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THE AARHUS METEORITES

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Synopsis

The stony meteorite Aarhus I was observed falling on October the second, 1951. A few days later another stone, Aarhus II, was found. It is supposed to belong to the same fall. The first part of the following paper contains a short revue of the fall and the circumstances about the observations of the meteorpath. (This introduction has been written by Professor, Ph. D., A. NOE-NYGAARD who handed the material over to the present authors).

The second part deals with the shape and size of the stones, the components and structure of Aarhus I, its non-opaque minerals of which bronzite and olivine are predominant, and the chondrules. The mineral composition is calculated from the analysis. The stone is to be classed as a veined brecciated gray bronzite-olivine chondrite, (by K. C.).

The latter part of the paper gives an account of an ore microscopic examination of the meteorite. Besides the well-known kamacite-taenite-troilite-chromite assemblage the examination revealed the presence of native copper in tiny specks mainly in the nickel-iron grains; pentlandite was seen as minute inclusions in the troilite both in this stone and in samples from the Mern and the Holbrook stones, used for comparison in the study of the Aarhus stone. The pentlandite was analyzed using the Castaing microprobe analyzer.

Two unidentified sulphides from the transition zone between crust and interior of the meteorite are mentioned. Some structural features are dealt with among which are the black veins which together with other phenomena seem to indicate extraterrestrial brecciation, (by H. P.).

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Introduction

"On the 2'nd of October 1951, at $17^h 13^m 5$ U.T. a bright fireball was seen from all parts of Denmark, southern Norway, and southern Sweden, and from Holstein almost as far south as Hamburg. The area of visibility may be estimated to amount to at least 250.000 km^2. The fireball left a persistent train, which at the endpoint of the path developed into a bright irregular cloud. Detonations were heard and a meteorite was seen falling to the Earth"; . . . "another meteorite was found later". (NIELSEN, 1953, p. 305) (5).

The meteorological conditions were favourable, the sky was bright and the fall took place a quarter of an hour after sunset, consequently the fireball was observed by many eye-witnesses. An appeal in newspapers and over the broadcasting service as a collaboration between the Ole Rømer Observatory in Aarhus and the Mineralogical Institute of the University of Copenhagen gave us about 400 eye-witnesses reports. Further, observator AXEL V. NIELSEN travelled round Denmark during a week of October, 8–14th, partly to interview observers personally, partly to measure the coordinates of the apparent path under the direction of the observer in question. In this way he succeeded in obtaining a large amount of observational material, "and the true path of the meteor may be said to have been more accurately determined than most paths hitherto recorded" (NIELSEN, 1953, p. 305) (5).

The point of the path at which the meteor was first seen was 143 km over a point on the Earth 50 km SSE of Warnemünde in Germany and 304 km from the endpoint of the path. The meteor flew over the western Baltic, over the Danish island Lolland, over the Great Belt, cutting across the island of Samsø in Kattegat and finally reaching the bay of Aarhus where it exploded at a height of 31.4 km. The two meteorites fell on the prolongation of the path at an interval of 1.3 km. (NIELSEN, 1953, p. 323–24) (5).

The meteorite, the fall of which was observed, fell into the small wood

Riisskov just north of the town of Aarhus, the second meteorite, which was found a few days later, fell into a timberyard in the northern outskirts of the town. The first stone, Aarhus I, broke into four pieces on falling, these were picked up by P. W. HOLM, engineer and K. HANSEN, mecanic. Aarhus II was found later by mr. H. ELGAARD, it was unbroken. The exact locality for Aarhus I, Riisskov is 56°11′ N, 10°14′ E.

The present investigation has been carried out on Aarhus I, while Aarhus II is kept as a monolith. The weight of Aarhus I, of which a little is missing along the fractures, is ca. 300 g, the weight of Aarhus II is 420 g. The biggest fragment of Aarhus I is kept in the Museum of Natural History in Aarhus (upper fourth of fig. 1), the rest in the Mineralogical Museum of the University of Copenhagen.

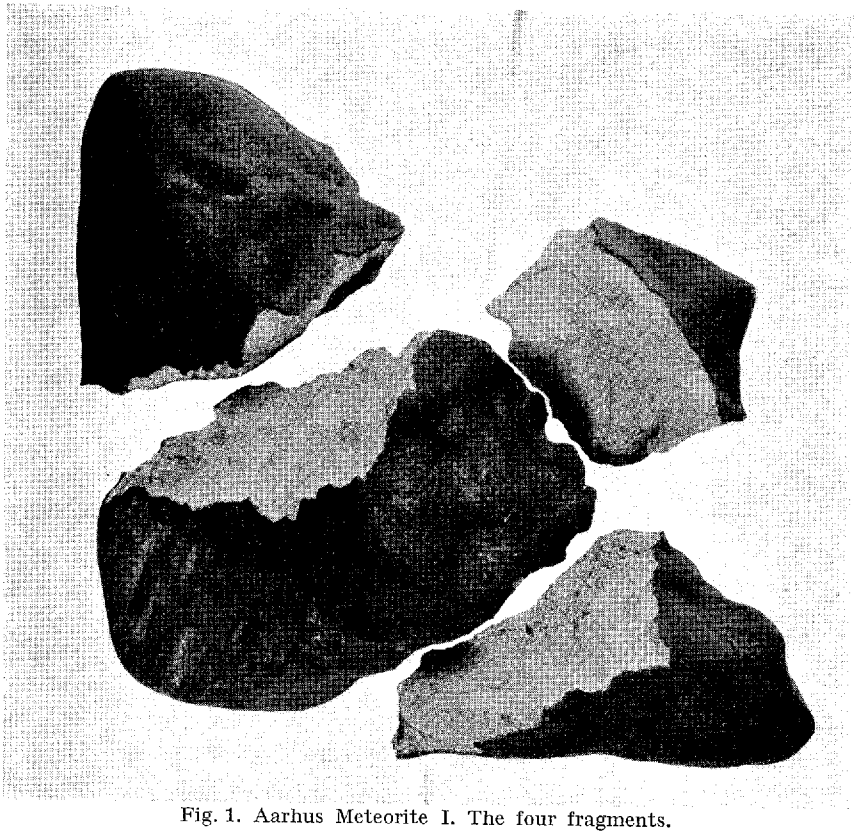

Fig. 1. Aarhus Meteorite I. The four fragments.

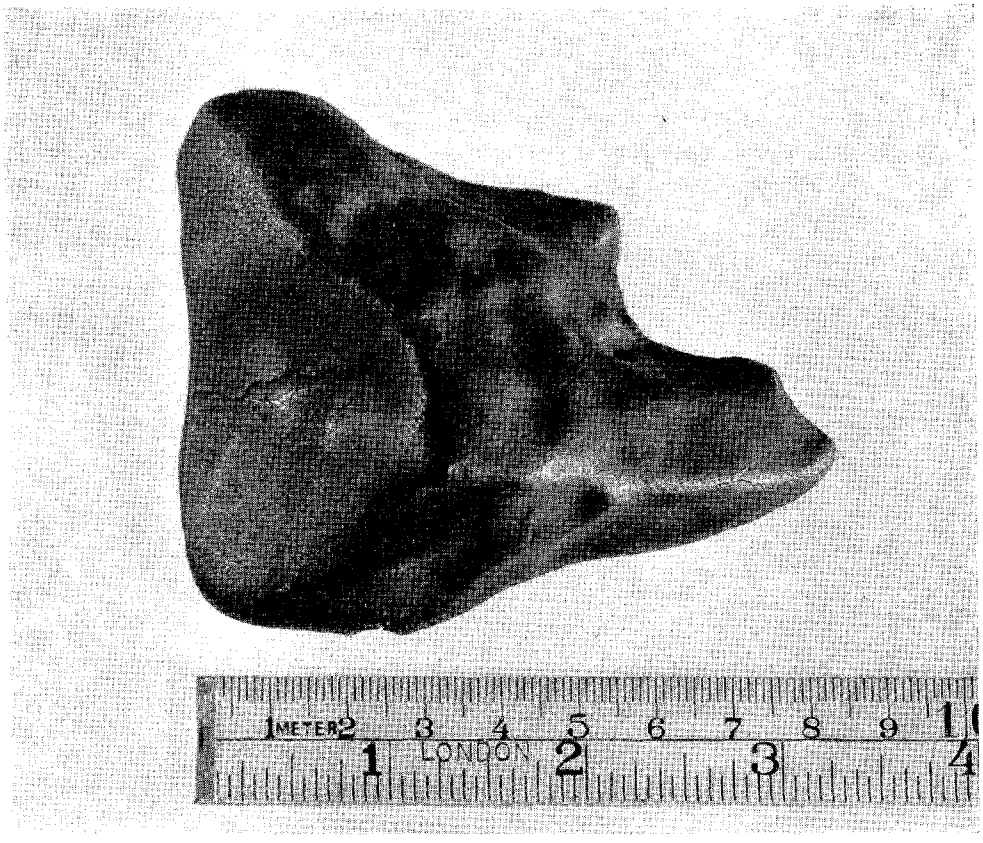

Fig. 2. Aarhus Meteorite I. Reconstruction, the cast.

