occur in some kamacite lamellae. The bulk phosphorus content is estimated to be about 0.08-0.09%.

Troilite is rather common as 0.05-5 mm angular or rounded bodies which usually contain about 15% daubreelite in the form of parallel, narrow lamellae. The troilite was once monocrystalline, but, as a result of the plastic deformation mentioned above, it is now severely brecciated and shows undulatory extinction or martensitic lenticular deformation twins. It is frequently sheared and displaced in successive steps, each 50-100 μ wide, but it is not shock-melted. Also present are small, 20-100 μ crystals showing rhythmic intergrowth of alternating 1 μ wide troilite and daubreelite lamellae.

Chromite occurs as 100-500 μ euhedric crystals, some of which have served as nucleation centers for troilite and for a minute quantity of phosphides. The troilite may have decomposed later to form some daubreelite and in these cases chromite and daubreelite are found in intimate contact. The aggregates are usually crushed by the plastic flow of the surrounding metal.

In the kamacite matrix are numerous hard, 20 x 1 μ, platelets of carlsbergite.

Norfolk is a weathered medium octahedrite which is structurally and chemically closely related to Boxhole, Henbury, Costilla Peak and other irons of the phosphorus-poor end of group IIIA.

Specimen in the U.S. National Museum in Washington:
110 g part slice (no. 1294, 9 x 3.5 x 0.7 cm)

Norfork, Arkansas, U.S.A.

36°13'N, 92°17'W; 150 m

Medium octahedrite, Om. Bandwidth 1.05±0.15 mm. Neumann bands. HV 250±15.

Group IIIA. 7.92% Ni, 0.50% Co, 0.14% P, 20.4 ppm Ga, 41.2 ppm Ge, 0.3 ppm Ir.

HISTORY

A mass of unknown weight fell in October 1918 near Norfork, Baxter County. Isaac C. Luther allegedly saw it fall. While searching for a large mass next day, he only located a fragment of 1,050 g which was recovered from a 120 cm deep hole. Unfortunately, very little detailed information was available when Nininger in the mid-thirties learned about the fall. The finder had been dead for several years and the community seemed to have no recollection whatsoever of the fall. Nininger (1937a) described the fragment and gave three photographs but was unable to locate the remaining, probably larger, mass. La Paz (1938) discussed the unusually deep impact hole of the small body. Nininger & Nininger (1950: plate 17) gave a photograph of the well-preserved exterior. Jaeger & Lipschutz (1967b) found the kamacite to be shocked between 130 and 400 k bar. Fireman & Schwarzer (1957) examined the ^{3}He, ^{3}H and ^{6}Li isotopes. Tilles & Tamers (1963) discussed the reasons for tritium being lower than expected in Norfork and other iron meteorites. Schaeffer & Heymann (1965) counted ^{36}Cl, ^{39}Ar and ^{38}Ar and found an exposure age of 690-700 million years. Voshage (1967) estimated the exposure age to be 700±80 million years. Hintenberger et al. (1967a) measured the concentration of the noble gases. In these works it was assumed that the mass of the fall was only 1 kg; it is, however, almost certain that a considerably larger body fell but only 1 kg was recovered. The coordinates above are those of Norfork.

COLLECTIONS

Tempe (481 g), London (97 g), Washington (60 g), Los Angeles (9 g).

Figure 1285. Norfork (Tempe no. 296.1). The recovered mass shows distinct regmaglypts and well-preserved fusion crusts. Scale bar approximately 2 cm.

NORFORK – SELECTED CHEMICAL ANALYSES

Berkey & Fisher (1967) mapped the chlorine distribution of a 2 cm^2 slice adjacent to the surface. The chlorine ranged from 0.05 to 2 ppm, a range similar to that for the other falls examined, but 10 to 10^4 times lower than for weathered finds.

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Wasson & Kimberlin 1967	7.88								20.4	41.2	0.3	
Moore et al. 1969	7.95	0.50	0.14	20	70		170					

DESCRIPTION

The recovered fragment has the approximate dimensions of 11 x 7 x 5 cm. A hackly fracture face of about 10 x 7 cm terminates one side, while another side is irregularly covered with marked regmaglypts, 2-4 cm across, and 1-2 cm deep. This part of the surface is smoothly rounded; ablation-melted metal spills over the edges but does not cover the hackly fracture face. This fracture must, as already pointed out by Nininger, be very late, either originating just before or upon the very impact with the ground. The fusion crust is a composite of metallic and oxidic sheets that, locally, build up to 0.5 mm thickness. In places the fusion crust is completely removed – probably by rough mechanical handling. Where it is best preserved, it is shiny black and full of hairy streamers formed during the flight. Under the fusion crust is an unusually wide heat-affected α_2 zone, ranging from 2-8 mm in thickness. The microhardness is 192±12 and the α_2 grain size is 20-50 μ. The recovered transition zone has a minimum hardness of 165±5 (hardness curve type I).

Etched sections display a medium Widmanstätten structure of straight, long ($\frac{L}{W} \sim 25$) kamacite lamellae with a width of 1.05±0.15 mm. There are numerous subboundaries, decorated with 0.5 μ phosphides. The kamacite shows a mixture of hatched substructure and Neumann bands, and its microhardness is 250±15. Most sections appear to have fine fractures which follow the Widmanstätten grain boundaries. They branch irregularly and terminate either at the ablated surface or at the hackly fracture face. They indicate that the parent body was severely cracked; all these fissures were potential fracture zones along which the final separation could have taken place. In several places there are narrow shear zones of cold-worked metal; within one of these the kamacite has recrystallized to a fine aggregate of 2-10 μ ferrite grains. Since this particular zone was only 5 mm under a wide α_2 zone, the recrystallization may well be the effect of reheating during the atmospheric flight.

Figure 1286. Norfork. The same as Figure 1285 from a slightly different angle so that the striated fusion crusts are clearly exposed. Scale bar approximately 2 cm. S.I. neg. M-106.

Taenite and plessite cover about 35% by area, mostly as comb and net plessite fields. They are degenerated; the taenite is in the process of being resorbed, so the taenite rims are often discontinuous. They are, however, better preserved than in Norfolk which they otherwise resemble strongly. Martensitic transition zones separate the brown-etching taenite borders from a fine-grained, duplex $\alpha + \gamma$ interior. In the α_2 zone the taenite is yellowish, and the adjacent metal is transformed to a carbon-rich nickel-bainite.

Schreibersite is somewhat more common in Norfork than in Norfolk, forming 10-40 μ wide grain boundary precipitates and an occasional 0.1 mm thick bleb. Rhabdites occur locally as 3-6 mm thick prisms.

Troilite is present as 0.2-8 mm lenses and irregular nodules, normally with parallel daubreelite lamellae. Since the bulk phosphorus content is low, 0.14%, very little schreibersite has precipitated upon the troilite inclusions.

In the kamacite there are numerous hard 20 x 1 μ platelets, similar to the oriented chromium nitrides (carlsbergite) reported in Costilla Peak, Norfolk and others.

Norfork is a medium octahedrite which appears to have fallen in 1918 or not too many years before. Only a minor part of the whole mass seems to have been found. Norfork is a typical group IIIA meteorite which is related to Casas Grandes, Dexter, Dimitrovgrad, Tonganoxie, Trenton and similar irons. Norfork has more nickel and phosphorus than Norfolk; this is clearly manifested in the structure which displays more taenite and more and larger schreibersite bodies. Norfork also has a considerably lower hardness than Norfolk.

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

60 g part slice (no. 942, 7.5 x 4 x 0.3 cm) neighbor slice to the one figured by Nininger (1937a: figure 3)

Norin-Shibir, Buryat Autonomous SSR

51°48'N, 107°54'E

A small fragment of 3.5 g in the Academy of Sciences, Moscow, is all that is known of this meteorite. It was thoroughly described, with figures, by Zavaritskij & Kvasha (1952: 59), but the precise origin is uncertain. The date of find is before 1937, but in the twentieth century; and the coordinates are assumed to be those given above. Quite different coordinate sets have, however, been given by other authors; see Hey (1966: 346).

DESCRIPTION

The 3.5 g mass measures 2 x 1 x 1 cm and is apparently an entire individual meteorite. From the description by Zavaritskij & Kvasha (1952: 59) it appears that Norin-Shibir is an aggregate of 0.5-1 cm precursor taenite grains and of olivine-troilite inclusions. Upon cooling, the individual taenite crystals have transformed to a medium Widmanstätten structure, with short, irregular kamacite lamellae, displaying widths of 0.8±0.2 mm.

The few structural observations, together with the chemical analysis, strongly suggest that Norin-Shibir is an unusual polycrystalline meteorite which may have as its nearest relatives either a pallasite or iron meteorites, such as Udei Station, Four Corners, Mesa Verde and Pitts. It is surprising that such a small fragment should ever have been found and secured for science. In view of the uncertain origin, it is recommended that the material is rechecked for a possible mislabeling of Four Corners or Krasnojarsk material.

Norquin, Neuquen, Argentina

Approximately 37°43′S, 70°37′W

Medium octahedrite, Om. Bandwidth about 0.8 mm.

Group unknown, but possibly group IIIAB. Probably 8.5-9.5% Ni.

HISTORY

A mass of 19.25 kg was recognized as being a meteorite when a preliminary description by Ducloux appeared in 1945. The date and place of discovery are unknown, but the mass appeared to have been found in the eastern part of the Andes near the village of Norquin which is situated 9 km south of El Huecu and north of the river Agrio. Ducloux provided three photographs of the exterior and a photograph of a deep-etched section – unfortunately without stating the scale of the pictures. Curatorial information was provided by Radice (1959: 105).

COLLECTIONS

La Plata (18.4 kg), Buenos Aires (about 800 g).

CHEMICAL ANALYSIS

Only an inappropriate analysis, far too low in nickel (4.5%), has been published (Ducloux 1945).

DESCRIPTION

The following are some hasty field notes, taken on a visit to the two museums referred to above in March 1973. Until more detailed work becomes available, these notes may serve for what they are worth.

The main mass is elongated, prismatic, somewhat like New Leipzig, and measures 30 x 15 x 14 cm. At one end there are two rough cuts of 4 x 4 cm and 9 x 7 cm, having provided two endpieces, the biggest of which is the 800 g sample in Buenos Aires. The mass is weathered and the original regmaglypts, 1.5-3 cm across, are now modified and separated by sharp-edged crests. It is estimated that, on the average, 2-3 mm were lost to weathering. The shape of the meteorite is, thus, in all major respects still essentially the same as just after its fall.

