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The Composition of the Bath, Frankfort, Kakangari, Rose City, and Tadjera Meteorites

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THE BATH METEORITE

This meteorite fell on August 29, 1892, at about 4 P.M., some 2 miles south of Bath, in Brown County, South Dakota. The coordinates of Bath, according to "The Times Atlas of the World," are latitude 45° 27′ N., longitude 98° 19′ W., so the coordinates of the actual place of fall can be given as latitude 45° 25′ N., longitude 98° 19′ W. The circumstances of the fall were briefly described by Foote (1893). A single stone weighing 46¾ pounds (21.2 kilograms) was observed to fall by a farmer and his son. The stone penetrated the hardened prairie surface to a depth of about 16 inches (40 cm.). The stone was evidently acquired by Foote and cut up, pieces of it being preserved in many of the important meteorite collections of the world. Since the only account of its composition is a brief description by Merrill (1919) of a petrographic thin section, we decided to analyze it, selecting for this purpose the specimen (No. 387) in the collection of the American Museum of Natural History.

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Mineralogical Composition and Structure

In hand specimen a cut surface of the meteorite shows an abundance of nickel-iron grains in a pale gray stony groundmass. Brown limonitic staining is associated with the metal grains. Paper-thin black veinlets are not uncommon. Chondrules are clearly visible with a hand lens.

The principal minerals are olivine and pyroxene. Other characteristic minerals are nickel-iron (both kamacite and taenite), plagioclase feldspar, and troilite. Minor and accessory minerals include chromite and a phosphate (apatite or merrillite, or both). Ramdohr (personal communication) has observed trace amounts of copper, chalcopyrrhotite, and ilmenite in polished surfaces. Notes on some of the minerals follow.

Olivine: The refractive indices are $\alpha = 1.675$, $\gamma = 1.709$, indicating a content of 19 mole per cent of the Fe_2SiO_4 component, according to the determinative curve of Poldervaart (1950). By the X-ray method of Yoder and Sahama (1957) the same composition was obtained. The olivine peaks on the diffractometer chart are sharp and symmetrical, indicating olivine of uniform composition. Keil and Fredriksson (1964), by microprobe analysis, reported 17.9 mole per cent Fe_2SiO_4 in the olivine.

Pyroxene: The refractive indices are $\alpha = 1.672$, $\gamma = 1.682$, indicating a content of 16 mole per cent of the $FeSiO_3$ component, according to the determinative curve of Kuno (1954). Keil and Fredriksson (1964) report the Fe/Fe+Mg mole percentage in the pyroxene to be 15.7. In terms of the conventional division of meteoritic orthopyroxene, this falls in the composition range of bronzite. The acid-insoluble concentrate of pyroxene and plagioclase contains a considerable amount of turbid and twinned clinopyroxene tentatively identified as clinobronzite.

Plagioclase: The plagioclase is fine grained, and only a mean refractive index, 1.536, could be measured, corresponding to a composition of An_{10}.

In thin section Bath is seen to be a highly chondritic meteorite (fig. 1). The chondrules range in diameter from 0.2 mm. to 1 mm. and show a variety of internal structure. Barred olivine chondrules are not uncommon, the bars being turbid and virtually opaque and probably consisting of devitrified glass. Occasional large chondrules are composed of euhedral olivine crystals in a gray turbid groundmass. Pyroxene chondrules are dense and fine grained, in some cases with a radiating structure. The limonitic staining noted above is associated with the metal grains and is absent around the grains of troilite. The groundmass is made up of the opaque minerals and granular olivine and pyroxene.

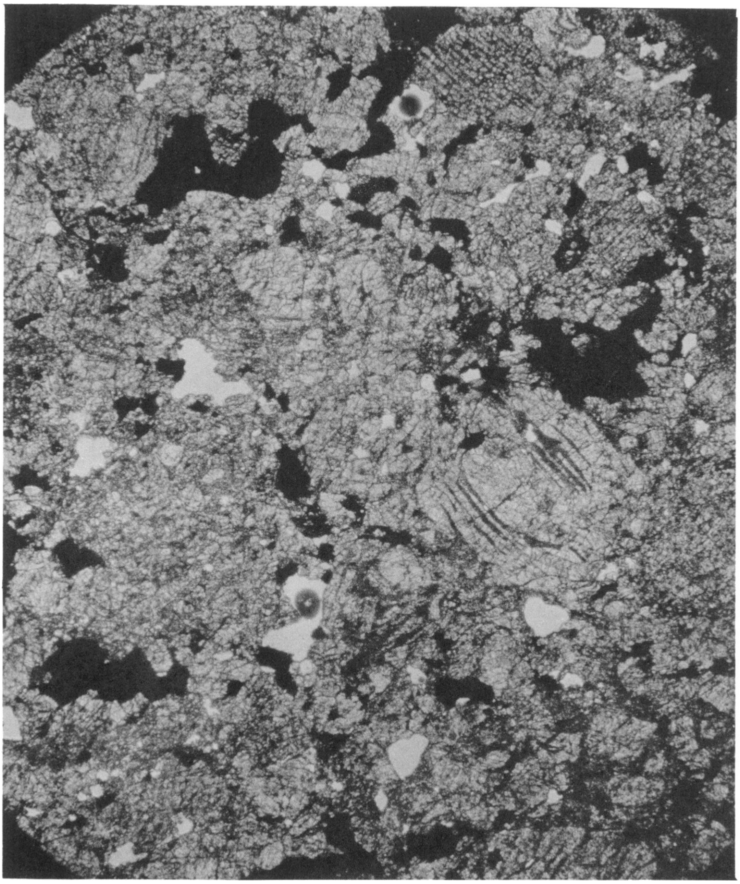

FIG. 1. Photomicrograph of a thin section of the Bath meteorite, showing chondrules of olivine and pyroxene (gray). Black is nickel-iron and troilite, white holes in the section. ×35.

Keil (1962) has published a modal analysis of the Bath meteorite and gave the following figures (weight per cent): nickel-iron, 17.09; troilite, 4.86; chromite, 0.10; silicates, 77.95.

