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The Composition of the Belly River, Bluff, Bremervörde, and Modoc Meteorites

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THE BELLY RIVER METEORITE

This meteorite was found in the winter of 1943–1944 as a result of a forced landing of a Royal Canadian Air Force airplane on the eastern side of and near the Belly River in southern Alberta, Canada. LaPaz (1953) published a preliminary report and placed the location as approximately in latitude 49° 30′ N., longitude 113° 00′ W. The meteorite was discovered by Boyd Wettlaufer while he was making a reconnaissance about the downed plane. It was a 7.9-kilogram stone.

We received a piece by exchange with the Geological Survey of Canada and were interested to observe the remarkable veining described by LaPaz. We therefore decided to investigate its structure and composition further.

MINERALOGICAL COMPOSITION AND STRUCTURE

The principal minerals are olivine, pyroxene, and nickel-iron. The usual amount of troilite is present, as well as a small amount of plagioclase. Accessory minerals include chromite and probably a phosphate mineral (apatite or merrillite, or both). Notes on the silicates follow.

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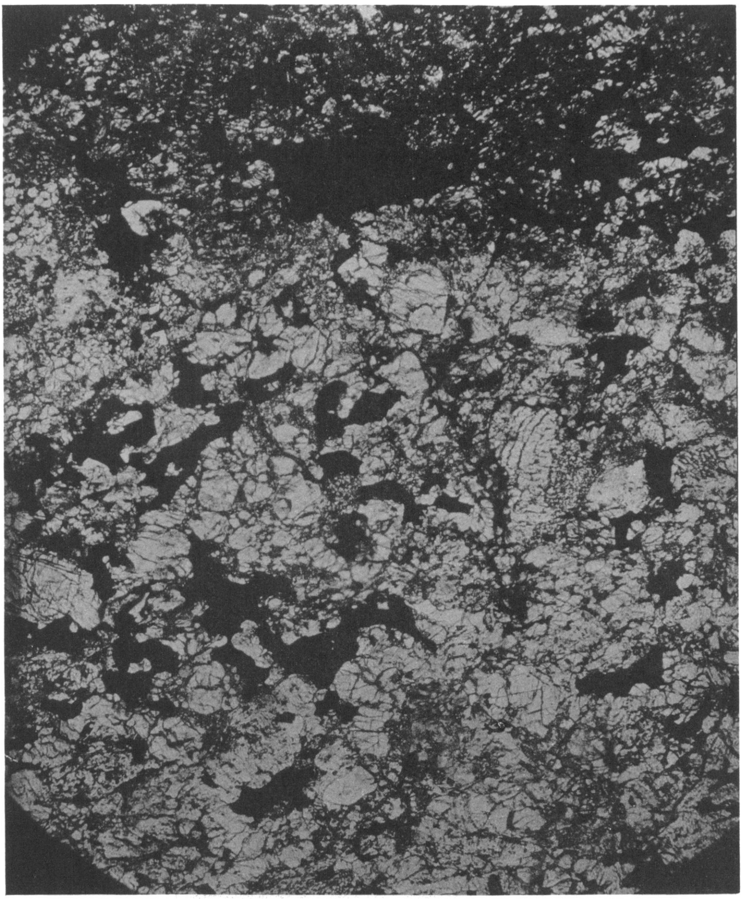

FIG. 1. Photomicrograph of a thin section of the Belly River meteorite, showing olivine and pyroxene (light gray) with interstitial opaque minerals (black); at the top the margin of a vein is seen, with comminuted silicates darkened by disseminated opaque material. ×35.

OLIVINE: The refractive indices are $\alpha = 1.673$, $\gamma = 1.706$, indicating a content of 18 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 20 mole per cent of the Fe_2SiO_4 component. The olivine peaks on the diffractometer chart are sharp and symmetrical, but their bases are somewhat broadened, indicating the possibility of some compositional variation or structural disorder.

PYROXENE: Most of the grains are turbid, and many show undulose extinction. 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). In terms of the conventional subdivision of meteoritic pyroxene, this falls in the compositional range of bronzite. An X-ray diffractogram shows that a considerable part of the pyroxene is actually clinobronzite.

PLAGIOCLASE: Only a few grains of this mineral were found in an acid-insoluble fraction of the meteorite. It is fine-grained and turbid, and only a mean refractive index, 1.536, could be measured; this corresponds to a composition of about An_{10}.