The deep-etched sections suggest that Norquin is a medium octahedrite with a bandwidth of 0.8±0.15 mm. The kamacite lamellae are straight and long ($\frac{L}{W} \sim 20$), and the fourth Widmanstätten direction appears as 2-3 mm wide patches with serrated borders. Taenite and plessite cover 40-50% by area. Schreibersite occurs as cuneiform skeleton crystals, 20 x 1 or 10 x 1 mm in size, and surrounded by 0.8-1.5 mm wide zones of swathing kamacite.

Ducloux (1945) reported graphite and olivine crystals in the residue from the chemical analysis, but these identifications need reconfirmation.

From the above very insufficient description, it may be cautiously suggested that Norquin is a medium octahedrite with 9.0±0.5% Ni and 0.4±0.1% P, probably belonging to group IIIB. It is recommended that the main mass be examined and analyzed for main and trace elements, and its mineralogy be fully described.

Norristown, Georgia, U.S.A.

32°31′N, 82°33′W

Medium octahedrite, Om. Bandwidth 0.65±0.10 mm. ε-structure. HV 275±15.

Group IIIB. 9.64% Ni, about 0.5% P, 18.2 ppm Ga, 32.4 ppm Ge, 0.016 ppm Ir.

HISTORY

A mass of 4.26 kg was found either in 1965 or 1966 by Joe Underwood while he was grading a road near Norristown, Emanuel County. The entire mass was acquired in 1969 by Dr. E.P. Henderson who kindly placed a couple of polished sections at my disposal for a preliminary examination.

COLLECTIONS

Small polished sections in the Smithsonian Institution, Washington.

DESCRIPTION

Two polished sections (No. 5295), each of 15 x 15 mm², and perpendicular to a weathered surface were examined.

The etched sections display a medium Widmanstätten structure of straight – or somewhat distorted – long ($\frac{L}{W} \sim 20$) kamacite lamellae with a width of 0.65±0.10 mm. The kamacite has subboundaries decorated with less than 1 μ phosphide precipitates. Superimposed on this primary

NORIN-SHIBIR – SELECTED CHEMICAL ANALYSES

	percentage			ppm							
Reference	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Dyakonova & Charitonova 1960	9.25	0.57					900					

structure is a hatched ε-structure, due to shock above 130 k bar; the kamacite shows a correspondingly high microhardness of 275±15.

Taenite and plessite cover 40-50% by area. Massive plessite fields are prominent. They exhibit tarnished taenite rims, martensitic-bainitic transition zones and dark-etching interiors with nickel-martensite developed parallel to the bulk Widmanstätten structure. Other fields have acicular α-lamellae, 5-40 μ wide, or are developed as comb or net plessite fields distinguished by concave taenite islands 10-50 μ across. Similar structures are common in, e.g., Narraburra, Bear Creek and Mount Edith.

Schreibersite is common as cuneiform skeleton crystals that attain sizes of 12 x 0.8, 2.5 x 1, or 2 x 0.5 mm and are enveloped in 0.6-1 mm wide rims of swathing kamacite. Schreibersite also occurs as 10-50 μ wide grain boundary veinlets and as 5-50 μ irregular blebs substituting for taenite in the net plessite. Finally, schreibersite occurs as rows of 5-20 μ particles located 5-10 μ outside the present taenite and plessite borders, a situation which is duplicated exactly in a number of other IIIB irons, e.g., Bear Creek and Narraburra. The bulk phosphorus content is estimated to be 0.5±0.1%.

Troilite was only seen once, as a 250 μ body, around which a large schreibersite crystal had grown in the solid state.

All minerals are severely distorted by cosmic deformation. The schreibersite is brecciated and shear-displaced and narrow veins (2-10 μ) of troilite penetrate along the fissures.

Unfortunately, the meteorite is considerably corroded. Locally, the limonitic crust is 6 mm thick, and all fusion crust and heat-affected α_2 zones have long since disappeared. Corrosion penetrates deep into the interior along the brecciated schreibersite bodies and along α - γ grain boundaries. Nevertheless, a hardness track perpendicular to the surface showed a significant drop from 275 to 210 in the oxidized near-surface zone, which indicates that, on the average, 4-5 mm has been lost (hardness curve I, where the left leg and part of the right are corroded away).

Norristown is a typically shock-hardened medium octahedrite of group IIIB. It is particularly closely related to Bear Creek and Narraburra.

North Chile, Antofagasta, Chile

Approximately 22°30'S, 69°30'W; Approximately 2000 m

Normal hexahedrite, H. Single crystal larger than 50 cm. Neumann bands. HV 150-270.

Group IIA. 5.59% Ni, 0.48% Co, 0.30% P, 44 ppm Cr, 58.9 ppm Ga, 177 ppm Ge, 3.6 ppm Ir.

Includes the individuals Coya Norte, Filomena, Puripica, Quillagua, Rio Loa, San Martin A, B and C, Tocopilla and Union. Mejillones, Negrillos and Sierra Gorda do not belong to the group.

HISTORY

Since 1875 when the first hexahedrite from North Chile, Mejillones, was reported, at least 12 other masses and fragments have turned up, the names of which have been given above. Various examiners have at various dates given somewhat differing descriptions of the material, and few have had an opportunity to study specimens from all the masses. Consequently, the conclusions reached by Merrill (1924b), Henderson (1941a), Wetzel (1952), Vilcsek & Wänke (1963), and Chang & Wänke (1969), to quote a few, all disagree in details. Quite recently Wasson & Goldstein (1968) examined nine of the thirteen hexahedrites and reported on the detailed structures and compositions. The following examination includes, in addition, the four last masses. It supports Wasson & Goldstein's conclusions, except for the idea that Puripica should be an independent fall. A general summary follows the detailed descriptions given below.

North Chile (Coya Norte), Antofagasta, Chile

23°20'S, 68°56'W

Hexahedrite, H. Single crystal larger than 20 cm. Neumann bands. HV 195±20.

Group IIA. 5.57% Ni, 0.43% Co, 0.30% P, 58.9 ppm Ga, 174 ppm Ge, 3.6 ppm Ir.

HISTORY

A mass of 18.6 kg was found in 1927 at Coya Norte near Chuquicamata. The coordinates of Chuquicamata are given above, but the locality may mean little since it is possible that the iron has been transported. It was apparently acquired by Nininger who cut and distributed it in the early 1930s. It was briefly mentioned by Nininger (1933a), Linsley (1934) and Nininger & Nininger (1950: 47). Nininger (1952a: plate 4) presented a photograph of an etched endpiece. Henderson (1941a) discussed the relationship between Coya Norte and other Chilean hexahedrites, and quite recently Wasson & Goldstein (1968) and Wasson (1969) resumed the discussion with a new and refined technique, based on trace element studies and microprobe data. They concluded that Coya Norte was part of a shower, formed by Rio Loa, San Martin, Filomena, Coya Norte and Tocopilla. Lovering & Parry (1962) included the meteorite in their thermomagnetic

NORRISTOWN – SELECTED CHEMICAL ANALYSES

	percentage			ppm								
Reference	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Scott et al. 1973	9.64								18.2	32.4	0.016	

study. Signer & Nier (1962) determined the amount of noble gases and estimated the preatmospheric mass to be about 200 t. The exposure age was found to be 250±200 million years. Bauer (1963) measured ^{3}He and ^{4}He and estimated the exposure age to be 220 million years.

COLLECTIONS

Washington (4,850 g), University of California, Berkeley (4,240 g), London (2,221 g), Tempe (2,200 g), Harvard (925 g), Calcutta (800 g), Ann Arbor (718 g), Chicago (164 g).

DESCRIPTION

The original size and shape is unknown. The 4.8 kg slice in the U.S. National Museum is 21 x 12 cm in area and 4 cm thick. Half the circumference is covered with irregular regmaglypts 2-4 cm across, but the other half shows coarse, hackly fracture surfaces as if this is a surface produced upon late splitting in the atmosphere. It cannot be ruled out, however, that the fractures are artificial, since the surface is very little corroded. The whole mass could, unfortunately, not be inspected; but it appears that the cubic cleavages along a large part of the surface are artificial. In connection with this, it should be remembered that at least one of the masses from this region was split by dynamiting (Wetzel 1952). Fusion crust and heat affected rim zones could not be identified and seem to have weathered away.

Etched sections demonstrate that Coya Norte is a single kamacite crystal in which numerous rhabdite plates are precipitated in several directions. The kamacite is mottled due to varying size and frequency of the smaller rhabdites. Neumann bands are common and run as 2-4 μ wide ribbons for long distances. In the 1-2 mm wide, phosphorus-depleted rim zones around the troilite-schreibersite aggregates there are subboundaries decorated with 1 μ rhabdites. A little farther out there are, in addition, a large number of 1 μ rhabdites precipitated in the grain interior. The microhardness is 195±20, varying with the amount and type of precipitation in the kamacite.

The rhabdites occur in two varieties: as extremely thin plates, e.g., typically 10 x 10 x 0.004 mm, and as normal prismatic rods, 5-15 μ thick. Fissures are frequently developed along the plates; they have later become partially filled with terrestrial corrosion products.

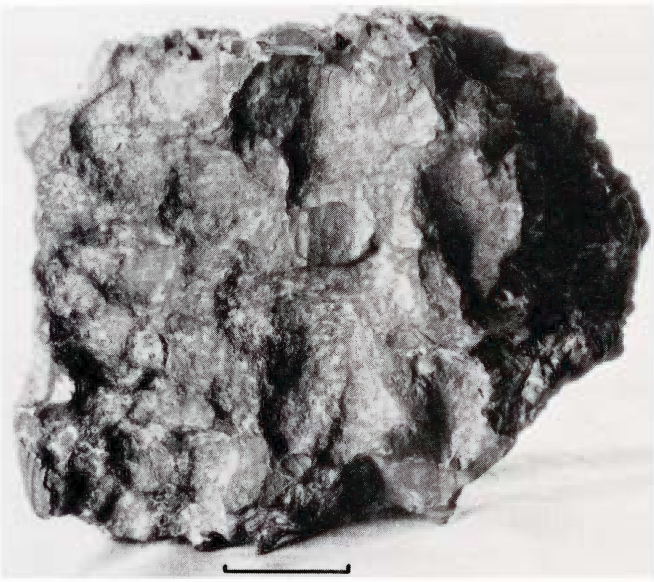

Figure 1288. North Chile. The Coya Norte mass before cutting (U.S.N.M. no. 859). This side shows irregular regmaglypts and several marks from artificial hammering. Scale bar approximately 5 cm. S.I. neg. 9865A.