The density of a piece of the meteorite was determined by measuring the apparent loss of weight in suspension in carbon tetrachloride (after evacuation under a bell jar to remove air) and found to be 3.73.

CHEMICAL COMPOSITION

The chemical analysis is given in table 1, 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 O, C, and S. The conventional form of presenting meteorite analyses involves certain assumptions, for example, that all S is present as FeS, that Fe in excess of free metal and FeS are present as ferrous iron, and that all Ni and Co are present in the metal phase. These assumptions are essentially valid for the Bath meteorite.

TABLE 1

CHEMICAL COMPOSITION OF THE BATH METEORITE

A		B		C	
Fe	14.74	Fe	26.10	Si	33.66
Ni	1.52	Si	17.38	Mg	32.42
Co	0.08	Mg	14.50	Fe	25.41
FeS	6.11	S	2.23	Al	3.12
SiO_2	37.23	Ni	1.52	Na	1.58
TiO_2	0.11	Al	1.55	Ni	1.40
Al_2O_3	2.93	Ca	0.90	Ca	1.22
FeO	9.62	Na	0.67	Cr	0.47
MnO	0.32	Cr	0.45	Mn	0.25
MgO	24.04	Mn	0.25	P	0.22
CaO	1.22	P	0.13	Ti	0.08
Na_2O	0.90	Co	0.08	Co	0.07
K_2O	0.09	Ti	0.07	K	0.10
P_2O_5	0.29	K	0.07		100.00
C	0.27	C	0.27		
Cr_2O_3	0.67	(O	33.83)		
	100.14		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 elimination of O, S, and C

The second procedure for 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 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 the elimination of O, C, and S was used by one of us (Wiik, 1956) for comparing analyses of different types of chondrites. The figures for Bath show that its composition is closely similar to Wiik's group of chondrites with 15 per cent to 19 per cent of metallic iron. These are the olivine-bronzite chondrites of Prior's classification (1920), and they belong to the high-iron (H) group of Urey and Craig (1953).

The normative mineral composition, calculated from the analysis as recommended by Wahl (1951), and expressed in weight percentages, is given in table 2. The observed mineral composition reported by Keil (1962) corresponds well with that calculated as the norm. It is noteworthy, however, that the norm gives 1.0 per cent of chromite whereas Keil reported only 0.1 per cent; the chromium is evidently combined in the pyroxene rather than as chromite.

TABLE 2
NORMATIVE COMPOSITION OF THE BATH METEORITE

Olivine	35.0
Bronzite	28.1
Diopside	0.4
Albite	7.7
Anorthite	3.7
Orthoclase	0.6
Chromite	1.0
Apatite	0.7
Ilmenite	0.2
Troilite	6.1
Nickel-iron	16.3

THE FRANKFORT METEORITE

The Frankfort meteorite fell about 3 P.M. on December 5, 1868, 4 miles south of Frankfort, a hamlet in Franklin County in northwestern Alabama. A single stone weighing about 650 grams was seen to fall. It was decribed by Brush (1869) and identified by him as a howardite. Small pieces of this meteorite are widely distributed in collections, but the major portions are in the Yale (186 grams) and Harvard (57 grams) collections.

MINERALOGICAL COMPOSITION AND STRUCTURE

In hand specimen a cut surface of the meteorite shows a light gray stony groundmass containing white spots of plagioclase up to 1 mm. across, and pale yellow to dark gray crystals of pyroxene up to 2 mm. long. Rare grains of black, highly lustrous chromite, one of them 2 mm. across, were also observed. Examination of a polished thin section shows rare flakes of metal, made more visible by a slight amount of limonitic staining surrounding them; occasional grains of troilite were al-

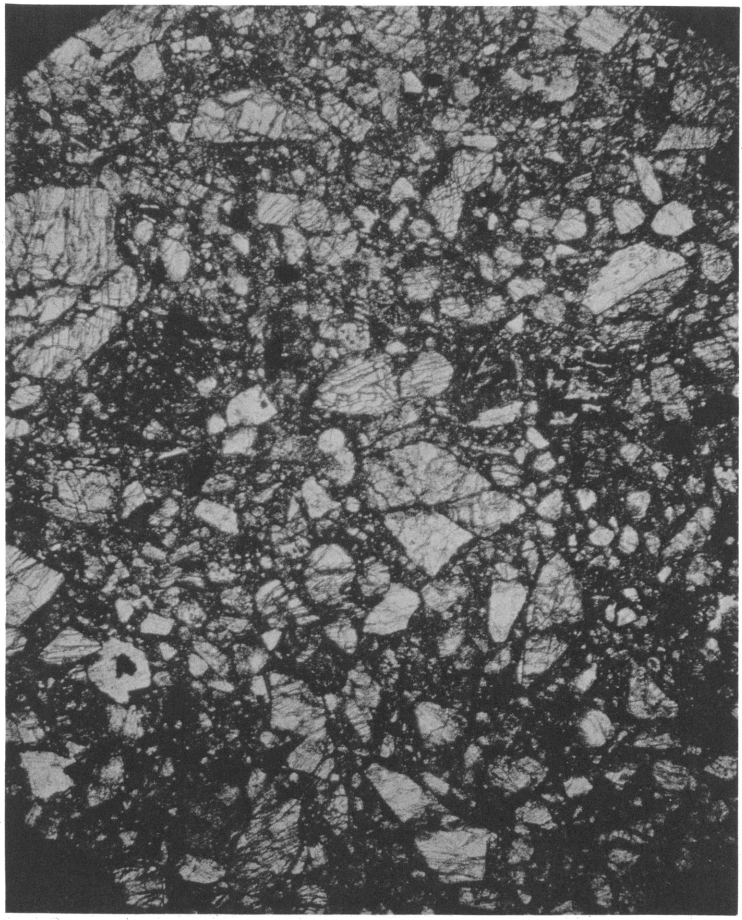

FIG. 2. Photomicrograph of a thin section of the Frankfort meteorite, showing angular fragments of pyroxene and minor plagioclase in a comminuted groundmass of the same minerals. ×35.

so seen. The fusion crust is coal black and highly lustrous. Notes on the silicate minerals follow.

