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The Composition of the Ottawa, Chateau-Renard, Mocs, and New Concord Meteorites

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THE OTTAWA, KANSAS, METEORITE

This meteorite fell near Ottawa, Kansas, on the evening of April 9, 1896. The only accounts of this fall we have been able to trace appeared in the Ottawa Weekly Times of April 16, 1896, and in the Ottawa Weekly Herald of the same date. The latter reads as follows:

"A meteorite, weighing 31 ounces, was on exhibition at C. L. Becker and Co.'s drug store last week which fell the evening of April 9 on the farm of J. T. Black, nine miles northwest of town. The surface of the meteorite was blackened as though it had been subjected to great heat. It is globular in form, with an uneven surface."

The account from the Ottawa Weekly Times reads as follows: "Last Thursday afternoon while Joe Black, of this city, was out to his farm northeast of Peoria, and was at work in his orchard trimming trees, between five and six o'clock, there was a terrific explosion in mid air just above him, followed by a number of explosions in quick succession resembling the fireing of musketry. The sky was clear; not a cloud was visible; the heavens appeared to be filled with explosives, and whizzing missiles, resembling bullets and cannon balls; the noise was heard in Ottawa, and reports say, at a distance of 30 to 40 miles.

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People in Ottawa who heard it remarked that it must be an earthquake. Mr. Black, who was awe-stricken and appalled by the sudden and unexpected visitation involuntarily took hold of a tree near by, and hugging it tightly cast his eyes upward hearing a terrific, whizzing noise, and in an instant a dull thud upon the ground; he saw nothing; but was satisfied that something had fallen to the ground near him, and, the noise having subsided, he began to search for it, but finally

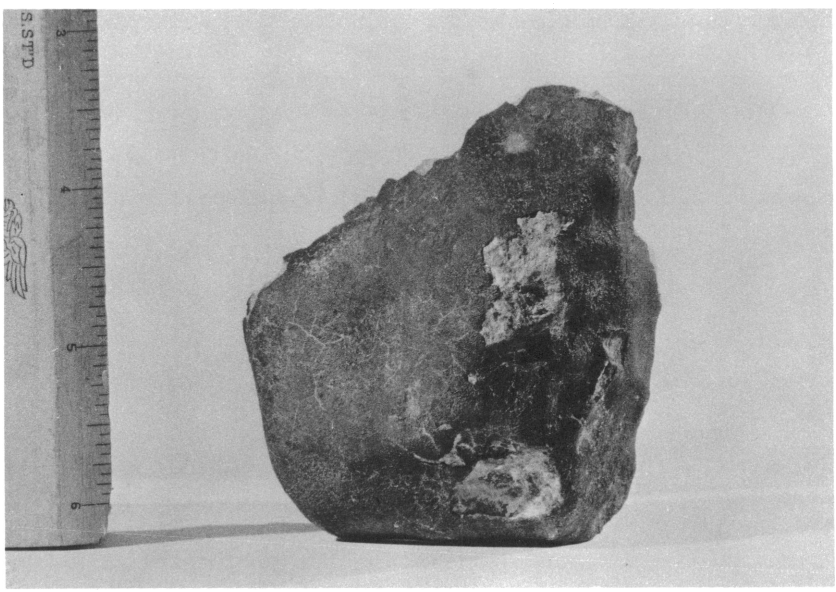

FIG. 1. The Ottawa, Kansas, meteorite. It is covered on the photographed side with black fusion crust, broken in a couple of places, showing the light gray interior.

gave it up, saying to his sister if she would find it he would give her a dollar. She found it in a short time the next morning about 200 yards from where Mr. Black stood, embedded in the earth about ten inches. Mr. Black brought it to town and has it now on exhibition at his shop corner Fifth and Railroad. The phenomena lasted for several minutes, and is undoubtedly another to be added to a long list recorded in history, the last we believe being in Iowa in 1875."

The stone passed into the possession of Mr. C. S. Bement, whose collection was purchased and presented to the American Museum of Natural History by the late J. Pierpont Morgan in 1900. This museum thereby acquired a piece of Ottawa weighing 360 grams (fig. 1), which from its form evidently represents about half the original stone, and some 33 grams of fragments. The Prior catalogue (1953) records that the stone originally weighed 840 grams, approximately equivalent to the weight of 31 ounces mentioned above. A total of 368 grams of this stone are recorded in the published accounts of the British Museum (Natural History), the Chicago Natural History Museum, the National Museum of Budapest, and the Naturhistorisches Museum in Vienna.

Mineralogical Composition

The minerals identified in the meteorite are olivine, hypersthene, plagioclase, troilite, nickel-iron, and chromite; a phosphate mineral (apatite or merrillite) is probably present in accessory amounts. Notes on the minerals follow:

Olivine: The refractive indices are: $\alpha = 1.686$, $\gamma = 1.724$, indicating a content of 27 mol per cent of the Fe_2SiO_4 component, according to the determinative curve of Poldervaart (1950). With the use of the X-ray method of Yoder and Sahama (1957), the composition was found to be 28 mol per cent of the Fe_2SiO_4 component. The olivine peaks on the diffractometer chart are sharp and well defined, indicating olivine of uniform composition.

Orthopyroxene: The refractive indices are: $\alpha = 1.679$, $\gamma = 1.691$, indicating a content of 24 mol per cent of the $FeSiO_3$ component, according to the curve of Kuno (1954). In terms of the conventional subdivision of the orthopyroxene series, this falls in the composition range of hypersthene.

Plagioclase: The refractive indices are: $\alpha' = 1.533$, $\gamma' = 1.541$, indicating a composition of An_{10}.

Nickel-Iron: The nickel-iron phase is present in small amount; the chemical analysis shows 3.92 per cent, and a micrometric measurement on a polished surface gave 4.1 per cent by weight. Both kamacite and taenite are present, sometimes as separate grains, sometimes as contiguous grains in a single piece of metal.

A thin section of the meteorite shows numerous chondrules of granular olivine, usually 0.5–1 mm. but occasionally up to 5 mm. in diameter, and rarer chondrules of fine-grained, somewhat fibrous hypersthene, in a groundmass of olivine, hypersthene, and opaque material. Around the opaque grains the silicates show a small amount of brown limonitic staining. A polished surface (fig. 2) illustrates the distribution of the grains of nickel-iron and troilite throughout the groundmass. A micrometric analysis of the polished surface gave the following weight percentages: silicate, 89.2; troilite, 6.2; nickel-iron, 4.1; chromite, 0.5; these figures are in good agreement with those calculated from the chemical analysis.