Figure 1289. North Chile. The Coya Norte mass seen from the opposite side. This side shows a coarse hackly fracture the origin of which is uncertain. Scale bar approximately 5 cm. S.I. neg. 9865.

NORTH CHILE (COYA NORTE) – SELECTED CHEMICAL ANALYSES

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Henderson 1941a	5.51	0.37	0.30			300						
Lovering et al. 1957		0.51				48	123		56	144		
Nichiporuk & Brown 1965											3.3	22
Moore et al. 1969	5.66	0.40	0.29	50	365		140					
Wasson 1969	5.55								58.9	174	3.6	

Troilite occurs as 1-5 mm scattered, rhombic nodules. Locally a 20 x 2 mm troilite lens was observed. The troilite contains 10-30% daubreelite in the form of parallel bars, 0.1-1 mm thick. The troilite is partially shock-melted and invades the shattered daubreelite and the enveloping, 200 μ wide schreibersite rims. Some 1-10 μ daubreelite fragments and a little metal are dispersed in the troilite. Troilite-daubreelite also occurs as fine lamellar intergrowths with alternating 1 μ thick lamellae.

Specimen in the U.S. National Museum in Washington:
4,850 g slice (no. 859, 21 x 12 x 4 cm)

North Chile (Filomena), Antofagasta, Chile
23°1'S, 69°24'W

Hexahedrite, H. Single crystal larger than 30 cm. Neumann bands. HV 157±15.

Group IIA. 5.54% Ni, 0.30% P, 58.7 ppm Ga, 176 ppm Ge, 3.6 ppm Ir.

HISTORY

A mass of 21 kg was found about 1922 in the Atacama Desert on the railroad between the stations of Sierra Gorda

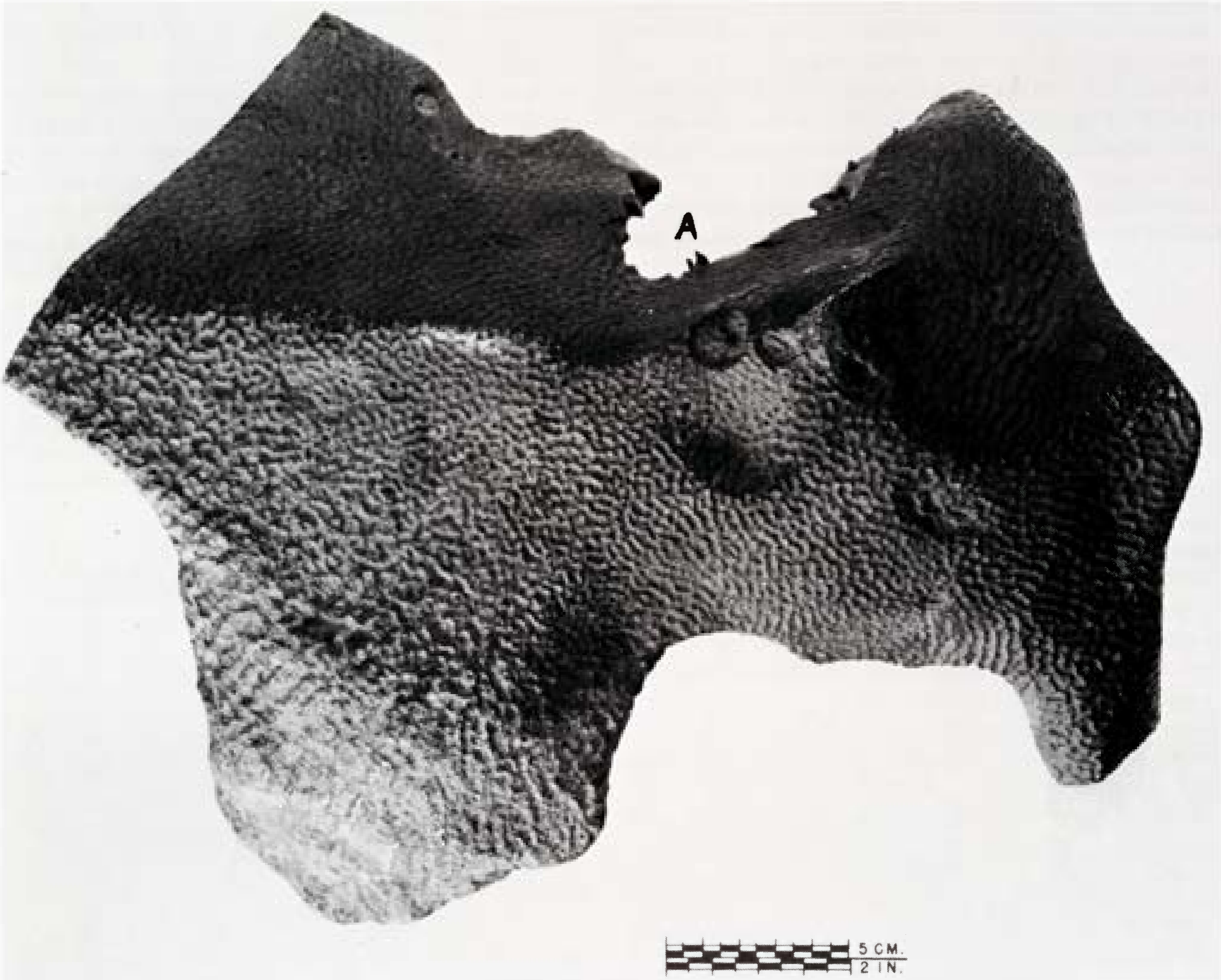

Figure 1290. North Chile. The Filomena mass (U.S.N.M. no. 1334). The top side is pock-marked by densely spaced pits that meet along razor-sharp ridges. A few large depressions indicate the location of troilite nodules. At A, a hemispherical cavity from the opposite side penetrates to the top side.

NORTH CHILE (FILOMENA) – SELECTED CHEMICAL ANALYSES

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Henderson 1941a	5.73	0.21	0.30									
Wasson 1969	5.54								58.7	176	3.6	

Part of the cobalt seems to have been included with the nickel in the old determination.

and Union (letter of August 8th, 1938, from the owner of the mass, A. Letelier of Santiago, and later information in the Smithsonian Institution). The whole mass was acquired in 1939 for the U.S. National Museum through the assistance of Dr. C.P. Butler. It was briefly mentioned with an analysis by Henderson (1941a; 1965) and was considered one of the North Chilean hexahedrites. Wasson & Goldstein (1968) found that Filomena was part of the shower which comprised Rio Loa, San Martin, Coya Norte and Tocopilla. Hintenberger et al. (1967) determined the amount of noble gases which was found similar to San Martin, but different from Tocopilla. Chang & Wänke (1969) found the cosmic ray exposure age to be 30±10 million years while the terrestrial age was estimated to be about 120,000 years. These authors also found Filomena and San Martin to be identical, while Tocopilla was found different. It should be added that the place of find along the railroad may indicate that it had been transported but had been left when it was discovered that it contained no noble metals. How the place name Filomena, a spring located at 26°45'S, 69°34'W, became associated with the meteorite is not clear.

COLLECTIONS

Main mass in Washington. Austin (331 g), Norman (96 g).

DESCRIPTION

The mass has the average dimensions of 28 x 24 x 9 cm, but it is extremely irregular. The top side of the mass is pock-marked by numerous small 2-4 mm wide pits which meet along sharp ridges. On the vertical sides they coalesce to subparallel grooves which seem to follow the direction of draining by gravity. The opposite side is extremely indented, both by normal slightly altered regmaglypts, 2-5 cm in diameter, and by a single spherical cavity, which is 10 cm in diameter and penetrates the mass along one edge. This may have been a spherical pit similar to the pits observed on Maria Elena, Gibeon and Sacramento Mountains and later excavated more deeply by corrosion. A 5-10 mm thick layered crust of terrestrial oxides is still present in the cavity. On etched sections it is observed that the heat-affected α_2 zone has disappeared, and it is further seen that the rhabdites survive for a long time, embedded in the 0.1-0.2 mm thick oxide crust that covers most of the iron.

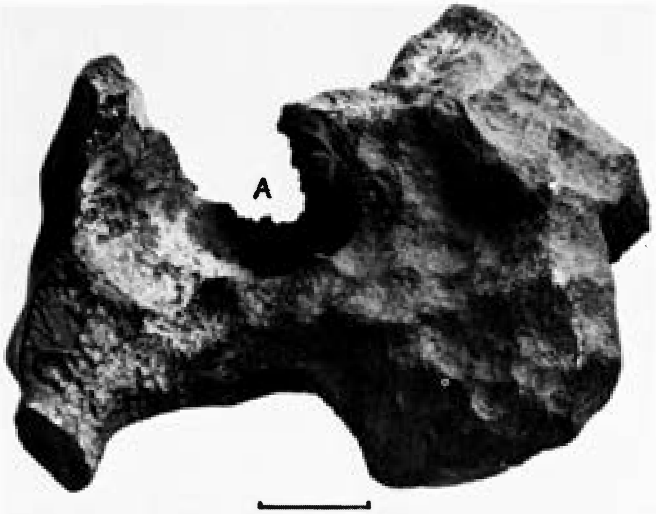

Figure 1291. North Chile. The Filomena mass from the opposite side than one shown in Figure 1290. The regmaglypts are slightly altered and irregularly covered with caliche. A large hemispherical cavity penetrates the whole mass at A. Scale bar approximately 5 cm.

Filomena is a ferrite single crystal. Neumann bands that pinch and swell cover the etched sections uniformly. No recrystallization was observed, and subgrain boundaries are only present in zones close to the few large inclusions. The hardness ranges from 172 to values as low as 144, probably due to inhomogeneities in nickel and phosphorus and to varying degrees of cold working. A mild artificial reheating to about 400° C, which led to recovery, cannot be ruled out.

Schreibersite proper, in the form of irregular 1-5 mm skeleton crystals, is rare. Instead, a dense population of rather uniform, sharp-edged 5-25 μ thick rhabdites occupy all sections. Locally, small rhabdites 1-2 μ across are found. Rhabdites, in the form of plates attain 5-15 mm lengths, at a thickness of 10-40 μ. They are frequently a little bent, distorted, or shear-displaced.