PYROXENE: Both orthopyroxene and clinopyroxene are present, the latter in lesser amount; the relative proportions are about 3/1. The orthopyroxene shows a considerable range in composition, judging from the refractive indices; the gamma index ranges from 1.690 to 1.710, indicating a range of 22–35 mole per cent of the $FeSiO_3$ component. Some of the orthopyroxene grains show exsolution lamellae of clinopyroxene.

TABLE 3

CHEMICAL COMPOSITION OF THE FRANKFORT METEORITE

A		B		C	
Fe	0.0	Si	23.11	Si	46.02
Ni	0.0	Fe	13.96	Mg	28.42
Co	0.02	Mg	12.36	Fe	13.97
FeS	0.69	Ca	2.77	Al	5.59
SiO_2	49.48	Al	2.70	Ca	3.85
TiO_2	0.46	Cr	0.92	Cr	0.98
Al_2O_3	5.10	Mn	0.41	Mn	0.41
FeO	17.39	Ti	0.28	Ti	0.32
MnO	0.53	S	0.25	Na	0.31
MgO	20.50	C	0.24	P	0.08
CaO	4.02	Na	0.13	K	0.03
Na_2O	0.17	P	0.05	Co	0.02
K_2O	0.03	K	0.02		100.00
P_2O_5	0.11	Co	0.02		
C	0.24	(O	42.78)		
Cr_2O_3	1.34		100.00		
	100.08				

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 O, S, and C

The clinopyroxene is a pigeonite, pale yellow-brown and weakly pleochroic, and does not show such a wide range in composition as the orthopyroxene; for a number of grains $\alpha = 1.708$, $\gamma = 1.735$, indicating a composition about $Ca_{10}Mg_{46}Fe_{44}$. A pigeonite of similar composition was described from the Moore County meteorite by Hess and Henderson (1949).

PLAGIOCLASE: The refractive indices are $\alpha = 1.571$, $\gamma = 1.582$, indicating a composition of An_{87}, i.e., a calcium-rich bytownite.

TRIDYMITE: A few grains of this mineral were found in a low-density fraction separated from the meteorite. The mean refractive index is 1.474, and the birefringence is low, about 0.004. Brush tentatively identified olivine in this meteorite, so a careful search was made for this mineral, but none was found.

The structure of the meteorite, as seen in thin section (fig. 2), is highly brecciated, angular fragments of pyroxene and plagioclase occurring in a comminuted groundmass of the same minerals. Some lithic fragments of intergrown pyroxene and plagioclase were seen. This brecciated structure appears to be typical of the howardites and hypersthene achondrites;

the thin section of Frankfort resembles closely that of the hypersthene achondrite Johnstown (Mason, 1963, fig. 1).

The density of this meteorite, determined as described for Bath, is 3.33.

Chemical Composition

The chemical analysis is given in table 3, in the conventional form expressed as nickel-iron, troilite, and oxides; in terms of the individual elements as determined by analysis, with oxygen added to bring the total to 100; and recalculated to atom percentages, with the elimination of O, C, and S. A discussion of these procedures is given under the description of the Bath meteorite. Since the amount of free nickel-iron was less than 0.1 per cent it was not separately determined.

The normative mineral composition, expressed as weight percentages, is given in table 4. It is in good agreement with the actual mineral composition, except for the appearance of 8.7 per cent of olivine in the norm. This is a consequence of assigning all Al_2O_3 to feldspar, whereas some aluminum replaces silicon in the pyroxenes. Replacement of silicon by aluminum in effect releases enough SiO_2 so that only pyroxene, and no olivine, is formed. Indeed, the presence of trace amounts of tridymite indicates a slight excess of SiO_2.

The presence of some of the aluminum in the pyroxene means that the actual amount of plagioclase is somewhat less than the normative amount; the estimated quantity is about 10 per cent. Chromite is considerably less than the 2.0 per cent calculated in the norm, because much of the chromium is combined in the pyroxene.

The composition of the Frankfort meteorite is of considerable interest. It has the lowest CaO content (4.02%) and the lowest FeO/FeO+MgO mole percentage (32) of any of the howardites. If we compare these figures for the hypersthene achondrites and the howardites, as follows:

	CaO, Weight Per Cent	FeO/FeO+MgO, Mole Per cent
Hypersthene achondrites	0.8–2.6	22–33
Howardites	4.0–8.6	32–46

the close relationship of Frankfort to the hypersthene achondrites is clearly seen. The principal difference between Frankfort and a hypersthene achondrite like Johnstown is that plagioclase is present only in assessory amounts in Johnstown, whereas it is a significant though minor constituent in Frankfort. It is interesting to note that this is manifested in the nature of the fusion crusts on these meteorites; Johnstown has a thin dull black crust, whereas that on Frankfort is thicker, lustrous, and glassy. Evidently the feldspar has a strong fluxing effect during the fiery passage of the meteorite through the atmosphere.

The essential continuity in composition between the hypersthene achondrites and the howardites, and the similarity in their structures, strongly suggest the possibility of a common origin.

TABLE 4

NORMATIVE COMPOSITION OF THE FRANKFORT METEORITE

Hypersthene	67.6
Diopside	5.0
Olivine	8.7
Anorthite	13.0
Albite	1.4
Orthoclase	0.2
Chromite	2.0
Ilmenite	0.9
Apatite	0.3
Troilite	0.7

THE KAKANGARI METEORITE

This meteorite fell about 8 A.M. on June 4, 1890, near the village of Kagankarai (latitude 12° 23′ N., longitude 78° 31′ E.) in the Salem district of southern India. Two stones were seen to fall; the total weight recovered was 347 grams, of which 191 grams is in the collection of the Geological Survey of India in Calcutta and 121 grams is in the British Museum collection. We received a small piece of this meteorite from the Geological Survey of India, and because of its unusual features and the lack of a published description we decided to make a detailed investigation of its composition.