The density of a piece of this meteorite was determined by measuring the apparent loss of weight on suspension in carbon tetrachloride

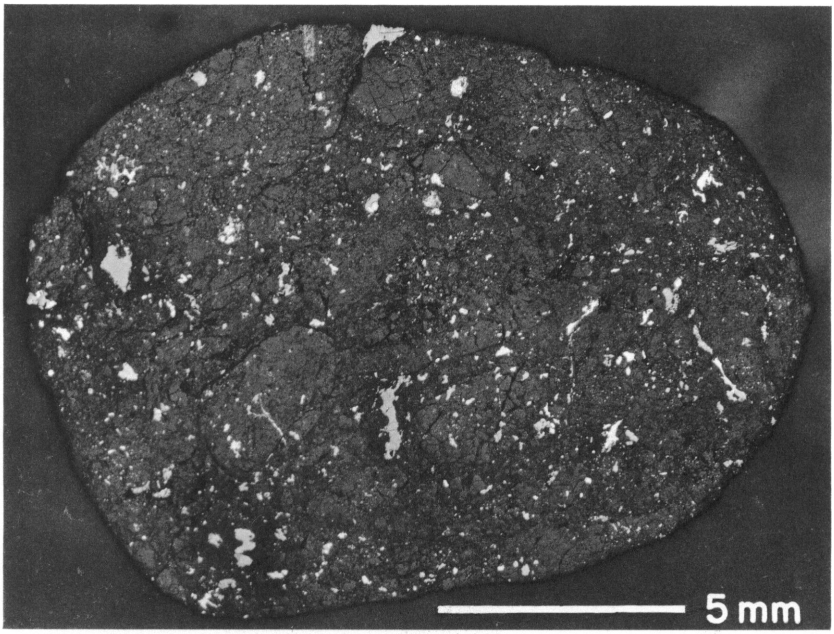

FIG. 2. Photomicrograph of polished surface of the Ottawa meteorite; white spots are nickel-iron and troilite, in dark gray ground mass of silicates.

(after evacuation by an oil pump under a bell jar to remove air from the pores) and was found to be 3.54.

CHEMICAL COMPOSITION

The chemical analysis is given in table 1, in the conventional form expressed as oxides, troilite, and metal; in terms of the individual elements as determined by analysis, with oxygen to bring the total to 100; and recalculated as atom percentages with the elimination of H, O, and S. The conventional form of presenting meteorites involves certain assumptions, for example, that all S is present as FeS, that Fe in excess of free metal and FeS is present as FeO, and that the H_2O given by the analysis is present in the meteorite as free or combined H_2O. In the

TABLE 1

CHEMICAL ANALYSIS OF THE OTTAWA METEORITE

A		B		C	
Fe	2.82	H	0.07	Na	1.44
Ni	1.04	Na	0.59	Mg	35.02
Co	0.058	Mg	15.48	Al	2.39
Cu	0.0119	Al	1.17	Si	36.37
FeS	6.31	Si	18.557	P	0.18
SiO_2	39.72	P	0.104	K	0.17
TiO_2	0.168	S	2.30	Ca	1.65
Al_2O_3	2.21	K	0.121	Ti	0.12
FeO	18.54	Ca	1.200	V	0.01
MnO	0.364	Ti	0.101	Cr	0.41
MgO	25.66	V	0.012	Mn	0.28
CaO	1.68	Cr	0.383	Fe	20.93
Na_2O	0.80	Mn	0.282	Co	0.05
K_2O	0.146	Fe	21.24	Ni	0.97
P_2O_5	0.24	Co	0.058	Cu	0.01
H_2O	0.66	Ni	1.04		100.00
Cr_2O_3	0.56	Cu	0.0119		
V_2O_5	0.023	(O	37.28)		
	101.01		100.00		

A Chemical analysis expressed as nickel-iron, troilite, and oxides.
B Chemical analysis expressed as elements, with oxygen added to make 100 per cent.
C Chemical analysis expressed as atom percentages with the elimination of H, O, and S.

Ottawa meteorite the first two assumptions are probably valid; the third will not be if small amounts of hydrocarbons are present to provide the hydrogen for the H_2O, which may well be the reason for the high summation (101.01) of the analysis when expressed in this way.

The second procedure of expressing the analysis reflects more closely the results actually obtained by the analysis. In effect, the chemical analysis determines the amounts of the different elements, except the amount of oxygen, no readily applicable method for this element being available. The results obtained are then recast in the conventional form with the assumptions outlined above.

The expression of the analysis as atom percentages after eliminating H, O, S (and C if determined) was used by one of us (Wiik, 1956) for comparing analyses of different types of chondrites. Such a procedure in effect distinguishes non-volatile elements from those likely to be lost or gained during heating in extra-terrestrial environments. The figures

TABLE 2

NORMATIVE MINERAL COMPOSITION OF THE OTTAWA METEORITE

Olivine	55.96%
Hypersthene	18.57%
Diopside	3.85%
Albite	6.76%
Anorthite	1.97%
Orthoclase	0.89%
Apatite	0.57%
Chromite	0.83%
Ilmenite	0.32%
Troilite	6.31%
Nickel-iron	3.92%

for the Ottawa meteorite show that its composition is closely similar to Wiik's group of chondrites with 7–8 per cent metallic iron—Monte das Fortes, Linum, Varpaisjarvi, McKinney, and Mern. Ottawa differs from these in having a lower content of metallic iron and a higher content of combined iron in the silicate minerals. Along with these meteorites, Ottawa belongs to the L group of Urey and Craig (1953).

The normative mineral composition, expressed as weight percentages, is given in table 2. The normative mineral composition corresponds well with the observed mineral composition. The proportion of olivine to pyroxene agrees with estimates from thin sections and X-ray powder photographs. No diopside was seen, but the small amount of this component is probably in solid solution in the hypersthene. The ratio of FeO to MgO in the olivine and hyperthene, as estimated from the refractive indices of these minerals, is in good agreement with the ratio of FeO to MgO shown by the analysis. Normative feldspar is 9.62 per cent, probably somewhat higher than the actual amount of plagioclase, as some of the Al_2O_3 calculated as feldspar will be in the pyroxene. Although neither apatite nor merrillite was observed in thin section, the 0.57 per cent apatite in the norm could well be present. It would be extremely difficult to recognize in a thin section, as it probably occurs in small grains intimately mixed with pyroxene and olivine.

