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The Composition of the Barratta, Carraweena, Kapoeta, Mooresfort, and Ngawi Meteorites

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THE BARRATTA METEORITE

More than 200 kilograms of meteorites have been found on Barratta Station, about 30 miles northwest of Deniliquin, New South Wales, Australia. Barratta lies on the vast floodplain between the Murray and Murrumbidgee rivers; the coordinates of the station homestead are latitude 35° 16′ S., longitude 144° 32′ E. At least five stones have been found at different times. The original weights were given by Hodge-Smith (1939) as follows: No. 1, 65.0 kilograms; No. 2, 14.0 kilograms; No. 3, 21.77 kilograms; No. 4, 21.77 kilograms; and No. 5, 79.37 kilograms. The No.-1 stone was described by Liversidge (1872); it had been obtained by the Government Astronomer, H. C. Russell, in April, 1871, when he visited Barratta. The actual discovery of the stone, according to Russell, was the subject of some disagreement. A stockman said that he saw a brilliant fireball in May 10 or 12 years earlier (i.e., about 1860) and that the following day some fencers who were camped about 4 miles northwest of the homestead reported seeing a stone fall near their

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camp. The stockman went to the place a few days later and saw the meteorite about half-buried in the ground. However, another man living in the neighborhood claimed that he found the meteorite when he was riding over the plain about the year 1845. In spite of additional inquiries, Russell was unable to resolve the matter. Examination of the specimens in the Australian Museum shows that they are rather fresh, and the fusion crust is well preserved; it is therefore not unlikely that this was an observed fall about 1860. Numbers 2 and 3 were received by Mr. Russell in 1889. The history of Nos. 4 and 5 is not recorded in the literature. One of us (Mason) visited Barratta Station in 1965, but found that no one in the vicinity was aware that meteorites had been found there. Since any stone would be conspicuous on the flat clay plains, which are frequently traversed by stockmen, it seems unlikely that further meteorites from this fall will be found.

Pieces of the Barratta meteorite, probably mostly of No. 3, are widely distributed in collections. The Australian Museum (Sydney) has the main masses of Nos. 1, 2, and 3, and pieces of Nos. 4 and 5; the main masses of the latter two are in the Field Museum of Natural History in Chicago.

We have examined specimens of all five Barratta meteorites. They are all olivine-hypersthene chondrites and appear identical in structure, so we conclude that they are all stones from a single fall. For the chemical analysis, we obtained a piece of a thin interior slice of No. 3 from the Australian Museum.

Mineralogical Composition and Structure

In hand specimen a broken surface of the Barratta meteorite is dark gray in color, with prominent light-colored chondrules up to 2 mm. or occasionally more in diameter. The meteorite is hard, well indurated, and not friable. A polished surface shows a moderate amount of troilite and nickel-iron as small grains, in some places concentrated around the margins of chondrules.

The principal minerals are olivine and pyroxene. Troilite and nickel-iron (kamacite and taenite) are present in minor amounts. Plagioclase in small amounts has been detected in X-ray diffractograms, but was not certainly identified optically. Ramdohr (1963) recorded the following accessory minerals: native copper, chalcopyrrhotite, valleriite or mackinawite, chromite, and ilmenite. Notes on the silicate minerals 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 (Fa) component, according to the determinative curve of Poldervaart (1950). By the X-ray method

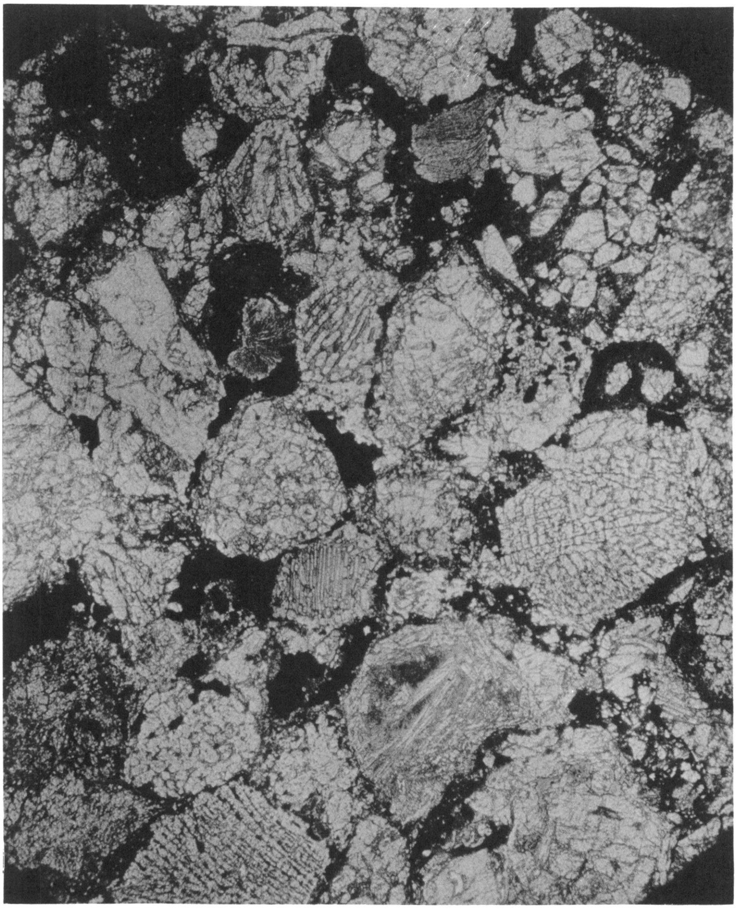

FIG. 1. Photomicrograph of a thin section of the Barratta meteorite, showing chondrules of olivine and pyroxene (light gray); near the center are two barred olivine chondrules, the glass bars being darker in color than the olivine; black is nickel-iron and troilite. ×35.

of Yoder and Sahama (1957) the composition was found to be 25 mole per cent of the Fe_2SiO_4 component. The (130) olivine peak on the diffractometer chart is sharp and well defined, but with a somewhat broadened base. Dodd and Van Schmuss (1965), by microprobe analysis, reported that the olivine composition in Barratta varies from grain, the range being from Fa_{20} to Fa_{33}, with a mean of $Fa_{23.3}$. This variability was not observed in the refractive index measurements recorded above, but the broadened base of the diffractometer peak suggests the possibility of some compositional variation. Certainly the great majority of the olivine grains have a composition close to Fa_{24}.