MINERALOGICAL COMPOSITION AND STRUCTURE

In hand specimen a cut surface of the meteorite is dark gray in color. Examination with a hand lens shows numerous well-formed chondrules in a fine-grained groundmass. Metal particles are visible but are not prominent or abundant. The meteorite is quite hard and not friable.

In transmitted light a thin section (fig. 3) shows numerous chondrules of olivine and pyroxene ranging from 0.3 mm. to 3 mm. in diameter. The chondrules are set in an isotropic groundmass, grayish brown and translucent but with a multitude of small black inclusions which renders it almost opaque in places. Some of the chondrules have narrow opaque rims. The groundmass also contains numerous angular grains of olivine and pyroxene ranging down to submicroscopic in size. The chondrules vary considerably in composition and structure. Some

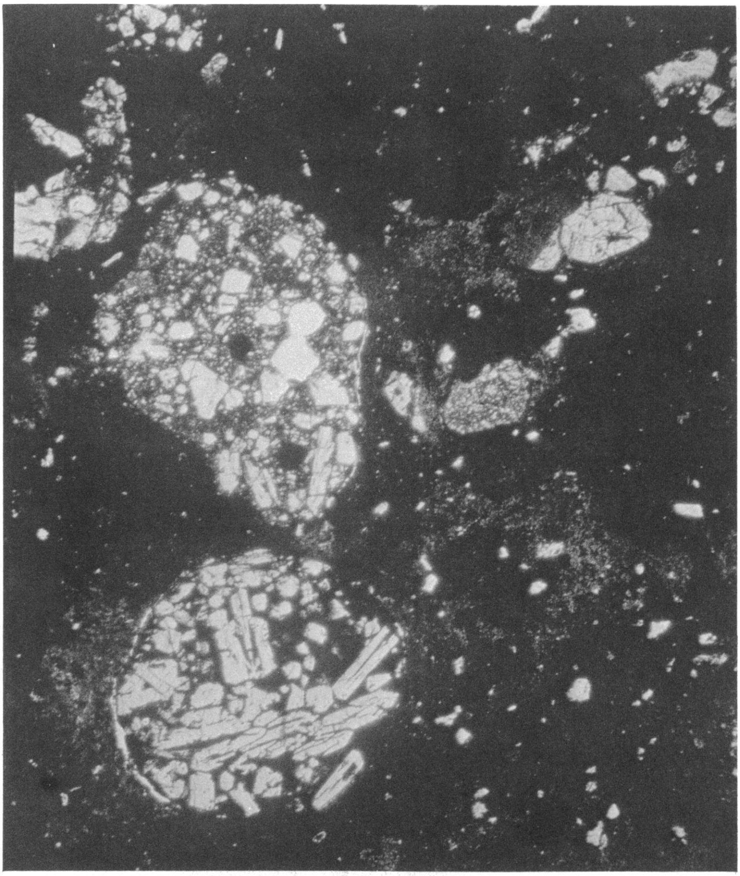

FIG. 3. Photomicrograph of a thin section of the Kakangari meteorite, showing chondrules of olivine and pyroxene in a grayish brown, almost opaque, groundmass. $\times 35$.

consist of euhedral olivine crystals in a turbid, weakly anisotropic groundmass. One consists of closely packed, twinned clinopyroxene crystals with poikilitically included olivines. Some consist entirely of pyroxene. In reflected light a polished thin section shows that the groundmass is filled with tiny grains of troilite (fig. 4). Larger grains of troilite, and grains of nickel-iron (kamacite and taenite) also occur. Troilite and nickel-iron are concentrated around the margins of some chondrules. Secondary iron oxides, probably the product of terrestrial weathering, are associated with some of the nickel-ion. Rare grains of chromite were observed.

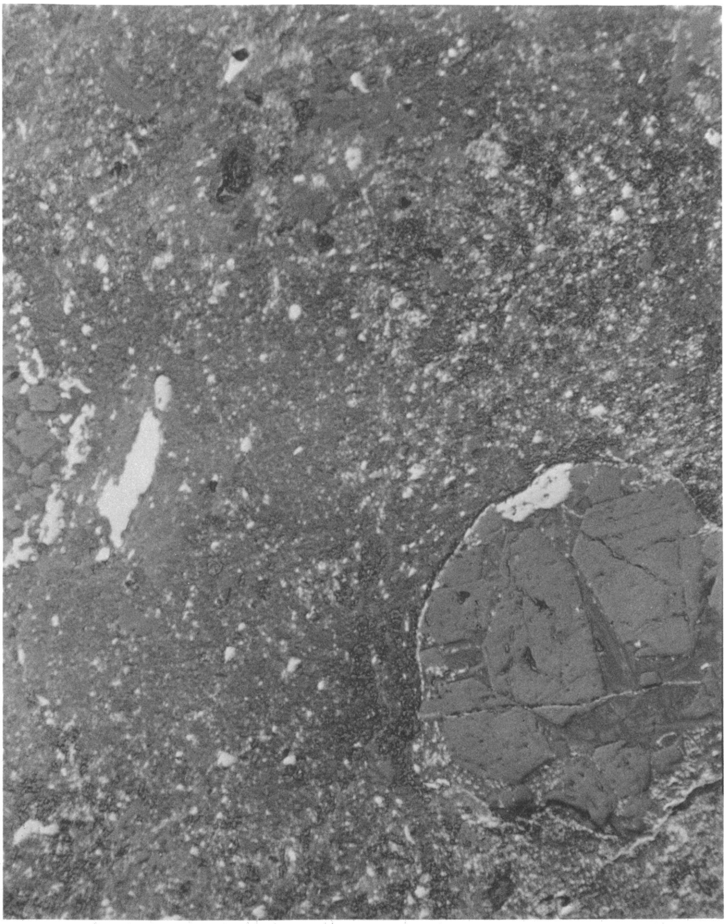

FIG. 4. Photomicrograph of a polished section of the Kakangari meteorite in reflected light, showing fine dispersion of troilite (white) throughout the groundmass. ×200.

