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The Composition of the Allegan, Bur-Gheluai, and Cynthiana Meteorites[1]

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The Allegan Meteorite

This meteorite fell on Thomas Hill, in Allegan, Mich., shortly after 8 a.m. on July 10, 1899. Landing within 50 feet of Walter Price, it buried itself to a depth of about 18 inches in sandy ground. It was dug up about 5 minutes later, reportedly too hot to handle, necessitating removal with a shovel. Merrill and Stokes (1900), however, who reported on the fall, remarked that grass welded to the surface of the meteorite by the impact was not charred. In what may well be a record for speed in recovery and display, the meteorite was on exhibit in the shop window of Stern and Company of Allegan some two and a half hours after the fall. The main mass of the stone, weighing 62½ pounds, together with an additional fragment weighing about 1½ pounds, was obtained by the U.S. National Museum from Stern and Company. Numerous fragments had been broken off the stone, and its original weight was probably about 80 pounds.

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Even allowing for its rapid recovery, the Allegan meteorite has a remarkably fresh appearance. Many chondrites, even fresh falls, soon develop rust stains around the nickel-iron particles. A plausible explanation of this rusty staining is the decomposition of minute amounts of lawrencite originally on the surface of the metal grains. The Allegan specimens have remained perfectly fresh and free from rusting after more than 60 years of exposure to the atmosphere.

In hand specimens the meteorite shows an even granular structure of gray color, with numerous chondrules that average one to two millimeters in diameter, rarely more. Nickel-iron is visible in the form of numerous brilliant metallic particles. The stone is extremely friable, crumbling easily with handling.

The Allegan meteorite was described by Merrill and Stokes (1900), whose chemical analysis, although rated by Urey and Craig (1953) as superior, shows some anomalous features, such as unusually high metal content (23.06 percent nickel-iron), low Na_2O, and high K_2O. Since this meteorite is ideal for research, being very fresh as well as available in comparatively large amounts, we have decided to reanalyze it.

Mineralogical composition and structure.—The principal minerals in the Allegan meteorite are olivine and pyroxene. Nickel-iron (kamacite and taenite), troilite, and plagioclase are present in minor amounts. Accessory minerals include chromite and merrillite. Buseck and Keil (1966) recorded trace amounts of rutile, and Prof. P. Ramdohr (pers. comm.) recognized chalcopyrrhotite (cubanite), native copper, and mackinawite in polished surfaces. Notes on some of these minerals follow:

Olivine: The refractive indices are $\alpha=1.668$, $\gamma=1.706$, corresponding to a composition of 18 mole percent of the Fe_2SiO_4 component, according to the determinative curve of Poldervaart (1950). Keil and Fredriksson (1964) reported an olivine composition of $Fa_{17.5}$ from microprobe analyses of this meteorite. By the X-ray method of Yoder and Sahama (1957) the composition was determined as Fa_{19}. The olivine peaks on the diffractometer chart are sharp, symmetrical, and well defined, indicating olivine of uniform composition.

Pyroxene: In an acid-insoluble fraction of this meteorite the pyroxene is a mixture of transparent orthopyroxene and turbid polysynthetically twinned clinopyroxene. The refractive indices of the orthopyroxene are $\alpha=1.672$, $\gamma=1.682$, indicating a content of 16 mole percent of the $FeSiO_3$ (Fs) component, according to the determinative curve of Kuno (1954). Keil and Fredriksson (1964), by microprobe analysis, determined the composition of the orthopyroxene to be $Fs_{16.0}$; they reported that the pyroxene contains 0.37 percent Ca. In terms of the conventional subdivision of meteoritic pyroxene, this falls into the compositional range of bronzite. The refractive indices of the turbid twinned clinopyroxene are similar to those of the orthopyroxene, and it is evidently clinobronzite of similar composition.

The acid-insoluble fraction was scanned optically for the presence of diopside, but none was seen.

Plagioclase: A small amount of this mineral is present. It is fine grained and turbid, and only a mean refractive index, about 1.536, could be measured; this corresponds to a composition of about An_{10}.