A thin section of the meteorite (fig. 1) shows numerous chondrules, 0.3–1 mm. in diameter, except in the veined areas, where they have been largely destroyed. However, the margins of the chondrules are frequently indistinct and merge imperceptibly with the groundmass. The veined areas are much finer-grained, apparently through crushing, and black opaque material is extensively dispersed through these areas. Within the veined areas are veinlets of comminuted silicates full of tiny spherical droplets of metal and mixed metal-sulfide. Films of nickel-iron and troilite coat cleavages and fractures in the silicate minerals.

The quantitative mineralogical composition, in weight per cent, determined by point-counting a polished section, is nickel-iron, 15.9; troilite, 4.1; chromite, 0.3; silicates, 79.7.

The density of a piece of this meteorite was determined by measuring the apparent loss of weight on suspension in carbon tetrachloride (after evacuation under a bell jar to remove air), and found to be 3.64.

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, H, 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 is present as ferrous iron, that all Ni and Co are present in the metal phase. These assumptions are essentially valid for the Belly River meteorite.

The second procedure for expressing the analysis reflects more closely the results actually obtained by the analyst. 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

TABLE 1

CHEMICAL COMPOSITION OF THE BELLY RIVER METEORITE

A		B		C	
Fe	13.00	Fe	25.89	Si	33.96
Ni	1.56	Si	17.45	Mg	32.30
Co	0.09	Mg	14.35	Fe	25.38
FeS	4.38	S	1.60	Al	2.65
SiO_2	37.37	Ni	1.56	Na	1.76
TiO_2	0.14	Al	1.30	Ni	1.46
Al_2O_3	2.47	Ca	0.98	Ca	1.35
Cr_2O_3	0.40	Na	0.74	P	0.31
FeO	12.93	Cr	0.27	Cr	0.29
MnO	0.32	Mn	0.25	Mn	0.25
MgO	23.80	P	0.17	K	0.12
CaO	1.38	Co	0.09	Ti	0.09
Na_2O	1.00	C	0.09	Co	0.08
K_2O	0.10	H	0.09		100.00
P_2O_5	0.40	Ti	0.08		
H_2O+	0.81	K	0.08		
H_2O-	0.03	(O	35.01)		
C	0.09		100.00		
	100.27				

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, H, and C

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, H, and S 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 during heating in extraterrestrial environments.

The composition of the Belly River meteorite shows that it is an olivine-bronzite chondrite in Prior's classification (1920). The total iron content, 25.89 per cent, places it in 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 as weight percentages, is given in table 2. The observed mineral composition agrees with that calculated from the analysis. However, the calculated FeO/FeO+MgO ratio for the olivine and pyroxene is somewhat greater than that deduced from the refractive indices of these minerals. This derives from the partial weathering the meteorite has undergone, whereby some of the FeO reported in the analysis is not combined in the silicates, but is present as limonite. As a result, the calculated $FeO/FeO + MgO$ ratio is greater than the true value for the silicates, and the norm gives somewhat higher olivine and somewhat lower pyroxene than are actually present.

TABLE 2
NORMATIVE COMPOSITION OF THE BELLY RIVER METEORITE

Olivine	42.5
Bronzite	23.0
Diopside	1.9
Albite	8.4
Anorthite	1.9
Orthoclase	0.6
Apatite	0.9
Chromite	0.6
Ilmenite	0.3
Troilite	4.4
Nickel-iron	14.7

THE BLUFF METEORITE

The original specimen of the Bluff meteorite, a single stone weighing about 320 pounds, was found in 1878 by Frank Rainosek on his farm about 3 miles south of the town of La Grange, in Fayette County, Texas. H. Hensoldt, a local school teacher, acquired the stone in 1888 and disposed of it to Ward and Howell (now Ward's Natural Science Establishment) of Rochester, New York, who cut it up and sold pieces to many institutions; Wülfing (1897) listed 41 collections that possessed specimens. It received the name Bluff because La Grange had already been used for a Kentucky meteorite. However, Bluff is not a recognized settlement, being merely a few farms scattered within a radius of a couple of miles. In 1890 C. L. Melcher found three stones on his farm, about 6 miles southwest of the original Bluff find. These were recognized as meteoritic in 1900, when chips were sent to G. P. Merrill. In view of their proximity, these stones were considered to be part of the Bluff fall. The largest specimen ultimately went to the Field Museum of Natural History and was illustrated in Farrington's catalogue (1916, pl. 64). Later, however, Merrill (1918) examined thin sections of both the 1878 and 1890 finds and decided that they were different meteorites; the 1890 find he called Cedar, after a small settlement 6 miles southwest of La Grange. Mason (1963) confirmed the separate identity of Bluff and Cedar, Bluff being an olivine-hypersthene chondrite and Cedar an olivine-bronzite chondrite. The history of the finds was recorded by Barnes (1940a), who reported the 1936 investigations of J. J. Sedlmeyer in the area. Sedlmeyer mapped the location of the earlier finds and also recovered three more stones. Barnes listed the stones as follows:

No. 1, Bluff (Rainosek, 1878), about 320 pounds
No. 2, Bluff (Sedlmeyer, 1936; found by Louis Hausmann about 40 years earlier), 17 pounds, 1 ounce
No. 3, Bluff (Sedlmeyer, 1936; found by George Bruns in 1917 or earlier), 30 pounds
No. 4, Cedar (Melcher, 1890), 16 pounds $9\frac{3}{4}$ ounces
No. 5, Cedar (Melcher, 1890), 2 pounds, 12 ounces
No. 6, Cedar (Melcher, 1890), 12 pounds, $3\frac{1}{2}$ ounces
No. 7, Cedar (Sedlmeyer, 1936; found by Henry Rainosek about 30 years earlier), 25 pounds, 7 ounces

The locations of nos. 1, 2, and 3 lie along a line 2.5 miles long centered at about latitude 29° 52′ N., longitude 96° 55′ W.; those of nos. 4, 5, 6, and 7 lie along a line 2 miles long centered at about latitude 29° 49′ N., longitude 96° 58′ W.

Of the three Bluff stones, no. 1 is widely distributed in collections; no. 2 is in the collection of the Bureau of Economic Geology, Austin, Texas; and no. 3 is in the Texas Observers Collection, Fort Worth, Texas. Of the Cedar stones, no. 4 is in the collection of the Field Museum of Natural History [labeled Bluff, according to the latest published catalogue (Horback and Olsen, 1965)]; no. 5, or most of it, is probably in the collection of Baylor University, Waco, Texas; 2.8 kilograms of no. 6 is in the United States National Museum collection; and no. 7 is in the collection of the Bureau of Economic Geology, Austin, Texas. It is possible that pieces of Cedar may be labeled Bluff in some collections.

There is a third find of stony meteorites in Fayette County, Texas, near Round Top (latitude 30° 04′ N., longitude 96° 42′ W.), a village 17 miles northeast of La Grange. This is also a multiple fall, three stones having been found. These meteorites are in the collection of Mr. O. E. Monnig of Fort Worth, to whom I am indebted for the opportunity of examining them. At least two different meteorites are represented, no. 1 being an olivine-bronzite chondrite; nos. 2 and 3 are olivine-hypersthene chondrites. In view of the distance separating them, it is unlikely that the Round Top stones are in any way related to the Bluff and Cedar meteorites.

Bluff was originally described by Whitfield and Merrill (1888). The amount and composition of the nickel-iron were determined by Prior