THE CHATEAU-RENARD METEORITE

The Chateau-Renard (also known as Triguères) meteorite fell near the village of the same name, some 70 miles south of Paris, at 1.30 P.M. on June 12, 1841. Two pieces fell close together and broke into fragments on impact with the ground. The largest fragment weighed 15

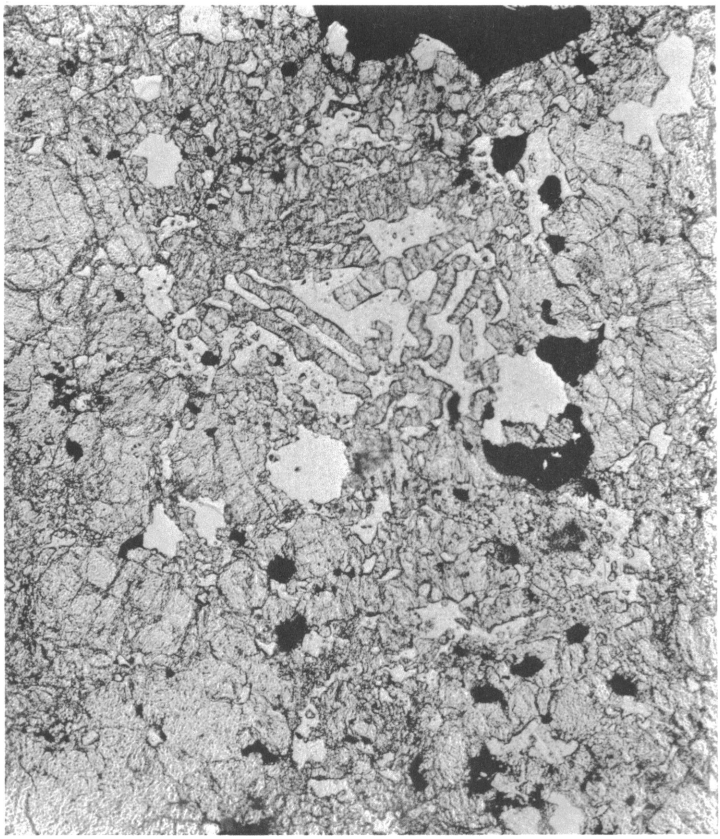

FIG. 3. Photomicrograph of thin section of the Chateau-Renard meteorite, showing (center) a patch of interstitial maskelynite (lighest gray); white are holes in the section. The largest prism of olivine (medium gray) enclosed in the maskelynite is 0.25 mm. long.

kilograms, and the total weight is estimated to have been about 30 kilograms.

This meteorite was described and analyzed by Dufrénoy (1841). As the analysis is old, and CaO was not determined, it was decided to make a new analysis, and a specimen (No. 435) from the collection of the American Museum of Natural History was used for this work.

MINERALOGICAL COMPOSITION

The minerals identified in the meteorite are olivine, hypersthene, maskelynite, nickel-iron, troilite, and chromite. A small amount (less than 1%) of a phosphate mineral (apatite or merrillite) is probably present. Notes on the minerals follow:

OLIVINE: The refractive indices are: $\alpha = 1.678$, $\gamma = 1.716$, indicating a content of 23 mol per cent of the Fe_2SiO_4 component, according to the determinative curve of Poldervaart (1950). With the use of the X-ray method of Yoder and Sahama (1957), the composition was found to be 23 mol per cent of the Fe_2SiO_4 component. The olivine

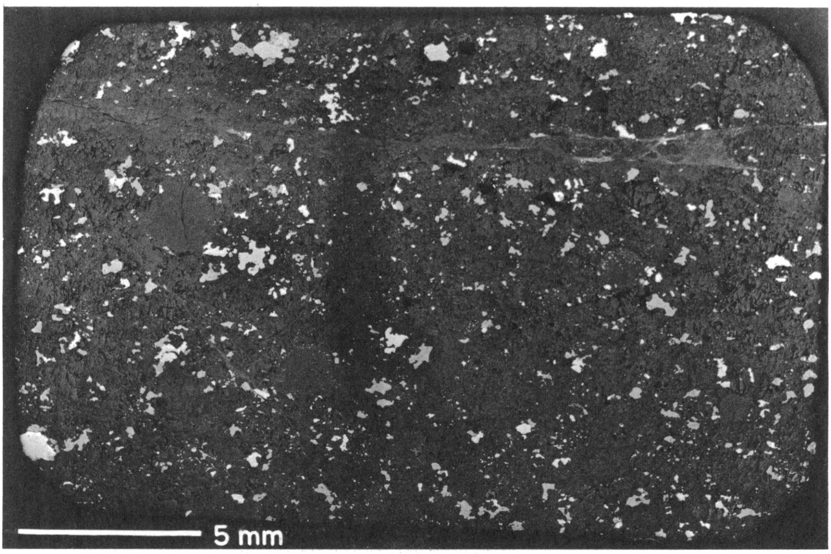

FIG. 4. Photomicrograph of a polished surface of the Chateau-Renard meteorite; white is nickel-iron, pale gray is troilite, dark gray is silicates.

peaks on the diffractometer chart are sharp and well defined, indicating olivine of uniform composition.

ORTHOPYROXENE: The refractive indices are $\alpha = 1.677$, $\gamma = 1.687$, indicating a content of 20 mol per cent of the $FeSiO_3$ component, according to the determinative curve of Kuno (1954). In terms of the conventional subdivision of the orthopyroxene series, this falls on the boundary between bronzite and hypersthene.

MASKELYNITE: This mineral, which is present in small amount, was isolated by digesting a sample of the meteorite powder in 1:1 HCl, and boiling the residue in Na_2CO_3 solution to remove the colloidal silica produced by the decomposition of olivine. This procedure dissolved the nickel-iron, troilite, and olivine, and left a residue of hypersthene, maskelynite, and a little chromite; the maskelynite was concentrated by centrifuging this residue in an acetone-methylene iodide mixture of density 2.9. It is isotropic with a refractive index of 1.506, corresponding to a plagioclase glass of composition An_{20}, according to the data of Foster (1955).

TABLE 3

CHEMICAL COMPOSITION OF THE CHATEAU-RENARD METEORITE

	A		B		C
Fe	8.10	H	0.05	Na	1.38
Ni	1.12	Na	0.58	Mg	35.01
Co	0.041	Mg	15.519	Al	2.30
Cu	0.0118	Al	1.13	Si	35.68
FeS	6.47	Si	18.262	P	0.12
SiO_2	39.09	P	0.070	K	0.13
TiO_2	0.17	S	2.36	Ca	1.67
Al_2O_3	2.13	K	0.096	Ti	0.12
FeO	12.85	Ca	1.222	V	0.02
MnO	0.346	Ti	0.102	Cr	0.38
MgO	25.73	V	0.016	Mn	0.27
CaO	1.71	Cr	0.359	Fe	21.82
Na_2O	0.79	Mn	0.268	Co	0.04
K_2O	0.117	Fe	22.20	Ni	1.05
P_2O_5	0.16	Co	0.041	Cu	0.01
H_2O	0.46	Ni	1.12		100.00
Cr_2O_3	0.525	Cu	0.0118		
V_2O_5	0.029	(O	36.59)		
	99.84		100.00		

A Chemical analysis expressed as nickel-iron, troilite, and oxides.
B Chemical analysis expressed as elements, with oxygen added to make 100 per cent.
C Chemical analysis expressed as atom percentages with the elimination of H, O, and S.

NICKEL-IRON: Both kamacite and taenite are observed on polished surfaces.

A thin section of the meteorite shows chondrules, averaging 1 mm. in diameter, of granular olivine and prismatic hypersthene, set in a groundmass of olivine, hypersthene, and opaque material; the maskelynite is interstitial (fig. 3). The stone is hard and compact and is traversed by narrow black veinlets, up to 0.5 mm. thick; these veinlets show a concentration of troilite (fig. 4).