Merrillite: Allegan was one of the meteorites in which merrillite originally was recognized by Shannon and Larsen (1925). Fuchs (1962) published an X-ray powder pattern of merrillite from Allegan which showed that this mineral is structurally identical with the terrestrial mineral whitlockite and a spectrographical analysis which indicated a composition corresponding to the formula $(Ca_{2.5}Fe_{0.2}Mg_{0.1}Na_{0.1})(PO_4)_2$. He did not find any chlorapatite in this meteorite, which is consistent with the very low chlorine content reported by Reed and Allen (1966).

Chromite: Snetsinger and Keil (1967) recently reported microprobe analyses of several meteoritic chromites, including that in Allegan. Their results are: Cr_2O_3 55.5, Al_2O_3 6.3, TiO_2 2.08, FeO 32.0, MgO 2.31, MnO 1.05, sum 100.24, i.e., the composition corresponds closely to the ideal formula $FeCr_2O_4$. The presence of over 2 percent TiO_2 is interesting, representing almost a 20-fold concentration of titanium over the amount reported in the bulk analysis of the meteorite; this is present in solid solution, not as exsolved ilmenite or rutile. The rutile in Allegan is disseminated as discrete grains within the silicate matrix, and Buseck and Keil suggest that it is a primary crystallization.

Tassin (1908), from chemical tests, recorded the occurrence of oldhamite, CaS, in the Allegan meteorite; however, he was unable to detect it microscopically, and we have found no trace of this mineral. Perusal of his original paper suggests that the evidence for this identification is unconvincing.

The structure of the Allegan meteorite as seen in thin section under the microscope is highly chondritic, the chondrules ranging from 0.3–2 mm in diameter. Many are perfectly spherical, some are less regular in form, and others appear to have been broken prior to aggregation with the groundmass. A wide variety of chondrule types are present: barred olivine chondrules, the bars consisting alternately of olivine and of dark, turbid, almost opaque material; chondrules consisting of numerous euhedral olivine crystals in a gray turbid matrix, probably devitrified glass; fibrous radiating pyroxene chondrules; and chondrules containing both olivine and pyroxene. The groundmass in which the chondrules are embedded consists of opaque material and fine-grained olivine and pyroxene, probably with some plagioclase.

The density of a piece of this meteorite was determined by measuring the apparent loss of weight upon suspension in carbon tetrachloride (after evacuation under a bell to remove air). It was found to be 3.75.

Chemical composition.—The method of chemical analysis of these meteorites is essentially that outlined by Duke et al (1961). Cobalt was determined colorimetrically in a citrate-phosphate-borate medium with nitrose-R salt, as recommended by Sandell (1959).

Table 1.—*Chemical analysis and normative mineral composition of the Allegan meteorite* (analysis: Maynes; norm: Mason)

Analysis		*Norm*	
Fe	17.23%	Olivine	32.8%
Ni	1.54	Bronzite	27.1
Co	0.09	Diopside	4.0
FeS	5.57	Albite	7.7
SiO_2	36.65	Anorthite	1.4
TiO_2	0.13	Orthoclase	0.4
Al_2O_3	2.10	Chromite	0.8
Cr_2O_3	0.51	Apatite	0.7
FeO	9.30	Ilmenite	0.2
MnO	0.30	Troilite	5.6
MgO	23.27	Nickel-iron	18.9
CaO	1.71		
Na_2O	0.90		
K_2O	0.08		
P_2O_5	0.31		
H_2O+	0.24		
H_2O-	0.03		
Sum	99.96%		

The chemical analysis of Allegan is given above in the conventional form expressed as metal, troilite, and oxides. This 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 Allegan meteorite. The composition shows that it is an olivine-bronzite chondrite in Prior's classification (1920). The total iron content, 28.00 percent, 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 also given above. The observed mineral composition agrees with that calculated from the analysis. The $FeO/FeO+MgO$ ratio from the analysis is consistent with that deduced from the composition of the olivine and pyroxene. The normative plagioclase has the composition An_{14}, a little more calcic than indicated by the refractive index, but, because of the fine-grained nature of the feldspar, the latter measurement is not very precise.

