collisions in space. The end result would be a number of fragments, mainly comprising entire parent taenite grains, but occasionally showing smaller fragments, or masses composed of a number of grains. Although searched for, no conspicuous silicate minerals were disclosed.

FURTHER WORK

It is recommended that the pile in Windhoek be thoroughly examined so that we may fully learn the variety of thermal and shock-induced alterations in the material. The verification that all members of the pile *are* in fact Gibeon specimens is also required.

In the author's opinion, it would be very interesting to examine and possibly calculate how and when the breakup occurred. Nothing like the Gibeon strewnfield or the Gibeon variation in microstructure has been reported from any stone or iron meteorite – except from the crater-forming Canyon Diablo iron – so the mechanism of breakup must have been rather peculiar to Gibeon. It would further be of interest to solve the problem of the hemispherical cavities, which are almost a hallmark of Gibeon but are known to occur on other iron meteorites, too.

Guadaloupe County, Texas, U.S.A.

Approximately 29°30'N, 98°W

A small specimen of 20½ g was listed by Nininger & Nininger (1950) as being in their collection. They assumed that it was a transported Canyon Diablo sample, and Hey (1966:185) supported this and listed the material *doubtful.*

However, a cursory examination of the specimen, an endpiece now in the Tempe Collection (No. 521.1, 27 x 19 x 8 mm), reveals that this can hardly be the case. It is a medium octahedrite with a bandwidth of 1.2±0.3 mm, and the kamacite is of the shock-hardened hatched ϵ-variety with marked contrasts between adjacent grains. There is 5-10% taenite and plessite, and the schreibersite crystals are in many places arranged in garlands of tiny grains just outside the taenite and plessite fields.

The material is corroded, but no more than the heat-affected α_2 zone is preserved along a significant part of the periphery.

Guadaloupe County is apparently an endpiece of a larger mass of which we have no record. A thorough examination is evidently needed. The remote possibility that it has been cut from the 6.8 kg Sanderson mass, also from Texas, should be considered.

Imilac, Antofagasta, Chile

24°12.2'S, 68°48.4'W

Pallasite. About 50 vol.% subangular olivine crystals in metal. Neumann bands. HV 160-295.

Pallasite. 9.8% Ni, 0.7% Co, 0.3% P, 22 ppm Ga, 47 ppm Ge, 0.07 ppm Ir.

An unusually large number of fragments from this shower have circulated under separate names. Many are still mislabeled in numerous collections: particularly as Ilimaes (pallasite), Gran Chaco, Del Parque, Calderilla, Potosi and Atacama. Further: Antofagasta, Campo del Pucará, Caracoles, Catamarca, La Encantada, La Rioja, Peine, San Pedro, Toconao, and, possibly, Salta and Ollague.

HISTORY

In 1828 a mass of 9.265 g (B.M. 90239) was presented to the British Museum and another of 1.8 kg was given to the Royal Scottish Museum in Edinburgh (Allan 1828; Hey 1966). The masses had been acquired for the museums by the British Consul-General at Buenos Aires from an Indian who had traveled from the Atacama Desert across the Andes Mountains to sell the specimens in the capital of Argentina. The precise locality was only given in very loose terms, but it was stated that there existed numerous other fragments in the place and that several had been collected into a heap, estimated to weigh about three quintals (i.e., about 140 kg).

In the second quarter of the nineteenth century many of these fragments were carried in small portions by Indians to Peruvian, Bolivian, Chilean and Argentinean coast towns from where they were slowly spread to a surprisingly large number of public museums and private collectors. See, for instance, the list in Buchner (1863: 127). Therefore, many examinations and descriptions appeared in these years, most valuable probably being those by Turner (1828), Partsch (1843) and Bunsen & Bronn (1857).

Bollaert (1851) in traveling through the Atacama Desert tried to pinpoint the finding place but in vain. Philippi (1855; 1856), at that time a professor in Santiago, was commissioned by the Chilean government to explore the Atacama Desert and make extensive reports on his geographical, botanical and geological observations. He happened to meet the original finder of the meteoric iron, José Maria Chaile, who guided him to the place in January 1854. Chaile had found the first samples about 1820 while hunting guanacos. Since he supposed them to be silver or silver ore, he removed two pieces, estimated to weigh 60-75 kg each, and buried them safely in the vicinity of the watering place Pajonal, 20 km southeast of the finding place. Later these specimens could not be found by Chaile, and it is uncertain whether they have ever been recovered.

Philippi found 673 small fragments, ranging in weight from less than 0.1 g to 60 g, and totaling slightly less than 1.5 kg. He estimated that his two companions collected a similar amount. A total of 4.5 kg was thus collected by three persons within a few hours. Philippi found no large masses and also stated that the field was now, after his visit, entirely deprived of meteoritic fragments. Many fragments had evidently already been collected by the natives who used the site as a veritable iron mine and had forged various items from the metal.

Philippi noted at one end of the small strewnfield a hole, about 6 m deep. According to Chaile and others (e.g.,

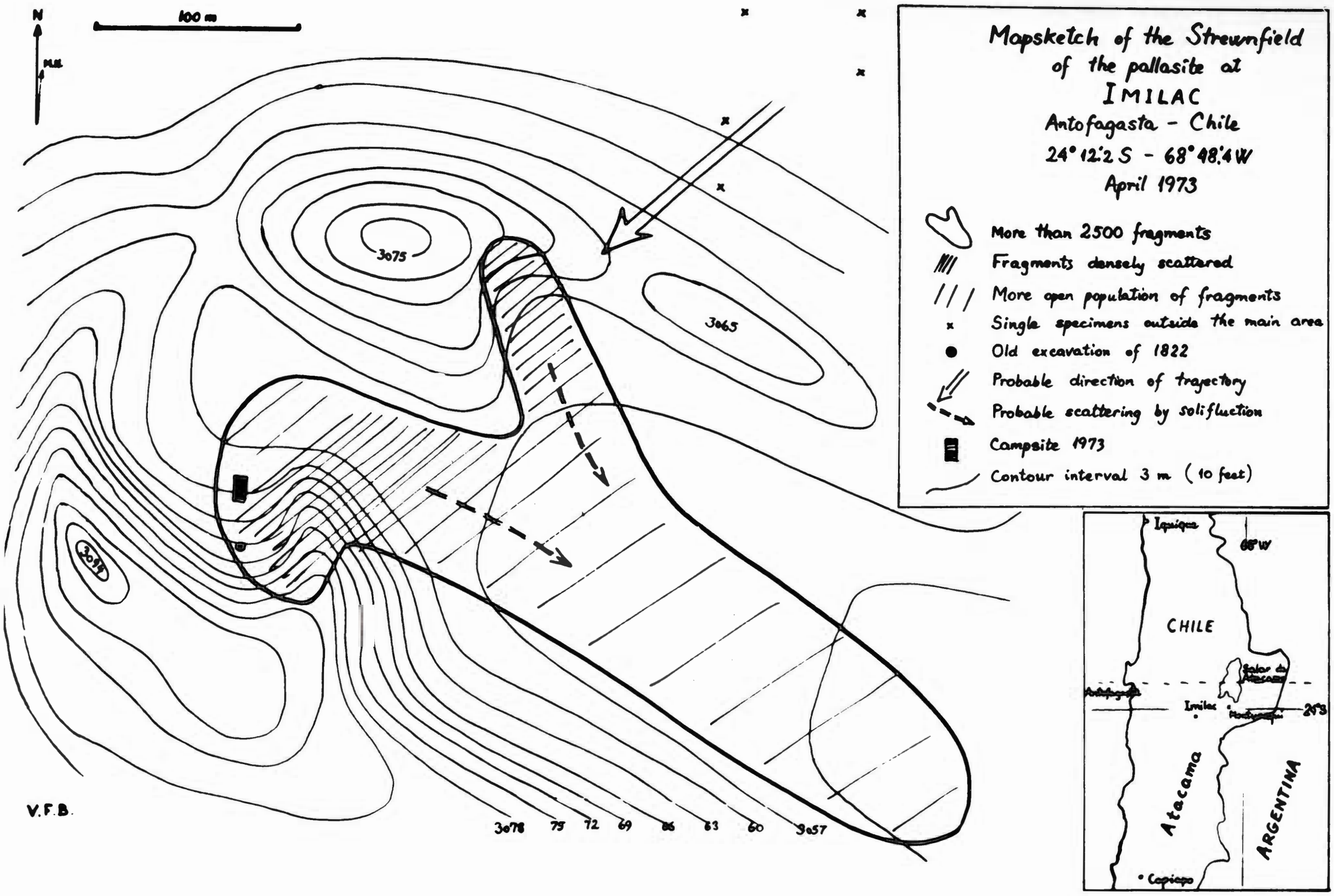

Figure 2080. A mapsketch of the Imilac strewnfield. More than 2400 fragments were collected within the area bounded by a heavy line. The concentration was very high in north and northwest, very low at the southeastern end.