Shape and Size of the Meteorites

The four fragments of Aarhus I (fig. 1) corresponded exactly to each other; each of them had preserved a part of the primary black crust which to all appearance covered the whole stone before it broke up. H. BRORSON CHRISTENSEN from National Museum, Copenhagen, with his great ability could join the fragments perfectly in their original positions and make a plaster cast which in all essentials shows the original form of the meteorite and the size slightly diminished due to loss of material by the fracturing. On the cast (fig. 2) a fracture is faintly seen across the left face.

The cast shows that the original shape of the whole stone was an irregular, almost triangular flat pyramid. While photographed it was lying on the largest face which is almost flat with only a few, comparatively large,

shallow depressions. The other faces and all the edges are more or less rounded. The lower left corner (fig. 2) corresponds to the lower left fragment in fig. 1. On this fragment a great many quite small flow-lines are seen, indicating that this corner is a part of the leading surface, the "Brustseite". The opposite part of the pyramid, corresponding to the rear, is uneven and rugged and shows a number of pittings; it probably belongs to the "Rückenseite".

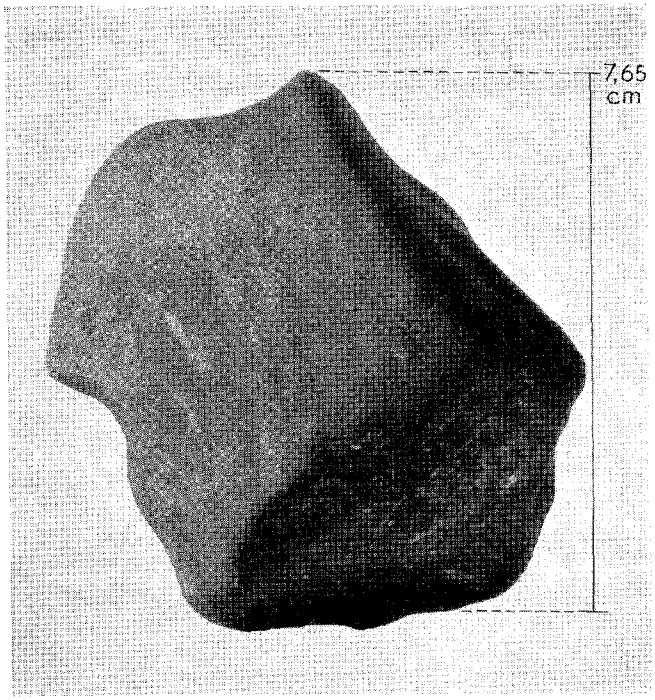

Fig. 3 a. Aarhus Meteorite II. The front surface.

The stone Aarhus II (fig. 3a–b) has a more indeterminate shape; edges and faces are rounded. Fig. 3a shows some rather weak flow-lines ("Brustseite") and on the opposite part of the stone (fig. 3b), probably the "Rückenseite", several shallow depressions are seen.

Aarhus II is a nearly complete stone except for two small scars at the corners (fig. 3b). A minor face on the left corner shows a secondary crust (fig. 3b).

The surface crust of the freshly fallen stones was shiny black, but few days later it became dull and a little grayish. Later on it became somewhat

cracked. In about the same time the originally whitish fracture-surface of the fragments changed to a slightly darker, grayish shade.

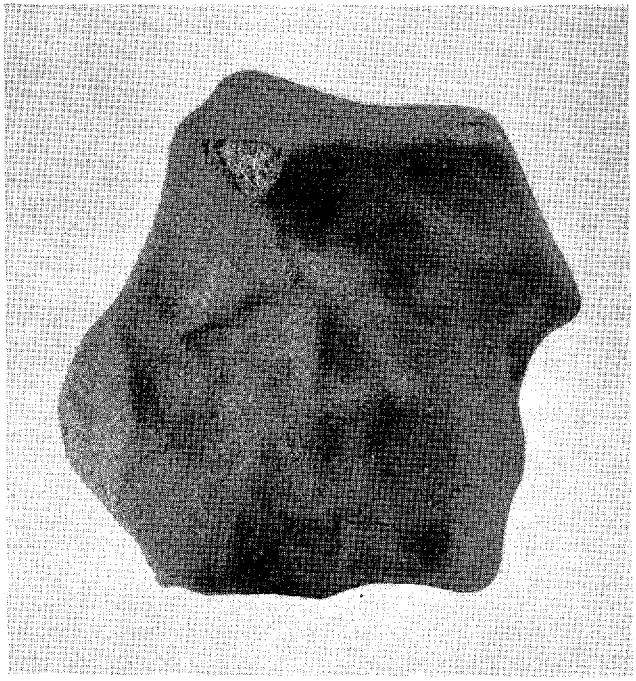

Fig. 3 b. Aarhus Meteorite II. The rear side.

Microscopical Investigations

Components and Structure

The light gray main mass of the meteorite is made up of a fine-grained crystalline aggregate predominantly consisting of *silicate minerals. Ore minerals,* however, occur rather abundantly and often as relatively large grains. Macroscopically a few *chondrules* are seen, or holes where chondrules have fallen out, the diameter of which does not exceed ca. 1 mm.

The stone is traversed by numerous dark or black *veins* (see fig. 1 and 4). They consist essentially of ore grains and small opaque particles, further some brown or black glass is seen. Very often the veins branch into crevices in the stone and enclose parts of the groundmass (fig. 4).

The dark veins are certainly due to a fracturing of the stone, and several microscopic features indicate that the texture of the meteorite before fracturing was considerably coarser than at present.

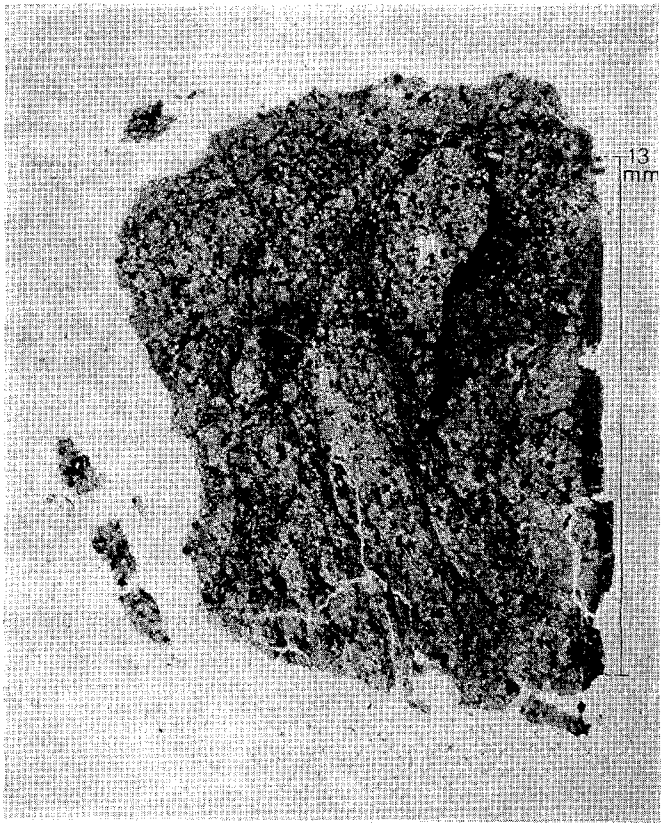

Fig. 4. Aarhus Meteorite I. Thin section in transmitted light showing dark veins.