The silicate minerals have been examined both optically and by X-ray diffraction, with the following results.

OLIVINE: An X-ray diffractogram shows a sharp olivine peak for the (130) reflection, but the peak is asymmetrical and skewed. According to the data of Yoder and Sahama (1957) this fact indicates that most of the olivine is close to forsterite in composition, but with a range in composition up to about 25 mole per cent of the Fe_2SiO_4 component. This is confirmed by the refractive indices, which vary from grain to

TABLE 5
CHEMICAL COMPOSITION OF THE KAKANGARI METEORITE

A		B		C	
Fe	7.46	Fe	22.47	Si	34.48
Ni	1.27	Si	16.90	Mg	34.26
Co	0.08	Mg	14.53	Fe	23.06
FeS	15.19	S	5.54	Al	2.50
SiO_2	36.16	Ni	1.27	Na	1.90
TiO_2	0.12	Ca	1.18	Ca	1.68
Al_2O_3	2.23	Al	1.18	Ni	1.24
FeO	6.90	Na	0.76	Mn	0.25
MnO	0.31	H	0.28	P	0.25
MgO	24.10	Mn	0.24	Cr	0.14
CaO	1.65	P	0.14	Ti	0.09
Na_2O	1.03	Cr	0.13	Co	0.08
K_2O	0.06	Co	0.08	K	0.07
P_2O_5	0.32	Ti	0.07		100.00
H_2O+	2.29	K	0.05		
H_2O-	0.18	C	0.20		
Cr_2O_3	0.19	(O	34.98)		
C	0.20		100.00		
	99.74				

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 elimination of O, S, C, and H

grain but with the majority having indices close to those for Mg_2SiO_4.

PYROXENE: The X-ray diffractogram shows that the pyroxene is largely clinopyroxene, with only minor amounts of orthopyroxene. In thin sections and grain mounts the clinopyroxene shows well-developed polysynthetic twinning. Most of the grains have refractive indices $\alpha = 1.653$, $\gamma = 1.661$, indicating a composition close to iron-free clinoenstatite, but some grains have higher indices and evidently contain some iron replacing magnesium.

PLAGIOCLASE: This mineral was not certainly identified in microscope preparations, but a weak plagioclase peak was seen on the X-ray diffractogram of the acid-insoluble fraction of the meteorite.

The gray-brown isotropic groundmass has not been mineralogically defined. In thin section it resembles the amorphous material characteristic of the Type-I carbonaceous chondrites, e.g., Alais. Judged from the bulk analysis, it is a hydrated magnesium-iron silicate similar in composition to serpentine.

The density of a small piece of the meteorite, determined as described for Bath, is 3.44.

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 O, H, C, and S. A discussion of these procedures is given under the description of the Bath meteorite.

Noteworthy features of the analysis are the comparatively high percentages of S, C, and H_2O+. Sulfur is 5.54 per cent, whereas the mean

TABLE 6
Normative Composition of the Kakangari Meteorite

Olivine	33.3
Orthopyroxene	24.1
Diopside	3.9
Albite	8.7
Anorthite	1.3
Orthoclase	0.3
Apatite	0.7
Chromite	0.3
Ilmenite	0.2
Troilite	15.2
Nickel-iron	8.8

for ordinary chondrites is 2.1 per cent. The only meteorites of comparable sulfur content are the Type-I and some of the Type-II carbonaceous chondrites, and some of the enstatite chondrites. In Kakangari the sulfur appears to be present entirely as troilite, whereas in the sulfur-rich carbonaceous chondrites much of it is combined in other forms. The C and the H_2O+ are evidently present in the groundmass, the gray-brown color of which may be due to organic compounds. Some of the H_2O+ is probably combined in the serpentine-like phase, and some of it may represent hydrogen combined in the organic material.

The normative mineral composition, expressed as weight percentages, is given in table 6. This only approximates the actual mineral composition, because only water-free minerals are calculated in the norm, and no account is taken of the serpentine-like phase. The amount of feldspar in the norm, 10.3 per cent, is certainly much greater than the amount of plagioclase that is actually present; much of the elements calculated as feldspar is probably combined in the pyroxene.

The classification of the Kakangari meteorite poses some problems. Chemically and mineralogically it shows some similarities to the carbonaceous chondrites, but it is considerably more reduced. Specifically, the elemental composition without O, C, S, and H is closely comparable to that of Mokoia, a Type-III carbonaceous chondrite, but Mokoia has no free metal and much less troilite. Kakangari has many features in common with Renazzo, also a difficult meteorite to classify (Mason and Wiik, 1962). However, the analysis of Renazzo has much less FeS and much more FeO than Kakangari. The over-all mineralogy and structure of Renazzo are remarkably similar to those of Kakangari. Under the circumstances it seems best to assign Kakangari to the carbonaceous chondrites but not to attempt to place it in any of the three types established by Wiik (1956).

THE ROSE CITY METEORITE

About 11 P.M. on October 17, 1921, a brilliant fireball was seen to pass from north-northwest to south-southeast over the northeastern part of the lower peninsula of Michigan. Near Rose City in Ogemaw County the fireball exploded, with the accompaniment of several loud reports, and three meteorites, weighing approximately 6.4, 3.2, and 1.5 kilograms, fell on the property of Mr. George Hall, about 9 miles northeast of the town. The largest piece fell only 40 feet from his house and penetrated the sod to a depth of some 2 feet. Hovey (1922) remarked that grass wedged into pits in the surfaces of the meteorite was not burned or even charred, showing that the stone was not hot when it hit the ground. Pieces of the Rose City meteorite are widely distributed in collections, but the largest part of the main mass is in the collection of the American Museum of Natural History (No. 3737).