Pyroxene: The refractive indices of the pyroxene vary somewhat, but are close to $\alpha = 1.676$, $\gamma = 1.687$, indicating a content of about 20 mole per cent of the $FeSiO_3$ component, according to the determinative curve of Kuno (1954). In terms of the conventional division of meteoritic pyroxene, this falls in the composition range of hypersthene. Many of the grains are polysynthetically twinned and are evidently clinohypersthene. An X-ray diffractogram indicates that clinohypersthene is actually the major constituent of the pyroxene fraction.

Plagioclase: A weak plagioclase reflection was seen on an X-ray diffractogram, but the mineral was not certainly identified optically. The turbid devitrified glass in some chondrules probably consists in part of plagioclase.

In thin section (fig. 1) the meteorite is seen to be an aggregate of well-formed chondrules, 0.3–3 mm. in diameter, with very little groundmass. The chondrules exhibit a wide range of structural types. A common type is composed of numerous euhedral olivine crystals in a glassy or cryptocrystalline pale brown groundmass. Similar chondrules with euhedral clinopyroxene are less common. Barred olivine chondrules are not uncommon, the bars being transparent pale brown glass. Several fibrous, radiating, pyroxene chondrules were seen. The opaque minerals are for the most part interstitial to the chondrules, many of which are quite free from opaque minerals; a few have numerous opaque inclusions, in some areas concentrated near the margins.

Keil (1962) reported the following mineralogical composition for the Barratta meteorite (in weight per cent): nickel-iron, 6.07; troilite, 5.78; chromite, 0.01; silicates, 88.14.

The density of a piece of Barratta 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 3.48.

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

TABLE 1

CHEMICAL COMPOSITION OF THE BARRATTA METEORITE

A		B		C	
Fe	4.89	Fe	21.07	Si	36.90
Ni	1.20	Si	18.96	Mg	34.30
Co	0.077	Mg	15.26	Fe	20.59
FeS	6.25	S	2.28	Al	2.81
SiO_2	40.61	Al	1.39	Na	1.67
TiO_2	0.12	Ni	1.20	Ca	1.52
Al_2O_3	2.63	Ca	1.10	Ni	1.14
Cr_2O_3	0.46	Na	0.70	Cr	0.33
FeO	15.63	Cr	0.31	Mn	0.25
MnO	0.33	Mn	0.25	P	0.20
MgO	25.32	P	0.11	K	0.13
CaO	1.56	K	0.09	Ti	0.08
Na_2O	0.95	C	0.09	Co	0.08
K_2O	0.11	Co	0.08		100.00
P_2O_5	0.26	Ti	0.07		
H_2O+	0.20	H	0.06		
H_2O-	0.10	(O	36.98)		
C	0.088		100.00		
	100.79				

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

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, 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 Barratta meteorite shows that it is an olivine-hypersthene chondrite in Prior's classification (1920). The low total iron content, 21.07 per cent, places it in the low-iron (L) 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 0.7 per cent of chromite whereas Keil reported only 0.01 per cent; the chromium is evidently combined in the pyroxene rather than as chromite.

TABLE 2

NORMATIVE COMPOSITION OF THE BARRATTA METEORITE

Olivine	46.9
Hypersthene	25.3
Diopside	2.8
Albite	8.0
Anorthite	2.6
Orthoclase	0.7
Chromite	0.7
Apatite	0.6
Ilmenite	0.2
Troilite	6.3
Nickel-iron	6.2

THE CARRAWEENA METEORITE

The Carraweena meteorite, a chondrite weighing 63½ pounds (29 kilograms) was found in 1914 by George Amesbury about 6 miles southwest of the old Carraweena homestead on Strzelecki Creek, in the northeast of South Australia (Alderman, 1936). Three other chondrites have been found within a few miles of Carraweena. The Artracoona meteorite, a stone weighing 46 pounds (21 kilograms), was also found by Amesbury in 1914, 8 miles north of Carraweena homestead and 6 miles west of Artracoona Hill. It was described by Kleeman (1936). Accalana (known before 1917, according to the Hey-Prior catalogue, 1953) is a stone weighing 6¼ pounds (3 kilograms), presumably from near Accalana Well, about 5 miles south of Carraweena homestead. Monte Colina, a stone weighing about 100 grams in the collection of the South Australian Mines Department, presumably was found near Monte Colina Bore, which is about 16 miles due south of Carraweena. All four meteorites are olivine-hypersthene chondrites; however, they are not identical. Carraweena, Accalana, and Monte Colina are very similar in structure and composition, and are probably three stones from a single meteorite shower. Artracoona shows distinct differences in mineralogy and structure and is almost certainly from a different fall. Heymann (1965), from the rare gas contents, has also deduced that Accalana and Carraweena are identical, whereas Artracoona appears to be an independent fall.

The original analysis of Carraweena shows some unsatisfactory features. Al_2O_3 (5.99%) is much higher than in most chondrites, and cannot be accounted for in terms of the observed mineralogy, and FeO (5.78%) is much lower than is indicated by the composition of the olivine and the pyroxene. We therefore decided to reanalyze this meteorite, using for this purpose a specimen (No. 3902) in the collection of the American Museum of Natural History.