Troilite occurs as 5-15 mm nodules and as smaller blebs. No large troilites are present in the sections, but on the top side of the mass two 5 mm, two 8 mm and one 15 mm nodule are exposed; and it is interesting to note that they are corroded more or less flush with the general iron surface. It is usually stated that the troilite nodules are easily attacked and disappear first. That the nodules now exist in this way proves that several millimeters of iron must have been removed in order to expose them. Had they been at the surface during atmospheric entry, they would have burned out.

A small troilite nodule, 400 x 100 μ, is composed of a stack of parallel, 1 μ wide lamellae of troilite and daubreelite; due to some plastic deformation, the lamellae are slightly curved. The nodule is surrounded by a 40 μ thick schreibersite rim.

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

19.45 kg	main mass (no. 1334, 27 x 24 x 9 cm)
322 g	slice (no. 1334, 14 x 4 x 0.7 cm)
230 g	part slice (no. 1334, 9 x 4 x 0.8 cm)

North Chile (Puripica), Antofagasta, Chile

Hexahedrite, H. Single crystal larger than 20 cm. Deformed Neumann bands. HV 215±10.

Group IIA. 5.68% Ni, 0.45% Co, 0.32% P, 59.5 ppm Ga, 174 ppm Ge, 3.8 ppm Ir.

HISTORY

A mass of 19 kg was found before 1931 in the region of Puripica, province of Antofagasta, department of El Loa. The exact locality is unknown, since this was all the information the original owner, Galvarino Ponce of Santiago de Chile, provided when he sold the mass in 1936 to the Smithsonian Institution (letters of May 19th, 1931, through April 4th, 1937, in the Smithsonian Archives). A spring named Puripica is located at 22°29'S, 68°10'W, but whether or not this has anything to do with the meteorite is not clear. It was listed as a new meteorite by A.D. Nininger (1939) and an analysis was provided by Henderson (1941a). Wasson & Goldstein (1968) examined a specimen in detail and concluded that, although similar in major and trace elements to the other North Chilean hexahedrites, its lack of "phosphide stringers" warranted Puripica a listing as an independent fall. As will be shown below, rhabdite plates are present in abundance, but somewhat irregularly distributed; and it is, therefore, concluded that Puripica belongs with the other North Chilean hexahedrites.

COLLECTIONS

Washington (15.3 kg), Ann Arbor (1,175 g), Calcutta (385 g), Berlin (335 g), London (273 g), Tempe (265 g).

DESCRIPTION

The main mass in Washington is a well rounded fragment measuring on the average 22 x 16 x 14 cm before cutting. About half of the surface is covered by the pockmarks characteristic for all North Chilean meteorites.

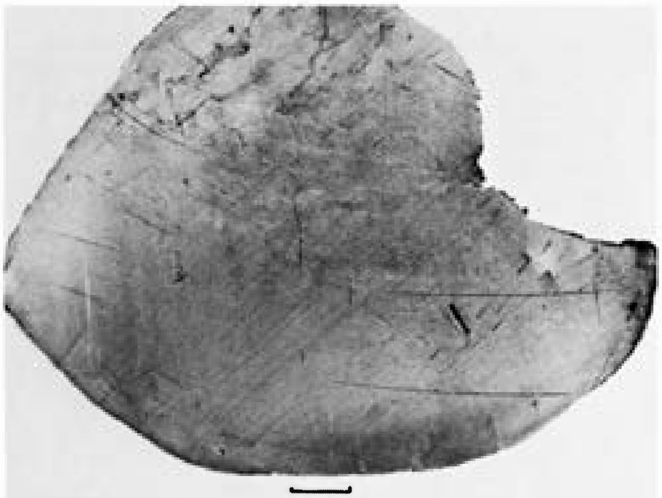

Figure 1292. North Chile. Section through the Puripica mass (U.S.N.M. no. 1227). There are several internal cracks which probably date from the atmospheric breakup. Deep-etched. Scale bar 2 cm. S.I. neg. 1443.

The marks are closely spaced, 2-4 mm in diameter, 1-2 mm deep and with sharp edges in between. The pock-marked sides appear to have been exposed above ground for countless generations. The opposite side is, in accordance with this interpretation, partially covered with an induration crust of caliche which is known to form very slowly on the underside of rocks in a semi-arid, warm climate. One-fourth of the surface still shows the somewhat corroded remnants of regmaglypts, 2-4 cm across and about 1 cm deep. In the protected parts of some of them a trifle of a much altered, warty fusion crust may be seen. The last part of the surface presents a rough hackly fracture zone, where the metallic matrix is plastically deformed and opened along the interfaces between the rhabdite plates and the metal. This part evidently represents the rupture face from atmospheric bursting. Locally a few hammer and chisel marks are present; the deformation introduced by this working is much less than the bulk deformation from the atmospheric breakup.

Etched sections show a normal hexahedrite structure with Neumann bands extending from edge to edge. Severe distortion of the Neumann bands and numerous lenticular deformation bands occur near the visibly torn surfaces. Here the phosphides are broken and displaced by the flow of the surrounding ductile metal. The hardness is 200±10, but increases to 250±20 in the cold-worked parts. It appears that all of the examined specimen of 5 x 3 x 0.5 cm. represents cold-worked material, since the hardness is higher than in most of the other examined North Chilean hexahedrites. Normally, it is not possible in the optical microscope to observe cold-worked areas with deformations of only 10-25%, but the hardness testing will reveal such deformations.

Schreibersite occurs as a few scattered skeleton crystals up to 1 mm across, frequently with a nucleus of troilite or daubreelite. The hardness is 910±30. Much more common and conspicuous on large sections are the plate-shaped rhabdites that range from 1 to 15 mm in length and have thicknesses of 2-40 μ. The plates occur in numerous directions, probably parallel to $\{221\}$ of the kamacite phase. Between the plates are numerous tetragonal, prismatic rhabdites, 5-25 μ across. Around the schreibersite crystals the rhabdites decrease to 0.5-1 μ in size; and in the immediate vicinity they disappear completely. A hardness trace through this zone perpendicular to the schreibersite shows a significant variation; hardness curves of similar shape, but on other levels, have been obtained on various other meteorites. Since it appears that we have here a general rule, it will be discussed in some detail.

NORTH CHILE (PURIPICA) – SELECTED CHEMICAL ANALYSES

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Wasson 1969	5.58								59.5	174	3.8	
Lewis & Moore 1971	5.77	0.45	0.32	50								

Wasson & Goldstein (1968) reported on the detailed composition of the kamacite phase.

The hardness of the kamacite around the schreibersite starts at a minimum (here 198 at a distance of 50 μ) and then rapidly increases through the zone of clear kamacite surrounding the schreibersite. In Puripica the maximum of 270 is reached at a distance of 1.0 mm from the 0.2 mm wide schreibersite crystal which was examined. The hardness thereafter slowly decreases over the next millimeter or so, and simultaneously 0.5-1 μ rhabdites begin to appear. At a distance of 2.5 mm the hardness has dropped to 225 and here the typical, large rhabdites reappear, both prismatic and plate-shaped. In this region the hardness is 215±10. A tentative explanation of the variation may be centered around the phosphorus and nickel atoms, which are known to increase the hardness of kamacite significantly when in solid solution, but contributing little if precipitated as visible rhabdites (Buchwald 1966: 18 ff.). The soft zone around the schreibersite is depleted in phosphorus and nickel, wherefore the hardness is at a minimum. Farther away the kamacite is considerably supersaturated with respect to both atoms, and the hardness reaches the surprising maximum of 270, part of which appears to be due to cosmic cold working. In the following zone the supersaturation gradually disappears by the precipitation of microrhabdites which themselves do not contribute significantly to the hardness. Finally, a kind of equilibrium, or average condition, is reached in the typical rhabdite region.

Troilite is present as 0.2-10 mm nodules and as scattered lenticular bodies, e.g., 11 x 1 mm in size. The large nodules contain 5-15% daubreelite in the form of 10-300 μ wide, parallel lamellae. The smaller ones contain relatively more daubreelite. The troilite is partly shock-melted, partly brecciated. The typical nodule is subdivided into monocrystalline, passive blocks, 50-400 μ across, separated by 10-100 μ wide veins of brecciated or microcrystalline troilite. In several places full shock melting has occurred, and troilite has dissolved part of the adjacent metal and invaded the shattered schreibersite rims in 1-10 μ wide veins. The daubreelite is only damaged to a limited extent and not melted.

In the kamacite matrix there are numerous hard, rose colored particles 1 x 2 to 1 x 10 μ across, of the chromium nitride, carlsbergite.

Puripica is, in structural respects, corrosion features and major and trace-element composition, identical to the other hexahedrites of the group. On the surface it shows significant distortions and fractures which must be due to its violent separation from a larger mass. Its hardness is higher than that of any of the other hexahedrites, but this appears to be due to its having become more cold-worked upon bursting. Almost similar variations are present between the individual Gibeon masses, which, however, display the deformation better because of the Widmanstätten structure and because of the prevalence of almost pure, ductile metal phases, uninterrupted by rhabdite plates.

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

15.25 kg main mass with 22 x 16 cm polished section (no. 1227, 22 x 16 x 11 cm)
35 g slice from distorted end (no. 1227, 5 x 3 x 0.6 cm)

North Chile (Quillagua), Antofagasta, Chile

Approximately 21°43′S, 69°30′W

Hexahedrite, H. Single crystal larger than 15 cm. Neumann bands. HV 175±15.

Group IIA. 5.62% Ni, about 0.3% P, 57.5 ppm Ga, 184 ppm Ge, 3.4 ppm Ir.

HISTORY

A mass of 78 kg was purchased by S.G. Gordon (1942) in Antofagasta; no precise locality or date of find was learned – except that the iron was said to have been found

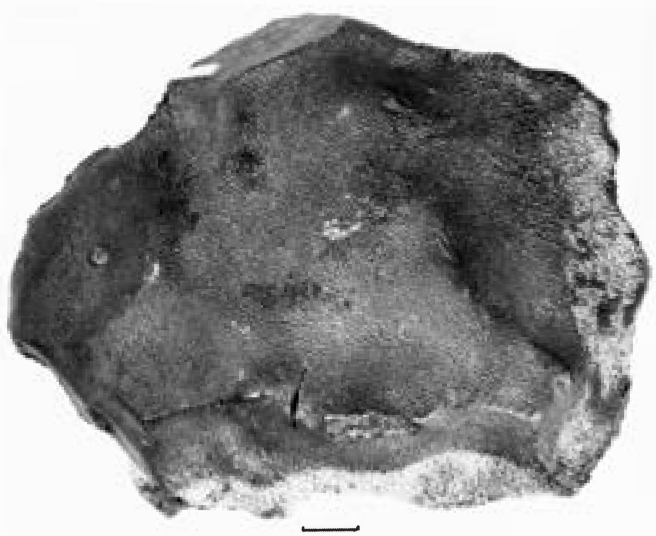

Figure 1293. North Chile. The Quillagua mass in the Academy of Natural Sciences, Philadelphia. This side, the top side, is pitted like Filomena due to long exposure to the arid, salty Atacama climate. Scale bar approximately 3 cm. S.I. neg. 1080A.