Mineralogical Composition and Structure

Figure 5 illustrates some of the remarkable features of this meteorite. The groundmass is coal black in color, very hard, and a cut surface takes a good polish, although the interior of the meteorite contains a multitude of tiny pores and occasional larger cavities. The groundmass is thickly impregnated with small metal particles. Particularly noteworthy features are stringers, veinlets, and irregular aggregates of nickel-iron, which seem to be associated with areas and veins of crushing and deformation.

The principal minerals are olivine, pyroxene, and nickel-iron.

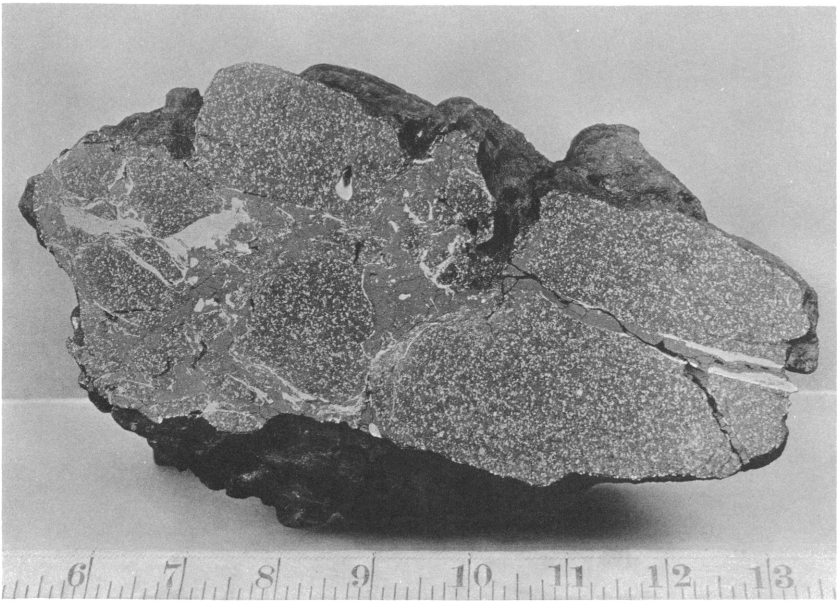

FIG. 5. Photograph of cut and polished surface of the Rose City meteorite, showing brecciation and veining; white is mainly nickel-iron, with some troilite. The scale is in inches.

Troilite and plagioclase are present in significant amounts. Accessory minerals include chromite, ilmenite, and a phosphate mineral (apatite or merrillite, or both). Notes on the silicates follow.

OLIVINE: The refractive indices are $\alpha = 1.674$, $\gamma = 1.707$, indicating a content of 19 mole per cent of the Fe_2SiO_4 component, according to the determinative curve of Poldervaart (1950). This composition was confirmed by the X-ray method of Yoder and Sahama (1957). The olivine peaks on the diffractometer chart are sharp, well defined, and symmetrical, indicating olivine of uniform composition.

PYROXENE: Pyroxene grains are usually turbid and frequently almost opaque from inclusions. The refractive indices are $\alpha = 1.672$, $\gamma = 1.681$, indicating a content of 15 mole per cent of the $FeSiO_3$ component, according to the determinative curve of Kuno (1954). In terms of the conventional subdivision of meteoritic pyroxene, this falls in the composition range of bronzite. X-ray diffractograms show that most of the pyroxene is clinopyroxene, along with lesser amounts of orthopyroxene; it is evidently a mixture of clinobronzite and bronzite.

PLAGIOCLASE: The plagioclase is extremely fine-grained, and only a

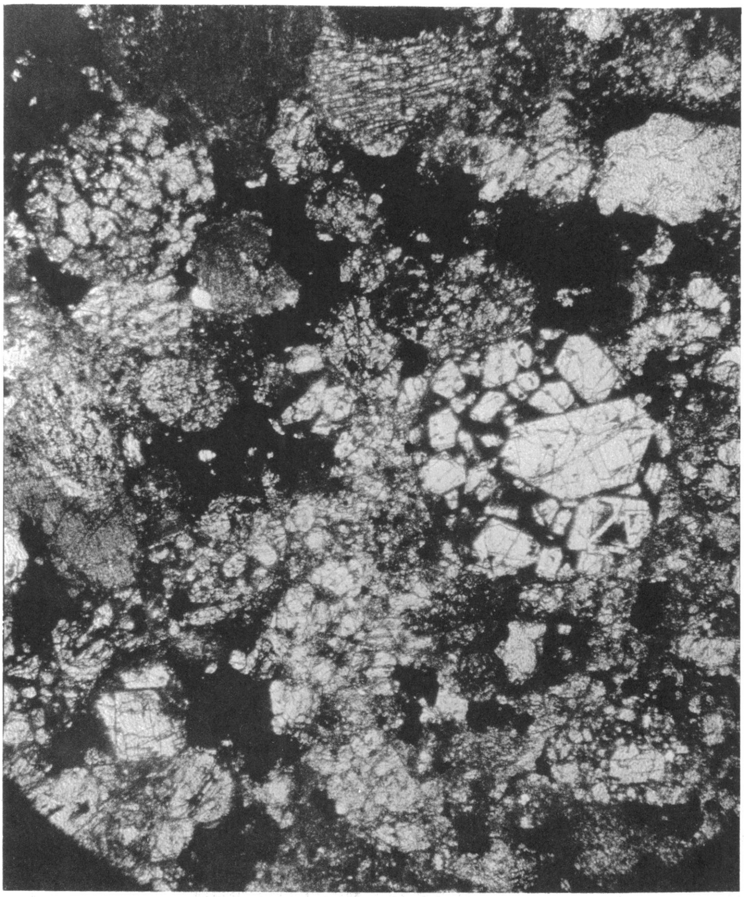

FIG. 6. Photomicrograph of a thin section of the Rose City meteorite, showing chondrules of olivine and pyroxene (gray); black is nickel-iron and troilite. × 35.

mean refractive index, 1.540, could be measured; this corresponds to a composition of about An_{15}.