Mineralogical Composition and Structure

The specimen has a dark rusty brown exterior, which appears to be the weathered fusion crust of the original surface of the meteorite. The interior is grayish brown and shows little weathering, except along cracks. A cut surface shows that the meteorite is highly chondritic and has numerous small particles of metal and troilite scattered throughout the groundmass between the chondrules. The chondrules are white or light gray, and the groundmass is dark gray to black. The meteorite is hard and takes a good polish.

The principal minerals are olivine and pyroxene. Nickel-iron (kamacite and taenite) and troilite are present in minor amounts. Accessory minerals include chromite and probably a phosphate (apatite or merrillite, or both). Plagioclase was not certainly identified, either optically or by X-ray diffraction, and if present is an accessory constituent only. Notes on the olivine and pyroxene follow.

Olivine: Most of the olivine grains are stained with limonite, and their refractive indices could not be accurately determined. An X-ray diffractogram shows a well-defined (130) olivine peak, indicating a composition of Fa_{24}, according to the data of Yoder and Sahama (1957). However, the base of the peak is considerably broadened, suggesting a range in composition from about Fa_{15} to Fa_{40}, but with most of the olivine close to Fa_{24}.

Pyroxene: The pyroxene is almost entirely polysynthetically twinned clinopyroxene, with little or no orthopyroxene. Refractive indices vary somewhat from grain to grain, but the average gamma index is about 1.69, indicating a content of approximately 22 mole per cent of $FeSiO_3$. The pyroxene can best be designated a clinohypersthene.

A thin section (fig. 2) shows that the meteorite is made up almost entirely of chondrules of olivine and pyroxene, ranging from 0.3 to

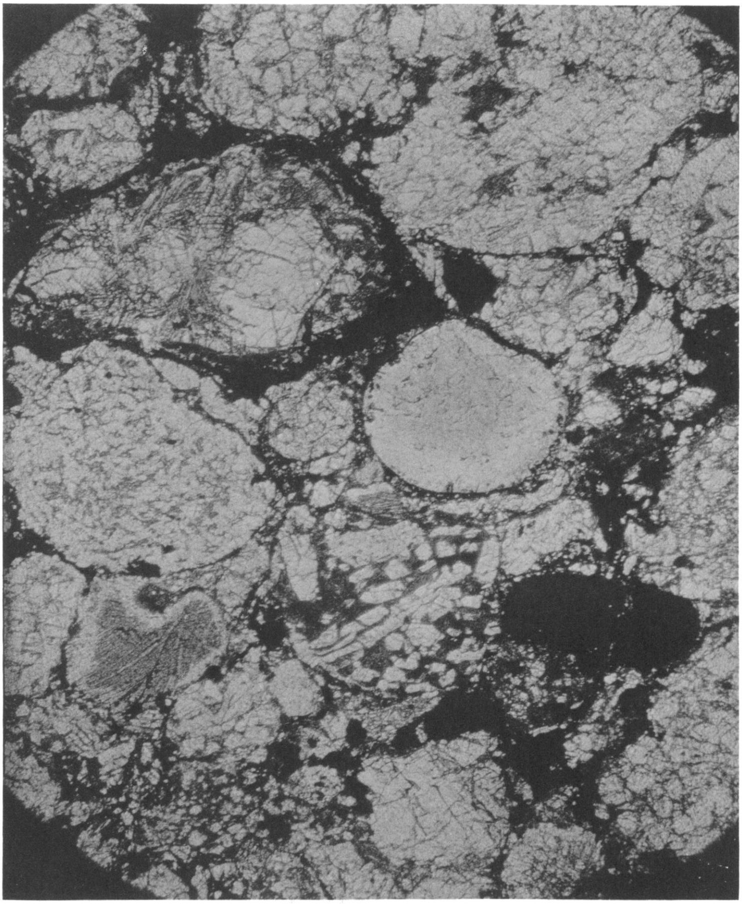

FIG. 2. Photomicrograph of a thin section of the Carraweena meteorite, showing chondrules of olivine and pyroxene (gray); black is nickel-iron and troilite. ×35.

3 mm. in diameter (and occasionally larger; one broken chondrule seen on a polished surface was 8 mm. across). Some of the chondrules are more ovoid than spherical, and in places they appear to be molded to each other, as if they were still plastic when they accumulated. They show a variety of structural types, the commonest being the porphyritic olivine type, consisting of euhedral olivine crystals with interstitial glass (usually somewhat devitrified). In some cases the individual olivine crystals appear to have coalesced into a large single crystal. Chondrules of olivine and pyroxene are not uncommon, the olivine in some areas being

TABLE 3

CHEMICAL COMPOSITION OF THE CARRAWEENA METEORITE

A		B		C	
Fe	4.55	Fe	19.83	Si	36.91
Ni	1.10	Si	18.86	Mg	35.66
Co	0.063	Mg	15.76	Fe	19.51
FeS	6.52	S	2.38	Ca	3.09
SiO_2	40.39	Ca	2.23	Al	1.71
TiO_2	0.10	Ni	1.10	Na	1.19
Al_2O_3	1.59	Al	0.84	Ni	1.03
Cr_2O_3	0.35	Na	0.50	Mn	0.27
FeO	14.32	Mn	0.27	Cr	0.25
MnO	0.35	Cr	0.24	P	0.16
MgO	26.15	P	0.10	K	0.11
CaO	3.15	C	0.09	Ti	0.06
Na_2O	0.67	K	0.07	Co	0.05
K_2O	0.09	Co	0.06		100.00
P_2O_5	0.22	Ti	0.06		
H_2O+	0.98	H	0.06		
H_2O-	0.17	(O	37.55)		
C	0.09		100.00		
	100.85				

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

poikilitically enclosed within the pyroxene grains. Dense fibrous pyroxene chondrules are occasionally seen. The sparse groundmass between the chondrules is mostly black and opaque; some of it is nickel-iron and troilite, and some is probably fine-grained silicates colored black by carbonaceous material.