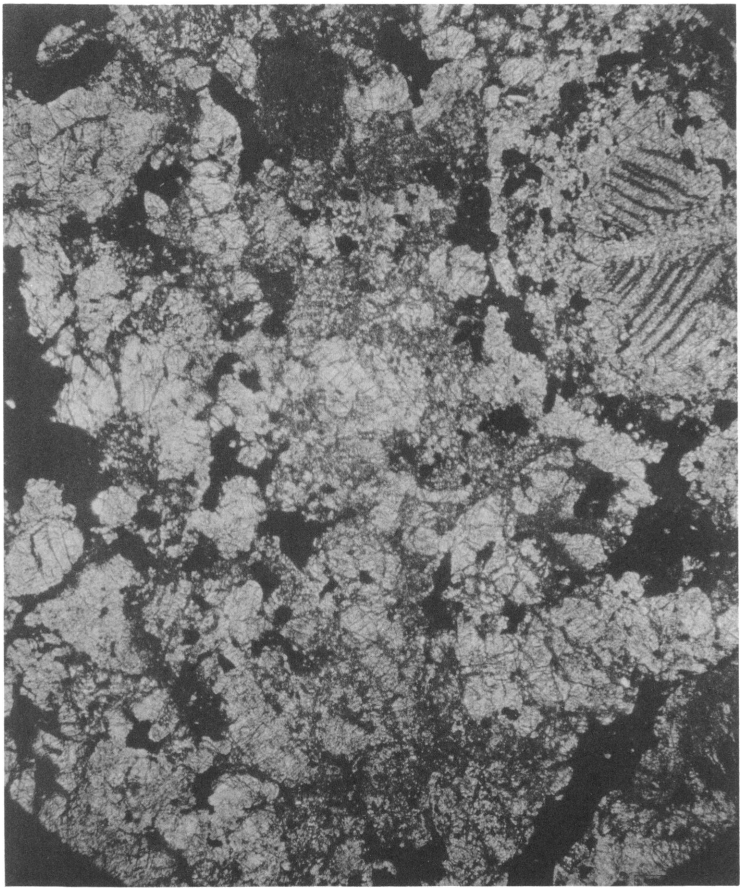

FIG. 2. Photomicrograph of a thin section of the Bluff meteorite, showing chondrules of olivine and pyroxene (light gray); black is nickel-iron and troilite. ×35.

(1919). Wahl (1950) pointed out that Whitfield's analysis shows no alkalies and is doubtful. On this account, and because of the wide distribution of the meteorite, we decided to reanalyze it.

MINERALOGICAL COMPOSITION AND STRUCTURE

Slices of the Bluff meteorite are stained uniformly dark brown with limonite as a result of terrestrial weathering. The surface crust is rusty brown and 1–2 mm. thick. The meteorite is hard and takes a good polish. Polished surfaces show numerous small particles of metal and troilite; chondrules can be seen, but are not conspicuous. Thin black veins cut

TABLE 3

CHEMICAL COMPOSITION OF THE BLUFF METEORITE

A		B		C	
Fe	7.43	Fe	21.11	Si	36.74
Ni	1.12	Si	18.61	Mg	33.18
Co	0.07	Mg	14.54	Fe	21.00
FeS	6.36	S	2.32	Al	2.83
SiO_2	39.80	Ca	1.90	Ca	2.61
TiO_2	0.12	Al	1.38	Na	1.45
Al_2O_3	2.61	Ni	1.12	Ni	1.06
Cr_2O_3	0.55	Na	0.60	Cr	0.40
FeO	13.70	Cr	0.38	Mn	0.26
MnO	0.33	Mn	0.26	P	0.23
MgO	24.11	P	0.13	K	0.09
CaO	2.64	C	0.11	Ti	0.08
Na_2O	0.81	K	0.07	Co	0.07
K_2O	0.08	Ti	0.07		100.00
P_2O_5	0.30	Co	0.07		
C	0.11	(O	37.33)		
	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 body of the meteorite, but they are not abundant, and many areas of the meteorite are quite free of them.

The principal minerals are olivine and pyroxene. Troilite, nickel-iron, and plagioclase are present in minor amounts. Accessory minerals include chromite and a phosphate (apatite or merrillite, or both). Notes on the silicates follow.

OLIVINE: The refractive indices are $\alpha = 1.682$, $\gamma = 1.718$, indicating 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 diffractometer chart are sharp, symmetrical, and well defined.

PYROXENE: The pyroxene is a mixture of hypersthene and clinohypersthene in approximately equal amounts. The hypersthene has refractive indices $\alpha = 1.677$, $\gamma = 1.688$, indicating a content of about 20 mole per cent of the $FeSiO_3$ component, according to the determinative curve of Kuno (1954). The refractive indices of the clinohypersthene are approximately the same as those of the orthopyroxene, but the grains of clinopyroxene are turbid, and optical properties are difficult to measure. A little diopside is also present.

PLAGIOCLASE: A small amount of this mineral is present. It is very fine-grained, and only a mean refractive index, 1.539, could be measured; this indicates a composition of about An_{15}.

In thin section (fig. 2) numerous chondrules of olivine and pyroxene, 0.2–1 mm. in diameter, are seen, but their boundaries are frequently ill defined, and they merge imperceptibly into a crystalline groundmass. The opaque minerals are largely confined to the groundmass, although small grains are included in some of the chondrules. No glass was seen, but a turbid gray material with low birefringence, probably devitrified glass, forms the interstitial material in a chondrule made up of euhedral olivine crystals. A thin section of one of the above-mentioned black veins, 2 mm. thick, shows an opaque groundmass including grains of colorless silicate minerals which do not extinguish between crossed nicols. The vein material also contains a good deal of finely divided metal and troilite. Barnes (1940b) has described these veins in considerable detail and points out their similarity to pseudotachylite veins in terrestrial rocks.