Woodbine Parish 1839: 260), this hole had been excavated by the Indians at an early date, probably 1822, in order to find the metallic vein from which they supposed the pallasite fragments to emanate. It is highly probable that one or more of the largest fragments were found *on the surface here*, and that the hole simply reflects the natives' efforts to find the vein.

Philippi's work helped to solve the mystery of the numerous pallasite fragments allegedly coming from a large area, about 100 x 100 km, of the Atacama Desert, and including such localities as Peine, Toconao, San Pedro de Atacama, Pajonal, Chiuchiu, and Huanaquero. He convincingly argued that all these locations were inaccurate synonyms of the only true place, Imilac, and that this was a small strewnfield located about 4 km west of the watering place of the same name. This has been entirely confirmed by the present field work and subsequent examinations, and many more synonyms have been added.

In the 1860s and 1870s there was considerable activity by prospectors in search of noble metals, mainly silver, and nitrates. Several additional fragments were discovered – or rediscovered – in these years, and the biggest of all was purchased in 1877 from an Indian by George Hicks and presented to the British Museum (No. 53.322 of 198.1 kg; Fletcher 1889: 249; Hey 1966). It took a cart and four men 10 days to transport this large mass the 200 km from Imilac to Antofagasta. It appears that most of the previously found masses had been carried away on mules which probably could carry no more than 75 kg.

At about the same time, Emeterio Moreno brought a 95 kg mass to the School of Mines in Copiapo, from a place variously called Illimaë, Ilimaes and Imalaes (Ward 1906). The sample was apparently unknown to science until Ward visited Copiapo in 1889. It was, however, only in 1905 on another visit, that Ward succeeded in having the mass cut and bringing a piece weighing 16.7 kg back to U.S.A. In his paper (1906) he concluded that it was an independent fall, but in this the present author cannot follow him since the two pallasites are similar in all essential respects – chemistry, mineralogy, morphology and deformation. The Ilimaes mass must be a transported mass. Even the name Ilimaes appears to be a corruption; the geologists at the Institute of Geology at Antofagasta do not know the name and claim that it is neither Indian nor Spanish. Nor can the name be found on any map in the author's possession. When Fletcher (1889: 260), in another context discussed the name, he was also forced to conclude that Ilimaes was a misspelling, probably of Imilac.

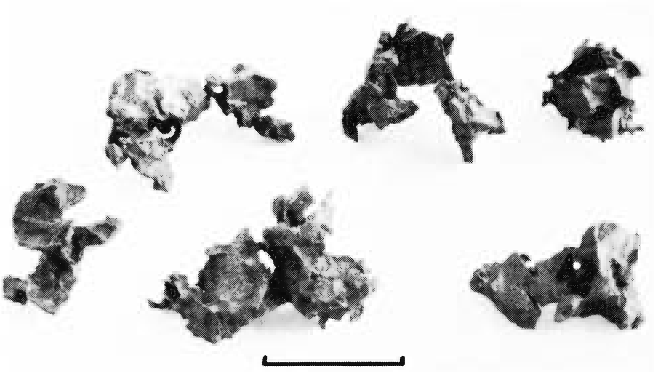

Figure 2081 A. Imilac (Copenhagen). Six typical fragments of 5-15 g mass collected on the surface in April 1973. The subangular depressions indicate where olivine crystals were previously located. Scale bar 20 mm.

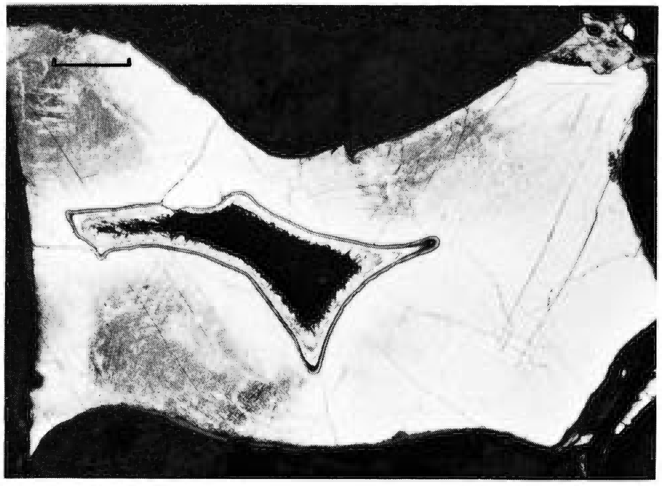

Figure 2081 B. Imilac (Copenhagen). The metallic parts of a pallasite form an almost continuous sponge with olivine crystals (black) in the interstices. The metal of the photograph was at high temperature a single taenite crystal; on cooling, kamacite was nucleated on the olivine crystals and grew toward the center. This became enriched in nickel (and carbon) and finally decomposed to bainitic-martensitic transformation products. Etched. Scale bar 400 μ.

Brezina & Cohen (1886-1906: Plate III) gave three photomacrographs of the structure, and Brezina (1896; and in Ward 1906) discussed various structural aspects. Meunier (1884: 147) gave a cut of a deep-etched section, but his description is only of historical value. He firmly believed that he had identified pyroxenes. Cohen (1887), in an eminent study, showed that the so-called Campo del Pucará specimens were in fact mislabeled Imilac fragments, and Wülfing (1897) gave an exhaustive bibliography. Schwarz & Baur (1936) studied the "Atacama" pallasite and presented several photomicrographs. Their interpretation is, however, highly uncertain because their specimens contained numerous disturbing veins from terrestrial corrosion. Owen & Burns (1939) examined the kamacite phase with X-rays and found a lattice parameter of 2.8627 Å.

Kvasha (1961) gave a photomicrograph of the Ilimaes fragment in Moscow, and Dyakonova & Charitonova (1963) also analyzed it. Mason (1963), Anders (1964), Wahl (1965) and Buseck & Goldstein (1969) included Imilac in their general studies of the pallasites. Trace-element analyses were presented by Smales et al. (1967) and Wasson & Kimberlin (1967). Goldstein & Short (1967a) and Short & Goldstein (1967) estimated the cooling rate to be 0.5° C per 10^6 years. However, their value was based on a bulk nickel content of 13.1% which appears high compared to other research results compiled in the present table. Fuchs (1969) reported that the rare phosphate mineral stanfieldite, $Ca_4Mg_5(PO_4)_6$, occurred in Imilac.

COLLECTIONS

London (198.1 kg mass and 14.2 kg fragments), Copiapo, Escuela de Minas (72 kg), Krakow (23.4 kg), Washington (about 20 kg), Chicago (11.8 kg), Oxford (10.5 kg), Santiago (9 kg in 1889; now lost?), Copenhagen (6.6 kg), Moscow (6.2 kg), Paris (5.1 kg), New York (5.0 kg), Berlin (3.8 kg), Vienna (3.7 kg), Budapest (3.7 kg), Göttingen (2.5 kg), London, Geological Society (about 2 kg), Edinburgh (1.8 kg), Oslo (1.7 kg), Paris, École des Mines (1.0 kg), Bonn (0.8 kg), Stockholm (0.6 kg).

IMILAC – SELECTED CHEMICAL ANALYSES

Metal phase

	percentage			ppm								
References	Ni	Co	P	C	S	Cr	Cu	Zn	Ga	Ge	Ir	Pt
Cohen 1887	9.02		0.30									
Dyakonova & Charitonova 1963*	10.19	0.69	0.23				100					
Smales et al. 1967						<5	140			45		
Wasson & Kimberlin 1967	9.8								21.2	45.5	0.071	
Wasson 1972, **pers. comm.	10.1								21.9	50.4	0.07	

*on material labeled Ilimaes (pallasite)
**on material labeled Antofagasta

Silicate phase: The olivine has the composition Fa 12.3%, i.e. $(Mg_{0.88}Fe_{0.12})SiO_4$ (Buseck & Goldstein 1969).

Because of its fragmentary character, Imilac is also distributed in small amounts in many other public and private collections. It is no doubt the most commonly represented pallasite in collections.

FIELD WORK

In April 1973 a small group of Danish scientists (Vagn Jensen, geologist; Bent Jörgensen, astronomer and the present author) visited a site said to provide meteorites. Largely unknown to the local population, we were guided to the place by the driver, Sergio Manquez from the Institute of Geology at Antofagasta. As it turned out, the place was identical to the Imilac site visited and described by Philippi (1855; 1856) and apparently never examined since by any scientist.

On April 11-13 we camped within the strewnfield and established its outer boundaries. We collected 2430 pallasite fragments and mapped their distribution. They ranged in size from 0.1 to 36 g and had a total weight of 4810 g, thus weighing on the average 2 g. A modern electronic mine detector failed to locate any large specimen. However, it was apparent where the large specimens of 10-200 kg had been found in the past. Several small – and one large – excavations, now eroded, indicated the places. The large hole, 6 m (?) deep when Philippi saw it 120 years ago, was now eroded and only 3 deep with a diameter of 6-8 m. It is situated at the extreme southwestern end on the lower part of a slope. Compare the map, Figure 2080.