The density of a piece of this stone was determined by measuring the apparent loss of weight on suspension in carbon tetrachloride and was found to be 3.55.

Chemical Composition

The chemical analysis is given in table 3, in the conventional form expressed as metal, troilite, and oxides; in terms of the individual elements as determined by analysis, with oxygen added to bring the total to 100; and recalculated in atom percentages with the elimination of H, O, and S. A discussion of these procedures is given in the description of the Ottawa meteorite. The chemical composition of the Chateau-Renard meteorite is very similar to that of Mocs and of New Concord, which are also described in this paper, and to Holbrook

TABLE 4

Normative Mineral Composition of the Chateau-Renard Meteorite

Olivine	44.18%
Hypersthene	23.97%
Diopside	4.46%
Albite	6.66%
Anorthite	1.89%
Orthoclase	0.72%
Apatite	0.37%
Chromite	0.77%
Ilmenite	0.32%
Troilite	6.47%
Nickel-iron	9.26%

(Mason and Wiik, 1961). All these meteorites belong to the L, or low-iron, group of Urey and Craig (1953).

The normative mineral composition, expressed in weight percentages, is given in table 4. The observed mineral composition corresponds well with that calculated as the norm. The proportion of olivine to pyroxene agrees with estimates from thin sections and X-ray powder photographs. No diopside was seen, but the small amount of this component is probably in solid solution in the hypersthene. The ratio of FeO to MgO in the olivine and pyroxene, as estimated from the refractive indices of these minerals, is in good agreement with the ratio of FeO to MgO shown by the analysis. Normative feldspar is 9.27 per cent, probably somewhat higher than the actual amount of maskelynite, as some of the Al_2O_3 calculated as feldspar will be in the pyroxene. Although neither apatite nor merrillite was observed in thin section, the 0.37 per

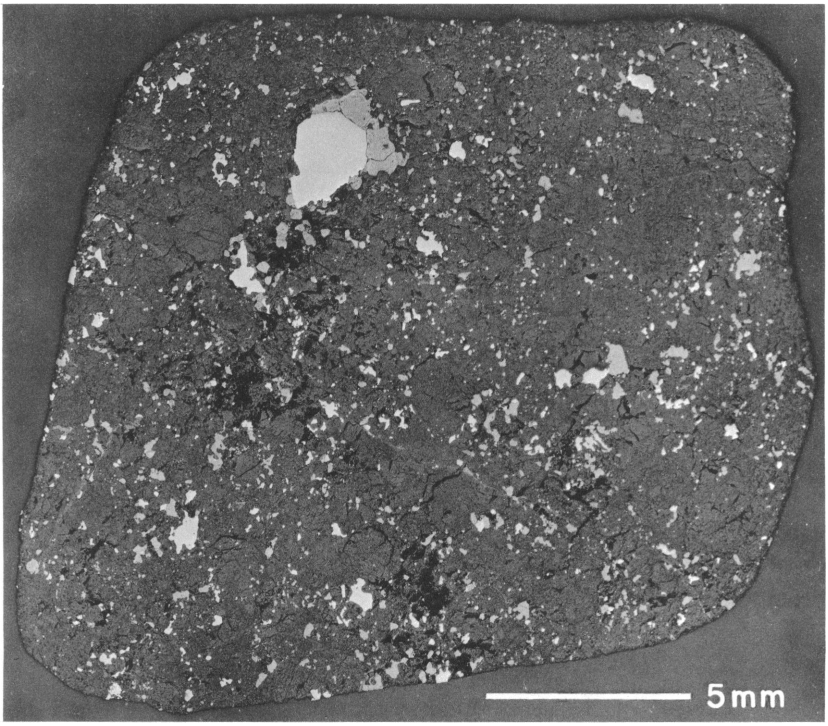

FIG. 5. Photomicrograph of a polished surface of the Mocs meteorite. Metal particles are white, troilite is pale gray, silicates are dark gray.

cent apatite in the norm could well be present. It would be extremely difficult to recognize in a thin section, as it probably occurs in small grains intimately mixed with pyroxene and olivine.

THE MOCS METEORITE

On February 3, 1882, after the appearance of a luminous meteor and detonations, a shower of stones fell near the village of Mocs in Hungary (now Mociu, Romania). The number of stones has been estimated at 3000 and the total weight about 300 kilograms, the largest stone weighing about 56 kilograms. The meteorite was described by Tschermak (1882) and analyzed by Koch (1883). The Mocs meteorite is a typical chondrite. It has been widely distributed, and a number of investigations have been made on it. Ansdell and Dewar (1886) analyzed the gases obtained from it; von Fellenberg (1927) determined the iodine; Manian, Urey, and Bleakney (1934) measured the $O^{16}:O^{18}$

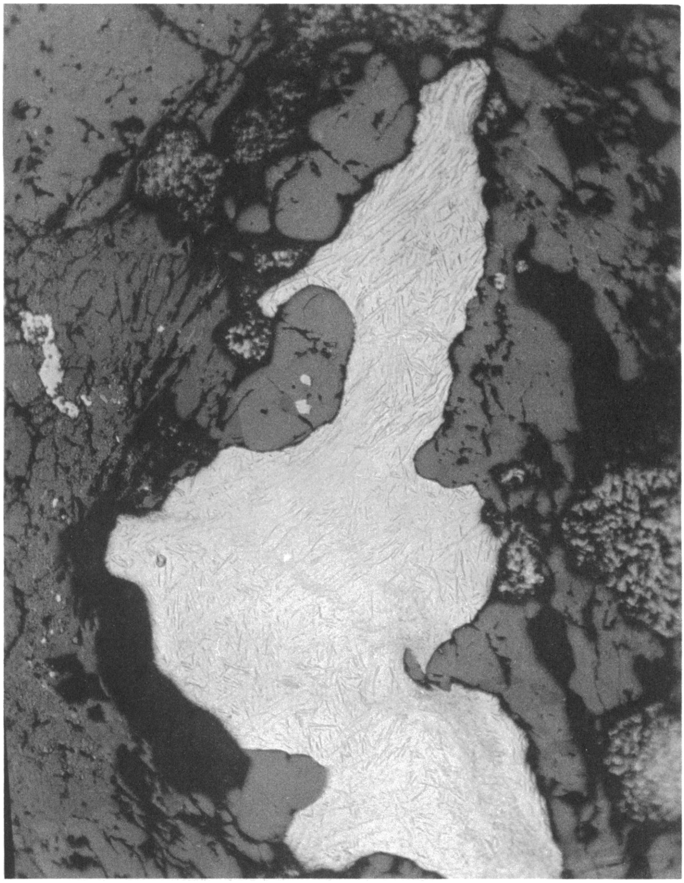

FIG. 6. Photomicrograph of a single crystal of kamacite from the Mocs meteorite, showing twinning. × 80.

ratio; and Pinson, Ahrens, and Franck (1953) determined Li, Sc, Sr, Ba, Zr, K and Rb. However, the original analysis, although given to four places of decimals, is clearly deficient (Al_2O_3 is reported as "trace," MnO is more than 1%). We therefore decided to reanalyze this meteorite and selected a single complete stone (A.M.N.H. No. 1077, weighing 642 grams) for investigation.