TABLE 4
NORMATIVE COMPOSITION OF THE BLUFF METEORITE

Olivine	40.6
Hypersthene	25.6
Diopside	6.4
Albite	6.9
Anorthite	3.2
Orthoclase	0.4
Chromite	0.8
Apatite	0.7
Ilmenite	0.2
Troilite	6.4
Nickel-iron	8.6

Keil (1962) reported the following mineralogical composition for the Bluff meteorite (in weight per cent): nickel-iron, 7.33; troilite, 5.89; chromite, 0.45; silicates, 86.33.

The density of the Bluff meteorite, determined as described for Belly River, was found to be 3.47.

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

The composition of the Bluff meteorite shows that it is an olivine-hypersthene chondrite in Prior's (1920) classification. The total iron content, 21.11 per cent, is that of a low-iron (L) group chondrite of Urey and Craig (1953). The normative mineral composition, calculated from the analysis and expressed as weight percentages, is given in table 4. This is in good agreement with the observed mineralogical composition, except that it reports considerably more plagioclase than was actually observed; probably most of the normative plagioclase is represented by devitrified glass.

THE BREMERVÖRDE METEORITE

This meteorite fell at Gnarrenburg, near Bremervörde in northwestern Germany, on May 13, 1855. At least five stones, with a total weight of about 5 kilograms, were recovered. The largest, weighing about 3 kilograms, is preserved in the collection of the Mineralogical Institute of the University of Göttingen, and the second largest, 1.2 kilograms, is in the Clausthal Bergsakademie. Small portions are present in many collections. There is a considerable nineteenth-century literature concerning it, which was listed by Wülfing (1897).

Some time ago one of us (Mason, 1963) reported that the composition of the olivine in Bremervörde was Fa_{24}, and that it was an olivine-hypersthene chondrite. This determination was made on a piece (No. 422) labeled Bremervörde in the collection of the American Museum of Natural History. However, Keil and Fredriksson (1964) reported an olivine composition of $Fa_{17.3}$, indicating that their sample was an olivine-bronzite chondrite. Because of this discrepancy, we obtained a sample from the stone in the Mineralogical Institute of the University of Göttingen. This proved to be an olivine-bronzite chondrite, the piece in the American Museum of Natural History being evidently a mislabeled specimen. Since the old analysis by Wöhler in 1856 is deficient in several respects, we decided to reanalyze the meteorite, using the sample obtained from Göttingen.

Mineralogical Composition and Structure

Broken pieces of the meteorite are medium gray in color, and chon-

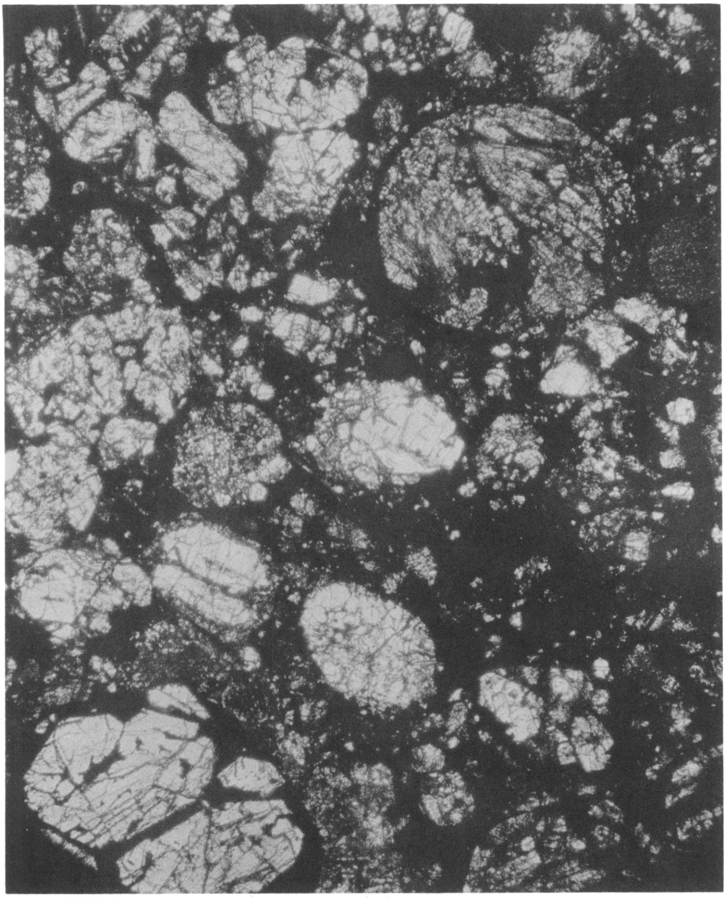

FIG. 3. Photomicrograph of the Bremervörde meteorite, showing well-formed chondrules of olivine and pyroxene (light gray) in a dark groundmass of fine-grained silicates and opaque material. ×35.

drules are clearly visible with the naked eye. A cut surface shows that the meteorite is an aggregate of well-formed chondrules, with a considerable amount of metal in the groundmass between the chondrules. Previous descriptions mentioned that Bremervörde was brecciated, but the small pieces that we have seen do not show such a feature.

