise resembling a distant cannon was heard there. A teacher who observed the fall from a point 30 km north of the impact reported:

> "On the northwestern sky, at an altitude of about 70°, there suddenly appeared a white-glowing mass. From its tail I saw fused drops fall off. The light phenomenon lasted 1-2 seconds and then disappeared on the southeastern sky, but the white trail of smoke could be distinguished for another eight minutes. Some minutes after the disappearance (of the light) a loud noise like a thunderclap was heard, and this continued for about a minute."

The iron was located in a small forest by a farmer who saw it fall. It was recovered immediately from an 80 cm deep hole in clay. The mass was acquired by the Metallurgical Institute of Kyoto University where it was described by Jimbō (1906) who gave a map, and by Chikashige & Hiki (1912) and Hiki (1912) who reproduced figures of the exterior shape and discussed the metallography – somewhat biased, however, by their erroneous finding of only 4.4% Ni.

COLLECTIONS

Kyoto (3.5 kg), Harvard (383 g), London (302 g), New York (205 g), Washington (17 g).

DESCRIPTION

The mass is roughly lenticular in shape with the overall dimensions 18 x 12 x 7 cm. One surface is rather smooth and convex, while the other shows numerous angular regmaglypts, 2-3 cm in diameter, and a small beak. The fusion crust covers most of the surface as a thick crust measuring up to 1 mm. On the specimen in Washington it is very thin, however, about 25 μ, and consists of fused oxides only.

Under the fusion crust is a 2-3 mm wide heat-affected zone of α_2. In the outer 50%, where the rhabdites are melted and phosphorus has become partly dissolved in the metal, the microhardness is 180±5; in the inner part the α_2 hardness is only 155±5, indicating that phosphorus in solid solution contributes significantly to the hardness of the α_2 phase (Buchwald 1966: 18).

Okano is a normal hexahedrite, a single ferrite crystal larger than 10 cm. Neumann bands are well developed and reach from α_2 to α_2 zone, more or less uninterrupted. The microhardness of the matrix is 170±5. Subboundaries are present and are best seen near the troilite inclusions where they are decorated by 1-2 μ phosphides. No taenite is present.

Schreibersite occurs as 50-200 μ thick precipitates on the troilite. Rhabdites are very common. They range from 0.5 to 25 μ in size. Where they are finest, around the troilite-schreibersite inclusons, the matrix appears matte to the naked eye, and the Neumann bands are narrow – about 1 μ. The microhardness increases in these areas to 180±5. Where they are coarsest, their mutual distance is larger, the matrix appears bright, and the Neumann bands are broad. It is this variation in morphology that is responsible for the subdivision of an etched surface in irregular patches conspicuous to the naked eye. In addition to the rhabdite rods mentioned above a number of plate shaped rhabdites occur. They are typically 1-2 mm in two dimensions and as little as 5-15 μ in the third dimension. They are frequently offset by the Neumann bands.

Troilite is common as 1-10 mm nodules with about 15% daubreelite. The troilite is monocrystalline but shows numerous lenticular-acicular twins from plastic deformation. The daubreelite forms parallel lamellae ranging from 10 μ to 1 mm in width.

Okano is a normal hexahedrite which is structurally and chemically closely related to Braunau, which fell in 1847.

OKANO – SELECTED CHEMICAL ANALYSES

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Moss in Hey 1966	5.4											
Cobb 1967	5.25	0.42					138		59		10	
Wasson 1969	5.55								59.9	180	11	

Chikashige & Hiki (1912) reported 0.23% P.