The fragments were concentrated within two rather narrow regions of 100 x 200 m. Outside there was a minor population, and even as far away as 500-600 m in a northeastern direction there were a dozen scattered fragments. The strewnfield has been reconstructed on the map. The meteorite probably came from the northeast (N40°E-

Figure 2082. Imilac (Copenhagen). Section through a 20 g distorted fragment. Severe shear zones penetrate the material and the structural elements are twisted or offset. Etched. Scale bar 400 μ.

Figure 2083. Imilac (Copenhagen). Distorted metallic matrix caused by violent fragmentation. Several schreibersite crystals have been sheared and fragmented while the kamacite yielded plastically. Etched. Scale bar 100 μ.

Figure 2084. Imilac (Copenhagen). Distorted kamacite with lenticular deformation bands and precipitates of submicron size. Etched. Scale bar 100 μ.

N45°E) and disintegrated violently late in its flight. The large masses fell in the southwestern end, while numerous fragments were scattered within an elongated, roughly ellipsoidal area measuring about 500 x 100 m.

Later, erosion and corrosion assisted in further splitting of the masses, and, as a result of solifluction which is common in the area, numerous of the smaller fragments were carried downhill, mainly in an eastern and southeastern direction. The present limits of the finding places for fragments are, therefore, entirely different from the original limits. No crater was detected.

The area is extremely arid, with an average annual precipitation below 5 mm. The daily temperature variation is 25-35° C, and the wind is often very strong. The granitic rocks are heavily weathered, and all hills display soft contours and angles of slope which rarely increase above 25°. The immediate surface is covered with granitic pebbles, locally mixed with basaltic "dreikanter." When excavating a hole, one penetrates sand or silt, rich in gypsum, apparently to depths of more than one meter and, locally at least, up to 3 m thick. All meteorites found on the present expedition were located on the surface between the pebbles. Compare also the Monturaqui field work, page 1404.

Figure 2085. Imilac (Copenhagen). The surface of a typical fragment produced by violent shear forces. A 100 μ wide zone adjacent to the shear fracture has been momentarily reheated so much, that the cold-worked kamacite recrystallized to imperfect 5-10 μ units. A schreibersite crystal has been torn asunder, and the fragments have become aligned along the shear zone. Etched. Scale bar 100 μ.

DESCRIPTION

The largest individual fragment weighs 198 kg and is now in London. It was not examined on this occasion and has apparently never been examined and described. A significant number of the medium-sized fragments display evidence of shearing with marked striations. The sheared faces are particularly well developed on the following

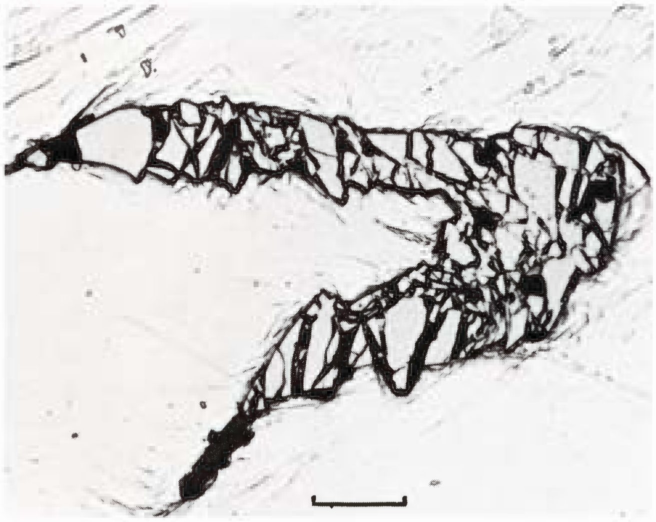

Figure 2086. Imilac (Copenhagen). A schreibersite crystal which has been entirely brecciated during the deformation. Etched. Scale bar 25 μ.

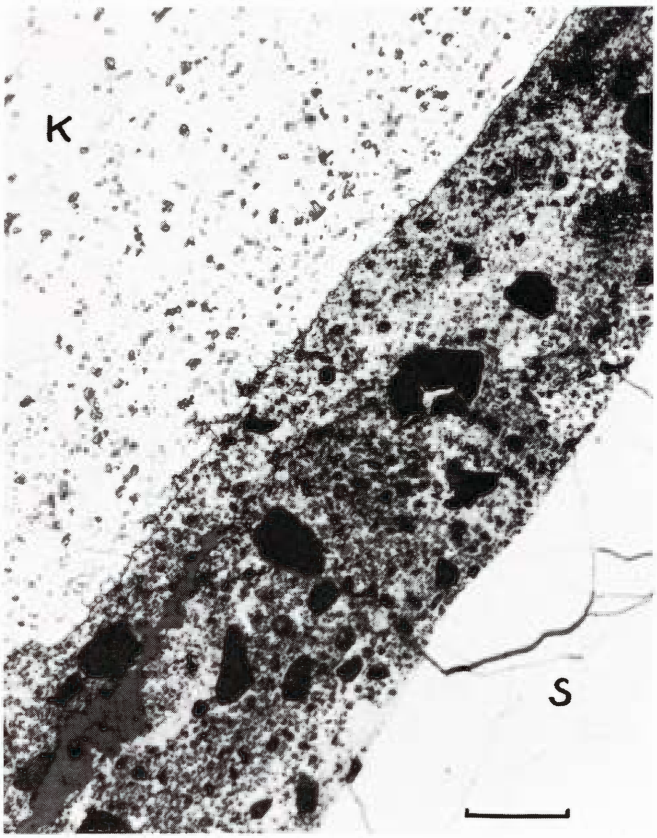

Figure 2087. Imilac (Copenhagen). A shear zone through a 15 g fragment. A mobile troilite melt has been injected along the fissured interface between schreibersite (S) and kamacite (K). In the troilite are numerous olivine fragments (black). Etched. Scale bar 25 μ.

samples: Copenhagen no. 8 (1.7 kg), Berlin (3.0 kg), London Brit. Mus. no. 27283 (1.9 kg), London Brit. Mus. no. 90239 (9.3 kg), London Brit. Mus. no. 40534 (half mass of 235 g), La Plata, labeled Gran Chaco (about 1.5 kg) and Museum Bern.Rivadaviva, Buenos Aires, labeled "Del Parque," (1.59 kg). Also the 25 kg mass, at the time in the possesion of Ignaz Domeyko, displayed several smooth shear faces, according to the brief description by Philippi (1855).

Since Copenhagen no. 8 is characteristic, it will serve as the type. It measures 10 x 9 x 6 cm and is roughly in the shape of a rhombohedron. Two of the six exterior faces are severely sheared and form an angle of about 20° so that the whole specimen appears wedge-shaped. The four other faces have irregular, very rough surfaces and the pallasitic iron protrudes in ragged edges above the olivine crystals. The striations on the two sheared surfaces are not strictly parallel and not very regular. Shallow and deep gouging alternate. The olivine crystals lie in low relief below the level of the gouged metal surface. A deep fissure which runs between the two shear faces almost separates the sample in two smaller masses. This fissure would have produced the ragged irregular type of fracture. The metal is superficially corroded while the olivine crystals are crushed and have assumed a yellowish sandy color.

The British Museum fragment no. 90239 (9.3 kg) is conical or roughly pyramidal. The pyramidal faces are sheared, with well defined striations in the smoothed out metal. The basal face is rough and broken by deeply penetrating cracks. Both metal and olivine are fresh (R. Hutchison, letter of July 17, 1973).

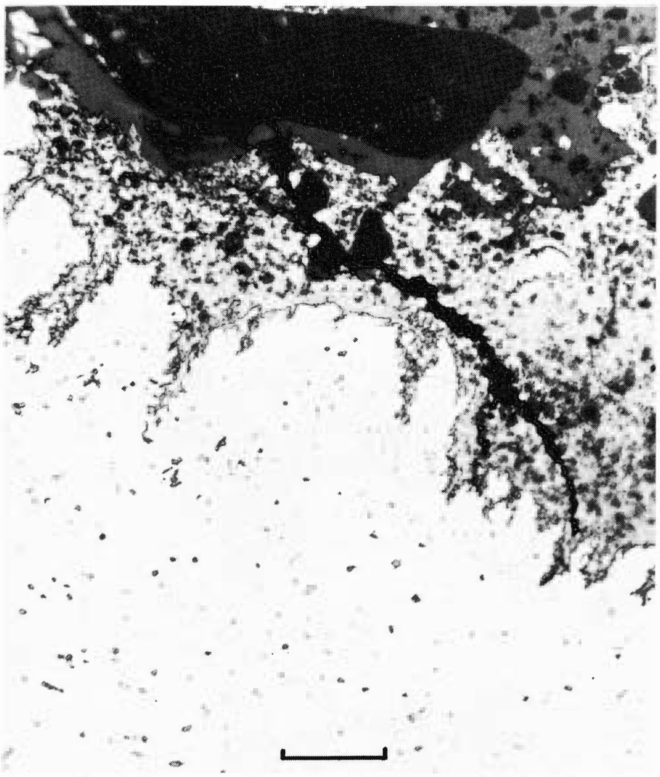

Figure 2088. Imilac (Copenhagen). The edge of a fused troilite pool with an olivine fragment (black). The troilite penetrates in an irregular way into the thermally altered kamacite. Corrosion products are dark gray. Etched. Scale bar 25 μ.