Mineralogical Composition

The minerals identified in the meteorite are olivine, hypersthene, plagioclase, troilite, nickel-iron, and chromite. A small amount (less

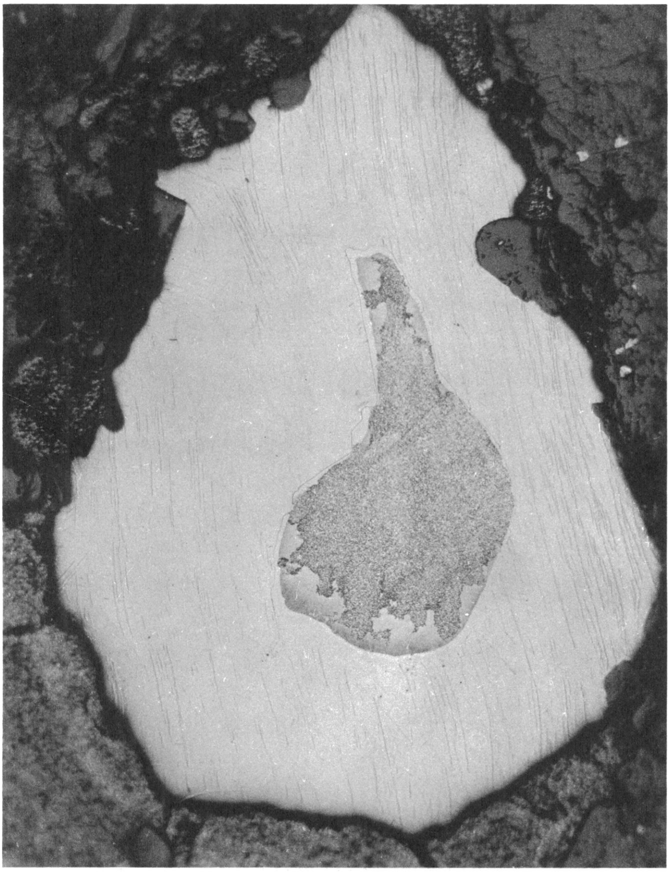

FIG. 7. Photomicrograph of a metal particle from the Mocs meteorite. The central part is plessite, surrounded by a narrow zone of taenite, followed by a wide outer zone of kamacite. × 40.

than 1%) of a phosphate mineral (apatite or merrillite) is present. Notes on the minerals follow:

OLIVINE: The refractive indices are: $\alpha = 1.676$, $\gamma = 1.716$, indicating a content of 22 mol per cent of the Fe_2SiO_4 component, according to the determinative curve of Poldervaart (1950). With the use of the X-ray method of Yoder and Sahama (1957), the composition was found to be 23 mol per cent of the Fe_2SiO_4 component. The olivine peaks on the diffractometer chart are sharp and well defined, indicating olivine of uniform composition.

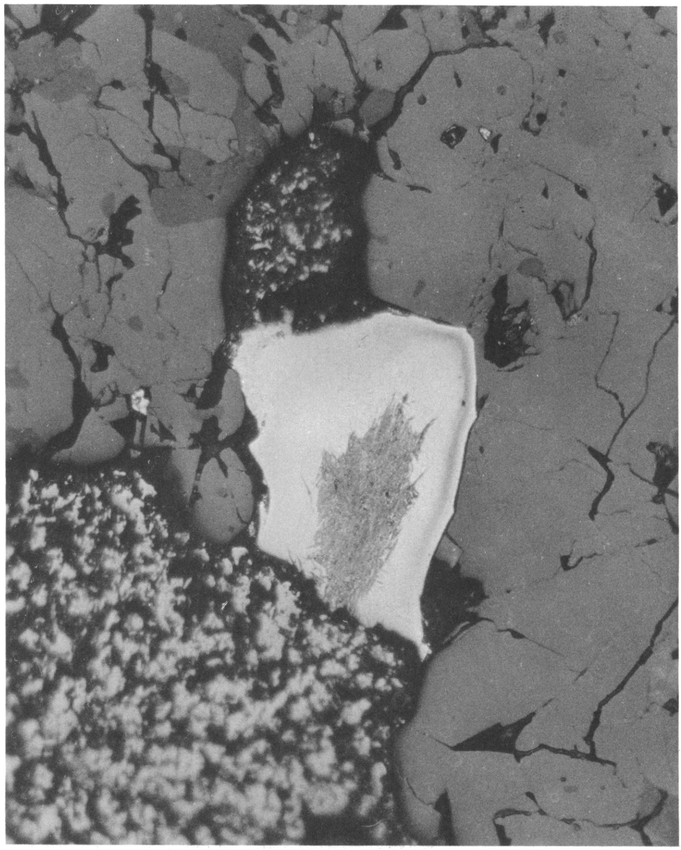

FIG. 8. Photomicrograph of a disrupted metal particle from the Mocs meteorite, with plessite in center surrounded by clear taenite. $\times$ 250.

ORTHOPYROXENE: The refractive indices are: $\alpha = 1.678$, $\gamma = 1.688$, indicating a content of 21 mol per cent of the $FeSiO_3$ component, according to the determinative curve of Kuno (1954). In terms of the conventional subdivision of the orthopyroxene series, this falls in the composition range of hypersthene.

Tschermak (1882) identified diopside in Mocs, but said that it was difficult to distinguish from bronzite, and present in small amount. We have made a careful examination of the acid-insoluble residue of Mocs, after treatment with 1:1 HCl, and have found no diopside, the only pyroxene present being hypersthene. Under these circumstances we believe that the record of diopside in this meteorite is erroneous.