The principal minerals are olivine, pyroxene, and nickel-iron (kamacite and taenite). Troilite and plagioclase are present in minor amounts. Accessory minerals include chromite and a phosphate (apatite or merrillite, or both). Notes on the silicates follow.

TABLE 5
CHEMICAL COMPOSITION OF THE BREMERVÖRDE METEORITE

A		B		C	
Fe	12.65	Fe	26.52	Si	34.08
Ni	1.52	Si	17.57	Mg	32.17
Co	0.10	Mg	14.35	Fe	25.82
FeS	5.95	S	2.17	Al	2.37
SiO_2	37.64	Ni	1.52	Na	1.69
TiO_2	0.10	Al	1.17	Ni	1.41
Al_2O_3	2.23	Ca	1.00	Ca	1.38
Cr_2O_3	0.50	Na	0.72	Cr	0.36
FeO	12.86	Cr	0.34	Mn	0.24
MnO	0.31	Mn	0.24	P	0.21
MgO	23.80	C	0.23	K	0.11
CaO	1.42	P	0.12	Co	0.09
Na_2O	0.97	Co	0.10	Ti	0.07
K_2O	0.09	K	0.07		100.00
P_2O_5	0.27	H	0.07		
H_2O+	0.23	Ti	0.06		
H_2O-	0.10	(O	33.75)		
C	0.23		100.00		
	100.97				

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, S, and C

OLIVINE: The refractive indices are $\alpha = 1.668$, $\gamma = 1.706$, corresponding to a content of 18 mole per cent of the Fe_2SiO_4 (Fa) component, according to the determinative curve of Poldervaart (1950). This was confirmed by the X-ray method of Yoder and Sahama (1957); the olivine peaks on the diffractometer chart are sharp and well defined, but possibly slightly broadened at the base. Keil and Fredriksson (1964), by microprobe analysis, reported the olivine composition to be $Fa_{17.3}$. Dodd and van Schmuss (1965), also by microprobe analysis, reported a variable olivine composition, Fa_{15}–Fa_{18}, with a mean value of $Fa_{17.1}$.

PYROXENE: Judged from the X-ray diffractogram, most of the pyroxene is clinobronzite, together with some bronzite. The clinobronzite grains are usually turbid to almost opaque, and unsatisfactory for optical measurements. The bronzite grains are clear and transparent, but the refractive indices vary from grain to grain. Keil and Fredriksson measured the composition of a number of pyroxene grains, and found that the Fe/Fe+Mg mole per cent varied from 6.5 to 22.5.

Plagioclase: This mineral was not certainly identified under the microscope, although it is probably a major constituent of the devitrified glass present in some chondrules. A weak plagioclase reflection was recognized in an X-ray diffractogram of the acid-insoluble fraction of the meteorite.

In thin section (fig. 3) numerous chondrules of olivine and pyroxene, 0.2–2.5 mm. in diameter, are seen. The chondrules show a wide range of structural type, although none of the barred olivine type were seen. The most prominent variety of chondrule is one consisting of numerous euhedral olivine crystals with interstitial glass. In some areas the glass is brown and transparent, but frequently it is partly or completely devitrified to a dark turbid material with weak birefringence, either plagioclase or a mixture of plagioclase and pyroxene. Eccentrically radiating pyroxene chondrules are not uncommon. Some chondrules consist of an aggregate of olivine and clinobronzite crystals, the olivine being euhedral against the pyroxene. The troilite and nickel-iron are concentrated in the groundmass between the chondrules; a minor amount of limonitic staining is associated with the nickel-iron.

TABLE 6

Normative Composition of the Bremervörde Meteorite

Olivine	41.3
Bronzite	23.9
Diopside	3.1
Albite	8.2
Anorthite	1.4
Orthoclase	0.6
Chromite	0.7
Apatite	0.6
Ilmenite	0.2
Troilite	6.0
Nickel-iron	14.3

The quantitative mineralogical composition, determined by point-counting a polished surface, is (in weight per cent): nickel-iron, 15.1; troilite, 6.6; chromite, 0.1; silicates, 78.2.