A large number of the small fragments (1-100 g) also show fluting and shearing upon one or more of the exterior faces. Discoidal and wedge-shaped fragments, measuring 3-5 cm in diameter and 1-2 cm thick, are quite common. The bounding faces usually display parallel striations, and the faces may meet along knife-sharp ragged edges. The thin edges are often bent and distorted, and the fragments then resemble the small twisted slugs which are known from the Henbury and Boxhole crater fields, for example. Another large portion of the small fragments (0.1-50 g) are irregular spongy metal skeletons from which the olivine crystals are largely lost. Sometimes they display the remnants of a striated shear face.

Terrestrial corrosion has altered the specimens to varying degrees. It is common to find fragments with thick coatings of silt and sand adhering to the meteorites and impregnated by limonite cement. While fusion crust was not detected on any of the examined fragments it appears that many fragments have lost only little by corrosion. Sheared and striated surfaces may thus be virtually unaltered. The olivine crystals are usually more attacked than the metal, probably due to both fragmentation and corrosion.

Sections through the larger masses display a normal pallasitic structure of olivine and metal, with about 50% by volume of each phase. The olivine crystals range in size from 1 to 20 mm, but most are about 10 mm. They are angular with slightly rounded edges, and, when fresh, they are yellowish white to greenish yellow in color. A significant proportion is, however, altered and now rust colored or sandy gray. On the sections the olivine crystals are seen to be extremely fractured and sometimes shear-displaced; the individual fragments are partly recemented by 0.5-2 μ wide veins of terrestrial corrosion products, but not so much so that they are prevented from popping out easily during grinding and polishing. Olivine is the only silicate phase present. Inside it, or in contact with it, there are a few subangular chromite crystals, 0.2-1 mm in size. They are less fractured than the olivine. In one instance a bluish-gray, entirely fissured mineral was observed. It measured 1 x 0.5 mm and was in contact with olivine, troilite and kamacite. It may be the stanfieldite, identified by Fuchs (1969).

The metallic part was, at austenite temperatures, a continuous sponge with uniform orientation over distances of at least 5-10 cm; i.e., the pallasite was composed of coarse austenite crystals in each of which occurred many olivine crystals. Upon slow cooling the olivine crystals acted as nuclei for kamacite when the austenite started to decompose below about 700° C. Therefore, each olivine crystal is now enveloped in 0.2-1.5 mm wide rims of swathing kamacite. The remaining austenite, squeezed between the rims that grew from all sides, now displays the typical plessite varieties, known from numerous medium octahedrites of group IIIB. The plessite fields occur as comb and net plessite or, with a higher bulk nickel average, as duplex unresolvable $\alpha + \gamma$ fields (HV 250±25) with zoned rims of brownish martensite parallel to $(111)_\gamma$ (HV 340±30), yellowish martensite (HV 380±30) and an exterior tarnished taenite rim (HV 340±40). Since the plessite fields formed by transformation from uniformly oriented austenite, the individual, now isolated, fields display uniformly oriented micro-Widmanstätten structures. No large scale Widmanstätten structure is present, however.

The kamacite is rich in subboundaries decorated with 0.5-2 μ angular phosphide precipitates. Inside the kamacite there often are numerous densely spaced and oriented rhabdite particles less than 1 μ in size. Neumann bands occur in profusion, and the hardness (100 g Vickers pyramid number) is 200±15. The hardness does, however, vary enormously because of late deformation as will be discussed below.

Schreibersite occurs as angular or rosette-shaped skeleton crystals up to 4 x 2 mm in size; these are early precipitates from the austenite and have nucleated 0.5-2.0 mm wide rims of swathing kamacite. Schreibersite is also present as late precipitates, forming 30-100 μ wide veinlets in α - α boundaries and along plessite rims. It further occurs as discontinuous 30-100 μ wide rims upon olivine and troilite and as 0.4-2 μ rhabdites. Some phosphide occurs as minute blebs inside the duplex $\alpha + \gamma$ plessite fields. The bulk phosphorus value may be estimated to be about 0.3%.

Troilite occurs in limited amounts as spherical or lenticular blebs, 0.1-2 mm across, and as 0.1-2 mm wide discontinuous rims around some olivine crystals. It penetrates some of the olivine crystals as 10-50 μ wide veins. The troilite blebs were probably originally monocrystalline.

While the above description pertains to the interior of the larger, undeformed masses, the smaller masses and fragments are severely distorted. The metal shows 50-200 μ wide shear zones within which the kamacite occasionally is recrystallized to 1-15 μ serrated grains. In other places the kamacite is rich in deformation bands, or the Neumann bands are bent and distorted. The microhardness varies correspondingly, from the "original" value of 200 to at least 295 in severely worked shear zones and back to minima about 160±5 within recrystallized shear zones. The striated shear faces which were discussed on page 1398, when sectioned, almost invariably show heavily worked and recrystallized metal, suggesting that the violent shearing released sufficient friction heat to heat the surface zones to recrystallization temperatures briefly. Experiments indicate that recrystallization of Imilac kamacite occurs at about 650° C in 10 minutes and at about 700° in one minute. The accumulated friction heat has thus been able to heat part of the material briefly to these temperatures.

The plessite fields suffered violent shearing and kneading at the same events, and the hardness increased in worked areas to above 400; no significant recovery took place in the short time available, in accordance with results from laboratory experiments. The schreibersite crystals were fissured and shear-displaced within the kamacite and sometimes drawn out to long rows of angular fragments which can hardly be recognized as once normal schreibersite crystals.

The troilite is shear-deformed and usually transformed into a polycrystalline mosaic of 5-10 μ serrated grains. In numerous cases the troilite is micromelted by the shock-accumulated friction heat and it is sometimes associated with the recrystallized kamacite shear zones where it apparently acted as a lubricant easing the shearing into fragments. The troilite is locally injected as fine veinlets into schreibersite, olivine and kamacite. The wider troilite melts include numerous 1-50 μ angular fragments of olivine and schreibersite. Terrestrial corrosion has somewhat blurred the picture, however.

Imilac is a typical pallasite. Structurally and chemically, it appears that its closest relatives are the 2.5 kg South Bend, the 32 kg Thiel Mountains and the 78 kg Finmarken pallasites. Imilac is particularly interesting by its remarkable size, which may be estimated to have been at least 500 kg briefly before it split at a late part in its trajectory. The fragmentation process led to severe gouging and local friction heating of the iron surfaces. Individual fragments became twisted and distorted to varying degrees, approaching the characteristics otherwise only associated with crater-producing meteorites, such as Henbury, Boxhole and Kaalijärv.

An unusually large number of pallasites have been reported from South America. It appears now that a significant portion of those previously considered as independent falls are, in fact, nothing else than transported fragments from the Imilac strewnfield. This is certainly the case for the masses labeled Ilimaes (95 kg), Gran Chaco (1.5 kg), Del Parque (1.6 kg), Calderilla (21 g), Potosi (about 1 kg), Campo del Pucará (about 50 g), and numerous other small masses labeled Atacama, Caracoles, Catarmarca, La Encantada, La Rioja, Peine, San Pedro and Toconao.

It is further strongly suspected that the two Antofagasta pallasites (14.0 and 3.45 kg) and the Salta pallasite (27.1 kg) are transported fragments from the Imilac strewnfield. Finally, the 6.6 kg Ollague pallasite should be checked; this mass seems, however, to have had a different history and a well documented (?) origin from a place near the Bolivian-Chilean border.

One of the early discoverers is quoted by Philippi (1855) to have stated that he had heard the Imilac pallasite fall in 1821 and that briefly thereafter he had found the locality. That the meteorite fell in 1821 has probably never been accepted by any serious worker, and the present study also suggests that the fall took place many hundreds of years before 1821. Since the corrosion is slow in the area which belongs to the most arid in the world, it is still possible to find specimens with striated shear faces that have lost less than 0.1 mm by exposure. It is remarkable that samples collected in 1973 look almost exactly like samples recovered about 1823, 150 years ago.

Kokstad (Matatiele), Kopjes Vlei and Kouga Mountains

These three important meteorites are all in the South African Museum, Cape Town, where the author had the opportunity to examine them briefly in July 1974. Since photographs of these irons are rare I include some typical views; unfortunately not of the best quality, however, because the light conditions were rather unfavorable.

Figure 2089. Kokstad. The main mass of Matatiele (South African Museum, Cape Town). The weight is 298 kg and the longest dimension 95 cm. Its shape is reminiscent of an oversize agitator of an automatic washing machine.

Figure 2090. Kopjes Vlei (South African Museum, Cape Town). A cast of the original mass shows that this was shaped as a triangular prism, measuring approximately 26 x 9.5 x 8.5 cm and weighing about 7-8 kg.