The quantitative mineralogical composition, obtained by point-counting a polished surface, is (in weight per cent): nickel-iron, 5.7; troilite, 7.0; chromite, 0.1; silicates, 86.8.

The density of the meteorite, determined as described for Barratta, is 3.46.

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

TABLE 4

NORMATIVE COMPOSITION OF THE CARRAWEENA METEORITE

Olivine	47.0
Hypersthene	21.1
Diopside	10.6
Albite	5.7
Anorthite	1.1
Orthoclase	0.6
Apatite	0.5
Chromite	0.5
Ilmenite	0.2
Troilite	6.5
Nickel-iron	5.7

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 Barratta meteorite.

The composition of the Carraweena meteorite shows that it is an olivine-hypersthene chondrite in Prior's (1920) classification, although, as pointed out above, the pyroxene is largely clinohypersthene rather than hypersthene. The total iron content, 19.83 per cent, is that of a low-iron (L) group chondrite of Urey and Craig (1953). The figure for FeO is a little higher than the true amount, since a small quantity of limonite, which should be reported as Fe_2O_3, is present; however, the amount is small, probably about 1 per cent.

The normative mineral composition, expressed as weight percentages, is given in table 4. This is in good agreement with the observed mineral composition, except that the normative plagioclase must be largely represented by the glass in the meteorite. The proportion of olivine to pyroxene is consistent with estimates from thin sections and X-ray diffraction patterns.

THE KAPOETA METEORITE

This meteorite, a single stone weighing 11.335 kilograms, was seen to fall on April 22, 1942, about 7 P.M. local time, on the Kapoeta-Nathalani road in southern Sudan. The meteorite was deposited in the Sudan Geological Survey, Khartoum. It has been the subject of considerable investigation in recent years, since Zähringer and Gentner (1960) discovered that it contains large amounts of primordial helium, neon, and argon. Further information regarding its composition and structure has been published by Zähringer (1962), Fredriksson and Keil (1963), and Müller and Zähringer (1966). It belongs to the comparatively rare group of howardites, and, because no complete chemical analysis has been made, we obtained a specimen from the Sudan Geological Survey for this purpose.

Mineralogical Composition and Structure

In hand specimen the groundmass of Kapoeta is fine-grained and pale gray in color, with numerous inclusions of crystal fragments up to 2 mm. across; it resembles a terrestrial crystal tuff. The crystal fragments are mostly pyroxene, and are pale yellow to dark gray in color. White fragments of plagioclase are also seen, and rare flakes of metal, in some cases made visible by the limonitic staining surrounding them.

A feature that has been commented on by previous investigators, and illustrated by Fredriksson and Keil (1963, fig. 3) is the light-dark structure. Irregular off-white patches are distributed through the gray material that evidently makes up the major part of the meteorite. The light material has a low rare-gas content compared to the darker material. Fredriksson and Keil demonstrated that both light and dark materials consist of the same minerals with identical composition range, but the two varieties differ markedly in grain size.

Pyroxene makes up 80–90 per cent of the meteorite. About 10 per cent of plagioclase is present. Accessory minerals include olivine, tridymite, nickel-iron (kamacite and taenite), troilite, and chromite. Notes on the silicates follow.

Pyroxene: Both orthopyroxene and clinopyroxene are present, the latter in lesser amount; the relative proportions are about 3/1. The orthopyroxene varies considerably in composition, judging from its refractive indices; the gamma index ranges from 1.680 to 1.710, indicating a range of 15–35 mole per cent of the $FeSiO_3$ component. The clinopyroxene is a pigeonite, pale brown and weakly pleochroic; some grains show exsolution lamellae of augite. The pigeonite also varies in composition from grain to grain; the gamma refractive index ranges from 1.720 to 1.745, indicating a range of about 35–60 in the Fe/Fe+Mg atom percentage. Fredriksson and Keil made an extensive study of the pyroxene composition by microprobe analysis, and obtained similar results. They measured Ca, Fe, and Mg in 264 individual grains, and found that the Fe/Fe+Mg atom percentage ranged from 14 to 70. The frequency distribution showed a strong peak at 26–30 (hypersthene) and a less prominent peak around 60 (pigeonite). For the hypersthene Ca ranged from 0.3–1.5 per cent (corresponding to 0.4–2.1% of CaO), whereas in the