NORTH CHILE (QUILLAGUA) – SELECTED CHEMICAL ANALYSES

	percentage			ppm								
References	**Ni**	**Co**	**P**	**C**	**S**	**Cr**	**Cu**	**Zn**	**Ga**	**Ge**	**Ir**	**Pt**
Collins in Gordon 1942	5.48	0.62	0.21		500							
Wasson 1969	5.62								57.5	184	3.4	

From the amount of phosphides present in the sections it appears to me that the phosphorus value is rather low.

near Quillagua. Quillagua is in the North Chilean salt desert and has the coordinates given above. Gordon described the meteorite and presented two photographs of the exterior showing how the upper surface was micropitted like, e.g., Iquique, Filomena and Maria Elena. Wasson (1969) included Quillagua with the North Chilean hexahedrites, a result which is supported by the present examination.

COLLECTIONS

In 1942 the main mass was in the Academy of Natural Sciences, Philadelphia; in a 1962 edition of the catalog (manuscript by R. Barringer) only 287 g is listed. Washington (741 g).

DESCRIPTION

The mass has the average dimensions 35 x 30 x 18 cm. Its upper and lower surfaces are quite differently developed due to terrestrial corrosion. Along the edge is a boundary below which distinct deposits, evaporates like caliche, may be seen. Above the boundary line only iron oxides are present. The upper surface resembles Filomena's upper surface very much, being checkered by small pits, 2-4 mm across, 1-2 mm deep, and with sharp jagged edges in between. The pattern does not reflect any particular internal structure but must be due to periodical corrosion under the particular salt desert conditions of Northern Chile. The lower, soil-covered surface appears to be less corroded; it is rather flat and encrusted with caliche. The overall appearance of the mass suggests that the present upper surface once was part of the exterior surface of the parent mass and was covered by regmaglypts, 6-8 cm in diameter. If this interpretation is correct, the body before it disrupted was perhaps 60-80 cm in diameter, corresponding to a mass of 1,000-2,000 kg.

Etched sections show Quillagua to be a hexahedrite with significant amounts of plate-shaped rhabdites which are rather evenly distributed through the mass. Neumann bands extend uninterruptedly from edge to edge and no fusion crust or heat-affected α_2 zones could be identified. At least 2-3 mm of the surface has been lost by terrestrial corrosion.

The kamacite has subboundaries with 1-3 μ rhabdites; the boundaries are present everywhere but are easily observed in the clear matrix around troilite and large phosphide inclusions. The hardness is 175±15 and rather variable from area to area, presumably due to variations in amount of phosphorus in solid solution and amount and size of phosphide precipitates. In the kamacite there are numerous tiny, oriented, hard carlsbergite particles, typically 10 x 1 μ, or 2 x 2 μ. They precipitated before the rhabdites, since they are often completely embedded in these. They are identical to the oriented chromium nitrides carlsbergite in Costilla Peak, Cape York and others.

Schreibersite as such is only present as 10-300 μ wide, discontinuous rims around troilite and graphite. Rhabdites are ubiquitous as (i) plates ranging in size from 20 x 20 x 0.04 mm to 2 x 2 x 0.003 mm and as (ii) prisms 3-25 μ across. The plate-shaped rhabdites occur in at least ten different directions on the U.S. National Museum section and may well be parallel to {100} and {221} as proved by Bøggild (1927) for Coahuila and other hexahedrites. The prisms are oriented with their long axes parallel to the cube axes < 100 >. The hardness of the rhabdites is 750±30.

Troilite occurs as scattered blebs or lenses, typically 1 x 1 or 5 x 0.8 mm in size. Daubreelite covers about 20% by area as 0.1-0.5 mm thick bars. The troilite is shock-melted and solidified to 1-10 μ mosaics. Some daubreelite fragments are scattered through the melts, while the schreibersite rims are unaffected. Some of the adjacent iron matrix has been dissolved and has created local iron-ironsulfide eutectics with a grain size of 1-2 μ.

An unusually large lamellar nodule of troilite and daubreelite is present in Quillagua. The 1.2 mm nodule is extremely regularly decomposed to alternating, parallel lamellae of troilite and daubreelite, each lamella being only 0.3-3 μ thick. About 60% by area is troilite, the balance being daubreelite, except for minute grains and lamellae of intercalated iron. The shock that altered the coarse troilite nodules did little damage to this nodule.

Upon cutting, three internal cavities were encountered. They were 1.5, 1.2 and 1.1 mm in diameter, and loose dust

Figure 1294. North Chile. Quillagua (U.S.N.M. no. 2324). The plate-shaped rhabdites are distinctly seen as numerous light and dark streaks in several directions. Deep-etched. Scale bar 20 mm.

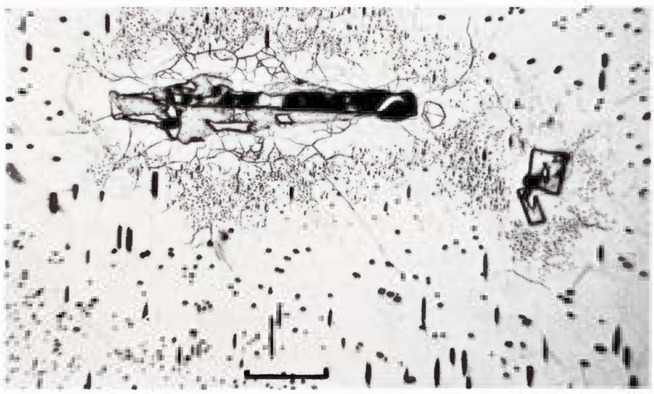

Figure 1295. North Chile. Quillagua (U.S.N.M. no. 2324). At center and to the right large schreibersite skeleton crystals. Farther out numerous normal prismatic rhabdites. Subboundaries are distinctly developed around the central phosphide group. Etched. Scale bar 500 μ.

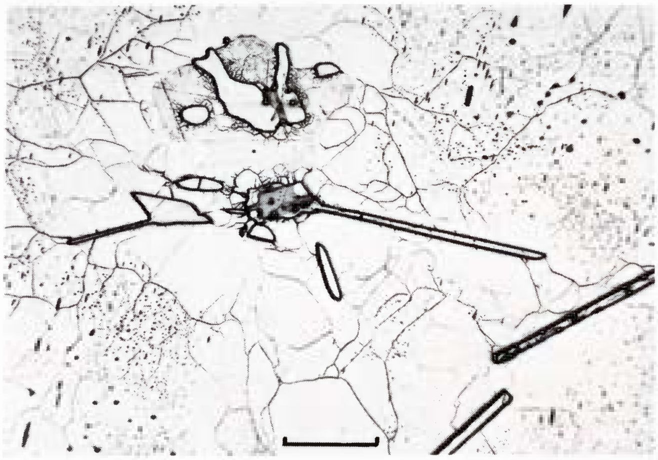

Figure 1296. North Chile. Quillagua (U.S.N.M. no. 2324). Two troilite-daubreelite nodules surrounded by a cluster of phosphide crystals, some of them continuing in plate-shaped rhabdites. Etched. Scale bar 300 μ.

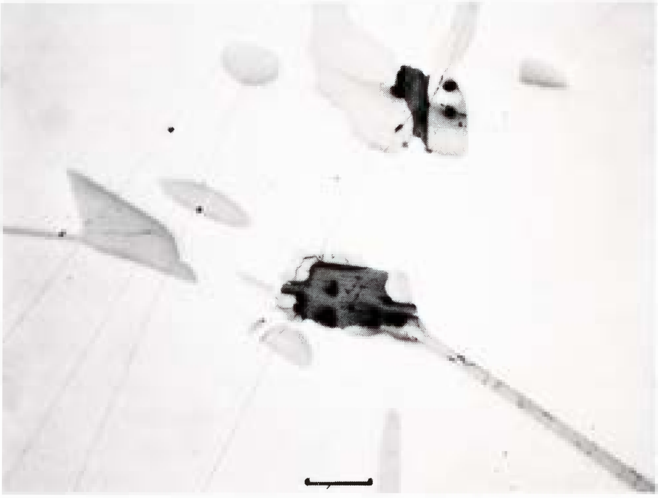

Figure 1297. North Chile. Quillagua. Detail of Figure 1296. The dark central crystals are lamellar stacks of troilite and daubreelite, the upper one showing plastic bending. The phosphide crystals are fissured. Polished. Scale bar 100 μ.

fell out during and after the cutting. Also, in one case, a very hard inclusion from one of these cavities was torn out and scored deep grooves in the metal before it disappeared with the cutting fluid. Enough material was left on the polished section to positively identify graphite. The graphite lined the cavities in 0.1 mm thick layers; it forms columnar or radiating sheaves or is in a microcrystalline, almost amorphous, form. Locally, along the metal interphase the graphite shows a cliftonitic morphology with 30 μ wide units. In other places the cavities are lined with a little schreibersite and perhaps cohenite. It appears that, before cutting, most or all of the cavities were loosely packed with graphite. Whether the hard inclusion was a diamond is anyone's guess.

The sections show distinct late deformation over many square centimeters. The rhabdites are bent and sheared and the kamacite shows lenticular deformation bands and shear

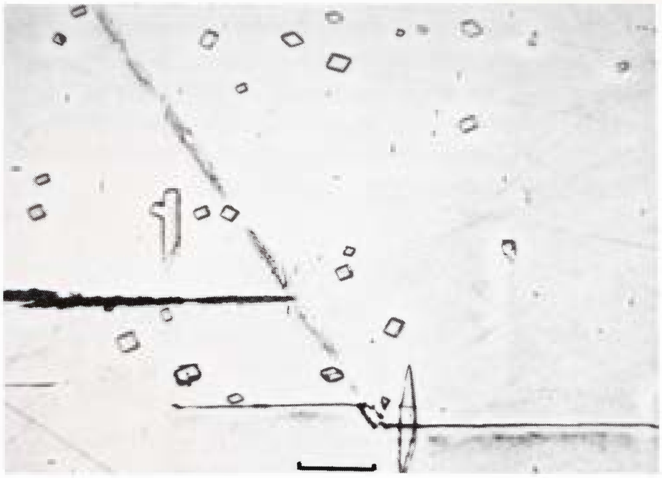

Figure 1298. North Chile. Quillagua (U.S.N.M. no. 2324). Rhabdites and an oblique, indistinct Neumann band. The horizontal streaks are fine fissures that mainly follow the cubic cleavage planes. Etched. Scale bar 50 μ.

zones in which the hardness increases to 275. Locally, the plastic flow of the metal has brecciated the included rhabdites and arranged them *en echelon.* The deformation features are probably due to rupturing of the parent body in the atmosphere.