Figure 2091. The Kouga Mountains monster (South African Museum, Cape Town). With a weight of 1,175 kg it belongs to our most prominent iron meteorites. Its overall dimensions are 133 x 56 x 56 cm, and one end terminates in a head-like projection. According to the label, it was donated to the museum by J. A. Kritzinger. Scale bar approximately 10 cm.

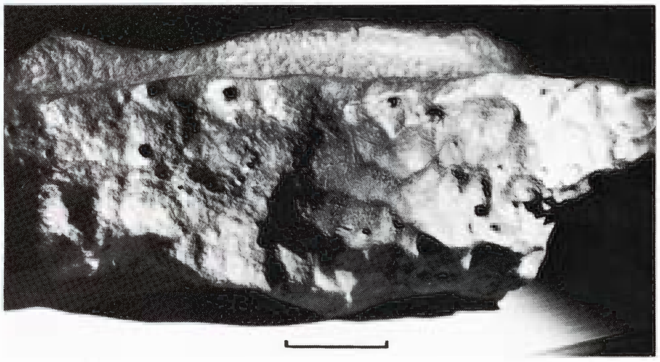

Figure 2092. Kouga Mountains (Cape Town). This side is relatively little affected by corrosion, showing holes and grooves after ablated troilite and schreibersite crystals, and retaining a distinct regmaglypt morphology. Locally, slightly weathered fusion crusts are preserved. Scale bar 20 cm.

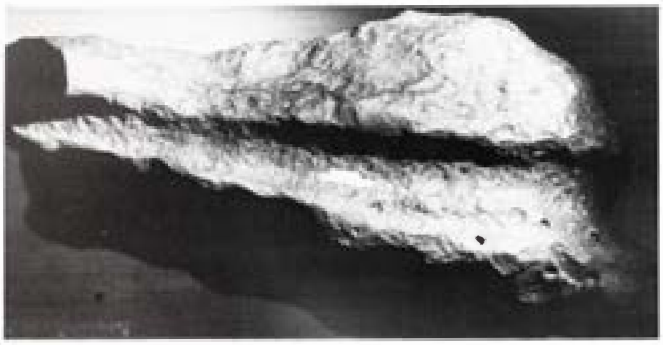

Figure 2093. Kouga Mountains (Cape Town). A remarkably straight and very large groove runs along the entire length of the mass. This feature was probably caused by terrestrial corrosion; what was just below the soil line weathered away, while what was above was hardly attacked, see Figure 2092. The only material distributed has been cut from the left, corroded end. Scale bar in the groove is 10 cm long.

Magnesia, Izmir, Turkey
37°52′N, 27°31′E

Medium octahedrite, Om. Bandwidth 0.60±0.08 mm. ϵ-structure. HV 330±15.

Group IIIC. 11.0% Ni, about 0.3% P, 14.5 ppm Ga, 22.4 ppm Ge, 0.18 ppm Ir.

HISTORY

All that is known of the history is reported in the handbook section. The following is based on a detailed study of the main mass, and of slices from the main mass, kindly put at my disposition by Mme. Christophe-Michel-Levy, Muséum National d'Histoire Naturelle, Paris.

ANALYSIS

J.T. Wasson found in a preliminary examination 10.99% Ni, 14.5 ppm Ga, 22.4 ppm Ge and 0.18 ppm Ir (personal communication 1974).

DESCRIPTION

The 5 kg endpiece is a well-preserved portion of a larger meteorite, which has never been recovered or at least reported. The low cone is covered with beautiful regmaglypts and with paper-thin, rather fresh fusion crusts on the conical ablated sides. Locally, straight grooves, e.g., 10 mm long, 3 mm wide and 3 mm deep, indicate where schreibersite lamellae were preferentially lost during ablation in the atmosphere.

The base of the cone exposes a hackly fracture surface with broken schreibersite lamellae and twisted and somewhat smoothed metallic protuberances. Sections through this part reveal that the fracture surface is imperfectly remelted and locally covered with fusion crust. The fusion crust is laminated and only 5-50 μ thick; the presence of fusion crust on the fracture surface is an unambiguous proof that the fracture took place during flight and so early that the new surface was partially remelted. This means that there did fall somewhere in the vicinity of Magnesia another fragment, probably larger than the one recovered, which had an independent long flight.

Etched sections display a medium octahedrite structure of straight and long kamacite lamellae ($\frac{L}{W} \sim 25$) with a

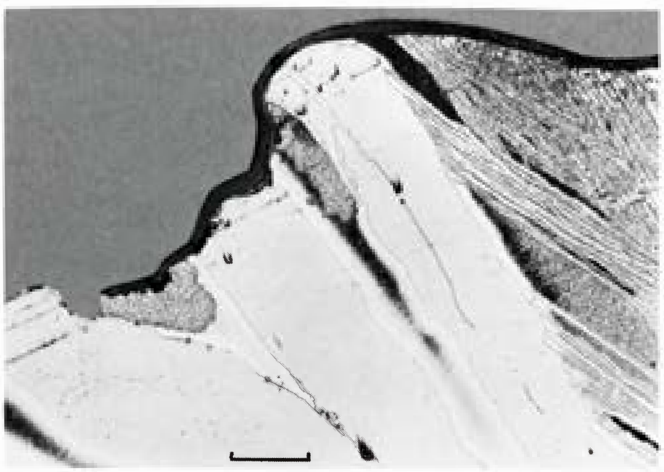

Figure 2094. Magnesia (Paris). A polished and etched section that includes the late fracture surface. The linear structural elements are distorted and the surface is partially covered by a thin laminated fusion crust. Scale bar 0.5 mm.

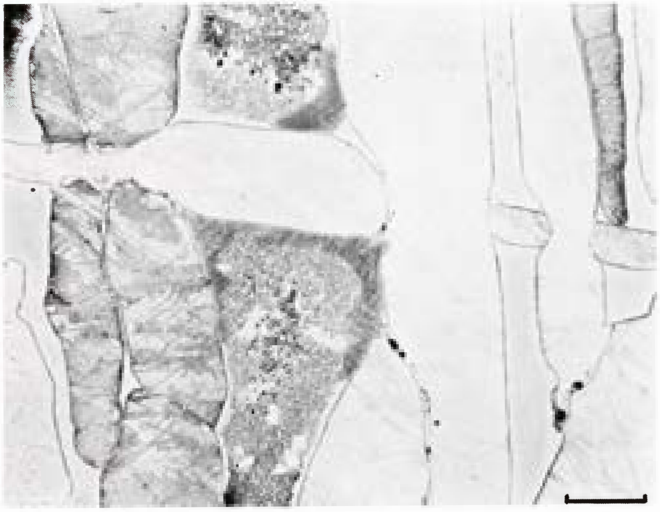

Figure 2095. Magnesia. Typical view of alternating shock-hatched kamacite and taenite and plessite fields. The whitish blebs inside some plessite fields are the carbide 'roses', composed of haxonite, taenite, kamacite and schreibersite. Etched. Scale bar 0.5 mm.

Figure 2096. Magnesia. A plessite field with acicular kamacite, spheroidized taenite particles and unresolvable black taenite. A narrow rim of cloudy taenite adjacent to kamacite, above right. Etched. Scale bar 50 μ.

bandwidth of 0.60±0.08 mm. The kamacite has numerous subboundaries that usually are decorated by 1-4 μ phosphide particles. The kamacite is of the hatched ε-variety, shock-hardened to the high values of 330±15, suggesting a shock intensity of about 200 k bar.

Taenite and plessite cover 40-45% by area and the fields may reach sizes of 6 x 4 mm. Many varieties of plessite occur: comb, net, pearlitic, martensitic, acicular and spheroidized types, but annealed fields are absent. The pearlitic types are usually restricted to 100-150 μ rim or transition zones within larger fields, and the individual taenite lamellae are here 1-2 μ wide. The spheroplessite is composed of 2-10 μ spheroidized taenite particles in a polycrystalline kamacite. The microhardness (50 g load) of the yellow-etching taenite rims is 450±30, while the martensitic interiors of many fields reach hardnesses of 500±20. The high hardness is in harmony with the hardness of the kamacite and is caused by shock-deformation.

Approximately one out of three plessite fields contains carbide roses, i.e., reflecting, irregular islands inside plessite, 50-500 μ across. High magnification reveals these to consist of an intricate intergrowth of haxonite, taenite, kamacite and a little schreibersite, with an aggregate hardness of 900±60.

Schreibersite occurs as prominent massive crystals, up to 4 x 2 mm in size. It is further present as 20-50 μ grain boundary precipitates and as occasional blebs, e.g., 0.5 x 0.2 mm in size, along the center of the kamacite lamellae. The larger schreibersite crystals are very early precipitates from taenite, and they have nucleated rims of swathing kamacite that have grown to a width of 1.5-2.0 mm. Rhabdites commonly occur as micron-sized precipitates in

Figure 2097. Magnesia. A wide taenite ribbon which is under decomposition to spheroidized (below) and pearlitic plessite (center). Subboundaries in the kamacite lamellae on either side. Etched. Scale bar 50 μ.