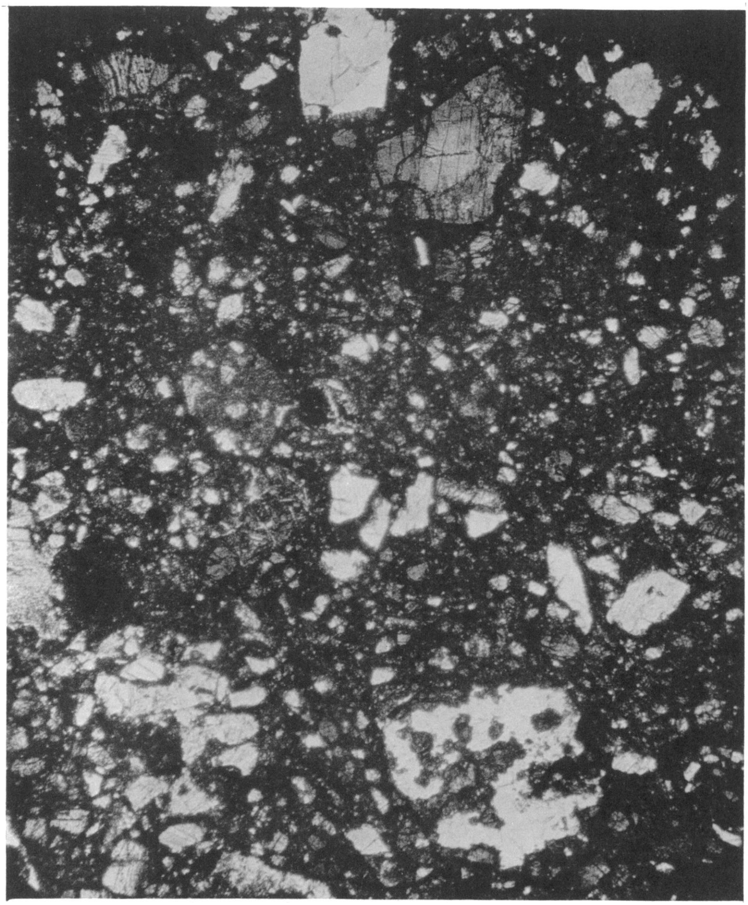

FIG. 3. Photomicrograph of a thin section of the Kapoeta meteorite, showing angular fragments of pyroxene and minor plagioclase in a comminuted groundmass of the same minerals. ×35.

pigeonite Ca is generally higher and more variable and tends to increase with increasing Fe content. They also measured the compositions of a number of exsolved augite lamellae in the host pigeonite grains.

PLAGIOCLASE: The refractive indices of a number of grains are α = 1.572, γ = 1.582, corresponding to a composition of An_{88}. Fredriksson and Keil measured Ca, Al, and Si in eight plagioclase grains, and their figures for Ca indicate a range of composition of about An_{75}–An_{90}. Judged from the refractive index measurements, most of the plagioclase has a composition close to An_{90}.

TABLE 5

CHEMICAL COMPOSITION OF THE KAPOETA METEORITE

A		B		C
Fe	0.40	Si	22.63	24.5
Ni	0.02	Fe	14.36	13.0
Co	0.00	Mg	7.23	7.5
FeS	0.98	Ca	5.73	5.9
SiO_2	48.47	Al	5.00	4.9
TiO_2	0.37	Cr	0.43	0.36
Al_2O_3	9.46	S	0.36	0.22
Cr_2O_3	0.63	Na	0.34	—
FeO	17.16	Mn	0.40	0.38
MnO	0.53	Ti	0.22	0.30
MgO	12.00	C	0.07	0.08
CaO	8.08	K	0.04	0.028
Na_2O	0.46	P	0.03	—
K_2O	0.05	Ni	0.02	0.01
P_2O_5	0.07	H	0.01	—
H_2O+	0.00	(O	43.13)	—
H_2O-	0.06		100.00	
C	0.07			
	98.81			

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 Elemental composition according to Müller and Zähringer (1966)

OLIVINE: Fredriksson and Keil identified five grains of olivine, with Fe/Fe+Mg atom percentages of 8.5, 13.5, 27.7, 34.7, and 37.7. Rare grains of olivine were recognized optically, and it was noted that the refractive indices varied from grain to grain.

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.

A thin section (fig. 3) shows that Kapoeta is a microbreccia, with angular fragments of pyroxene and plagioclase (and occasional composite fragments) in a groundmass of comminuted pyroxene and plagioclase. The angular fragments of the minerals range up to about 1 mm. across, whereas the composite fragments are somewhat larger, up to 3 mm. The plagioclase and the orthopyroxene are colorless; the clinopyroxene is colorless to pale brown. The composite fragments consist of plagioclase and clinopyroxene in ophitic intergrowth; one such fragment also contained phenocrysts of clinopyroxene. Opaque minerals are decidedly rare. Commonest is chromite; minute particles of metal are scattered through the groundmass, and a little troilite was seen.

The density of the meteorite, determined as described for Barratta, is 3.26.

Chemical Composition

The chemical analysis is given in table 5, in the conventional form expressed as metal, troilite, and oxides, and in terms of the individual

TABLE 6

Normative Composition of the Kapoeta Meteorite

Hypersthene	53.8
Diopside	13.3
Olivine	0.5
Anorthite	23.6
Albite	3.9
Orthoclase	0.3
Chromite	0.9
Ilmenite	0.7
Apatite	0.2
Troilite	1.0
Nickel-iron	0.4

elements as determined by analysis, with oxygen added to bring the total to 100. Müller and Zähringer (1966) have recently published the results of analyses (by X-ray fluorescence spectrography) of both the light and dark portions of Kapoeta. They found considerable differences between light and dark portions for some elements, especially Mg, Al, Ca, and K, Mg being considerably higher and the other elements considerably lower in the darker portions. This indicates that the darker portions contain more pyroxene and less plagioclase than the lighter portions. However, table 5 shows that the mean of Müller and Zähringer's analyses is in excellent agreement with the bulk analysis.

The normative mineral composition, expressed as weight percentages, is given in table 6. It is in good agreement with the actual mineral composition. Diopside is not present as such, this component being represented by the calcium in the hypersthene and pigeonite. Olivine is actually much less in amount than the 0.5 per cent shown in the norm, and a little tridymite is also present.

Kapoeta is a typical pyroxene-plagioclase achondrite and can be classified as a howardite, as that term was defined by Prior (1920).