Apart from the opaque minerals the Aarhus meteorite essentially consists of *pyroxene* and *olivine*, the pyroxenes being *bronzite* and *clinoenstatite*, more rarely *hypersthene*. *Feldspar* (oligoclase), and *maskelynite* occur frequently as quite small grains filling out interstices between the main minerals. In all probability *merrillite* and *oldhamite* are present though not proved with absolute certainty.

The shape of the silicate minerals is irregular and fragmental (see fig. 5). The pyroxenes are split up into fragments along the cleavage planes or into quite irregular splinters. Usually the fragments from one crystal show a more or less different extinction and sometimes they are a little displaced. But not infrequently the original size of a crystal may be judged from the fractures along parallel cleavage cracks, the simultaneous extinction and a

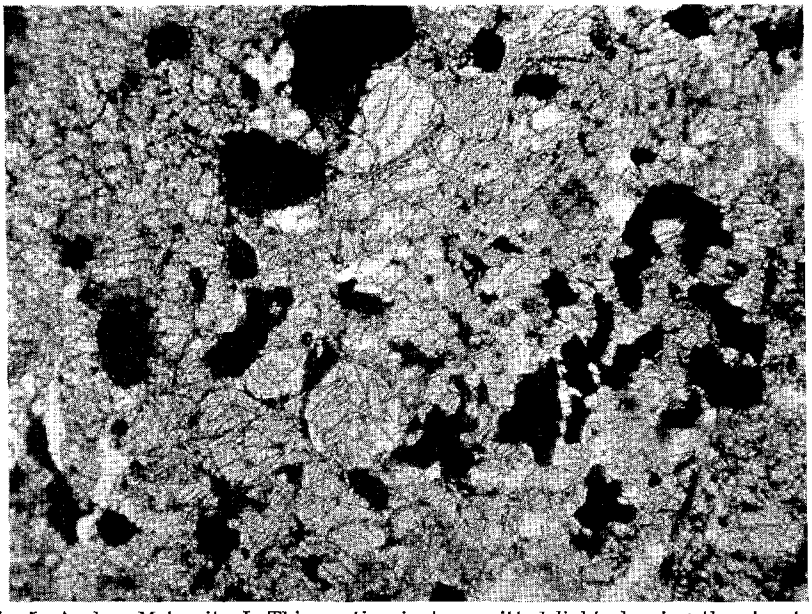

Fig. 5. Aarhus Meteorite I. Thin section in transmitted light showing the structure of the interior; in the lower part three small bronzite chondrules. Enlargement 70×.

crystallographically parallel position of the fragments, f. i. in one case where all the fragments were cut perpendicular to an optic axis. The original dimensions of several such pyroxenes were measured to about 0.3 à 0.4 mm whereas now the grain size of the silicates is generally below 0.1 mm varying down to that of dust.

The olivine is broken into irregular fragments which due to the less perfect cleavage of this mineral are sometimes of larger size than the pyroxenes. In fig. 5, upper part, a conspicuous crystal with characteristic conchoidal olivine cracks is seen; it is 0.22 mm long. On the left side it borders on a nickel-iron grain, on the other side it is surrounded by an extremely fine, crushed aggregate in which two small olivine fragments are observed; they are crystallographically parallel to the main olivine and were evidently separated by fracturing. Some other olivines are still larger, up to 0.52 mm in length.

The material filling in the fractures and cleavage cracks is usually an opaque black mass but not infrequently it also contains a brown or colourless, isotropic *glass* with refractive index a little above that of Canada balsam. Glass furthermore occurs in the silicate minerals as inclusions together with smaller amounts of opaque particles. In some small areas around the

nickel-iron the stone is coloured brown by limonite, seen especially in the cracks.

No fragments of other rock types are seen in the meteorite.

The rock of the Aarhus meteorite is extremely friable and crumbling so that ordinary good thin sections could not be prepared. The slices obtained are uneven and fragmental; it is impossible to estimate the relative amounts of the main minerals by their microscopical features. The probable quantitative mineralogical composition of the stone must therefore be deduced by calculation from the analysis (see p. 13).

For the microscopical determination of the minerals a number of preparations of finely crushed rock were used in addition to the thin sections. In these preparations individual colours, smaller inclusions and cleavage cracks usually appear more clearly than in the thin sections.

The Non-Opaque Minerals

Pyroxenes

Bronzite. In accordance with the immediate impression pyroxene is the prevalent mineral, and among the pyroxenes again bronzite is dominant in the groundmass as well as in the chondrules. Neither pyroxenes nor other minerals occur in good crystal form.

The colour is slightly brownish; thin splinters are colourless. Cleavage cracks and irregular cracks are abundant and because they are usually filled with dark material they may give the impression that the pyroxene is generally rather dark coloured, as seen for example in fig. 5 (the upper left corner). Otherwise ore-inclusions are not very common. In chondrules the pyroxene is lamellar, elongation positive. Parting on (001) is common. The optic axial angle 2V is nearly 90° and the average refractive index n: $1.709 > n > 1.679$.

Hypersthene is found as sporadic fragments or splinters in immersion preparations but its presence is not proved in thin sections. It shows pyroxene cleavage and distinct pleochroism: α' colourless, γ' yellow-brown. The average refractive index n: $1.731 > n > 1.699$.

Diopsidic monoclinic pyroxene. Some few individuals distinctly twinned on (100), are observed; sometimes they show a thin penetrating twin-lamella. Refractive index $1.661 > n$.

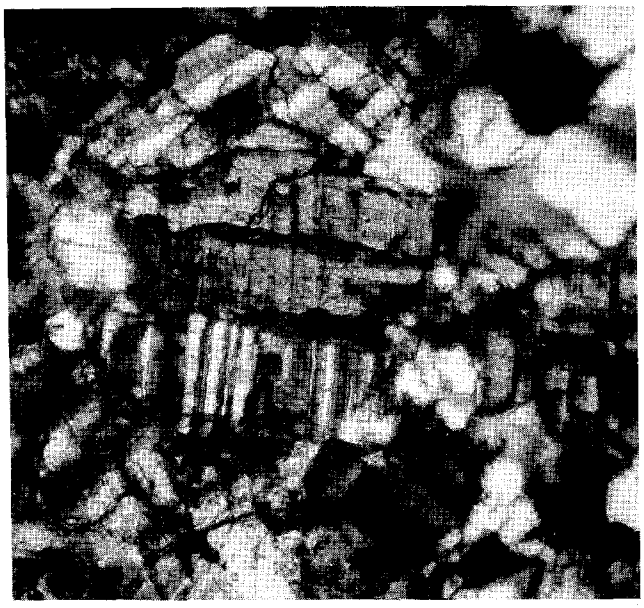

Fig. 6. Aarhus Meteorite I. Clinoenstatite in transmitted light. Nicols +. Enlargement 450×.

Clinoenstatite is found as an ordinary constituent of the groundmass. With a magnification of above 200× it is conspicuous by its polysynthetic twinning with lamellae parallel to (001), elongation negative (fig. 6). Sometimes it is found between the bronzite chondrule lamellae in a crystallographic orientation different to that of the bronzite. Observations in immersion preparations were: $\gamma' > 1.689 > \alpha'$; α' iridescent.

Olivine appears in thin sections as relatively large rounded grains with conchoidal fracture and irregular cracks. It differs from the darker, more strongly cracked pyroxene by being almost clear and colourless. Sections perpendicular to an optic axis are found in immersion preparations; they show two systems of cleavage cracks perpendicular to each other, the most distinct of them is parallel to (010). Other properties include $2V$ = ca. 90°; dispersion slight; β = ca. 1.7, $\gamma' = 1.71$, iridescent; these properties indicate an olivine with about 20 Mol% Fe_2SiO_4.