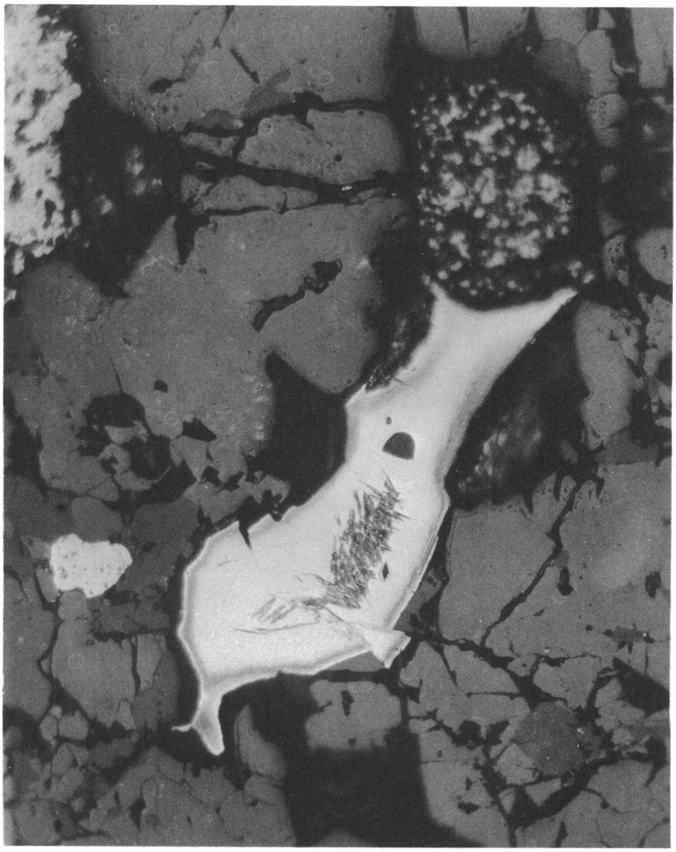

FIG. 9 Photomicrograph of a metal particle from the Mocs meteorite, similar to figure 8, and showing incipient disruption. × 250.

PLAGIOCLASE: The refractive indices are: $\alpha' = 1.530$, $\gamma' = 1.540$, indicating a composition of An_5.

APATITE: Tschermak (1883) recognized what he called a monticellite-like mineral as a rare constituent of Mocs. He describes it as weakly birefringent irregular grains with traces of cleavage, soluble in hydrochloric acid. We have seen this mineral in thin sections of Mocs, and believe it to be apatite or merrillite.

NICKEL-IRON: The grains of nickel-iron are irregular in shape, and range up to several millimeters in length. Urey and Mayeda (1959) reported extensively on the nickel-iron from this meteorite, and wrote: "Clear kamacite in large crystals does not occur. Kamacite of intermediate and fine crystal sizes is common. The intermediate or mottled kamacite is commonly in contact with clear or nearly clear taenite. Taenite particles with diffusion borders and plessite interiors are common and are often badly distorted and broken. Some taenite particles are sometimes mixed with troilite in complicated ways. One taenite particle of elongated shape and large size (230 μ long broken at the ends and 60 μ wide) with plessite interior and diffusion border was observed in this meteorite. It is the only taenite particle observed in any meteorite that has the appearance of coming from an octahedrite metal meteorite. The particle is only partly preserved. One end seems to be disintegrated and mixed with polycrystalline kamacite. No corrosion can be detected and no well-formed spherical chondrites can be found. The meteorite in many ways indicates extreme crushing and distortion of all constituents."

Urey and Mayeda claim that the metal particles originated in the break-up of pre-existing bodies and were incorporated as fragments in the chondritic meteorites such as Mocs. However, Mr. R. E. Maringer, of the Battelle Memorial Institute, who has kindly examined a polished surface of Mocs (fig. 5), reports as follows: "The metal particles in Mocs show a variety of structures, many of which are heavily twinned kamacite. Most of the kamacite particles appear to be single crystals (fig. 6). Sometimes (fig. 7) kamacite, plessite, and taenite appear in the same particle. Frequently the particles appear to be entirely taenite and plessite (figs. 8 and 9). Figure 8 is a good example of a particle which has been torn apart. This is the type of particle which led Urey and Mayeda to their thesis. Figure 9, however, shows a similar particle in the process of being disrupted. After scanning many particles under the miscroscope, I'm pretty much convinced that the 'disruptions' observed occurred *in situ.*"

A thin section of the meteorite shows occasional chondrules, about 1 mm. in diameter, of granular olivine and prismatic orthopyroxene, set in a groundmass of olivine, orthopyroxene, and opaque material. Limonitic staining surrounds the grains of opaque material, which is somewhat surprising, as the section was cut from a complete stone with a closely adherent black fusion crust; the staining may result from the decomposition of a small amount of lawrencite originally present in the stone. Tschermak (1882) remarks on this limonitic staining in specimens collected soon after the fall of the meteorite.

The density of a piece of this meteorite was determined by measuring the apparent loss of weight on suspension in carbon tetrachloride, and found to be 3.58. To eliminate as far as possible any air

TABLE 5

CHEMICAL COMPOSITION OF THE MOCS METEORITE

A		B		C	
Fe	8.56	H	0.06	Na	1.39
Ni	1.25	Na	0.58	Mg	34.21
Co	0.057	Mg	15.085	Al	2.25
Cu	0.0095	Al	1.10	Si	36.41
FeS	6.42	Si	18.538	P	0.17
SiO_2	39.68	P	0.096	K	0.15
TiO_2	0.175	S	2.34	Ca	1.77
Al_2O_3	2.07	K	0.107	Ti	0.12
FeO	11.80	Ca	1.286	V	0.02
MnO	0.355	Ti	0.105	Cr	0.44
MgO	25.01	V	0.020	Mn	0.28
CaO	1.80	Cr	0.410	Fe	21.55
Na_2O	0.79	Mn	0.275	Co	0.05
K_2O	0.13	Fe	21.81	Ni	1.18
P_2O_5	0.22	Co	0.057	Cu	0.01
H_2O	0.52	Ni	1.25		100.00
Cr_2O_3	0.60	Cu	0.0095		
V_2O_5	0.036	(O	36.87)		
	99.48		100.00		

A Chemical analysis expressed as nickel-iron, troilite, and oxides.
B Chemical analysis expressed as elements, with oxygen added to make 100 per cent.
C Chemical analysis expressed as atom percentages with the elimination of H, O, and S.

in the slightly porous stone, it was evacuated by an oil pump under a bell jar before the carbon tetrachloride was run in.

CHEMICAL COMPOSITION

The chemical analysis is given in table 5, in the conventional form expressed as metal, troilite, and oxides; in terms of the individual elements as determined by analysis, with oxygen added to bring the total to 100; and recalculated in atom percentages with the elimination of H, O, and S. A discussion of these procedures is given in our description (above) of the Ottawa meteorite. The chemical composition of the Mocs meteorite is very similar to that of Chateau-Renard and of New Concord. All these meteorites belong to the L, or low-iron, group of Urey and Craig (1953).

The normative mineral composition, expressed in weight percentages, is given in table 6. The observed mineral composition corresponds well with that calculated as the norm. The proportion of olivine to pyroxene agrees with estimates from thin sections and X-ray powder photographs. No diopside was seen, but the small amount of this component is probably in solid solution in the hypersthene. The ratio of FeO to MgO in the olivine and pyroxene, as estimated from the refractive indices of these minerals, is in good agreement with the ratio of FeO to MgO shown by the analysis. Normative feldspar is 9.14 per cent, probably somewhat higher than the actual amount of plagioclase, as some of the Al_2O_3 calculated as feldspar will be in the pyroxene. Apatite or merrillite was observed in thin section, corresponding to 0.50 per cent of apatite in the norm.