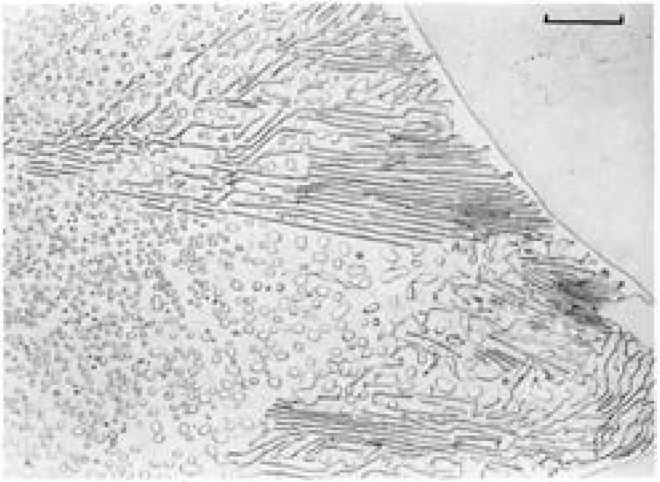

Figure 2098. Magnesia. Another example upon taenite under decomposition to mixed spheroidized and lamellar textures. Etched. Scale bar 50 μ.

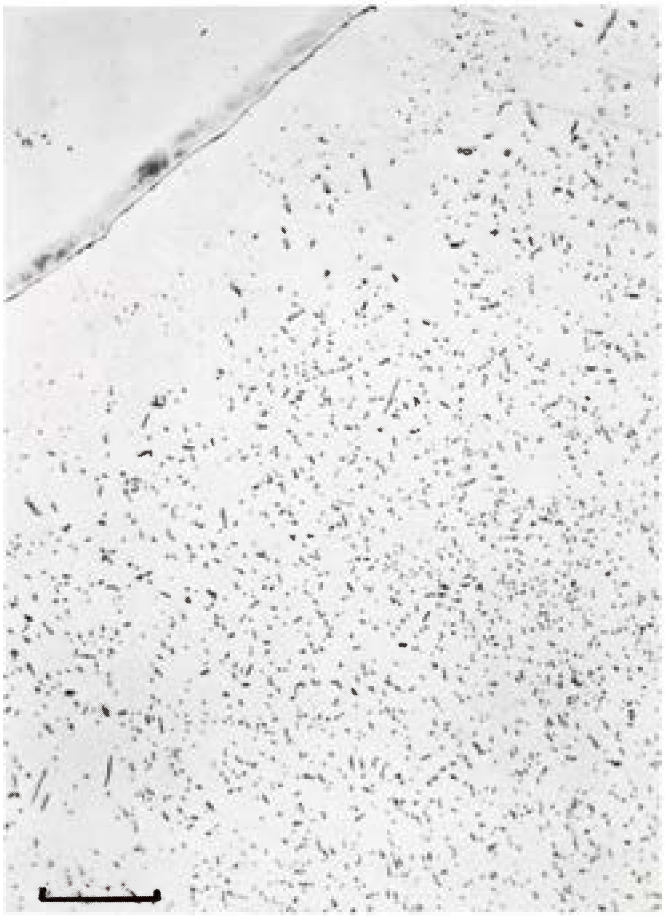

Figure 2099. Magnesia. In the kamacite are numerous densely spaced, micron-sized rhabdite particles. Above left, a cloudy taenite rim. Etched. Scale bar 50 μ.

such kamacite that is distant from the larger schreibersite bodies. The bulk phosphorus content is estimated to be 0.30±0.05%.

Troilite is not common. It was only observed as tiny single crystals, 40-60 μ across, that had served as nuclei for some of the large schreibersite crystals. No shock-melting has occurred.

Cohenite, silicates and phosphates are apparently entirely absent.

Under the fusion crust there is a distinct heat-affected α_2 zone, up to 3 mm in thickness. Under the late fracture surface the α_2 zone is very thin, some 0.3-0.4 mm, and here the fusion crust is, as noted above, also thin or absent. The α_2 zone consists of serrated, unequilibrated kamacite crystals that are small (20-30 μ across) because they were formed by transformation of shock-hardened kamacite; they have a hardness of 195±10 (hardness curve type I). Wherever haxonite happens to be situated in the α_2 zone it is decomposed. The thermal alterations include formation of a 5-15 μ dark-etching bainitic rim zone (at 800-1000° C) and a more thorough decomposition (above 1100° C) to graphite and austenite which again, on rapid cooling, transformed to martensite and retained austenite. Some taenite lamellae which extend through the heat-affected zone are thermally altered. Carbon, previously in solid solution in the taenite, has diffused away from the lamellae, and upon cooling, caused a dark-etching martensite rim to

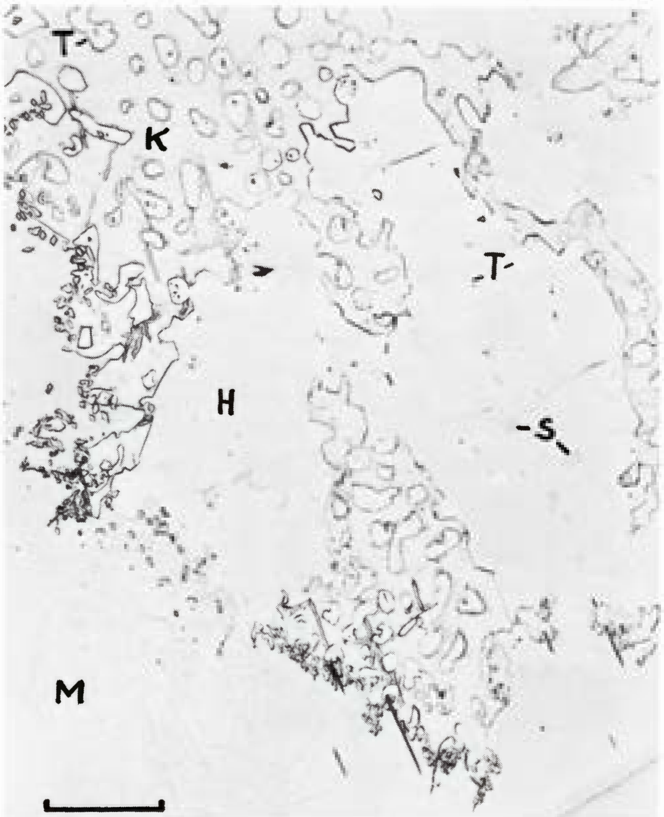

Figure 2100. Magnesia. An enlarged view of a carbide 'rose' like those of Figure 2095. Pure taenite (T) and schreibersite (S) particles are embedded in haxonite (H), which evidently is a rather late precipitate. Martensitic plessite (M) and kamacite is also apparent. Etched. Scale bar 40 μ.

Figure 2101. Magnesia. A carbide 'rose' which happened to be located in the heat-affected α_2 zone and started to decompose. Carbon that diffused away from the haxonite formed a supersaturated austenite that, upon cooling, transformed to martensitic and bainitic structures according to the local nickel and carbon level. Some graphitization also occurred. Etched. Scale bar 50 μ.

form; compare, e.g., Kayakent. This observation indicates that carbon, besides being bound in haxonite, is also present in solid solution in the taenite phase.

The meteorite is almost uncorroded. The insignificant weathering may be attributed to artificial handling and to corrosion caused by cutting fluids. It is not out of the question that Magnesia was observed to fall in 1899 as maintained by the original owner.

Magnesia is a shocked and unannealed medium octahedrite which structurally and chemically is closely related to Carlton, Edmonton (Kentucky) and Mungindi. Common to these is the relative high carbon content that is mainly precipitated as haxonite inside plessite. Magnesia has a low sulfur content in common with Carlton and Edmonton. It belongs with these and a few other meteorites to the resolved chemical group IIIC.

Monturaqui, Antofagasta, Chile

23°56′S, 68°17′W; 3100 m

Probably a coarse octahedrite, Og, with a bandwidth of 2.0±0.5 mm.

Crater 360-380 m across and 21-39 m deep.

The crater-forming meteorite probably belonged to group I and was similar to Canyon Diablo in composition.

HISTORY AND FIELD WORK

A previously undescribed meteorite crater in the Andes Mountains of Northern Chile was described by Sanchez & Cassidy (1966). Sanchez had located the crater on aerial photographs in 1962 and had assumed that it was not of volcanic origin although located not far from the numerous, partly active volcanoes of the high Andes. Sanchez and Cassidy performed field work in the remote place in November 1965; they reported on the geological environment and collected various fragments which were supposed to be meteoritic iron shale and impact glass.

In order to verify the meteoritic nature of the crater, a small expedition was planned from Denmark, supported by the Carlsberg Foundation. The members were Bent Jørgensen, astronomer, Vagn Aage Jensen, geologist, and the author, and the purpose was to measure the crater and instigate a thorough search for possible surviving meteorite fragments. It was hoped that at least some fragments could be found that still had sufficient metallic material for chemical analyses to be performed. In this we were disappointed. However, quite a few results came directly or indirectly as a spin-off from the expedition.