Feldspar, oligoclase occurs rather commonly but only as quite small colourless grains in the interstices of the other minerals (see fig. 7). Crystal form is not seen. More rarely the oligoclase is found between the bronzite lamellae in the chondrules or inclosed in pyroxene and olivine. Its refractive

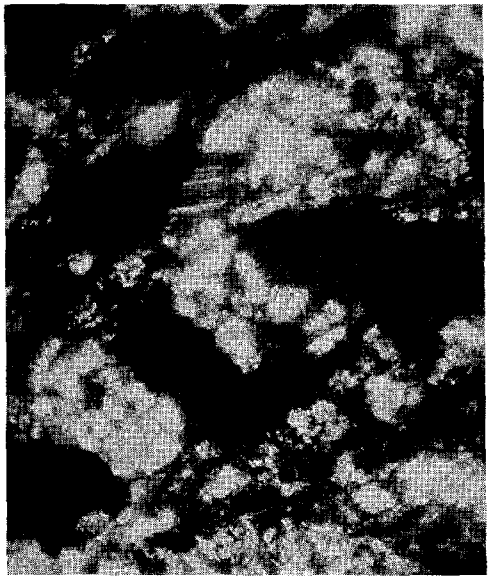

Fig. 7. Aarhus Meteorite I. Plagioclase, oligoclase, in transmitted light. Nicols +. Enlargement 200×.

indices are a little above that of Canada balsam. Twinning on the albite law is common, extinction angles small. Usually the oligoclase contains numerous small black particles besides some other brown and isotropic inclusions with high refractive index.

Several small grains are considered to be *maskelynite*. These occur in interstices and are much like oligoclase with regard to form and refractive indices but they are isotropic or have a very low double refraction and no twin lamellae.

Merrillite is not easily proved but seems to be present. In powder embedded in acethylene tetrabromide with refractive index 1.635 small colourless fragments are seen with a relief so low that some of them were almost invisible, that is: $n \leq 1.635$. The double refraction is very low. Probably these fragments consist of merrillite.

Oldhamite is probably present. In thin sections small brown isotropic inclusions in pyroxene are frequently seen; most of them consist of glass with low refraction index. But some others have a refractive index much above that of pyroxene. In immersion preparations the same brown grains

are conspicuous by their high relief and marked outlines; their refractive index is much above 1.74 (methylene iodide). Cubic cleavage is not seen.

The Mineralogical Composition

as calculated from the analysis (see p. 17)

$KAlSi_3O_8$	1.06 %	
$NaAlSi_3O_8$	4.15 -	.... 6.66 % Feldspar silicates
$CaAl_2Si_2O_8$	1.45 -	
$FeSiO_3$	6.34 -	
$FeTiO_3$	0.30 -	
$MnSiO_3$	0.63 -	.... 40.31 % Pyroxene silicates
$MgSiO_3$	29.52 -	
$CaSiO_3$	2.50 -	
Na_2SiO_3	1.02 -	
Fe_2SiO_4	5.09 -	... 26.47 % Olivine silicates
Mg_2SiO_4	21.38 -	
$3CaO.Na_2O.P_2O_5$	0.41 -	.....Merrillite
$FeCr_2O_4$	0.63 -	..... Chromite
Fe,Ni	19.23 -	..... Metal
FeS	5.64 -	..... Troilite etc.
	99.35 %	

Ilmenite has not been observed in this stone wherefore $FeTiO_3$ has been computed together with the pyroxene components of the analysis.

The glass component has not been accounted for.

The Chondrules

Chondrules are, on the whole, not numerous in the meteorite Aarhus I. They are irregularly distributed in the stone; in one thin section they may appear rather frequently, in another but sparingly.

Most of the chondrules consist mainly of bronzite, some few of olivine. The largest of them scarcely reach 1 mm in diameter. Usually they merge into the granular groundmass; only some quite small chondrules are well rimmed.

Only the following few types were found.

Pyroxene chondrules

The predominating chondrules consist of bronzite lamellae, some of them with a more or less fan-shaped radiating structure. The best developed are rounded and roughly ellipsoidal.

Fig. 8 shows a lamellar bronzite chondrum about 1 mm across. The longer direction of the lamellae is parallel to the crystallographic c-axis; the elongation is positive and 2V ca. 90°. The lamellae are all optically

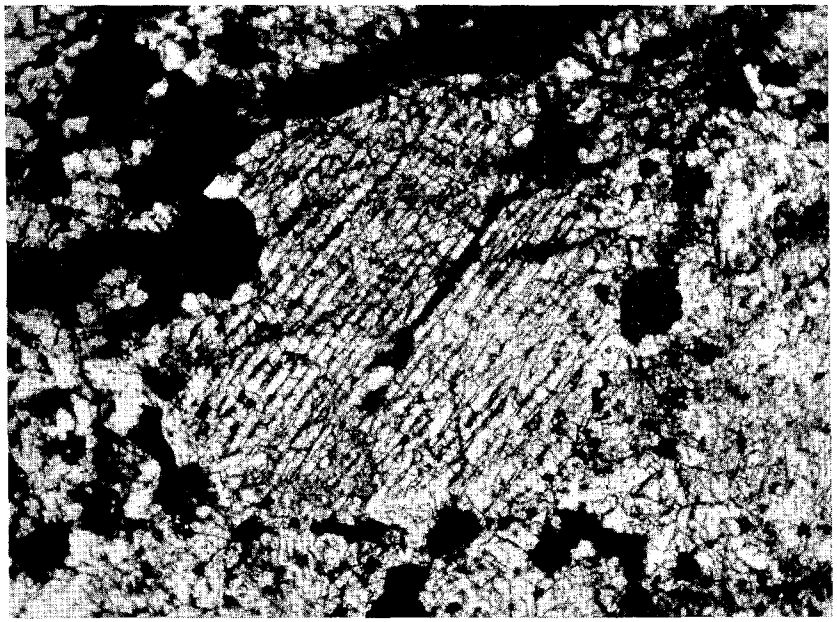

Fig. 8. Aarhus Meteorite I. Bronzite chondrum in transmitted light. Enlargement 85×.

parallel and show simultaneous straight extinction; they all belong to one individual. A parting across the lamellae is clearly seen besides irregular cracks which do not seem to have caused any displacement.

Between the lamellae are interposed quite thin colourless feldspar plates, feebly double refracting, and brown or black glass with refractive index a little above that of Canada balsam, and furthermore dark opaque inclusions of vein substance containing relatively large grains of nickel-iron and rarely yellow iron sulphide.

The upper part of the chondrum is bordered by a thick dark vein containing numerous grains of nickel-iron. From the surrounding vein an offshoot has penetrated into the chondrum along the lamellae. On the other

sides the chondrum is bordered by close-lying grains of nickel-iron. It seems probable that some resorption may have taken place with the vein formation.

In fig. 9 is seen a complex of two bronzite chondrules (1 and 2) together with one olivine chondrum (3); they are situated near the surface

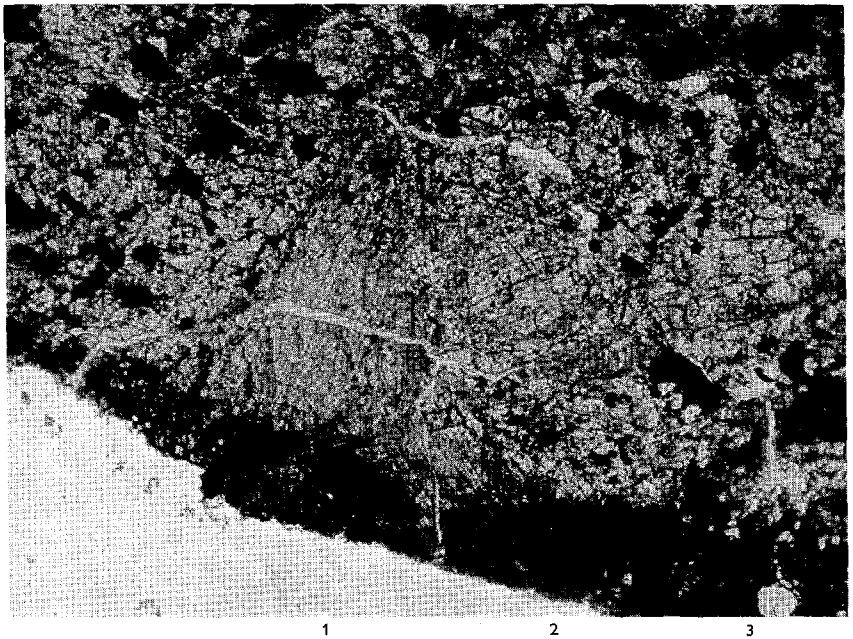

Fig. 9. Aarhus Meteorite I. Two bronzite chondrules (1–2) and one olivine chondrum (3) in transmitted light. Enlargement 30×.

crust. The left chondrum (1) has an elongate form, the other (2) is merely rounded; the borders are but slightly marked.