The density of this meteorite, determined as for Belly River, is 3.60.

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

The composition of the Bremervörde meteorite shows that it is an olivine-bronzite chondrite in Prior's (1920) classification, although, as pointed out above, the pyroxene is largely clinobronzite rather than bronzite. The total iron content, 26.52 per cent, is that of a chondrite of the high-iron (H) group of Urey and Craig (1953). The normative mineral composition, expressed as weight percentages, is given in table 6. This is in good agreement with the observed mineral composition, except that the normative plagioclase must be represented largely by the glass in the meteorite.

THE MODOC METEORITE

The Modoc meteorite fell as a shower of stones on the evening of September 2, 1905, after a brilliant fireball was seen over a wide area in eastern Colorado and western Kansas. The circumstances of the fall were described by Merrill (1906) and Farrington (1907). Farrington recorded the recovery of 15 stones, with an aggregate weight of about 16 kilograms. He mapped the distribution of the stones, which were found along an east-west strip of country 7 miles long and 2 miles wide, centered approximately on Modoc, Kansas, a station on the Missouri Pacific Railroad. Many more stones must ultimately have been recovered. The largest stone, which weighs more than 9 kilograms, was plowed up by J. K. Freed on his farm near Modoc in May, 1908, and acquired by the American Museum of Natural History, which subsequently obtained 15 stones of this fall with the Howell collection in 1914 and 20 more by purchase in 1920. The total weight recorded in collections is at least 35 kilograms. The largest stones are as follows: 9110 grams (the American Museum of Natural History); 4560 grams (United States National Museum); 3184 grams (Field Museum of Natural History); 2317 grams (the American Museum of Natural History); 2045 grams (British Museum).

Nininger (1950) recorded the recovery of a meteorite which he called Modoc No. 2 in the following terms: "This weathered stone was said to have been found by Frank Novak some years earlier and was reported by J. K. Freed to us in 1948. It proved to be distinct from both Modoc and Scott City. It has the appearance of a very old fall." Modoc No. 2 is an olivine-bronzite chondrite and is evidently a distinct fall; the composition of its olivine is Fa_{19}, not Fa_{22} as reported by Mason (1963).

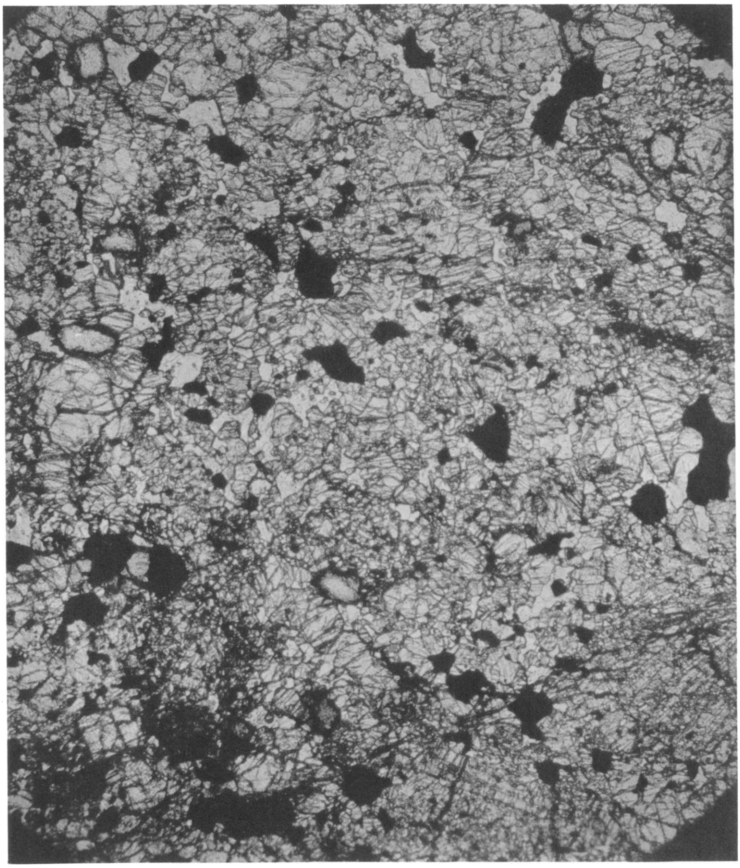

FIG. 4. Photomicrograph of the Modoc meteorite, a recrystallized aggregate of silicate material (light gray) and opaque minerals (black), in which the chondritic structure has largely disappeared. ×35.