In the meantime Bunch & Cassidy (1972) had published a thorough study, by petrographic and electron-microprobe techniques, of the glasses collected on the crater rim and verified their impactite nature. I wish here to thank Dr. Cassidy for his cooperation in putting data and some specimens at my disposal later for comparison with materials we had collected.

The members of the Danish expedition met in Antofagasta in March 1973, and, excellently supported by Mr. Guillermo Chong of the Instituto de Investigaciones Geologicas, Antofagasta, we started from the coast town on March 31. Two Chilean workmen from the Institute joined us. With two four-wheel drive trucks we drove 300 km through rough desert country to the Monturaqui site and set up camp, supplied with water, gasoline and provisions for a three-week campaign. The crater was measured by triangulation; and the crater floor and the walls, but particularly the slopes and mountains around the crater, were systematically searched for meteorite fragments and impactites. A modern electronic mine detector was applied; it was carried in a strap across the shoulder, and calibrated against metallic dummies which indicated that it would give a signal for 1 kg masses at 20-30 cm depth, and better signals for correspondingly larger masses.

The search was conducted within an area of 1000-1200 m from the crater rim, i.e., up to about three crater diameters, but most intensively within the nearest

Figure 2102. Monturaqui. Vagn Aage Jensen, Fernando Benavides and Bent Jørgensen walking along the softly rounded crater rim. The crater interior is at left. The distance to the double lava cone, 3380 m high, is about 5 km in a southwesterly direction. April 1973.

100-200 m. However, no meteoritic bodies were revealed. The signals obtained always came from basaltic boulders, from magnetite in pegmatite or from unidentified weathered products that apparently were non-meteoritic in origin.

Better luck came from the close visual inspection of the surface. The surface itself was composed of several successions of ignimbrite from adjacent volcanoes, and these sheets were at least 3-4 meters thick, as revealed in the gullies and dry rivers. The ignimbrite was very young, of Pleistocene age, and not weathered very much. The meteoritic iron shale was found between weathered ignimbrite fragments on the surface, and they were mainly located about 100 m southeast and 100-200 m southwest of the crater rim. Occasional fragments were collected at a slightly larger distance and in other directions. A total of less than two kg was found.

Impactites were much more common than meteoritic iron shale. These cindery, extremely heterogeneous aggregates were mainly located within 50 m of the southern and southeastern rim of the crater, and some 20 kg were collected, but much was left on the site for future research. They are much more resistant to terrestrial weathering than iron meteorite fragments.

Sanchez & Cassidy (1966) believed that the absence of iron meteorites around the crater was caused by the activity of Indians and traders. An old Inca trail runs in a northeasterly direction towards Peine at a distance of 100-200 m from the crater, and we found, in fact, an ancient Indian arrowhead (of stone, however) in the vicinity of one of the numerous old cairns. However, in view of the age of the crater, I am inclined to conclude that almost all iron meteorite material has corroded away long ago, rather than having been removed by human activity.

The crater itself is nothing like the sharp and well defined Meteor Crater in Arizona (Canyon Diablo). The rims are weathered and the shoulders are rather softly rounded. The crater floor extends over an area of 140 x 160 m almost horizontal, and fine yellow silt has been washed and blown in and now covers part of the bottom. According to the meteorological observations, the region presently belongs to the most arid areas of the world, with an annual precipitation of less than 1 mm. Therefore, the crater is dry and excavations to 150 cm depth in the bottom revealed nothing else than bonedry dusty silt. There was no vegetation at all within miles.

The dimensions of the crater are 360 m in a north-south direction and 380 m in an east-west direction, measuring between the highest points on the present soft rim. The crater is situated in a sloping, roughly hilly terrain that slowly descends towards the large Salar de Atacama, situated 25 km farther north. Because of this location, the northern rim is about 11m lower than the southern rim. The vertical distance from the horizontal crater floor to the northern rim is 21 m, and to the southern rim 32 m. In southeast and southwest there occur two slightly higher rim parts of 33 and 39 m, respectively.

Figure 2103. Monturaqui. A view across the crater in a southeasterly direction. On the horizon the volcanoes Pular (left, 6225 m) and Pajonales (right, 5960 m), at a distance of about 45 km near the boundary to Argentina.

The dimensions of the crater given here have been verified by comparison with vertical photographs taken from an altitude of 7 km. They are, however, some 20% smaller than the dimensions reported by Sanchez & Cassidy (1966). Personal discussions and comparisons of the observational data revealed that the earlier set of data unfortunately was systematically high because of an erroneous calibration of a basic triangle.

The rough descriptions above will be followed elsewhere by a thorough description by the geologist of the expedition, Vagn Aage Jensen.

DESCRIPTION OF THE MATERIAL

With reference to the impactites, the reader is referred to the paper by Bunch & Cassidy (1972), whose observations can be fully supported. We have, in addition, started a project in order to fix the absolute age of the crater. Our preliminary data, obtained by thermoluminescence analysis of the impactites, suggest that the crater is more than 100,000 years old. This is in harmony with the weathered appearance of the crater itself.

The meteoritic iron shales are rather inconspicuous shapeless chunks, which were mainly picked up on the surface immediately outside the southern rim zone. The samples ranged from 5 g to 100 g in weight, and almost all of them were magnetic to some degree. Twelve samples, which appeared promising with respect to unaltered meteoritic interiors, were studied in considerable detail. The individual weight of these samples were from 18 to 80 g, and the specific gravity ranged in an unsystematic way from 3.57 to 3.92 g/cm^3. No specimen was found with a specific gravity higher than 3.92. The exterior appearance was either that of laminated to fibrous shales, or breadcrust morphology with embedded terrestrial feldspar grains. In rare cases, the weathering had led to an octahedral exterior, suggesting that the original meteorite was a coarse octahedrite.

Polished sections through the twelve fragments failed to reveal any coherent metallic matrix. Almost complete transformation to "limonitic" terrestrial corrosion products had occurred. However, a close examination revealed the following structural elements:

(i) Schreibersite as 20-100 μ wide brecciated fragments, entirely embedded in "limonite," and itself partially altered, judging from the loss of anisotropy in polarized light, compared with fresh schreibersite.

(ii) Cohenite as up to 1 x 0.2 mm angular breccias embedded in limonite. Although it was evident that much cohenite had been transformed by corrosion, the crystal breccias which were left were in a surprisingly fine condition. The anisotropy was good, and the ductility was fine, and the microhardness (100 g load) was 1100±50, with no fissuring around the Vickers pyramid indentation.

(iii) Taenite ribbons and plessite fields occurred locally; the fields were up to 1.1 x 0.4 mm in size, but were "fossil"; i.e., what remained was really only the high-nickel