Mineralogically they resemble the above mentioned chondrum very much and show the same properties. In the greater part of each chondrum the lamellae are in crystallographically parallel position, only in the lower part of the left chondrum the lamellae are slightly radiating and here they penetrate into the surface crust.

In the lower part of fig. 5 are seen three small chondrules, only ca. 0.1–0.2 mm in diameter. They are perfectly spherical or oval and are surrounded by black rims containing small troilite grains. They consist of bronzite crystals with $2V$ = ca. 90°. Each chondrum contains 2–3 bronzite

individuals besides one or two quite small plagioclase grains. In the chondrum to the right a clear white plagioclase is seen at the periphery of the left side. The left chondrum is a double chondrum.

Several small pyroxene chondrules of this type are seen, especially in that part of the meteorite which surrounds the area illustrated in fig. 5.

Olivine chondrules

Only one small olivine chondrum of about the same size as the last mentioned bronzite chondrules is found. It has a slender oval form, 0.5 mm in the longest direction. This chondrum consists of two olivine grains, one of them quite small, and it is bordered by a number of very small olivine grains in parallel crystallographic position to the main individual. On the outside it is fringed with a thin black rim.

The chondrum (3) in fig. 9 is a polysomatic olivine chondrum. Its form is rounded and on the left side marked by an incomplete collar of nickel-iron grains; on the right side the border is faintly indicated by brown pigmented cracks. Between crossed nicols it is seen that the chondrum consists of a number of olivine grains, different in both size and optical orientation. As minor constituents a few ore grains occur besides plagioclase which as usual contains small dark particles. Interstices and cracks are filled with dark brown glass with refractive index a little above that of Canada balsam. Pyroxene is not found. Around the outer bordering grains of nickel-iron the stone is somewhat discoloured by limonite derived from oxydation of the ore.

Chemical Analysis

(by Miss Me Mouritzen)

The Aarhus meteorite was first analysed under the instruction of Dr. H. B. Wiik of the laboratory of the Geological Survey of Finland, Helsingfors (see Wiik (7)). At a later date part of the results were checked by different methods at the Mineralogical Institute, Copenhagen. There was a general agreement of results.

SiO_2, Al_2O_3, TiO_2, CaO, MgO, total iron and water were determined by the methods of the classical analysis. In this way the aluminia content is calculated as a difference, and is therefore apt to be incorrect; a control is made using the titration method for aluminia determination by H. L. Watts (Anal. Chem. vol. 30, p. 967, May 1958); an automatic titrator TTTl from

Fe	17.30 %
Ni	1.93 -
FeS	5.64 -
SiO_2	37.49 -
TiO_2	0.16 -
Al_2O_3	1.53 -
FeO	7.39 -
MnO	0.34 -
MgO	24.03 -
CaO	1.69 -
Na_2O	1.08 -
K_2O	0.18 -
P_2O_5	0.15 -
H_2O^+	0.11 -
H_2O^-	0.05 -
Cr_2O_3	0.43 -
	99.50 %

"Radiometer" was used for the titration. Further it was tried to isolate aluminia from the sesquioxides by use of the solubility of aluminium hydroxide in excess of sodium hydroxide. By these different methods of aluminia determination corresponding results were found.

Phosphorus and manganese were determined by decomposition with $HF + HNO_3$. The phosporus was weighed as ammonium phosphomolybdate and the manganese was colorimetrically determined.

Sodium and potassium were obtained using both the Lawrence Smith's and the flame photometer method (A Beckman DU flame photometer was used). The latter method gave slightly lower results than the Lawrence Smith's method.

Metallic iron was determined by treating a specimen with $HgCl_2$ and NH_4Cl in a water solution and a CO_2-environment, subsequently titrating with potassium permanganate. A part of the same solution was used for a control of the nickel determination; citric acid was added to prevent the precipitation of iron hydroxide, when ammonia is added before the precipitation of nickel with dimethylglyoxime. A check on nickel was moreover made on the main analysis as well as on a fusion of sodium carbonate and potassium nitrate. From this fusion chromium was determined colorimetrically, and sulphur was precipitated as barium sulfate.

A treatment with dilute acetic acid gave no calcium content to establish an amount of CaS (WAHL 1950); therefore all of the sulphur is calculated as belonging to iron in FeS. The value for ferrous iron is not determined directly, but is calculated as a difference between total iron minus that found in FeS and metallic iron.

Ore Microscope Examination

The ore microscope examination of the Aarhus stony meteorite was carried out on several small pieces – 5 mm in diameter or less. These pieces were obtained when the material for the chemical analysis was being prepared. Among the pieces are samples from the interior as well as from the outer part of the stone, a few of them showing the molten crust of the meteorite.

Interior

Silicates

Fig. 1* gives a characteristic picture of the mineralogical components of the meteorite as seen in the ore microscope. The non-opaque silicates show distinctive reflection properties due to which the distribution of the two main groups of silicate minerals can be studied.

A rough estimate of 1:9 as the proportion of silicates with low refractive index (about 1.5) to silicates with high refractive index (about 1.7). Non-opaque phases other than these have not been observed.

Oxides

Of the usually observed oxides chromite has been found throughout the meteorite, magnetite occurs only in the outermost, molten crust.

Chromite mostly appears as rounded grains somewhat smaller that the sulphidic and metallic grains (see fig. 1). Very characteristic of these grains are the numerous cracks; the grains seem to have been shattered through some mechanical action. The mineral is always found in the silicate with low RI and the same silicate fills the cracks.

Sulphides: Troilite and Pentlandite

The chemical analysis indicates the presence of 5.64 % of FeS. The amounts of metallic iron and nickel have been found to make up 19.23 %. Recalculated to volume percentages this means about 5 % of sulphide and

* For the following figures see PLATES I-IV.

10 % of metal, and this seems to be in accordance with the observed proportions.

The grain size of the sulphides is about .2 mm. A few grains over one mm in diameter have been seen. Sulphide grains less than 10 μ seem to be rare.

Troilite grains mostly occur as individual optic units. Now and then adjoining grains can be seen with the same optical orientation indicating that they belong to the same individual. Such an assumption may be supported by the lobate form of the troilite.

Now and then troilite grains can be built up of two or more individuals. In these the single individuals have irregular polygonal outlines. Single grains of troilite composed of numerous individuals seem to be very rare in this stone. Another phenomenon, however, is rather frequently met with. One-individual-grains often show wavy extinction between crossed nicols. This is illustrated on fig. 2 a and b. Even though this is from the Holbrook stone it very accurately shows what can be observed in Aarhus I too. Such an extinction indicates that the mineral has been subject to dynamic forces giving rise to some recrystallisation through which lamellae were formed. On closer inspection these lamellae are seen to be subdivided into even smaller areas perpendicular to their length. There is a possibility that grains showing wavy extinction to a varying degree occur regularly distributed in the meteorite. Thus an examination of the situation of such grains within the meteorite could give information as to how and when the dynamic forces created this pattern. Due to lac of material it was not possible to investigate this question in the study of the Aarhus I stone.

Dr. V. BUCHWALD of the Technical University of Denmark has kindly determined the Vicker hardness of the troilite and found 310 ± 25, in fairly good agreement with the hardness of pyrrhotite.