A thin section (fig. 6) shows that Rose City is a fairly chondritic meteorite, but many of the chondrules are irregular and ill defined and appear to have suffered mechanical deformation. In some areas of the thin section chondritic structure has completely disappeared, apparently as a result of crushing. Many areas of the thin section are rendered almost opaque by the abundance of minute grains of troilite and metal.

The density of this meteorite, determined as described for Bath, is 3.74.

TABLE 7

CHEMICAL COMPOSITION OF THE ROSE CITY METEORITE

A		B		C	
Fe	26.19	Fe	36.40	Fe	36.20
Ni	2.24	Si	14.05	Si	27.80
Co	0.13	Mg	11.92	Mg	27.22
FeS	9.65	S	3.52	Al	3.03
SiO_2	30.08	Ni	2.24	Ni	2.12
TiO_2	0.13	Al	1.47	Na	1.24
Al_2O_3	2.78	Ca	0.86	Ca	1.19
FeO	5.25	Na	0.51	Cr	0.36
MnO	0.22	Cr	0.34	P	0.28
MgO	19.77	Mn	0.17	Mn	0.17
CaO	1.20	P	0.16	K	0.16
Na_2O	0.69	C	0.23	Co	0.13
K_2O	0.13	Co	0.13	Ti	0.10
P_2O_5	0.36	K	0.11		100.00
H_2O+	0.15	Ti	0.08		
H_2O-	0.00	H	0.02		
Cr_2O_3	0.50	(O	27.79)		
C	0.23		100.00		
	99.70				

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 elimination of O, H, C, and S

CHEMICAL COMPOSITION

The chemical analysis is given in table 7, in the conventional form expressed as nickel-iron, 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 O, H, C, and S. A discussion of these procedures is given under the description of the Bath meteorite.

The normative mineral composition, calculated from the analysis and expressed in weight percentages, is given in table 8. The actual mineral composition of the analyzed sample, obtained by point-counting a polished surface, is (in weight percentages): nickel-iron, 27.4; troilite, 8.4; chromite, 0.2; and silicates, 64.0. This is in good agreement with the norm.

The composition of the Rose City meteorite shows that it is an olivine-bronzite chondrite in Prior's (1920) classification, but the analysis shows some unusual features. The total iron content, 36.40 per cent, is very high, higher than normal for the high-iron (H) group of Urey

TABLE 8

NORMATIVE COMPOSITION OF THE ROSE CITY METEORITE

Olivine	24.3
Bronzite	24.3
Albite	5.8
Anorthite	3.6
Orthoclase	0.8
Apatite	0.8
Chromite	0.7
Ilmenite	0.2
Troilite	9.7
Nickel-iron	28.6

and Craig (1953). Furthermore, the nickel, cobalt, and sulfur content is higher than in any of the bronzite chondrites investigated by us. Rose City is a brecciated and inhomogeneous meteorite, and it is possible that the sample selected for analysis was from a metal and sulfide-rich part of the meteorite, and to that extent was not truly representative of the meteorite as a whole. The original analysis by Whitfield (*in* Hovey, 1922) reported 17.25 per cent of metal and 27.4 per cent of total iron, and these figures are close to the averages for olivine-bronzite chondrites.

THE TADJERA METEORITE

This meteorite fell at about 10:30 P.M. on June 9, 1867, some 15 kilometers southeast of the town of Sétif, in eastern Algeria. Two stones were recovered, with a total weight of about 8 kilograms. Most of the material is preserved in the Museum National d'Histoire Naturelle in Paris, but the meteorite is represented by small pieces in a number of collections. It was decribed by Daubrée (1868), with a chemical analysis by Meunier. Meunier (1871) later assigned the meteorite to a distinct type of chondrite which he named tadjerite, characterized specifically by the black color and the hardness.

Our interest in this meteorite arose from our investigation of Farmington (Buseck, Mason, and Wiik, 1966), which resembles Tadjera closely. A small piece of Tadjera in the collection of the American Museum of Natural History (No. 558) was available for investigation, and an additional specimen was obtained by exchange from the Paris museum.

MINERALOGICAL COMPOSITION AND STRUCTURE

In hand specimen Tadjera is coal black and extremely hard, break-

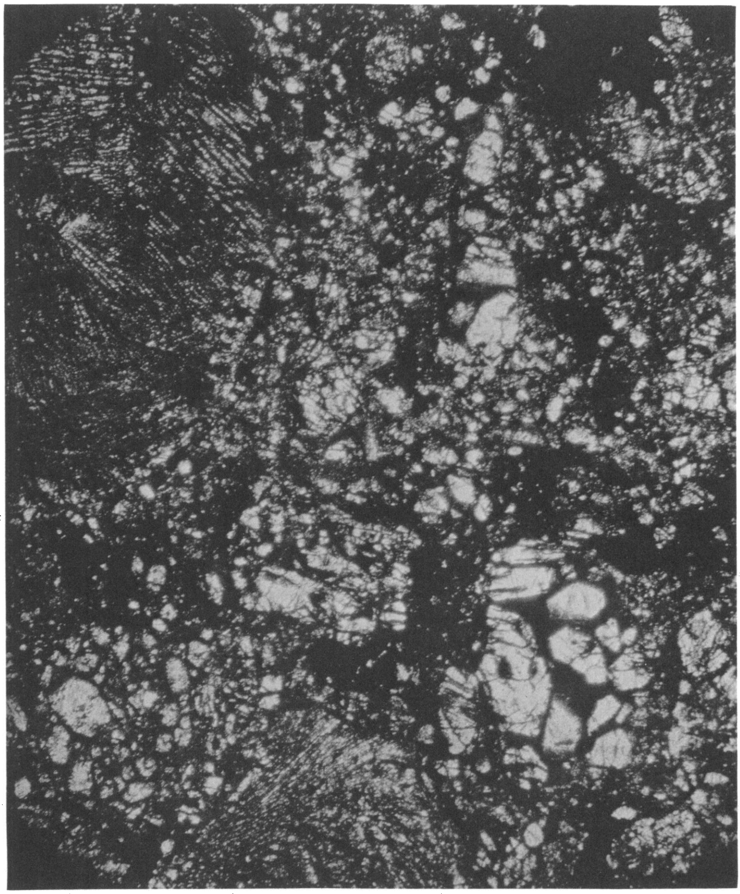

FIG. 7. Photomicrograph of a thin section of the Tadjera meteorite, showing chondrules of olivine and pyroxene (gray); black is nickel-iron and troilite. ×35.

ing with a splintery fracture. It takes a high polish, and the polished surface shows numerous small grains of nickel-iron and troilite; one large piece of troilite, 4 mm. across, was also seen. Chondrules can be distinguished with a hand lens, some of them partly rimmed by grains of nickel-iron and troilite.