Quillagua corresponds in all structural details to Coya Norte, Filomena, Union and Rio Loa; in the available sections some specific features, like graphite and heavy deformation from rupturing, are particularly well represented.

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

691 g slice (no. 2324, 14 x 10 x 0.9 cm)

North Chile (Rio Loa), Antofagasta, Chile

Hexahedrite, H. Originally a single crystal; now recrystallized and with α_2 zones. HV 150±5.

Group IIA. 5.61% Ni, 0.56% Co, 0.28% P, 59.5 ppm Ga, 181 ppm Ge, 3.6 ppm Ir.
Reheated artificially to a maximum of about 1000° C.

HISTORY

This meteorite, of 4.2 kg, was first mentioned by Henderson (1941a) who analyzed it and concluded that it belonged with Mejillones and other North Chilean hexahedrites. Perry (1944) gave eight photomicrographs, most of which show heavy alteration, allegedly from the atmospheric flight. Nininger (1952a: plate 10) gave a photomacrograph and also commented upon what he believed was an example of uniform heat penetration during oriented flight. Wasson & Goldstein (1968) concluded, on the basis of the analytical data, that Rio Loa belonged to a narrow group of North Chilean hexahedrites. They observed a "recrystallized" structure but did not explain how one specimen of an otherwise uniform shower could be recrystallized.

Signer & Nier (1962) determined the occluded, noble gases and estimated the preatmospheric mass to be 2 x 10^5 kg and the cosmic ray exposure age to be 150±50 million years. Bauer (1963) arrived at 30% higher helium contents, but found the same ^3He-^4He ratio and the same exposure age, within the experimental errors.

The only information available as to the circumstances of find (notes in the Smithsonian Institution) is the following. The meteorite was found about 1915, possibly near the mouth of Rio Loa. It weighed originally 4,215 g but had been divided into two pieces when Mark Bandy, on a mineral collecting trip for the Smithsonian Institution, saw it in 1936. He acquired the smaller piece, of about 1.2 kg; and this piece has later been divided as noted below under "Collections." The larger piece, of 3 kg, appears to have been shipped to Hamburg at about the same time; it must be this sample which was later briefly mentioned and figured by Wetzel (1952) as San Martin C.

COLLECTIONS

Washington (840 g), Ann Arbor (211 g), Tempe (40 g), (London 39 g).

DESCRIPTION

The largest specimen preserved is in the U.S. National Museum and is a wedge-shaped slice of 785 g measuring approximately 7 x 5.5 x 5 cm. It is on the domed side covered with jagged pits, 2-4 mm across and 1-2 mm deep, of the same type as seen upon Filomena, Quillagua, etc. A heavy chisel mark is conspicuous and in one place hammer marks are common. The flat opposite side shows less distinct pitting. No fusion crust and no heat-affected α_2 zones are present.

Etched sections reveal a hexahedral structure with numerous scattered rhabdite plates. The original structure is similar in all details to that of Filomena and Puripica; so Rio Loa, no doubt, is another member of the North Chilean shower.

The puzzling problem with Rio Loa is, however, the many references to a heat-altered zone from oriented flight. None of the other members of the shower contain extensive heat-altered zones; they are mostly removed by terrestrial weathering or have never existed because many surfaces are late rupture surfaces.

A close examination of various sections and faces of Rio Loa discloses that, at one end, micromelted rhabdites are present, located in a distinct, serrated α_2 phase. Perry's micrographs (1944) illustrate this structure well. At the opposite end, the rhabdites have 1-3 μ wide reaction halos against the kamacite and show thorns protruding into the kamacite, but they are unmelted. The kamacite itself is recrystallized or converted to α_2; the Neumann bands have disappeared in most places. The hardness is variable, but mostly about 150, indicating significant recovery and recrystallization. These observations indicate that Rio Loa was briefly reheated, and while the heat penetrated far deeper than during atmospheric flight, a complete state of equilibrium was not attained, since one end reached 1000° C while the other only reached approximately 700° C.

A further clue lies in the corrosion products. They are heat-altered. Creamcolored reaction zones, 1-2 μ wide, separate the rhabdites from the limonitic corrosion products. The interfaces between the terrestrial oxides and the metal are decomposed to intricate, 20 μ wide laceworks, and tiny metal-grains, about 0.5 μ across, are precipitated everywhere in the oxides. Such textures prove unambiguously that the reheating took place after the mass had been exposed to terrestrial corrosion for a long time.

Although no record of the meteorite having been artificially reheated is extant, the structures prove that this is the case. The irregular heating, with a temperature gradient across the mass, suggests that one end was well inside a primitive fireplace while the opposite end was outside. With this interpretation of the structure, Rio Loa now takes its natural position together with the other members of the shower.

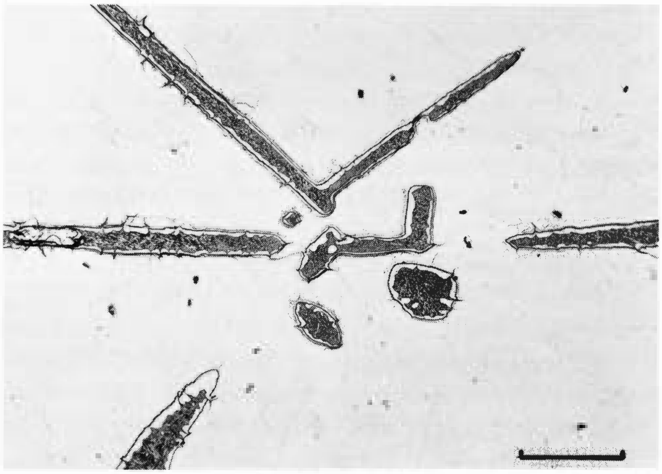

Figure 1299. North Chile. Rio Loa (U.S.N.M. no. 1220). Artificially reheated specimen. The kamacite is transformed into unequilibrated α_2, while the phosphides are fused. Etched. Scale bar 200 μ. (Perry 1944: plate 58.)

NORTH CHILE (RIO LOA) – SELECTED CHEMICAL ANALYSES

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Henderson 1941a	5.70		0.28									
Lovering et al. 1957		0.56				36	189		47	228		
Nichiporuk & Brown 1965											3.4	27
Wasson 1969	5.52								59.5	181	3.8	

Rio Loa is not the only iron meteorite which exhibits an artificial temperature gradient across the mass. Similar observations are for example discussed under Petropavlovsk and Kingston.

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

785 g wedge-shaped slice (no. 1220, 7 x 5.5 x 5 cm)
55 g polished section (no. 1220, 3 x 3 x 0.7 cm)

North Chile (San Martin), Antofagasta, Chile

Hexahedrite, H. Single crystal larger than 20 cm. Neumann bands. Group IIA. 5.51% Ni, 59.4 ppm Ga, 117 ppm Ge, 3.7 ppm Ir.

HISTORY

A mass of 29 kg (A) was found in 1924 on the Pampa San Martin, a little south of the high voltage lines between Tocopilla and Chuquicamata. The mass was cut into two pieces and while the larger specimen remained in private possession, a 12 kg endpiece came to Kiel, Germany, and was described by Wetzel (1952). Wetzel found the material to be identical to Tocopilla, both with respect to the pock-marked surface and the interior structure. He gave drawings of the mass and noted that two more masses were known to him. San Martin B was an 890 g fragment, allegedly detached from a larger mass by dynamiting; it was acquired from a gas station in the same area of Chile in 1925, but when transported to Germany, it was lost with many other minerals in Kiel during World War II. The probability is that it was one of the fragments which was violently detached from Coya Norte.

San Martin C was a 3,033 g piece which in the 1930s was sent to Hamburg from the Tocopilla nitrate works but remained in private possession. I have compared the drawing and the description provided by Wetzel with Rio Loa in the Smithsonian Institution and must conclude that San Martin C is the missing main mass of Rio Loa.

Wetzel supported the conclusion by Heide et al. (1932) that the peculiar pockmarks were due to corrosion rather than wind erosion. He noted that the particular desert area is characterized by acid weathering, since the condensation from fogs is rich in nitric acid. The geologic and climatic settings have been discussed by Wetzel (1927; 1928) who also provided a map of the region.

Small specimens of San Martin A were, at an early date, circulated by Wetzel; the helium content was determined by Paneth (1928; 1954) and the trace elements by Goldschmidt (1935). Herr et al. (1961) determined the osmium and rhenium abundances, and Hintenberger et al. (1967) the occluded noble gases. Vilcsek & Wänke (1963) found a low ^{36}Cl concentration, which together with a low ^{10}Be concentration (Chang & Wänke 1969) suggested a high terrestrial age of about 1.3 million years. The cosmic ray exposure age was estimated to be 30±15 million years, significantly different from Tocopilla.

Wasson & Goldstein (1968) examined San Martin A in detail and concluded that it was identical to Tocopilla, based upon major and trace-element studies and upon the structure which was elucidated with a photomicrograph.

COLLECTIONS

Kiel (about 11 kg), Berlin (323 g), Mainz. A major part of 17 kg, appears to have remained in private possession.

DESCRIPTION

According to Wetzel (1952), the mass measured about 31 x 21 x 11 cm before dividing. It was pock-marked over much of the surface by 2-5 mm wide, closely spaced pits, in exactly the same way as Tocopilla; and Wetzel believed the pock-marked end to have been the buried part. This is, however, doubtful. From the sketches given by Wetzel, it appears that San Martin A resembles Puripica in its smoothly curved exterior, broken by corrosion-altered regmaglypts and showing a few pits from weathered troilite inclusions.