A yellow-cream coloured sulphide has been observed enclosed in the troilite, in most cases only as areas less than 10–20 μ across. The reflectivity of this mineral is slightly higher than that of troilite, the hardness is near to or a little higher than that of troilite and the mineral appears isotropic between crossed nicols. Fig. 3 gives an impression of the mineral.

Based on the properties mentioned it has been possible to recognize this mineral in two other stony meteorites (MERN and HOLBROOK) and likewise in two irons, those from Savik and Thule. Concerning the latter see V. BUCHWALD (2).

Analysis carried out by means of the Castaing electron-probe microanalyzer on the yellowcream mineral in samples from Aarhus I and the Holbrook

stone gave the following results. In the same runs it was possible to analyze troilite in both mentioned stones and a valleriite-like mineral found in Holbrook. Native copper and taenite in Aarhus I was also examined in this way:

	Cu %	Fe %	Ni %	S* %
Aarhus I				
Troilite	0.1	62	–	–
Pentlandite	0.2	43	21	34
Taenite	0.4	41	58	–
Copper	80.–	–	–	–
Holbrook				
Troilite	–	62	–	38
Pentlandite	–	43	21	34
Valleriite-like sulphide	–	59	1–3	38

The analyses were carried out by civil engineer N. LANGE at Metallografiska Institutet in Stockholm.

The analyzed sulphide phases are shown in fig. 2a and 3. In order to establish a basis for comparison the surrounding troilite was also analyzed.

As is seen from fig. 3, a small metallic grain occurs inside the pentlandite. It was assumed to be taenite and the analysis came out in agreement with the assumption. The high Ni should be noted.

The troilite in fig. 2 – of the Holbrook stone – was found to contain not only pentlandite but also in a tiny area in the one corner a vividly anisotropic sulphide resembling valleriite. With one nicol the mineral shows strong bireflection–in one position it has a colour near that of troilite and in another it is much like sphalerite. The analysis shows it has a composition very near to troilite. Whether the small nickel content has some influence on the structure of the phase or not is not clear but so far it seems reasonable to regard this mineral a variety of FeS and perhaps identical with some earlier described minerals, see f. i. KOUVO and VUORELAINEN (4).

The copper grains shown in fig. 12 were tested for Cu. Unfortunately it was not possible to undertake analyses for Au, Ag etc., due to lack of material.

* Due to lack of a good FeS-standard the S-determinations are not completely reliable.

Shape and relation of troilite to the other minerals

The outlines of troilite grains are dominated by concave forms as is evident from fig. 1. Even grains which at the first glance seem to show rounded forms can be seen by closer study to have their boundaries built up of concave lines where they border silicates. Troilite grains may show pointing branches but such branches never seem to attain noticeable lengths. As a matter of fact the troilite seems to have its forms determined by its surroundings – the silicates – but, contrary to terrestrial occurrences where its intergranular position often gives rise to pronounced amoeboid forms, elongate branches seem rare.

Chromite has been seen in a few cases with idiomorphic borderlines against troilite.

Sulphide and nickel-iron show "mutual boundaries" relations, the borderlines are convex-concave. In a few cases advanced islands of troilite can be observed in the nickeliron. Whether these represent corrosion remnants, replacements or merely parts of the sulphide left over in the solidification can hardly be decided.

Cracks in the troilite, as for instance shown in fig. 2a and fig. 4, are rather often met with. In all cases they seem to contain the same substance, namely the silicate with low refractive index (about 1.5), feldspar or the glass component. The crack pictured in fig. 4 illustrates this and in addition it shows a displacement of the troilite without any corrosion. Even though this picture illustrates Holbrook material this observation is also valid for the Aarhus I stone.

Metal phases: Taenite, Kamacite and Copper

The analysis indicates the presence of 17.30 % Fe, 1.93 % Ni and to these can certainly be added small amounts of Cu, Co etc.

As is already known from some newer papers (3,6) on stony meteorites both taenite and kamacite occur in these. Both minerals may constitute single grains and they can be found together in a variety of intergrowth structures. Examples of this for the Aarhus I meteorite are given in fig. 5–11.

Kamacite in stony meteorites sometimes exhibits nicely developed Neumann bands. The examination of Aarhus I has, however, not revealed the existence of these bands, but a polygonal structure of the kamacite has been observed in several grains, see fig. 8 and 11.

In Aarhus I as well as in the earlier mentioned stones from Mern, Holbrook and Alfianello, metallic copper has been found as tiny particles mostly included in the nickel-iron, see fig. 12. Rather often copper occurs

on the borderline between troilite and nickel-iron and in a few cases the author has found copper grains in troilite. Due to the small dimensions of the copper grains – only a few μ in diameter – the mineral can be regarded as a sparse constituent of the meteorites but in spite of this remarkably many copper grains can be found in the samples. So in this sense it does not seem to be rare. This also appears from YUDINS observations, YUDIN (8).

Transition Zone

Fig. 13 shows a typical view of that part of the meteorite which constitutes the zone between the outer molten crust and the interior. The appearance is quite the same in the other meteorites mentioned which the author has had an opportunity to examine, and it corresponds closely to figures published by other authors (see HENTSCHEL (3)).

The width of the zone averages a few tenths of a mm and it is rarely more than .5 mm. It is characterized by the presence of numerous veins often, but not invariably, starting from larger grains of metal or sulphide. Both in their way of occurrence and in their constituents the veins clearly demonstrate the melting processes which led to their formation.

Fig. 14 illustrates the compound nature of this material which is an emulsion of metal – nickel-iron – in sulphide. Fig. 15 shows that the same structure is found in the thin veins. The metal always occurs with convex borders against the sulphide. In larger grains where both sulphide and metal are present the border between the two components appears as a serrate line and as a rule the sulphide area is seen to hold small droplets of metal. Sometimes a thin lining of sulphide can be observed along metal grains in this zone.

Veins with this emulsion structure can be seen veining both silicates and chromite grains.

In consequence of the clearly demonstrated melting processes one could expect the occurrence of sulphides other than FeS, such as compounds containing Ni. If copper happened to be present also sulphides of this element could have been formed. With these ideas in mind it was rather interesting to find at least two kinds of sulphides in the Aarhus meteorite different from troilite and pentlandite (and the mentioned valleriite resembling sulphide). Fig. 16 is a picture of a composite sulphide grain where the main part – a little darker than the rest – seems to be troilite and the rest is a lighter pentlandite resembling sulphide. Its optical properties seems to differ from those of pentlandite. Also another sulphide of a rather intense yellow cream colour much like chalcopyrite, but not as yellow as this mi-

neral(?), was found in the transition zone. Both of these unidentified minerals were so small that nothing else could be done in order to identify them.

Molten Crust

The outermost zone of the stony meteorite is .1 to hardly .2 mm in width. It is characterized by its content of numerous tiny crystallites of magnetite. When in a few cases it is possible to observe the magnetite in areas the mineral is seen to be built up of two zones of different shades of grey as seen in the ore microscope.

Black Veins of the Interior

These veins, so conspicuous in thin sections and characteristic of the macro appearance of the Aarhus I stone, are easily overlooked in the ore microscope. But when the polished samples are viewed between crossed nicols, all the non-opaque minerals are brightly lit up through internal reflexes. This view is more or less comparable to the ordinary appearance of a thin section and in this way the black veins can easily be observed. In ordinary light in the ore microscope these veins are seen to carry rows of elongated grains mostly of troilite; a few nickel-iron grains are present.

The most conspicuous thing about this feature of the stone is seen where the veins border on troilite of normal grain size. The outline of the troilite grain gives the impression that the grain was cut along a line at the side where it borders the vein, and often a tail of troilite is seen stretching in the direction of the vein. This no doubt indicates mechanical action, i. e. brecciation. The tail extending from after a troilite grain in such a position may attain a length of some hundredths of a mm, but this does not indicate more than the minimum distance of movement. Whether the total movement has been a few or many times this distance can hardly be said.

The general appearance of these veins in the ore microscope gives an impression of the veins being composed of many small more or less continuous parallel pieces. Thus, in a sense, each vein is a narrow zone (often only a few hundreths of a mm thick) of veinlets. They are marked by the presence of sulphides, and only small amounts of "glass" are seen. In places where veins branche larger amounts of "glass" can be seen and sulphides often form a pigmentation here.