THE MOORESFORT METEORITE

This meteorite, a single stone weighing 7¾ pounds (3.5 kilograms), was seen to fall in August, 1810, near Mooresfort in County Tipperary, Ireland. Small pieces of it are widely dispersed in collections, but the major portion is preserved in the National Museum of Ireland in Dublin. Numerous references to it appear in the nineteenth-century meteorite literature (Wülfing, 1897), but it has never been analyzed or described in detail. Keil (1962) reported the following quantitative mineralogical composition, in weight per cent: nickel-iron, 7.62; troilite, 5.24; chromite, 0.16; silicates, 86.98. Mason (1963) reported an olivine composition of Fa_{19}. Keil and Fredriksson (1964) reported an olivine composition of $Fa_{22,2}$. They classified Mooresfort as a low-iron (L group) chondrite in the Urey-Craig (1953) classification, whereas Mason considered it to be a high-iron (H group) chondrite. These disagreements suggested the possibility of one or more mislabeled specimens, so, to resolve the situation, we obtained for investigation a sample of the meteorite from the original specimen in the National Museum of Ireland.

Mineralogical Composition and Structure

In hand specimen a broken surface of the Mooresfort meteorite is medium gray in color, with numerous rusty brown spots. Examination with a hand lens shows many chondrules (usually lighter in color than the groundmass) and occasional bronze grains of troilite. The specimen is seamed with extremely thin black veinlets. On a cut surface abundant grains of nickel-iron are visible; these give rise to the rusty brown spots mentioned above. The meteorite is quite hard and not friable.

The principal minerals are olivine and pyroxene; other significant constituents are nickel-iron, troilite, and plagioclase. Chromite is present in small amounts, as is probably a phosphate mineral (apatite or merrillite, or both). Notes on the silicates follow.

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 19 mole per cent of the Fe_2SiO_4 component. The olivine peaks on the diffractometer chart are sharp, symmetrical, and well defined, indicating olivine of uniform composition.

Pyroxene: The refractive indices are $\alpha = 1.671$, $\gamma = 1.681$, 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

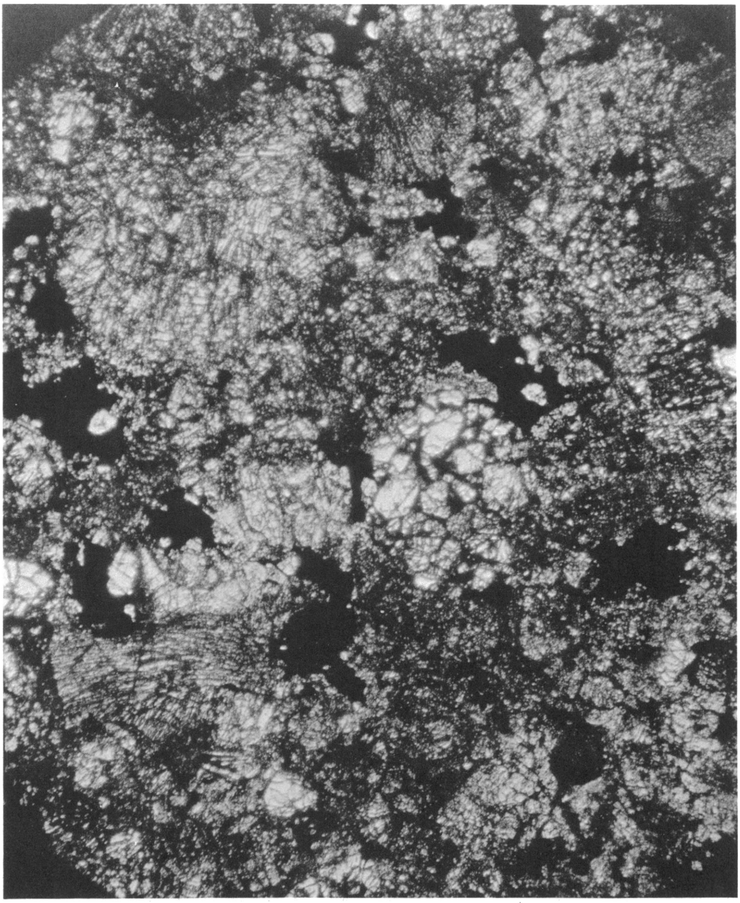

FIG. 4. Photomicrograph of a thin section of the Mooresfort meteorite, showing chondrules of olivine and pyroxene (gray), their boundaries somewhat obscured by recrystallization; black is nickel-iron and troilite. ×35.

division of meteoritic pyroxenes this falls in the composition range of bronzite. Many of the pyroxene grains are polysynthetically twinned clinobronzite, and X-ray diffractograms confirm that the pyroxene is a mixture of bronzite with a considerable amount of clinobronzite.

PLAGIOCLASE: A small amount of this mineral was isolated as a light fraction from an acid-insoluble residue of the meteorite. It is turbid and very fine-grained, and only a mean index of refraction, 1.536, could be measured; this indicates a composition about An_{10}.

A thin section (fig. 4) shows that Mooresfort is a highly chondritic meteorite, but the boundaries of the chondrules are frequently ill defined, and some of the chondrules appear to be fragmented. Chondrules range in diameter from 0.2 to 0.9 mm., and the usual variety of types are present, the commonest being the porphyritic olivine chondrules and the radiating fibrous pyroxene chondrules. No glass was seen in the chondrules, but in the porphyritic olivine type the turbid groundmass

TABLE 7

Chemical Composition of the Mooresfort Meteorite

A		B		C	
Fe	14.12	Fe	25.97	Si	33.16
Ni	1.67	Si	16.98	Mg	32.71
Co	0.08	Mg	14.50	Fe	25.49
FeS	5.37	S	2.15	Al	2.95
SiO_2	36.36	Ni	1.67	Na	1.59
TiO_2	0.15	Al	1.45	Ni	1.56
Al_2O_3	2.75	Ca	0.90	Ca	1.24
Cr_2O_3	0.72	Na	0.67	Cr	0.52
FeO	10.80	Cr	0.49	Mn	0.25
MnO	0.32	Mn	0.25	P	0.21
MgO	24.06	C	0.24	K	0.14
CaO	1.27	P	0.12	Ti	0.10
Na_2O	0.90	K	0.09	Co	0.08
K_2O	0.12	Ti	0.09		100.00
P_2O_5	0.27	Co	0.08		
C	0.24	(O	34.35)		
	99.20		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

between the euhedral olivines is weakly birefringent, has low relief, and is evidently plagioclase. The opaque minerals are largely interstitial to the chondrules. The quantitative mineralogical composition, obtained by point-counting a polished section, is (in weight per cent): nickel-iron, 16.5; troilite, 4.9; chromite, 0.1; and silicates, 78.5. The differences between these figures and those reported by Keil (1962) show clearly that the specimen he examined must have been mislabeled. His specimen was obtained from the Mineralogical Institute of the University of Tübingen.