Owing to its freshness and availability, the Allegan meteorite has been used for many determinations of minor and trace elements. These elements, in parts per million, are as follows (numbers in parentheses indicate references under "Literature Cited"):

C	160 (1)	Te	0.3 (4)
F	140 (2); 170 (5)	I	0.07 (4)
Na	6700 (3); 5730 (14)	Cs	0.063 (7)
P	1350 (3); 1280 (5)	Ba	4.6 (5)
Cl	9 (4); 57 (5)	La	0.33 (10)
K	660 (3)	Ce	0.54 (10)
Sc	5.0 (5); 8.1 (14)	Pr	0.12 (10)
Ti	533 (5); 780 (3)	Nd	0.65 (10)
V	72 (5)	Sm	0.24 (10)
Cr	2070 (5); 3500 (3); 3640 (14)	Eu	0.087 (10)
Mn	2210 (5); 2300 (3); 2380 (14)	Gd	0.34 (10)
Co	908 (5); 900 (3); 900 (14)	Tb	0.049 (10)
Cu	80 (5); 125 (11); 105 (14)	Dy	0.39 (10)
Zn	43 (5); 48 (11)	Ho	0.082 (10)
Ge	13 (5)	Er	0.22 (10)
Br	0.16 (4)	Tm	0.043 (10)
Rb	2.20 (7)	Yb	0.19 (10)
Sr	10.1 (5)	Lu	0.035 (10)
Zr	8 (6)	Re	0.077 (12)
Ru	0.9 (8)	Os	0.87 (8); 0.89 (12)
Cd	0.015 (9)	Th	0.039 (12)
Sb	0.080 (13)	U	0.011 (12)

Schmitt et al (1965) have compared the abundances of Na, Sc, Cr, Mn, Fe, Co, and Cu in chondrules and in the meteorite as a whole, comparing the abundances by the ratio of the concentration in the chondrules to the concentration in the meteorite as a whole. For the elements Na, Sc, and Mn, this ratio is somewhat greater than unity, indicating that these elements are relatively enriched in the chondrules. For Cr the ratio is 0.7, indicating lower chromium in the chondrules than in the groundmass; for Fe and Cu this ratio is about 0.3, and for Co it is very low, 0.05. This correlates well with the geochemical behavior of these elements and the distribution of minerals within the meteorite. The chondrules are made up almost entirely of silicates, whereas the metal and sulfide phases are practically confined to the groundmass. Thus, the lithophile elements Na, Sc, and Mn are relatively enriched in the chondrules; Cr is present partly in the pyroxene, but also as chromite, and the chromite is mostly in the groundmass; some of the Fe is in the silicates, but most is present as metal and sulfide in the groundmass; Co is probably entirely in the metal phase and is therefore almost completely absent from the chondrules.

The Bur-Gheluai Meteorite

After detonations and the appearance of a fireball in the sky, many stones fell near Bur-Gheluai in the district of Bur-Hacaba, Somalia, at 8 a.m. on Oct. 16, 1919. This must have been a very large shower; over 120 stones were recovered. The largest weighed 15.4 kg, 5 others weighed between 4 and 8 kg, 8 between 2 and 3 kg, 21 between 1 and 2 kg, 16 between 0.5 and 1 kg, 52 between 0.1 and 0.5 kg, and 18 between 0.01 and 0.1 kg (Neviani, 1921).

Bur-Gheluai does not appear on any maps available to us, but the statement that it is 70 km from Bur-Hacaba and 80 km from Baidoa places it at approximately 3°N, 44°E, or about 200 km northwest of the capital city of Mogadishu.

Since a complete chemical analysis of this meteorite is lacking, we have decided to remedy this, using a piece from a 1.3 kg stone (no. 778) in the collection of the U.S. National Museum.

Mineralogical composition and structure.—The principal minerals are olivine, pyroxene, and nickel-iron (kamacite and taenite). The usual amount of troilite is present as well as a small amount of plagioclase. Accessory minerals include chromite and merrillite. Prof. P. Ramdohr (pers. comm.) has examined a polished surface and reports the occurrence of small amounts of native copper and ilmenite, plus a trace of pentlandite.

Olivine: The refractive indices are $\alpha=1.670$, $\gamma=1.708$, indicating a content of 19 mole percent 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).