The author's examination of Alfianello, however, provided an opportunity to see corresponding veins in another development.

From the ore microscopic examination of the veins seen in material from Alfianello it was found that the sulphides in the veins contained many

tiny drops of metal, and grains of clear emulsion structure were also found. This seems to indicate that the material has been subject to high temperatures causing the formation of sulphide-metal emulsion. The emulsion-veins characteristic of the transition zone do not occur here and no magnetite was seen. It is therefore possible that the material filling the fracture has been placed there before the stone entered the atmosphere, and this seems to be supported by the observation of such veins with no visible connection to the surface of the stone.

In the case of the veins in the Aarhus I stone no indications of temperature could be found. The author would, however, be inclined to ascribe to these veins the same extraterrestrial mode of formation as that of the veins observed in Alfianello, only the temperature of the environment at the time of brecciation has been different in the two cases.

Atmospheric Heating's Penetration into the Stone

It is interesting to note the different zones into which the meteorite can be subdivided. The outermost zone, the molten crust, corresponds to temperatures exceeding 1500°C, because silicates and all other components of the stone here underwent melting and for a large part were blown off the surface of the stone, only leaving the thin crust which we now find sprinkled with magnetite crystallites.

In the transition zone the emulsion structure formed by sulphidic and metallic material must indicate temperatures from 1100°C to, say, 900°C in the inner part of the zone. This indicate a fall in temperature from 1500°C to 900°C within only about .5 mm. In other words a gradient of about 120°C per .1 mm. If this gradient persisted, the temperature only a few mm inside the meteor would have been very low.

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PLATES

PLATE I

Fig. 1. Pol. prep. 200×, Aarhus.
General view illustrating the different components: chromite (grey), troilite (light grey), nickel-iron (white), and silicates, one darker grey (RI ca. 1.5) than the other (RI ca. 1.7). Part of the largest troilite grain is reproduced in fig. 3.

1

PLATE II

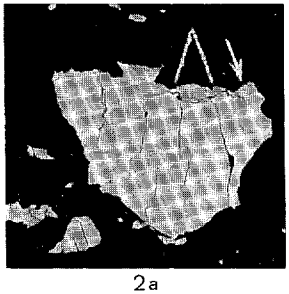
Fig. 2 a & b. Pol. prep. 100×, Holbrook.

a. With one nicol, showing troilite transected by fine cracks. The marginal area between the tips of the inverted V is pentlandite. The area at arrow consists of the valleriite resembling mineral.

b. The same, but with nearly crossed nicols, showing the troilite grain built up by wedgeshaped lamellae, giving rise to wavy extinction between crossed nicols.

Fig. 3. Pol. prep. 750×, Aarhus.
Inclusion of pentlandite in troilite. Taenite inside pentlandite appears white.

Fig. 4. Pol. prep. 333×, Holbrook.
Troilite with a crack cemented by "glass" or at least silicate with RI about 1.5. The rounded silicate has a RI about 1.7.



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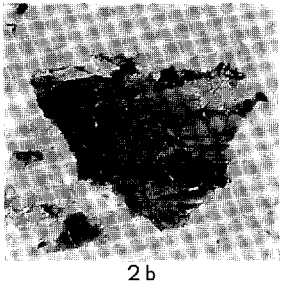

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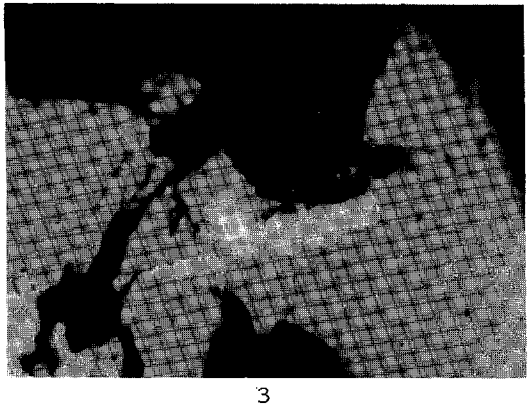

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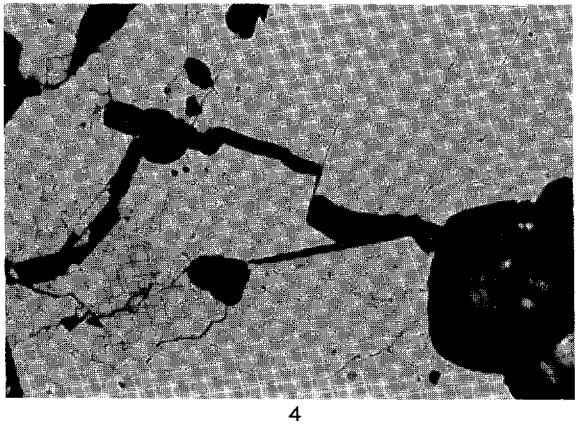

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Plate III

Fig. 5. Pol. prep. 700×, etched, Aarhus.
Taenite with a non-etching borderzone and a weakly etching central zone. Part of a troilite grain is also seen.

Fig. 6. Pol. prep. 600×, etched, Aarhus.
Taenite with non-etching border and central zone; grey and blue (against central zone) etching intermediate zone.

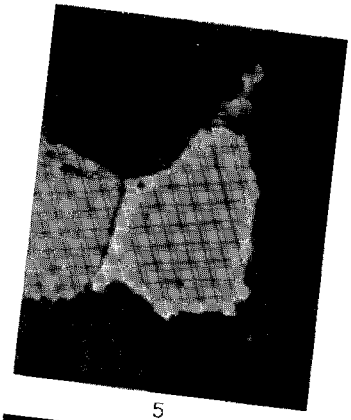
Fig. 7. Pol. prep. 750×, etched, Aarhus.
Kamacite with taenite border and oriented bodies of taenite.

Fig. 8. Pol. prep. 400×, etched, Aarhus.
Kamacite with lamella-structure and faint polygonal division. Besides six taenite grains along the border small elongated taenite grains occur oriented in the kamacite.

Fig. 9. Pol. prep. 600×, etched, Aarhus.
Kamacite with oriented taenite grains. Two larger taenite grains are also present.

Fig. 10. Pol. prep. 700×, etched, Aarhus.
Kamacite with inclusions of irregular rounded taenite grains.

Fig. 11. Pol. prep. 500×, etched, Aarhus.
Kamacite showing polygonal structure. Troilite bottom left.



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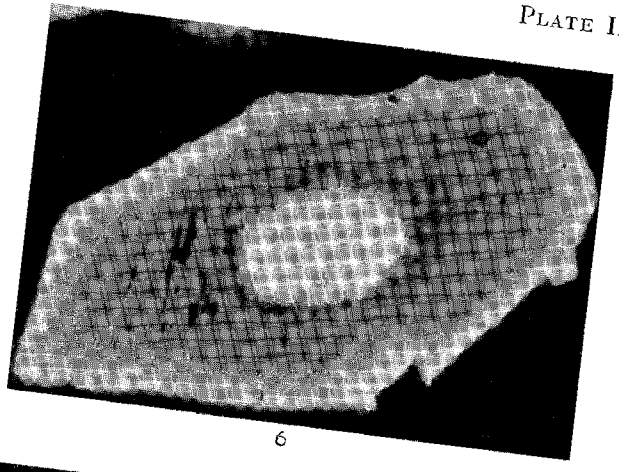

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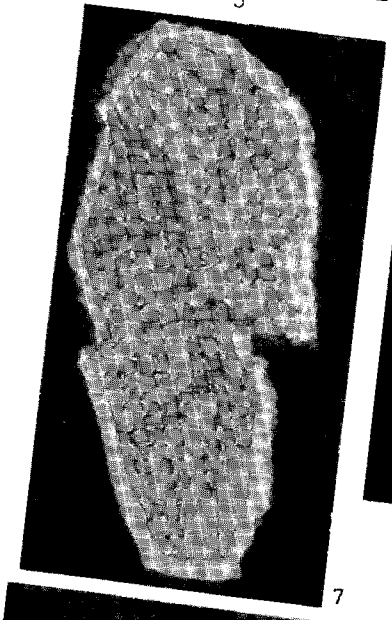