The density of this meteorite, determined as described under Barratta, is 3.70.

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

TABLE 8

Normative Composition of the Mooresfort Meteorite

Olivine	40.0
Bronzite	22.9
Diopside	1.2
Albite	7.7
Anorthite	3.1
Orthoclase	0.7
Chromite	1.1
Apatite	0.6
Ilmenite	0.3
Troilite	5.4
Nickel-iron	15.9

The composition of the Mooresfort meteorite shows that it is an olivine-bronzite chondrite in Prior's (1920) classification. The total iron, 25.97 per cent, is that of a high-iron (H) group chondrite of Urey and Craig (1953).

The normative mineral composition, expressed as weight percentages, is given in table 8. The actual mineral composition is consistent with the calculated norm. Measured troilite is a little lower than the calculated figure, probably because a considerable amount of the troilite is finely dispersed and thus tends to be underestimated in the point-counting. Observed chromite is much lower than calculated chromite, mainly because most of the chromium is evidently combined in the pyroxene. The proportion of olivine to pyroxene is consistent with estimates from thin sections and X-ray diffraction patterns. No diopside was seen, but the small amount of this component is presumably in solid solution in the bronzite and clinobronzite.

THE NGAWI METEORITE

This meteorite fell on October 3, 1883, near the town of Ngawi in east-central Java. At least three stones fell. One was broken into three pieces by a native, and these pieces were examined and analyzed by von Baumhauer (1884). One, weighing 202 grams, was figured by von Baumhauer and is preserved in its original condition in the Rijksmuseum van Geologie en Mineralogie, Leiden. A third stone, original weight 1191 grams, was figured and described by Bosscha (1887). The major part of the third stone is also preserved in the Leiden museum, but pieces of it (and probably of the fragments described by von Baumhauer) are present in a number of collections.

One of us (Mason, 1962) classified Ngawi with the olivine-pigeonite chondrites, a class comprising the Type-III carbonaceous chondrites and a number of non-carbonaceous chondrites of similar chemical and mineralogical composition. At that time it was thought that the olivine-pigeonite chondrites all belonged to the high-iron (H) group of Urey and Craig (1953). However, Schmitt (1965) has shown that Ngawi is a chondrite of the low-iron (L) group, and he has classified it as a Type-IIIB carbonaceous chondrite to distinguish it from his Type-IIIA carbonaceous chondrites, which belong to the H group. Since Schmitt and his co-workers have determined many trace elements in Ngawi, we decided to reanalyze this meteorite, and obtained for this purpose a piece of the 1191-gram stone from the Leiden museum.

Mineralogical Composition and Structure

A cut surface of the Ngawi meteorite is medium gray in color, with some yellow-brown limonitic staining. Small irregular areas are light gray to almost white; at first sight they appear to be xenoliths, but on closer examination they are seen as lighter-colored areas continuous with the main mass. Examination with a hand lens shows that the meteorite is made up almost entirely of chondrules, with very little groundmass; many of the chondrules have black rims. Metal particles are notably sparse in comparison to most chondrites.

The principal minerals are olivine and pyroxene. Nickel-iron (kamacite and taenite) and troilite are present in minor amount. Accessory minerals include magnetite, chromite, and a phosphate (apatite or merrillite, or both). A small amount of plagioclase is present. Notes on the silicates follow.

Olivine: The refractive indices are different in different grains, indicating variable composition. This is confirmed by an X-ray diffractogram; olivine peaks are sharp and well defined, but the peaks are somewhat skewed and their bases are broadened. From the data of Yoder