Pyroxene: Judging from optical and X-ray examinations, the pyroxene is a mixture of bronzite and clinobronzite in approximately equal amounts. The bronzite grains are transparent and untwinned, and their refractive indices are $\alpha=1.672$, $\gamma=1.682$, indicating a content of 16 mole percent of the $FeSiO_3$ component, according to the determinative curve of Kuno (1954). The refractive indices of the clinobronzite are approximately the same as those of the orthopyroxene, but the grains are turbid, and optical properties are difficult to measure.

Plagioclase: This mineral is fine grained, and only a mean refractive index, about 1.538, could be measured, which indicates a composition of about An_{12}.

A cut surface of the Bur-Gheluai meteorite is pale gray in color, with numerous silvery-white metal particles. The metal particles are surrounded by brown limonitic staining, indicative perhaps of the former presence of trace amounts of lawrencite. Chondrules can be distinguished with the aid of a hand lens, but they are not prominent.

In thin section under the microscope the meteorite is seen to be highly chondritic, but the boundaries of the chondrules are frequently ill defined and tend to merge with the groundmass. The grain size of the groundmass is similar to that within the chondrules. Chondrules range from 0.3 to 1.5 mm in diameter and are of diverse types. Commonest are aggregates of euhedral olivine crystals in a dark gray turbid matrix, probably a devitrified glass. Similar chondrules with euhedral crystals of clinobronzite also occur. Other chondrules consist of an aggregate of radiating platy or prismatic crystals of pyroxene. Barred olivine chondrules—the bars being alternately olivine and turbid gray devitrified glass—are not uncommon. The opaque minerals are interstitial to the chondrules.

The density of this meteorite, reported by Neviani (1921), is 3.76.

TABLE 2.—*Chemical analysis and normative mineral composition of the Bur-Gheluai meteorite* (analysis: Maynes; norm: Mason)

Analysis		*Norm*	
Fe	16.58%	Olivine	33.6%
Ni	1.26	Bronzite	26.9
Co	0.08	Diopside	3.8
FeS	6.04	Albite	7.2
SiO_2	36.07	Anorthite	1.6
TiO_2	0.11	Orthoclase	0.6
Al_2O_3	2.10	Chromite	0.8
Cr_2O_3	0.52	Apatite	0.7
FeO	10.35	Ilmenite	0.2
MnO	0.29	Troilite	6.0
MgO	22.81	Nickel-iron	17.9
CaO	1.68		
Na_2O	0.85		
K_2O	0.09		
P_2O_5	0.30		
H_2O+	0.66		
H_2O-	0.11		
Sum	99.90%		

CHEMICAL COMPOSITION.—The chemical analysis is given above along with the normative mineralogical composition calculated according to Wahl (1951). The composition is very similar to that of the Allegan meteorite. Bur-Gheluai is an olivine-bronzite chondrite in Prior's classification (1920), and the total iron content, 28.45 percent, places it in the high-iron (H) group of Urey and Craig (1953).

The Cynthiana Meteorite

This meteorite fell about 4 p.m. on Jan. 23, 1877, after a brilliant fireball was seen over a considerable region of southern Indiana and northern Kentucky. The place of fall was in Harrison County, Ky., about 9 miles from the town of Cynthiana. It is remarkable that this was the third meteorite fall in the Middle West within a month's span, the others occurring in Rochester, Ind., on Dec. 21, 1876, and Warrenton, Mo., on Jan. 3, 1877.

A single stone weighing 6 kg was recovered; it was described and analyzed by Smith (1877). He commented on its brecciated appearance and remarked that in this and other characteristics it resembled the Parnallee meteorite. Urey and Craig (1953) rejected Smith's analysis because of the very low Al_2O_3 content shown therein. Because of this, we decided to reanalyze the meteorite, using a piece from the specimen (no. 748) in the U.S. National Museum.

Mineralogical composition and structure.—A cut surface of the meteorite is medium gray in color with prominent chondrules, some lighter and some darker than the groundmass. Many of the chondrules show dark rims; occasionally one sees a dark chondrule with a light-colored rim. A moderate amount of metal and troilite is scattered through the groundmass, some of the grains being unusually large, from 2 to 3 mm across. The brecciated structure commented on by Smith is not especially prominent in our hand specimen. The stone is remarkably fresh, the broken surfaces showing no sign of limonitic alteration after nearly a century of exposure to the atmosphere.