TABLE 6

NORMATIVE MINERAL COMPOSITION OF THE MOCS METEORITE

Olivine	37.30%
Hypersthene	29.44%
Diopside	4.68%
Albite	6.66%
Anorthite	1.70%
Orthoclase	0.78%
Apatite	0.50%
Chromite	0.88%
Ilmenite	0.33%
Troilite	6.42%
Nickel-iron	9.87%

The result obtained by Pinson, Ahrens, and Franck (1953) on trace elements in Mocs are as follows (in parts per million): Li, 2.1; Sc, 5; Sr, 9; Ba, 7; Zr, 29; Rb, 10. The figure for rubidium is probably about twice the true value, as a result of a systematic error (Ahrens, Edge, and Taylor, 1960). According to von Fellenberg (1927), Mocs contains 0.18 parts per million of iodine. Wiik (unpublished) determined scandium, yttrium, and ytterbium and found the following contents, in parts per million: Sc, 8.19; Y, 1.9; Yb, 0.6.

THE NEW CONCORD METEORITE

On May 1, 1860, after detonations and the appearance of a luminous meteorite, a shower of stones fell over an area about 10 by 3 miles, near New Concord, Ohio. Over 30 stones were found, the heaviest weighing 103 pounds; the total weight recorded is about 500 pounds. The circumstances of the fall and the nature of the meteorite were described by Andrews, Evans, Johnson, and Smith (1860), by Smith (1861), and by Madelung (1862). Three chemical analyses were made, by Johnson, Smith, and Madelung; they vary considerably one from the other, and none is satisfactory by modern standards. We therefore decided to reanalyze this meteorite and selected a broken stone (A.M.N.H. No. 385, weighing 376 grams) for investigation.

Mineralogical Composition

The minerals identified in the meteorite are olivine, orthopyroxene, plagioclase, troilite, nickel-iron, and chromite; chlorapatite and merrillite were found by Shannon and Larsen (1925). Notes on the minerals follow:

Olivine: The refractive indices are: $\alpha = 1.678$, $\gamma = 1.717$, indicating a content of 22 mol per cent of the Fe_2SiO_4 component, according to the determinative curve of Poldervaart (1950). With the use of the X-ray method of Yoder and Sahama (1957), the composition was found to be 24 mol per cent of the Fe_2SiO_4 component. The olivine peaks on the diffractometer chart are sharp and well defined, indicating olivine of uniform composition.

Orthopyroxene: The refractive indices are: $\alpha = 1.678$, $\gamma = 1.688$, indicating a content of 21 mol per cent of the $FeSiO_3$ component, according to the determinative curve of Kuno (1954). In terms of the conventional subdivision of the orthopyroxene series, this falls in the composition range of hyperstene.

Plagioclase: The refractive indices are: $\alpha' = 1.530$, $\gamma' = 1.539$, indicating a composition of An_4.

Apatite: Shannon and Larsen (1925) separated and analyzed apatite from the New Concord stone; they showed that it is a pure chlorapatite, with refractive indices: $\omega = 1.655$, $\varepsilon = 1.651$, and density 3.20.

Merrillite: Shannon and Larsen (1925) separated and analyzed merrillite from the New Concord stone; they decided on a formula $Na_2Ca_3(PO_4)_2O$ for this mineral. According to their determinations the mineral is uniaxial negative, with refractive indices: $\omega = 1.623$, $\varepsilon = 1.620$; the density is 3.10. The merrillite and apatite are present in approximately equal amounts. They comment: "It seems probable that merrillite will form only if there is insufficient fluorine, or probably chlorine, and carbon dioxide to form a member of the apatite group. This condition is the rule in meteorites but is exceptional or absent in terrestrial rocks."

Shannon and Larsen identified merrillite in the Allegan and Waconda meteorites also. These are the only well-established identifica-

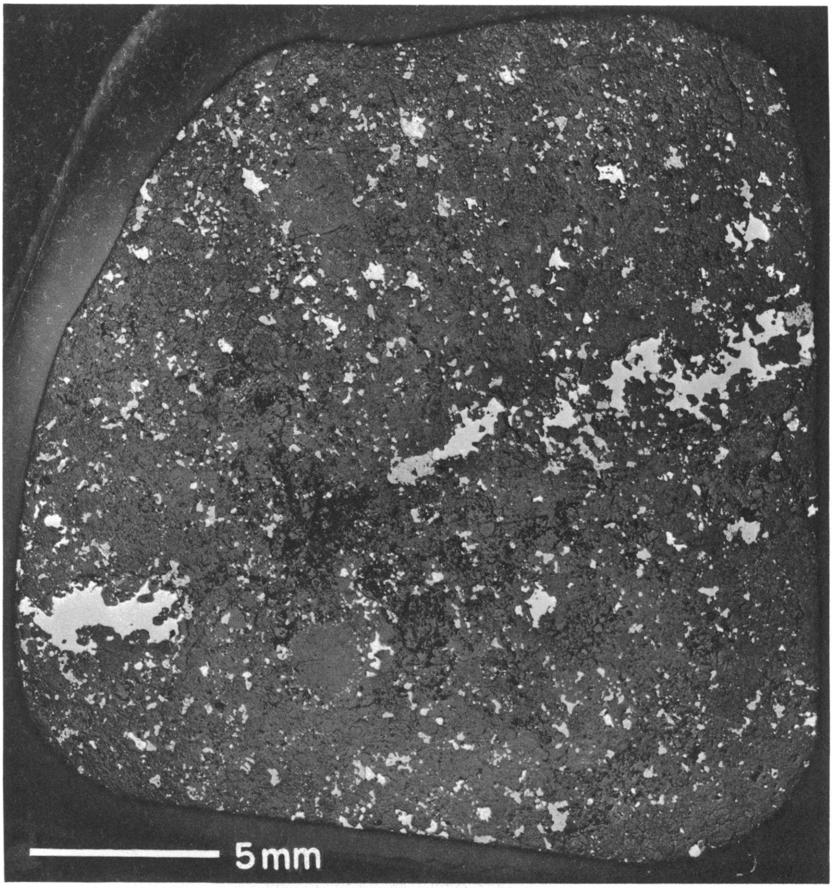

FIG. 10. Photomicrograph of a thin section of the New Concord meteorite (ordinary light). Chondrules of granular olivine and platy or fibrous hypersthene in a ground mass of olivine, hypersthene, and opaque material. White is hole in section. Largest chondrule has a diameter of 1.5 mm.

tions of merrillite, although some investigators have mentioned its occurrence in other stony meteorites. It is indistinguishable from apatite in thin section, and certain identification seems possible only by separation and chemical or X-ray tests. No X-ray data on merrillite are yet available. McConnell (1938) suggested that merrillite may be a sodium hydroxyl-apatite; it is possibly identical with or closely similar to the terrestrial mineral dehrnite.