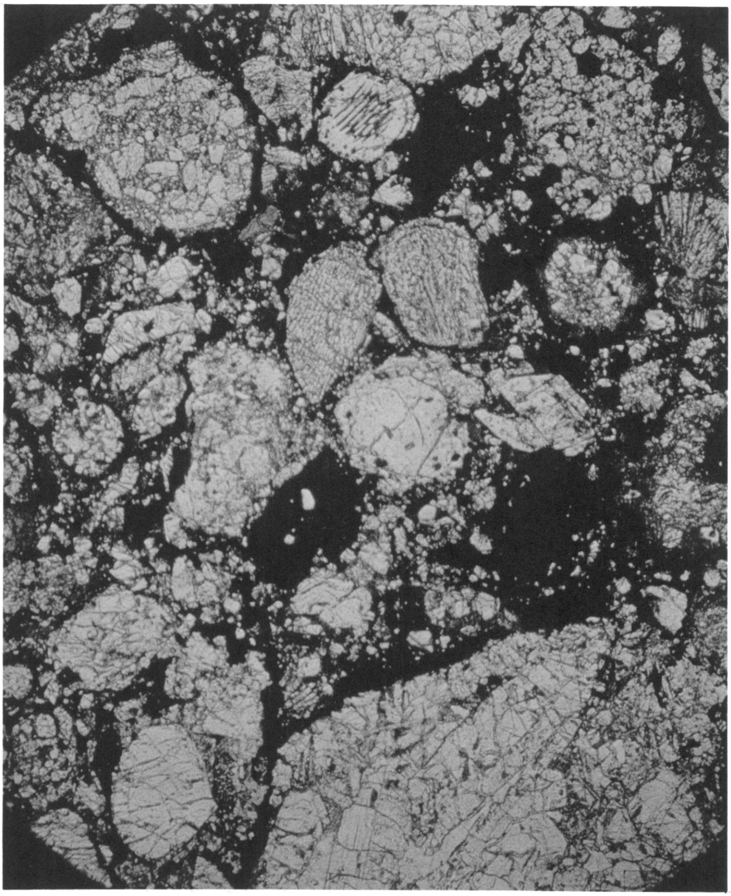

FIG. 5. Photomicrograph of a thin section of the Ngawi meteorite, showing chondrules of olivine and pyroxene (gray); black is partly nickel-iron and troilite, partly carbonaceous material. ×35.

and Sahama (1957), most of the olivine has a composition about Fa_{30}, but it ranges from about Fa_5 to Fa_{40}.

PYROXENE: An X-ray diffractogram of the acid-insoluble material shows that the pyroxene is almost entirely clinopyroxene, with little or no orthopyroxene. The pyroxene is polysynthetically twinned, and its refractive indices vary considerably, indicating a range in composition from nearly pure clinoenstatite to clinohypersthene with about 30 mole per cent of the $FeSiO_3$ component.

PLAGIOCLASE: This mineral was not positively identified optically,

TABLE 9

CHEMICAL COMPOSITION OF THE NGAWI METEORITE

A		B		C	
Fe	0.60	Si	18.84	Si	37.45
Ni	1.06	Fe	18.57	Mg	35.48
Co	0.048	Mg	15.43	Fe	18.55
FeS	6.08	S	2.22	Al	2.80
SiO_2	40.36	Al	1.35	Ca	1.82
TiO_2	0.10	Ca	1.29	Na	1.79
Al_2O_3	2.57	Ni	1.06	Ni	1.01
Cr_2O_3	0.62	Na	0.73	Cr	0.46
FeO	18.14	Cr	0.42	Mn	0.28
MnO	0.36	C	0.39	P	0.15
MgO	25.60	Mn	0.27	K	0.11
CaO	1.83	H	0.19	Ti	0.06
Na_2O	0.99	P	0.08	Co	0.04
K_2O	0.09	K	0.07		100.00
P_2O_5	0.18	Ti	0.06		
H_2O+	1.40	Co	0.05		
H_2O-	0.38	(O	38.98)		
C	0.39		100.00		
	100.80				

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, C, H, and S

but a weak plagioclase peak was present on the X-ray diffractogram of the acid-insoluble fraction of the meteorite.

A thin section (fig. 5) shows numerous chondrules, from 0.3 to 3 mm. in diameter, set in a fine-grained groundmass. Some of the chondrules have prominent black rims which consist in part of troilite and in part of opaque material which is probably carbonaceous. The brown to black color of some of the groundmass may also be due to the presence of carbonaceous matter. The chondrules show a variety of internal structures; commonest are those made up of euhedral olivine with interstitial glass, which is usually devitrified to a greater or lesser extent. Eccentric radiating pyroxene chondrules are not uncommon, and some barred olivine chondrules were seen.

The quantitative mineralogical composition, determined by point-counting a polished section, is (in weight per cent): nickel-iron, 1.4; troilite, 5.3; magnetite and chromite, 0.3; silicates, 93.0.

The density of this meteorite, determined by von Baumhauer, is 3.56.

Chemical Composition

The chemical analysis is 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, H, and S. A discussion of these procedures is given under the description of the Barratta meteorite.

The normative composition, expressed as weight percentages, is given in table 10. This is consistent with the observed mineral composition,

TABLE 10

Normative Composition of the Ngawi Meteorite

Olivine	52.5
Hypersthene	19.4
Diopside	4.5
Albite	8.4
Anorthite	2.3
Orthoclase	0.6
Chromite	0.9
Apatite	0.4
Ilmenite	0.2
Troilite	6.1
Nickel-iron	1.7

except for the plagioclase; normative plagioclase is 11.3 per cent, whereas the meteorite contains only a little of this mineral. Most of the feldspar components are evidently present as glass. Observed chromite is much lower than calculated chromite, mainly because most of the chromium is combined in the pyroxene.

The composition of the Ngawi meteorite resembles that of the average olivine-hypersthene chondrite, except for the following features: (1) a low content (1.7%) of nickel-iron; (2) a low total Fe content (18.84%); the average for the olivine-hypersthene chondrites is 21.5 per cent, and few of them have less than 20 per cent; (3) a notable content of C (0.39%) and H_2O+ (1.40%), which probably indicates the presence of complex organic compounds; and (4) a considerable variability in olivine and pyroxene composition.

Ngawi shares the first two features with the amphoterites, which have been classified as a subclass of the olivine-hypersthene chondrites (Mason and Wiik, 1964). However, the amphoterites are essentially non-carbonaceous (averaging about 0.1% of C) and are usually poorly chondritic and much recrystallized.

Ngawi closely resembles Chainpur (Keil, Mason, Wiik, and Fredriksson, 1964) in composition and structure. Other meteorites of this kind include Bishunpur and Semarkona, and possibly Hallingeberg and Khohar, recently analyzed by Jarosewich (in press). Hallingeberg and Khohar have the average nickel-iron and total Fe content of the olivine-hypersthene chondrites, but are carbonaceous and have variable olivine and pyroxene composition. Bishunpur and Semarkona have low total Fe content, are carbonaceous, and have variable olivine and pyroxene composition.

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