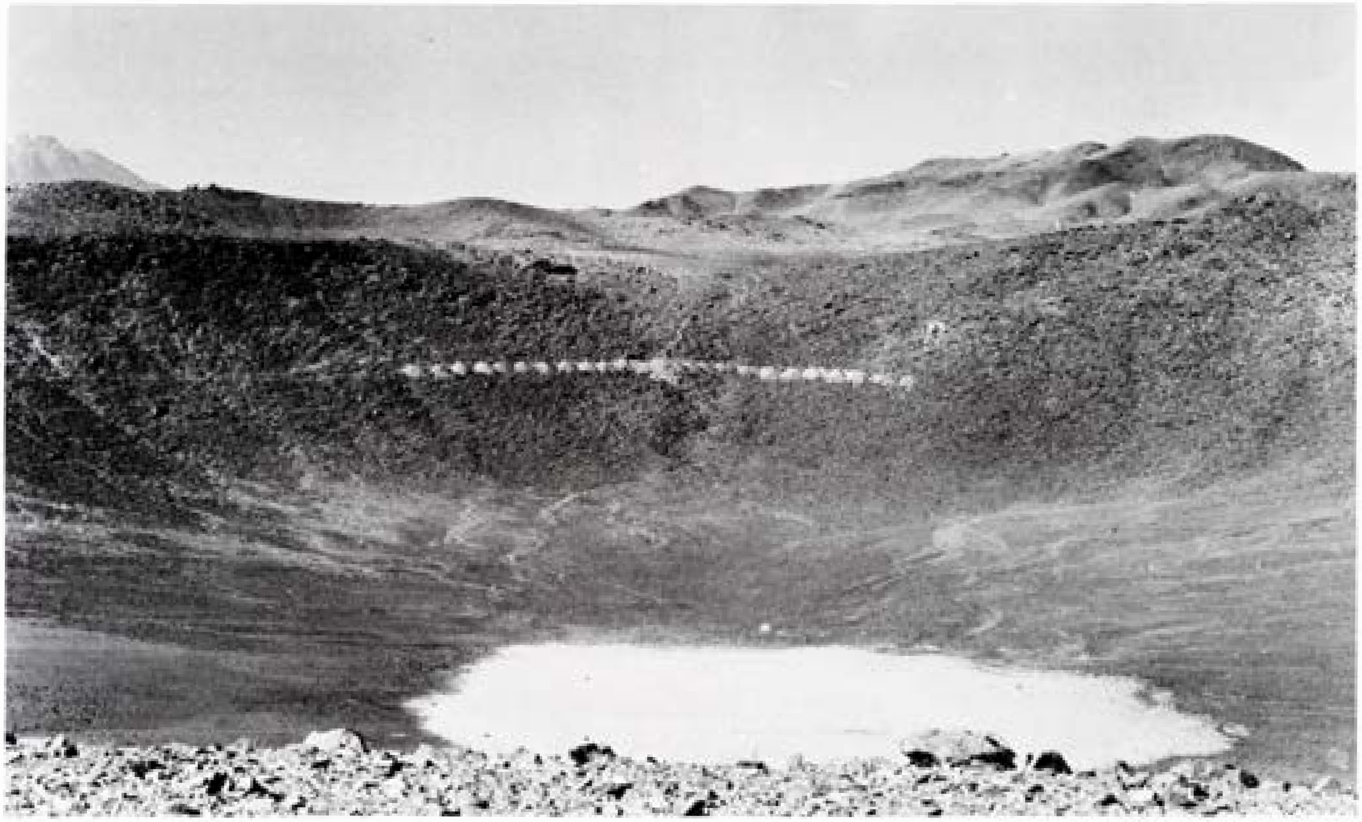

Figure 2104. Monturaqui. A view towards south across the crater. The fine yellow silt on the bottom is bone dry. The 25 whitish cones are granite rubble from the excavation that Cassidy with assistance of the Instituto de Investigaciones Geologicas, Antofagasta, accomplished on the inner south wall about 1965. The hole was taken to a depth of about 10 m and is in the center of the picture. Photo April 1973.

rim zones and the retained taenite (austenite) around martensite of high-nickel, high-carbon morphology. The $30 \times 3\ \mu$ martensite plates were themselves entirely converted to limonite; however, the contrast between these black needles and the yellowish retained austenite was striking.

(iv) Kamacite was not identified as such, but had clearly been present around the taenite, plessite and schreibersite. It appeared that the original kamacite bandwidth was of the order of 2.0±0.5 mm, and that the average amount of taenite and plessite was below 5%. The bulk morphology also suggested some deformation with twisting, necking and straining of the metallic elements.

Although searched for, no graphite, troilite or silicate crystals were identified. On the other hand, the minerals and phases discussed above (i-iii) were confirmed by electron microprobe analysis.

The material resembles what may be found in the vicinity of Meteor Crater, Arizona, but it is in a much more weathered state. The presence of the meteoritic phases and

Figure 2105. Monturaqui. Searching with a mine detector on the plain outside the crater. On numerous occasions the signals suggested the presence of meteorites; however, each time an excavation revealed nothing but magnetite in weathered pegmatite or basalt. From left to right, the author, Vagn Aage Jensen and Hugh Cotapos. April 1973.

Figure 2106. Monturaqui. The typical windblown surface just outside the crater rim. Ignimbrite, basalt and up to fist-sized impactite fragments occur here mixed. Ruler measures 15 cm.

Figure 2107. Monturaqui. Another windblown surface or 'desert floor'. Angular, weathered granite pebbles are situated in a close fitting puzzle. Under the pebble layer there are often 20-100 cm silt and sand, loosely cemented by gypsum and nitrates. The handlens measures 45 mm.

Figure 2108. Monturaqui (Copenhagen). Weathered octahedral fragments like this is all that survives of the impacting iron meteorite. From a close study of the few 'fossil' elements it can be concluded that the Monturaqui meteorite was a coarse octahedrite of group I, related to Canyon Diablo. Weight 71.2 g, specific gravity 3.80. Ruler in cm and mm.

minerals prove unambiguously that the object that caused the Monturaqui crater was an iron meteorite. However, the long, probably more than 100,000 years of exposure to a terrestrial climate – which previously may have been slightly more wet, judging from the prominent erosion in the area – has almost entirely devoured the little material that survived the crater-forming impact.

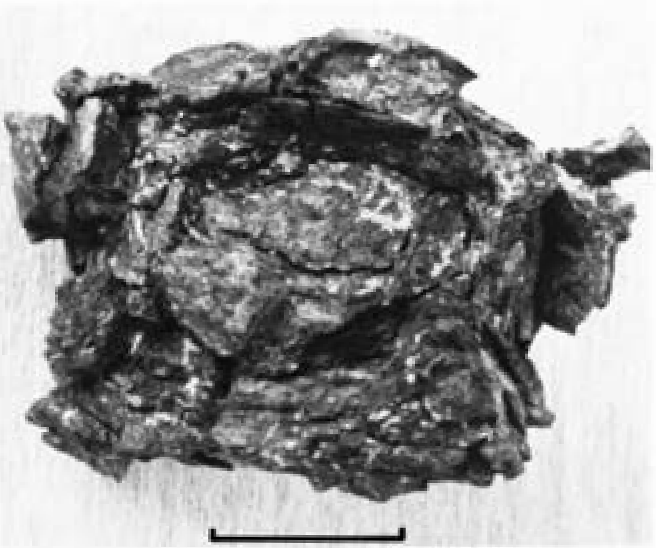

Figure 2109. Monturaqui (Copenhagen). Other fragments are of the breadcrust type. When the octahedral and breadcrust-shaped fragments disintegrate, smaller laminated fragments are produced. Weight 49.6 g, specific gravity 3.60. Scale bar 10 mm.

In an attempt to classify the weathered remnants of what seems to have been slugs and distorted specimens similar to those described from, e.g., Henbury and Canyon Diablo, we will have to rely on the few discernible, but important details: the cohenite, the high-nickel, high-carbon morphology of the martensite inside some plessite fields, and the bandwidth of about 2 mm. These structural elements all point to a coarse octahedrite of the resolved chemical group I, possibly with about 7% Ni and 0.25% P, and closely related to the Canyon Diablo object that formed Meteor Crater, Arizona. Being familiar with Canyon Diablo specimens, one might perhaps expect that graphite, troilite and silicate should also be present in the Monturaqui samples. It should, however, be remembered that these components are very rarely seen in the small Canyon Diablo slugs, probably because the fracturing followed the minerals, so that they were preferentially lost during the breakup.

In conclusion, it can be stated that (i) the Monturaqui crater is definitely proven to be of meteoritic origin, with the present dimensions 360 x 380 x 34 m; (ii) the impact probably occurred more than 100,000 years ago; (iii) the impacting object probably was a coarse octahedrite of group I related to Canyon Diablo; and (iv) the high terrestrial age and a previously more wet climate, combined with the nitrates and chlorides of the region, sufficed to transform virtually all metallic material to limonite.

In Table 18, Chapter Four, several meteorite craters were discussed. We may now add more precise data on Monturaqui, the most important piece being that of the classification as a coarse octahedrite of group I. Out of ten established craters with surviving meteoritic debris, four thus belong to group III (Wabar, Henbury, Boxhole and Wolf Creek) and four to group I (Canyon Diablo, Odessa, Monturaqui and Kaalijärv), confirming the previous conclusion that these two iron meteorite classes are by far the most important types.

Mount Sir Charles, Australia

Preliminary information indicates that this new meteorite belongs to group I and has the following composition: 6.8% Ni, 90 ppm Ga and 394 ppm Ge (Wasson 1974).

Nutwood Downs, Australia

In the 1970s several small twisted and ear-shaped slugs, of 25 to 100 g weight, have been offered for sale by various dealers, e.g., David New, under the name Nutwood Downs. Analytical data were presented by Scott et al. (1973) who found 7.66% Ni, 18.5 ppm Ga, 35.2 ppm Ge and 11 ppm Ir. The morphology, structure and composition clearly indicate that the Nutwood Downs material must be transported fragments from the central Australian crater fields, most probably Henbury.

The same is equally true of the older Nuleri material, briefly treated in the handbook, which in a new analysis (Wasson 1974) shows: 7.44% Ni, 18.0 ppm Ga, 36.7 ppm Ge and 9.3 ppm Ir.

Otasawian, Alberta, Canada

Coarse octahedrite, Og. Bandwidth 2.0±0.3 mm. Neumann bands. HV 180±10.

Group I. About 7.0% Ni, 0.25% P.
It is concluded below that Otasawian is a transported Canyon Diablo mass.

HISTORY

Meteorite fragments totaling 8.7 kg were briefly mentioned by Baldanza et al. (1969) and by Baldanza & Pialli (1969). The authors, who presented photomacrographs and photomicrographs and discussed the mechanical deformation, assumed that Otasawian was an independent fall, discovered near Otasawian in Alberta, Canada.

When I had had the opportunity to examine significant parts of the material, it occurred to me that the macro- and microstructure, see below, is remarkably similar to Canyon Diablo masses of shock-transformation stage I. In August 1973, Dr. Baldanza kindly gave me the following details which had not been included in the above mentioned papers.

> On a visit to Arizona in the sixties, Dr. Baldanza had stopped at a curio shop near Meteor Crater. The proprietor was the proud owner of a meteorite which he maintained had been found by his father near Otasawian in 1907. When the family moved to Arizona