San Martin is a normal hexahedrite with Neumann bands and numerous rhabdites. The rhabdites occur as conspicuous plates, typically 5-15 mm long and less than 30 μ wide, and as tetragonal prisms, 5-20 μ across. Troilite is present as a few, rounded inclusions, rarely reaching 10 mm across.

The chemical composition, the state of corrosion and the structure show that San Martin A is identical to Puripica, Tocopilla and the other North Chilean hexahedrites.

North Chile (Tocopilla), Antofagasta, Chile
22°32'S, 69°55'W

Hexahedrite, H. Single crystal larger than 30 cm. Neumann bands. HV 170±20.

Group IIA. 5.54% Ni, 58.6 ppm Ga, 176 ppm Ge, 3.5 ppm Ir.

HISTORY

In 1927 a mass of about 74 kg was discovered by miners who were prospecting for saltpeter in the Cerros del Buen Huerto, in the department of Tocopilla. The meteorite was purchased by the mineral firm Krantz, in Bonn, and

NORTH CHILE (SAN MARTIN) – SELECTED CHEMICAL ANALYSES

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Smales et al. 1967					13.9	42	124	<1	53.5	187		
Wasson 1969	5.51								59.4	177	3.7	

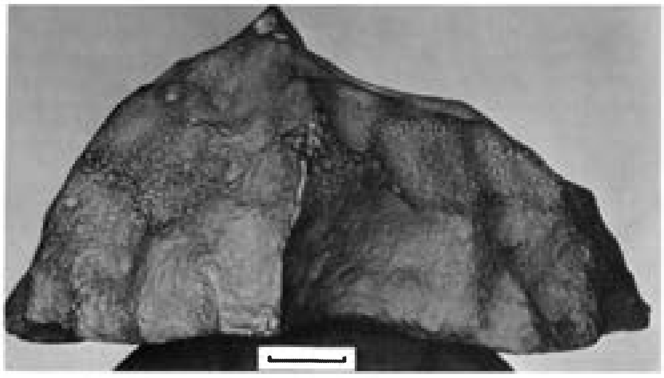

Figure 1300. North Chile. The Tocopilla mass before cutting. Regmaglypts are prominent. They are slightly altered by terrestrial corrosion, showing numerous densely spaced pits. Compare Filomena and Quillagua. Scale bar approximately 5 cm. (Courtesy A.R. Allen, Trinidad, Colorado.)

was thoroughly described by Heide et al. (1932) who marked the locality on a map and gave the coordinates quoted above. [The correct name for the locality is Cerros del Buei Muerto (Wetzel 1952).] In an unusually instructive description of the hexahedrite (Heide et al. 1932), the lattice constants of kamacite (a=2.859±0.002Å), troilite, and rhabdite (with 28% Ni) were also determined. The crystallographic system of daubreelite (cubic spinel-type) was determined for the first time, and the unit cell was found to contain eight molecules, corresponding to the newly determined specific gravity of 3.81. The rhabdite plates were found to be oriented parallel to {100}, {210} and {211}, a result which was different from the conclusion reached by Böggild (1927), who observed parallellity to {100} and {221} when examining Coahuila and similar hexahedrites. The problem was reexamined by Borchert & Ehlers (1934) who evidently didn't know of Böggild's publication. By examining Laue-photographs of various sections they established that the rhabdite plates were oriented parallel to {221}, partly confirming Böggild's results. They found, however, no rhabdite plates parallel to {100}, so it appears that some new work is needed in order to solve, finally, the problem whether the plates may occur in both the {221} and {100} planes of the kamacite. Wasson & Goldstein (1968) concluded on the basis of trace-element and microprobe data that Tocopilla was one of a limited group of North Chilean hexahedrites. Doenitz (1968) examined rhabdites with 28% Ni isolated from Tocopilla and found the space group S_4^2 - I4, with eight molecules per unit cell, and with nickel atoms occupying preferentially the M_2 and M_3 sites.

Herr et al. (1961) determined the Os/Re ratio and found a total age of 4 x 10^9 years for the meteorite. Signer & Nier (1962) reported the amounts of occluded noble gases and estimated a cosmic ray exposure age of 250±100 million years. Hintenberger et al. (1967) extended the noble gas work of Signer & Nier but found absolute and relative amounts that were significantly different from Filomena and San Martin, two other irons of the shower. Vilcsek & Wänke (1963) and Chang & Wänke (1969) also found Tocopilla to possess noble gas characteristics that put it apart from the other irons with a cosmic age of 100 million years; in addition, ^{36}Cl and ^{10}Be were found to be significantly higher, indicating a terrestrial age of about 470,000 years. As discussed below, the structure and the composition indicate that Tocopilla belongs with the remaining irons, so it must be the interpretations of the gas and isotope data that still are uncertain.

COLLECTIONS

Paris (2.76 kg), London (2.56 kg), Washington (1.46 kg), Mainz (1.32 kg), Harvard (1,080 g), Los Angeles (495 g). Heide et al. (1932) noted that many slices were cut and distributed, but that a 41 kg endpiece remained uncut. Much of the material appears to be in private collections after having been distributed through the mineral dealer F. Krantz in Bonn, Germany.

DESCRIPTION

According to Heide et al. (1932) the mass resembled a four-sided pyramid with a flat base; its maximum dimensions were 42 x 36 x 21 cm. It had been partly buried in the desert and only the projecting part was covered by closely spaced 1-5 mm wide pits with jagged edges. The authors pointed out that this particular corrosion phenomenon might be a result of the socalled *Camanchaquas,* a coastal fog which occurs in the winter as frequently as three times a week. If the condensation-water, probably rich in mineral salts, is allowed to work for uncounted thousands of years, the result may well be the checkered, pitted surface. The lower surface is partially encrusted with caliche. The large shallow depressions, 3-10 cm across, seem to be the corroded remnants of original regmaglypts; a few scattered deep pits, 5-15 mm in diameter, may be due to the burning out and corrosion of troilite nodules. The external sculpture and state of corrosion resemble Filomena, San Martin and Quillagua remarkably. No fusion crust and no heat-affected α_2 zone are present on the sections examined by me; the altered, 3-4 mm wide zone discussed by Heide et al. (ibid: 485, 486, 494, and plate 2) does not have the characteristics of a heat-affected rim zone

NORTH CHILE (TOCOPILLA) – SELECTED CHEMICAL ANALYSES

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Smales et al 1967						48	121		56	172		
Wasson 1969	5.54								58.6	176	3.5	

Heide et al. commented that their P-determination (0.19%) was too low and did not represent the true bulk value. This is probably about 0.3%.

and seems to require a different explanation. It was not observed in the present study.

Etched sections display a hexahedrite structure with Neumann bands extending from edge to edge and with characteristic, plate-shaped rhabdites in a multitude of directions (at least ten). The kamacite has subboundaries with 0.5-1 μ phosphides, best visible near the troilite nodules. The kamacite has a hardness of 170±20. There is an unusual large variation in the hardness within the same 2 x 2 cm^2 section; this appears to be due to inhomogeneities in the kamacite with respect to phosphorus and nickel, as already noted by Wasson & Goldstein (1968) when they microprobed a section.

Schreibersite occurs as isolated skeleton crystals, 1 x 0.2 mm in size, and as 10-100 μ wide discontinuous rims around the troilite. Rhabdites are ubiquitous as (i) plates, which typically are 20 mm across and 0.004-0.03 mm thick and (ii) as tetragonal prisms ranging from 5-30 μ in thickness. No parallel rows of rhabdites are present.

Troilite forms elongated bodies, e.g., 20 x 1 mm in size, and rounded nodules, 1-15 mm in diameter. Daubreelite covers about 15% by area as 0.01-1 mm wide bars in the troilite. The nodules show various degrees of alteration due to shock. The same nodule may have passive blocks, 0.5 mm across, which exhibit twinning only, separated by channels of shear zones of recrystallized or shock-melted material. Near phase boundaries, the shock melting is most pronounced and some of the adjacent metal is dissolved and has, with the sulfide, formed fine-grained eutectics. Heide et al. (Plate 2), already in 1932, showed a figure of this confusing mineral assemblage, although the reason for its existence was not discussed.

Characteristic blebs, composed of alternating, parallel lamellae of troilite and daubreelite are common. The individual lamellae are 0.5-10 μ thick; troilite occupies about 60% by volume and is polycrystalline whenever its thickness exceeds 3 μ.

Fine hard particles, 1 x 2 or 10 x 1 μ in size, occur scattered in the α-phase and embedded in the rhabdite. The mineral is identical to the oriented chromium nitride, carlsbergite, of Cape York and Schwetz. Heide et al. reported graphite in the undissolved residue from their analysis.

From the structural and morphological examination only one conclusion is possible: Tocopilla is identical to Quillagua, Rio Loa, Coya Norte, Filomena and San Martin. From trace-element and microprobe data Wasson & Goldstein (1968) and Wasson (1969) reached the same conclusion. Conclusions, based on gas analytical data and isotope data, have separated Tocopilla from the others. However, since several of the gas data are mutually inconsistent, I must conclude that the first mentioned methods are, at the present date, the more reliable.

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

645 g part slice (no. 936, 10.5 x 8.5 x 1 cm)
822 g part slice (no. 2306, 13 x 8 x 1 cm)

North Chile (Union), Antofagasta, Chile

Approximately 22°40'S, 69°30'W

Hexahedrite, H. Single crystal larger than 10 cm. Neumann bands. HV 165±10.

Group IIA. 5.63% Ni, about 0.3% P.

HISTORY

A mass of 22 kg was found about 1930 in the regions worked for saltpeter about 50 km north of the station Union, on the railway from Antofagasta via Calama to Oruro (Bolivia). The corresponding coordinates are given above. In 1932 the meteorite was purchased by the Museum of Natural History, in Geneva, where it was described by Galopin (1937) with an analysis by Buffle. They presented twelve photomicrographs showing, among other things, nodules of troilite with extremely fine intergrowths of parallel lamellae (Figures 7-9). They assumed, and so did Henderson (1941a), that Union was a paired fall with Mejillones, which, however, may be ruled out on the basis of the widely different structures alone. Bauer (1963) examined the amount of helium isotopes and estimated a cosmic ray exposure age of 500 million years.

COLLECTIONS

Geneva (main mass), Washington (172 g).

ANALYSIS

The original analysis by Buffle (1937) is insufficient. A redetermination by Buffle, for nickel only, gave 5.63% (Henderson 1941a). Wasson (personal communication 1974) found 5.79% Ni, 60.5 ppm Ga, 187 ppm Ge and 3.2 ppm Ir.