The principal minerals are olivine and pyroxene. Troilite and nickel-iron are present in minor amounts. Plagioclase was not certainly identified optically although rare grains with a refractive index of about 1.54 and a low birefringence were seen in an acid-insoluble fraction of the meteorite; a very weak peak corresponding to feldspar was seen in an X-ray diffractogram. Accessory minerals include chromite and a phosphate (apatite or merrillite, or both).

Olivine: The refractive indices are $\alpha = 1.684$, $\gamma = 1.720$, indicating a content of 25 mole percent 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, symmetrical, and well defined, indicating olivine of uniform composition. Dodd, Van Schmus, and Koffman (1967) made microprobe analyses of the olivine in Cynthiana and report an essentially uniform composition of $Fa_{25.6}$.

Pyroxene: Optical and X-ray examinations show that the pyroxene is largely clinohypersthene with some hypersthene. The clinohypersthene shows close-spaced polysynthetic twinning, and the grains are turbid with tiny inclusions, which makes precise refractive index measurements difficult. The hypersthene has $\alpha=1.677$, $\gamma=1.688$, indicating a content of 20 mole percent of the $FeSiO_3$ (Fs) component, according to the determinative curve of Kuno (1954). Dodd, Van Schmus, and Koffman (1967), by microprobe analysis, reported a mean composition of $Fs_{20.7}$ for the pyroxene with some variability from grain to grain.

In thin section under the microscope this meteorite is seen to be a close-packed mass of chondrules, from 0.3 to 3 mm. in diameter, with comparatively little interstitial material. A wide variety of chondrules is present. Many consist of numerous euhedral crystals of olivine and/or clinohypersthene in a turbid brown matrix that is probably a devitrified glass. Barred olivine chondrules—the bars being alternately olivine and turbid devitrified glass—are not uncommon. Some chondrules consist of fibrous radiating clinohpyersthene, others are made up of intergrown prismatic crystals of olivine and clinohypersthene. The opaque minerals are mostly interstitial to the chondrules or concentrated as rims around individual chondrules.

The density of this meteorite, determined by the method described for Allegan, was found to be 3.47.

TABLE 3.—*Chemical analysis and normative mineral composition of the Cynthiana meteorite* (analysis: Maynes; norm: Mason)

Analysis		*Norm*	
Fe	3.80%	Olivine	45.4%
Ni	1.01	Hypersthene	25.6
Co	0.03	Diopside	5.2
FeS	6.05	Albite	8.6
SiO_2	41.61	Anorthite	1.6
TiO_2	0.13	Orthoclase	0.6
Al_2O_3	2.36	Chromite	0.9
Cr_2O_3	0.58	Apatite	0.6
FeO	14.89	Ilmenite	0.2
MnO	0.35	Troilite	6.1
MgO	25.74	Nickel-iron	4.8
CaO	1.96		
Na_2O	1.02		
K_2O	0.10		
P_2O_5	0.25		
H_2O+	0.24		
H_2O-	0.02		
C	0.11		
Sum	100.25%		

CHEMICAL COMPOSITION.—The chemical analysis and the normative mineral composition calculated from it as recommended by Wahl (1951) are given above. The observed mineral composition is in good agreement with the calculated norm, except for the presence of 10.8 percent feldspar in the norm. Only a small amount of feldspar actually was observed, and most of this component is evidently in the devitrified glass.

The composition of the Cynthiana meteorite shows that it is an olivine-hypersthene chondrite in Prior's classification (1920). The total iron content, 19.2 percent, places it in the low-iron (L) group of Urey and Craig (1953). This iron content is considerably less than the average (22.33 percent) for Urey and Craig's L group, and suggests the assignment of this meteorite to Keil and Fredriksson's (1964) LL subgroup (low iron-low metal). The metal content, however, is not unusually low for an L group chondrite, and the iron content of the olivine is not as high as in those chondrites classified as LL group by Keil and Fredriksson.

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