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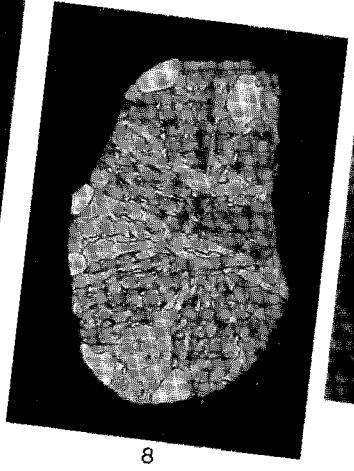

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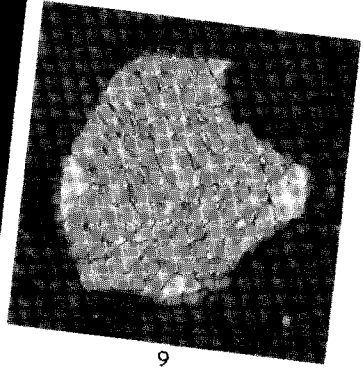

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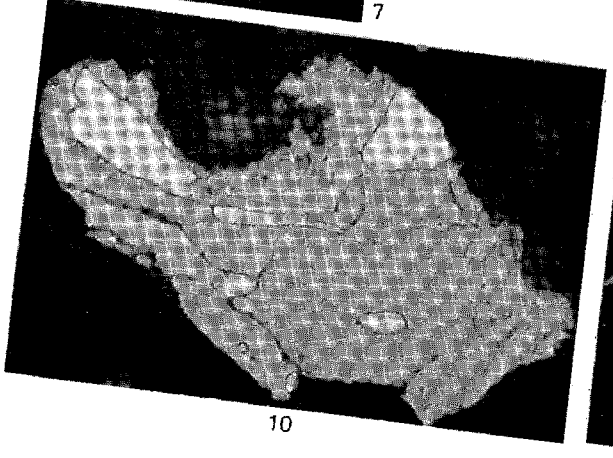

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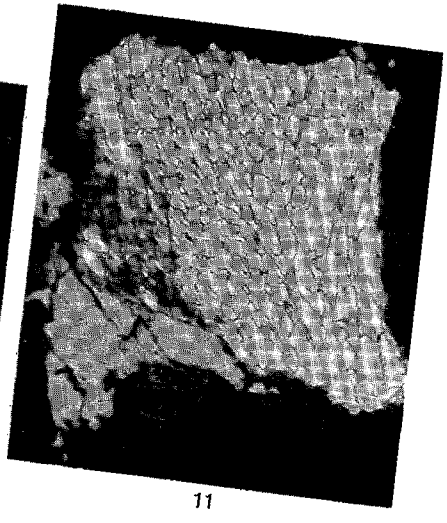

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Plate IV

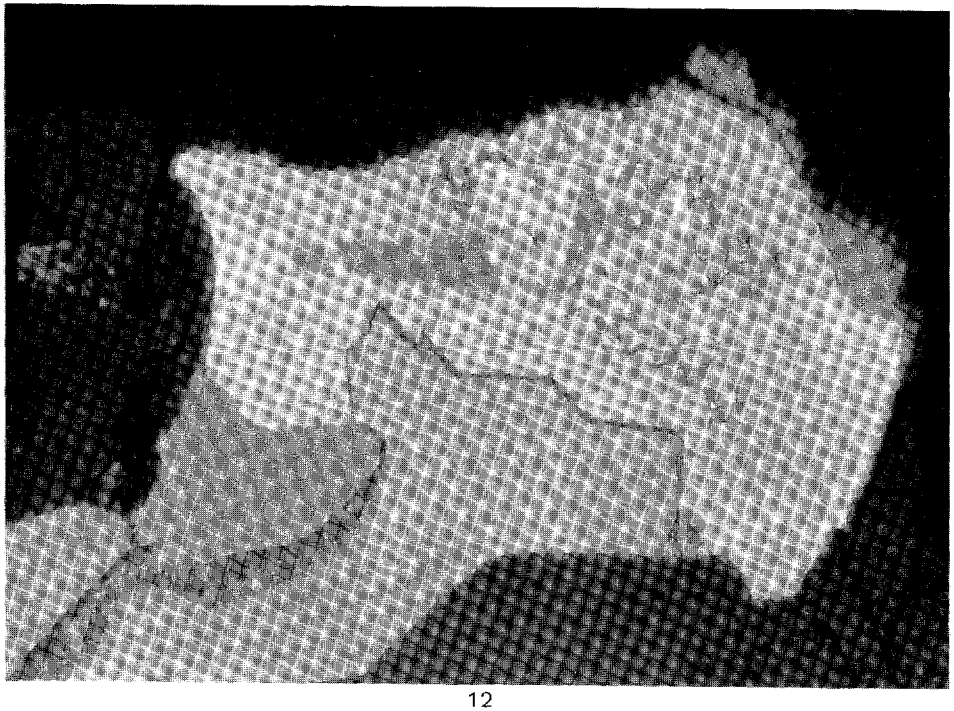
Fig. 12. Pol. prep. 650×, etched, Aarhus.
Taenite (nearly white) with inclusions. Kamacite (light grey) and troilite (grey). In the taenite irregular inclusions of troilite and tiny kamacite grains together with two grains of metallic copper (white, but this is caused by retouching).

Fig. 13. Pol. prep. 175×, Mern.
General view illustrating the zone between the interior of the meteorite and its molten crust. White grains and veins are metals and sulphides. Black are holes.

Fig. 14. Pol. prep. 800×, Aarhus.
Metal-sulphide emulsion. Grain from the transition zone.

Fig. 15. Pol. prep. 800×, Mern.
Metal-sulphide emulsion. The picture illustrates that this structure also exists in the narrow veins.

Fig. 16. Pol. prep. 750×, Aarhus.
Sulphide grain mainly consisting of troilite containing a lighter pentlandite coloured sulphide having serrate borderline against the troilite. Two tiny metal grains occur in the surrounding silicates, grey is cromite.



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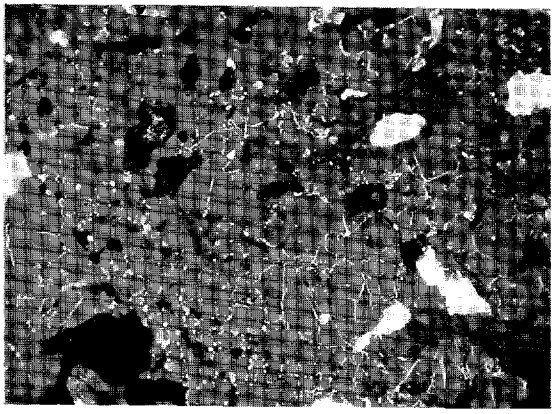

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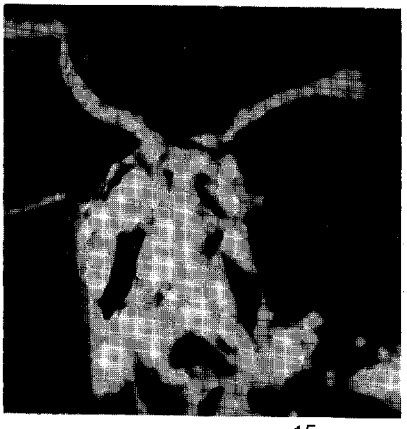

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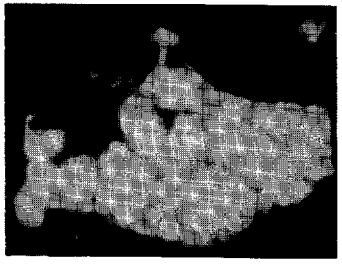

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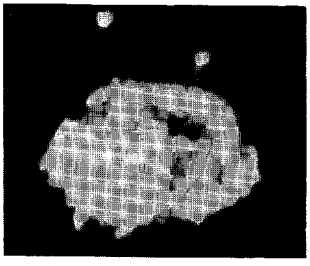

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