DESCRIPTION

The main mass measures approximately 20 x 17 x 15 cm and weighs 22 kg. It has an irregular surface partly covered with regmaglypts which are modified by terrestrial weathering. That an essential part of the pits really are regmaglypts is indicated by the fact that a 0.5-1 mm thick zone of heat-altered α_2 is present locally. A large portion of the exterior is covered with a hackly fracture following cubic cleavage planes, presumbaly due to rupturing in the atmosphere.

Etched sections display a normal hexahedral structure. The matrix is a single kamacite crystal in which Neumann bands extend across the whole surface. Only in the narrow rim zone, mentioned above, are they wiped out and replaced by serrated α_2 units, 50-100 μ across. The hardness of the interior is 165±10, but increases to 185±5 in the α_2 zone (hardness curve type III). Severe plastic distortion with broken and shear-displaced rhabdite crystals is seen in several places along the rupture zone. Union is, so far, the only one of the North Chilean hexahadrites upon which an unambiguous α_2 zone from the atmospheric penetration could be identified on sections. Surfaces of the other members of this group are somewhat more corroded or represent late fracture faces without heat altering. Also, some of the other masses are cut insufficiently well to reveal fusion crust and heat-affected α_2 zones.

Schreibersite is present as a few rosette-shaped crystals or as stumpy bars which appear to be precipitated upon nuclei of troilite-daubreelite or daubreelite. The schreibersite crystals attain sizes of 1.5 x 0.2 mm and have hardnesses of 940±15. Rhabdites are prominent as (i) tetragonal prisms, 5-20 μ across, and (ii) as extremely thin but large plates that are parallel to the $\{221\}$ directions of the kamacite. The bulk phosphorus content is estimated to be about 0.3%.

Troilite occurs as 50-500 μ irregular nodules which are microcrystalline due to shock melting. Many of the smaller nodules, about 100 μ across, are composed of alternating, parallel lamellae of daubreelite and troilite; and whenever the lamella thickness decreases to below about 5 μ, the troilite appears unaffected by the shock. The lamellar stacks are, however, frequently distorted by shear and compression.

In the α-matrix, and frequently embedded in rhabdites, a conspicuous number of hard, rosy platelets occur, typically 2 x 1 or 10 x 1 μ; they are identical to the chromium nitride, carlsbergite, described from Cape York and Schwetz.

Where the meteorite is somewhat distorted due to the atmospheric rupturing, fine fissures have developed along rhabdite plates. The fissures have subsequently become partially filled with terrestrial oxidation products. Locally, along the surface, 100-400 μ thick limonitic pockets occur; surviving rhabdites are distinctly visible in them. Otherwise the meteorite is not severely corroded.

Specimen in the U.S. National Museum in Washington:
172 g part slice (no. 1299, 8.5 x 6 x 0.5 cm)

NORTH CHILE SUMMARY

Distribution. – From the descriptions above, it is obvious that the localities are only known in the vaguest terms. Although precise coordinates are frequently used in the literature, I believe that only San Martin and Tocopilla can be ascribed a reasonably precise set of coordinates. Some of the masses have been associated with localities along the railroads and may have been transported from the original locality. At least five of the specimens have been recovered from the arid, nitrate-rich desert around 22°30'S, 69°30'W. The three most remote masses, Rio Loa, 100 km northwest; Quillagua, 100 km north; and Puripica, 100 km southwest of this area, are also those with the most doubtful localities attached. It remains a purely subjective estimate when I here conclude that the masses have been found within an area of about 60 x 60 km centered around the mentioned coordinates and less than 100 km from the coast; there is, indeed, reason to believe that the actual area from which the masses were recovered is significantly smaller.

For exactly one hundred years the activity of prospectors and miners has been high in the Antofagasta Province. First it was because of the nitrates, then it was the copper ores. The nitrate deposits occur in a zone, 500 km long, parallel to the coast and up to about 100 km from it. The deposits were, in the beginning, primitively worked; but when they became a bonanza in the first third of this century, heavy machinery was installed. Today, only five factories (*Oficinas*) are in operation, albeit on a large scale, using modern equipment. The bulk of the surprisingly many North Chilean iron meteorites (e.g., North Chile, La Primitiva, Iquique and Tamarugal) were discovered between 1870 and 1930, just in those years of maximum activity. It becomes understandable why this strip of desert should yield so many meteorites when one remembers the meteoritiphile aridity of the province and the intensive mining methods. The nitrate-enriched top soil, of 1-5 m thickness, is entirely stripped from the rocky base and transported to the central *oficina* for processing. Either during stripping or during the crushing, grading and leaching that follows at the *oficina*, any foreign rock or meteorite is bound to be discovered. The question seems mainly to be whether the meteorites become reported and provided with decent information as to circumstances of finding. Usually the meteorites have passed through many hands before they are acquired by the large museums, and in the process all detailed information is lost.

The Salars, e.g., Salar de Atacama, always distinctly marked on topographical maps, are something else. They occur farther inland and are, if at all, exploited in a different way. They have, to the best of my knowledge, not yielded meteorites.

Total Mass. – The eight known irons have a total weight of 266 kg. Several of them, e.g., Coya Norte, exhibit artificial cleavage faces, suggesting that the nitrate prospectors were quite active in splitting the irons and that a significant proportion of what has been found has passed unrecorded. There is no exact way of estimating the preatmospheric total mass. Estimates based upon the regmaglypt size lead to weights of about 2 tons; but these estimates are probably of little value, since, in order to be valid, the measured regmaglypts must be those of the exterior of the unbroken main mass, and not those of the later atmospheric disruption surfaces. The correct diagnosis of the regmaglypts is difficult. The total mass before atmospheric entry has been estimated by Signer & Nier (1962) to be 200,000 kg. Their estimate loses, however, some credibility, since they simultaneously estimated the preatmospheric mass of the independent small iron Negrillos, to have been of a similar size.

Cosmic Ray age. – The reported cosmic ray ages are mutually inconsistent.

Exterior. – Common to the eight hexahedrites is the peculiar mixture of three different surface morphologies, with regmaglypts, cleavage faces and pockmarks. The corroded remnants of regmaglypts range from 2 to 10 cm across and are particularly well observed on Coya Norte, Filomena, Tocopilla and Union. A heat-affected α_2 zone was identified on Union, and it appears that most specimens have had long independent atmospheric flights. The incoming mass probably burst in the high atmosphere. No large main mass survived to produce a crater or any twisted bombshell-like slugs of the kind so familiar around the Canyon Diablo and Henbury craters.

Several specimens, e.g., Puripica, present cleavage and fracture faces which are not artificial but were formed during the fragmentation. The interior structure shows correspondingly significant necking and distortions and a high degree of cold working, with local peak hardnesses of 270.

Terrestrial corrosion appears on the specimens to a varying extent. Previous descriptions of the pock-marked, checkered surfaces do not agree as to the cause. It appears, however, that Heide et al. (1932) in their description of Tocopilla have made significant observations. The pits, 2-5 mm in diameter, appear on the exposed surfaces and cover them surprisingly uniformly, probably due to condensed water, distinctly acid from the nitrate deposits. The condensed water is at irregular intervals provided in small quantities by the Chilean *camanchaqua* which is active between the coastal mountain range and Sierra Domeyko. Since troilite inclusions are now exposed on several of the pitted surfaces and since the regmaglypts have almost or wholly disappeared, it is estimated that on the average 3-6 mm of the surfaces have been lost. The pockmarks are only to a minor extent conditioned by the metallic structure, since quite similar markings are present on, e.g., the octahedrite Maria Elena and the ataxite Iquique.

The lower, soil-covered surfaces remained relatively unattacked and became slowly encrusted with caliche deposits. It is on such surfaces that the best preserved regmaglypts are to be observed.

The corrosion picture is thus different from what is seen on meteorites from other parts of the world. Usually it is the exposed part of the iron which is slowest to corrode. Compare for example with the descriptions of Cape York and Quinn Canyon. The corrosion problem, therefore, deserves a thorough study. Here it can only be pointed out that the arid climate displays extreme daily temperature variations and that the recorded rainfall today is of the order of 1 mm per year and, thus, smaller than anywhere else in the world. The region has, at least since the beginning of the caenozoic period, been a highland protected from any salt-containing coastal atmosphere. The process of salt formation is not entirely clear; it has been discussed by Wetzel (1927; 1928) and Zeil (1964). It appears that the salts mainly originate from precipitation of soluble salts which have been carried into closed lakes since Pleistocene times. The salinas depend on regional structures; most of them are elliptical in shape because they are conditioned by the elongated fault basins of the Atacama desert. The topographical gradient of the salinas is about 0.15 m/km, and they are, therefore, not differentiated from lakes on standard topographic maps.

Whether the absolute very high terrestrial ages, determined by Chang & Wänke (1969) but mutually inconsistent, are valid remains to be seen. It would certainly be surprising to have heat-affected α_2 zones preserved after the lapse of one million years, indicating a corrosion rate as low as 1 mm per million years.

Structure. – The primary characteristics of the group are the rhabdites which irregularly cover all sections in the form of conspicuous plates. Fractures, cosmic and artificial, follow these plates and the cubic cleavage planes of the kamacite. The individual specimens are single kamacite crystals; no grain boundaries have been identified, and there is reason to believe that the main mass was a single kamacite crystal larger than 50 cm in diameter.

The kamacite phase displays undecorated Neumann bands and is violently deformed in places. Its hardness ranges from 145 to 270, both as a result of inhomogeneities in nickel and phosphorus in solid solution and as a result of

NORTH CHILE – SUMMARY OF ANALYTICAL DATA

The analyses tally very well for both major and trace elements. The other three North Chilean hexahedrites, Mejillones, Negrillos and Sierra Gorda, are different particularly in the phosphorus, chromium and iridium contents.

Meteorite	kg Weight	percentage Ni	Co	P	ppm C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Coya Norte	18.6	5.57	0.43	0.30	50	365	48	130		58.9	174	3.6	22
Filomena	21	5.54		0.30						58.7	176	3.6	
Puripica	19	5.68	0.45	0.32						59.5	174	3.8	
Quillagua	78	5.62								57.5	184	3.4	
Rio Loa	4.2	5.61	0.56	0.28			36	189		59.5	181	3.6	27
San Martin A	29	5.51				14	42	124	<1	59.4	177	3.7	
Tocopilla	74	5.54					48	121		58.6	176	3.5	
Union	22	5.63											
Average	–	5.59	0.48	0.30			44	141	<1	58.9	177	3.6	25

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