Since Modoc has been extensively used for trace element determinations, and since the original analysis shows unusually high SiO_2, low Ni, and low Na_2O, we decided to reanalyze this meteorite.

MINERALOGICAL COMPOSITION AND STRUCTURE

A broken surface of the meteorite is pale gray, almost white in color, with rusty specks surrounding the small grains of nickel-iron. It is rather friable. Chondrules can be distinguished with a hand lens but are not conspicuous. The black fusion crust, about 0.5 mm. thick, is unusually thick for a chondrite.

TABLE 7
CHEMICAL COMPOSITION OF THE MODOC METEORITE

A		B		C	
Fe	6.68	Fe	22.42	Si	35.91
Ni	1.30	Si	18.37	Mg	33.75
Co	0.08	Mg	14.94	Fe	22.04
FeS	6.46	S	2.36	Al	2.69
SiO_2	39.29	Al	1.32	Na	1.65
TiO_2	0.12	Ni	1.30	Ca	1.59
Al_2O_3	2.49	Ca	1.16	Ni	1.22
Cr_2O_3	0.55	Na	0.69	Cr	0.40
FeO	14.96	Cr	0.38	Mn	0.25
MnO	0.33	Mn	0.26	P	0.23
MgO	24.78	C	0.18	K	0.12
CaO	1.62	P	0.13	Ti	0.08
Na_2O	0.93	K	0.09	Co	0.07
K_2O	0.10	Co	0.08		100.00
P_2O_5	0.30	Ti	0.07		
C	0.18	(O	36.25)		
	100.17		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 principal minerals are olivine and pyroxene. Nickel-iron (kamacite and taenite), troilite, and plagioclase are present in minor amounts. Accessory minerals include chromite and a phosphate (apatite or merrillite, or both). Notes on the silicates follow.

OLIVINE: The refractive indices are $\alpha = 1.680$, $\gamma = 1.716$, indicating a content of 23 mole per cent of the Fe_2SiO_4 component, according to the determinative curve of Poldervaart (1950). This was confirmed by the X-ray method of Yoder and Sahama (1957). The olivine peaks on the diffractometer chart are sharp and symmetrical, indicating olivine of uniform composition.

PYROXENE: The pyroxene is orthopyroxene, with accessory amounts of diopside. The refractive indices are $\alpha = 1.679$, $\gamma = 1.689$, indicating a content of 21 mole per cent of the $FeSiO_3$ component, according to the determinative curve of Kuno (1954). In terms of the conventional subdivision of meteoritic orthopyroxene, this falls in the composition range of hypersthene. The refractive indices of the diopside are $\alpha = 1.676$, $\gamma = 1.705$; microprobe analyses show that the composition is about $Ca_{40}Mg_{52}Fe_8$.

Plagioclase: The refractive indices are $\alpha = 1.532$, $\gamma = 1.540$, indicating a composition of An_9.

A thin section (fig. 4) shows that Modoc is an extensively recrystallized chondrite. Few of the chondrules show sharp boundaries against the groundmass, and the texture of the latter is not notably different from the chondrules themselves. Plagioclase is unusually well developed, in grains averaging 0.05–0.1 mm. across, and in some cases shows polysynthetic twinning; in some places it is seen to form the bars in what were originally barred olivine chondrules, but which are now almost obliterated by recrystallization.

TABLE 8

Normative Composition of the Modoc Meteorite

Olivine	46.1
Hypersthene	23.6
Diopside	3.1
Albite	7.9
Anorthite	2.3
Orthoclase	0.6
Chromite	0.8
Apatite	0.7
Ilmenite	0.2
Troilite	6.5
Nickel-iron	8.1

The quantitative mineralogical composition, obtained by point-counting a polished surface, is (in weight per cent): nickel-iron, 7.5; troilite, 6.8; chromite, 0.7; silicates, 85.0. The amount of chromite is unusually high; it appears that extensive recrystallization probably expels chromium from the pyroxene structure and causes it to recombine as chromite.

The density of this meteorite, determined as for Belly River, is 3.58.

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

The composition of the Modoc meteorite shows that it is an olivine-hypersthene chondrite in Prior's (1920) classification. The total iron content, 22.42 per cent, is that of a chondrite of the low-iron (L) group of Urey and Craig (1953). The normative mineral composition, expressed as weight percentages, is given in table 8. This agrees well with the observed mineral composition.

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