The principal minerals are olivine and pyroxene, with minor amounts of nickel-iron (kamacite and taenite) and troilite. Accessory minerals include chromite, ilmenite, and a phosphate mineral (apatite or merrillite, or both). Notes on the silicate minerals follow.

OLIVINE: The refractive indices are $\alpha = 1.682$, $\gamma = 1.717$, indicating

TABLE 9

CHEMICAL COMPOSITION OF THE TADJERA METEORITE

A		B		C	
Fe	5.21	Fe	20.94	Si	36.27
Ni	1.11	Si	18.76	Mg	35.40
Co	0.03	Mg	15.85	Fe	20.36
FeS	5.90	S	2.15	Al	2.65
SiO_2	40.17	Al	1.31	Na	1.65
TiO_2	0.11	Ni	1.11	Ca	1.35
Al_2O_3	2.47	Ca	1.00	Ni	1.03
FeO	15.41	Na	0.70	Cr	0.51
MnO	0.36	Cr	0.49	Mn	0.28
MgO	26.29	Mn	0.28	P	0.27
CaO	1.41	P	0.16	K	0.12
Na_2O	0.95	C	0.13	Ti	0.08
K_2O	0.11	K	0.09	Co	0.03
P_2O_5	0.36	Ti	0.07		100.00
C	0.13	Co	0.03		
Cr_2O_3	0.72	(O	36.93)		
	100.74		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 O, S, and C

a content of 24 mole per cent of the Fe_2SiO_4 component, according to the determinative curve of Poldervaart (1950). By the X-ray method of Yoder and Sahama (1957), the composition was found to be 25 mole per cent of the Fe_2SiO_4 component. The olivine peaks on the diffractogram are sharp and well defined, indicating olivine of uniform composition.

PYROXENE: Many of the pyroxene grains are very turbid and almost opaque, and it is thus difficult to measure the optical properties. The refractive indices are $\alpha = 1.677$, $\gamma = 1.687$, indicating a content of 20 mole per cent of the $FeSiO_3$ component. An X-ray diffractogram shows that the material is almost entirely clinopyroxene, with little or no orthopyroxene. The peaks on the diffractogram are considerably broadened, probably indicating a considerable degree of disorder. The pyroxene can best be described as a clinohypersthene.

PLAGIOCLASE: This mineral was not identified in thin sections or in the X-ray diffractograms. However, on centrifuging an acid-insoluble fraction in an acetone-methylene iodide mixture of density 2.9, we obtained a very small amount of lower-density material. This consisted mostly of colorless isotropic grains of maskelynite, n = 1.502, indicating a composition of about An_{12}, according to the data of Foster (1955). A small amount of fine-grained plagioclase was also present, with a mean index of 1.538, indicating a composition of about An_{15}.

Examination of a thin section (fig. 7) shows that the meteorite is an aggregate of closely packed chondrules, averaging 0.5 mm. to 1 mm. in diameter. The boundaries of the chondrules are sometimes well defined by a concentration of opaque material at the margins. The chondrules show a considerable variety in composition and structure. A common type is an aggregate of euhedral olivine crystals in a gray, turbid, weakly anisotropic base. In one such chondrule, however, the base is colorless, isotropic, and with low relief, and is probably maskelynite. In other chondrules the olivine is seen as long prismatic crystals. Dense, fine-grained chondrules showing low birefringence are probably made up of pyroxene. The silicate minerals are colorless and transparent, and the deep black color of the meteorite is evidently due to finely disseminated opaque material. Examination of a polished thin section shows that this finely disseminated material is largely troilite, as extremely small, dustlike particles, and as thin films, particularly along cleavages and fractures in the silicate minerals.

The black color, the highly indurated condition, the disseminated troilite, and the disordered pyroxene all suggest that the Tadjera meteorite was subjected to intense shock some time during its extraterrestrial history.

The density of this meteorite, determined as described for Bath, is 3.56.

Chemical Composition

Since Meunier's original analysis reported only traces of sodium and potassium, we decided to make a new analysis, and the results are given in table 9, 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 O, C, and S. A discussion of these procedures is given under the description of the Bath meteorite.

The composition of the Tadjera meteorite shows that it is an olivine-hypersthene chondrite in Prior's (1920) classification. The total iron content, 20.94 per cent, places it in the low-iron (L) group of Urey and Craig (1953). As we expected, the composition of Tadjera is quite similar to that of Farmington (and many other hypersthene chondrites).

The normative mineral composition, expressed as weight percentages, is given in table 10. The actual mineral composition, obtained by point-counting a polished surface, is nickel-iron, 7.9 per cent; troilite, 5.5 per cent; chromite, 0.2 per cent; and silicates, 86.4 per cent. This is in good agreement with the norm, except that normative chromite

TABLE 10

NORMATIVE COMPOSITION OF THE TADJERA METEORITE

Olivine	49.9
Hypersthene	23.2
Diopside	2.0
Albite	8.0
Anorthite	2.1
Orthoclase	0.7
Chromite	1.1
Apatite	0.8
Ilmenite	0.2
Troilite	5.9
Nickel-iron	6.4

is high—not all the chromium is combined as chromite, a good part of it being in the pyroxene. The amount of feldspar in the norm, 10.8 per cent, is much higher than the amount of plagioclase and maskelynite actually present; probably a large part of the elements calculated as feldspar is also combined in the pyroxene.

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