NICKEL-IRON: An X-ray powder photograph of material separated

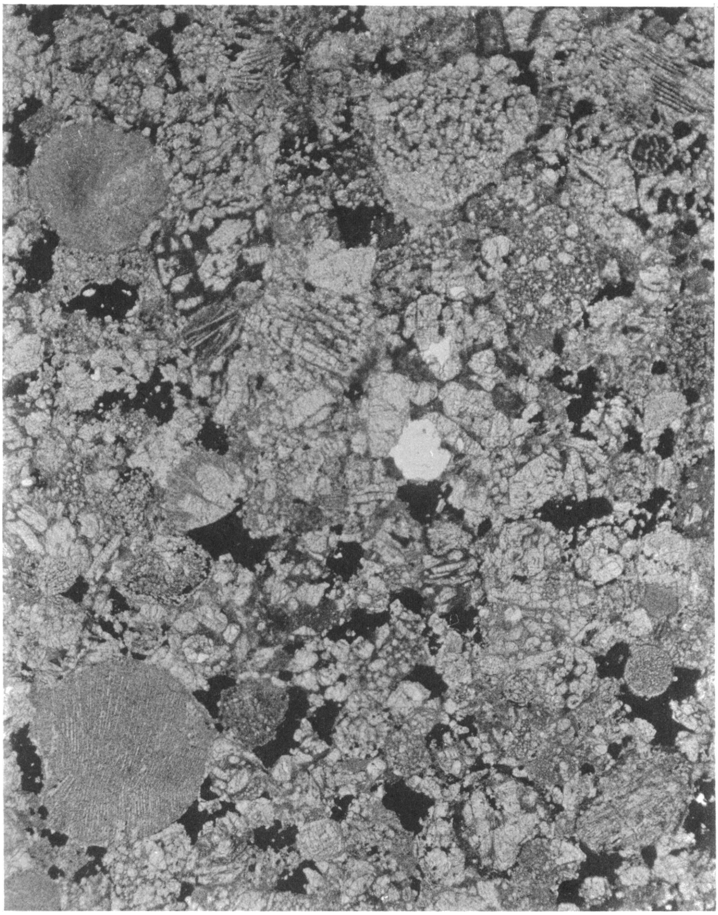

FIG. 11. Photomicrograph of a polished surface of the New Concord meteorite; nickel-iron is white, troilite is pale gray, silicates are dark gray.

magnetically from the New Concord stone showed strong lines of kamacite and weak lines of taenite.

A thin section of the meteorite (fig. 10) shows numerous chondrules, up to 1.5 mm. in diameter, of granular olivine and fibrous to prismatic orthopyroxene, set in a groundmass of olivine, orthopyroxene, and opaque material. The opaque material is usually interstitial to the silicates and sometimes is concentrated around the chondrules (fig. 11). Merrillite and apatite can be recognized by their low birefringence and somewhat greater transparency than the olivine and orthopyroxene.

TABLE 7

CHEMICAL COMPOSITION OF THE NEW CONCORD METEORITE

A		B		C	
Fe	8.18	H	0.10	Na	1.35
Ni	1.26	Na	0.56	Mg	34.71
Co	0.045	Mg	15.20	Al	2.31
Cu	0.0090	Al	1.12	Si	36.05
FeS	6.64	Si	18.235	P	0.20
SiO_2	39.03	P	0.113	K	0.13
TiO_2	0.17	S	2.42	Ca	1.70
Al_2O_3	2.12	K	0.095	Ti	0.12
FeO	11.84	Ca	1.229	V	0.02
MnO	0.346	Ti	0.102	Cr	0.41
MgO	25.20	V	0.017	Mn	0.27
CaO	1.72	Cr	0.383	Fe	21.49
Na_2O	0.75	Mn	0.268	Co	0.04
K_2O	0.115	Fe	21.60	Ni	1.19
P_2O_5	0.26	Co	0.045	Cu	0.01
H_2O	0.87	Ni	1.26		100.00
Cr_2O_3	0.56	Cu	0.0090		
V_2O_5	0.031	(O	37.24)		
	99.14		100.00		

A Chemical analysis expressed as nickel-iron, troilite, and oxides.
B Chemical analysis expressed as elements, with oxygen added to make 100 per cent.
C Chemical analysis expressed as atom percentages with the elimination of H, O, and S.

Yellowish brown limonitic staining surrounds some of the opaque grains. This was noted by the first investigators in 1860 and may represent trace amounts of lawrencite originally present in the stone.

The density of a piece of this meteorite was determined by measuring the apparent loss of weight on suspension in carbon tetrachloride and found to be 3.53. To eliminate as far as possible any trapped air in the slightly porous stone, it was placed under a bell jar and evacuated by an oil pump before the carbon tetrachloride was run in.

CHEMICAL COMPOSITION

The chemical analysis is given in table 7, in the conventional form expressed as metal, troilite, and oxides; in terms of the individual elements as determined by analysis, with oxygen added to bring the total to 100; and recalculated in atom percentages with the elimination of H, O, and S. A discussion of these procedures is given above in the description of the Ottawa meteorite. The chemical composition of the New Concord meteorite is very similar to that of Chateau-Renard and Mocs. All these meteorites belong to the L, or low-iron, group of Urey and Craig (1953).

The normative mineral composition, expressed in weight percentages, is given in table 8. The observed mineral composition corresponds well with that calculated as the norm. The proportion of olivine to pyroxene agrees with estimates from thin sections and X-ray powder photographs. No diopside was seen, but the small amount of this component is probably in solid solution in the hypersthene. The ratio of

TABLE 8

NORMATIVE MINERAL COMPOSITION OF THE NEW CONCORD METEORITE

Olivine	38.93%
Hypersthene	28.10%
Diopside	3.88%
Albite	6.34%
Anorthite	2.03%
Orthoclase	0.72%
Apatite	0.61%
Chromite	0.82%
Ilmenite	0.32%
Troilite	6.64%
Nickel-iron	9.49%

FeO to MgO in the olivine and pyroxene, as estimated from the refractive indices of these minerals, is in good agreement with the ratio of FeO to MgO shown by the analysis. Normative feldspar is 9.09 per cent, probably somewhat higher than the actual amount of plagioclase, as some of the Al_2O_3 calculated as feldspar will be in the pyroxene. The 0.61 per cent of apatite in the norm corresponds to the amount of apatite and merrillite seen in thin sections.

Wright (1876) determined the gases released from the New Concord meteorite on heating, with the following results:

TEMPERATURE	CO_2	CO	CH_4	H	N	VOLUMES
500°	82.28	2.16	2.26	12.37	0.93	2.06
Red heat	16.79	8.71	1.66	69.43	3.41	0.93
Total	59.88	4.40	2.05	31.89	1.78	2.99

DuFresne (1960) has analyzed two samples of New Concord for selenium and tellurium, and found 7.3 and 7.4 parts per million selenium, and 2.12 and 1.66 parts per million tellurium; she also reports

0.12 per cent sulphur, which must be an error, or a misprint for 2.12 per cent.

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