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SECOND REPORT ON RESEARCHES ON THE CHEMICAL AND
MINERALOGICAL COMPOSITION OF METEORITES.

BY

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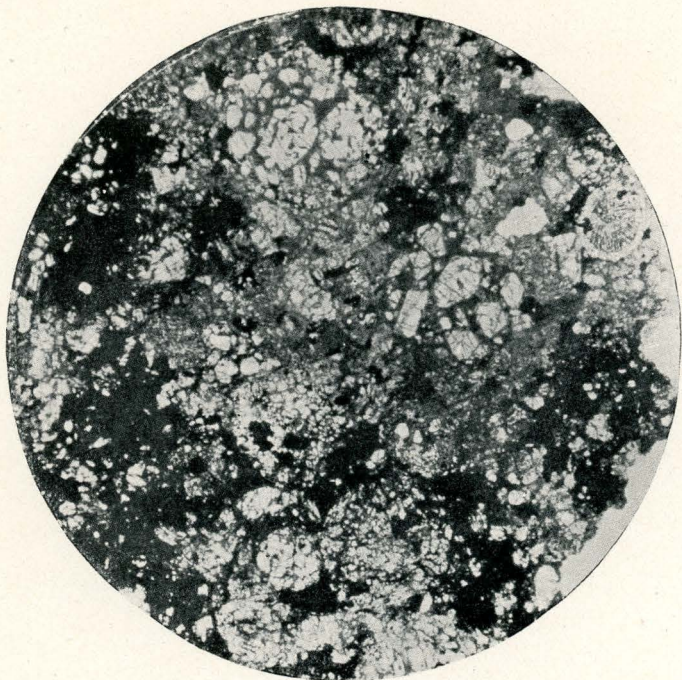


FIG. 1.

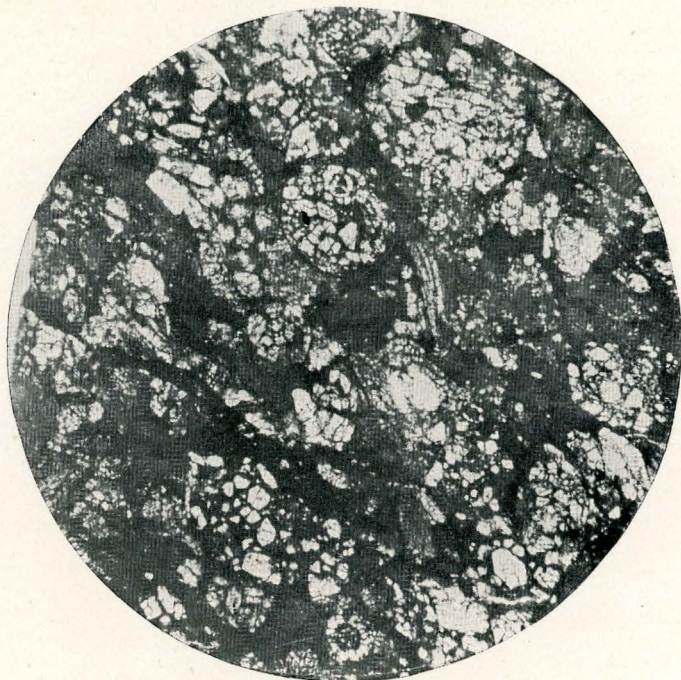


FIG. 2.

SECOND REPORT ON RESEARCHES ON THE CHEMICAL AND MINERALOGICAL COMPOSITION OF METEORITES.¹

By GEORGE P. MERRILL,

Head Curator of Geology, United States National Museum.

The paper here presented contains the detailed results of studies made during the past year under a grant from the J. Lawrence Smith fund. The immediate purpose of the investigation, as noted in my first report, these *Memoirs*, volume 14, 1916, pages 7-29, was the determination of the presence or absence of sundry reported elements existing in minor quantities, but naturally it was found advisable to extend these boundaries from time to time, as interesting or important features developed in progress of the work. In several instances results deemed of special importance have already received publication elsewhere.²

For convenience of reference, the meteorites studied are, in the following pages, considered alphabetically.

Bath, Brown County, S. Dak.—The fall of this stone and the attendant phenomena were briefly described by Foote.³ Later, Brezina,⁴ with even greater brevity, described its lithological features. There is nothing to indicate that he examined the stone in thin sections, and as it has never been subjected to chemical analysis it seemed a fit subject for further investigation.

Macroscopically the stone is gray, but, owing to oxidation, so filled with rust spots as to give it a brownish cast. The crust is rough and dull, a characteristic of stones of this class. The texture is firm, but the chondrules, for a large part at least, break free from it when the stone is fractured. The most unusual feature, when examined with a pocket lens, is the abundance of glittering crystalline facets of nickel-iron. The slipping faces mentioned by Brezina are not evident to the unaided eye in the pieces in the museum collection, but in the thin section are numerous fine black fracture lines, along some of which a differential movement has plainly taken place.

In thin section the stone is seen to be a spherulitic chondrite with crystalline base. (Fig. 1, Pl. I.) The chondrules are extremely variable in detail, but present no unusual features. The essential minerals are olivine and enstatite; more rarely polysynthetically twinned monoclinic forms appear. Fragmental forms are common, particularly among the radiating and cryptocrystalline enstatite types. In one of the latter was observed a single granule of a distinctly red, translucent, but not transparent, mineral, of somewhat rounded outline as though corroded, and completely isotropic. (Fig. 1.) It is believed to be a spinel; possibly osbornite; it is impossible to decide from the single occurrence of so small an object. (See further under *Homestead*.) The phosphatic mineral I have of late had so frequent occasion to note occurs but rarely.

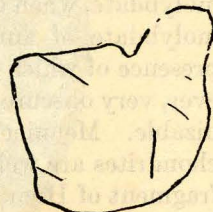


FIG. 1.

Bjelokrynitshie, Volhynia, Russia.—This stone, which fell on January 1, 1887, has apparently as yet received but brief notice and been subjected to no chemical analyses. Four references to descriptions are cited by Wülfing, two of which are by B. K. Agafonov, the others being even briefer notes in the catalogues of Brezina and Meunier. I have had access to but

¹ Presented April, 1918; read November, 1918.

² On the Calcium Phosphate of Meteorites, *Amer. Journ. Science*, vol. 43, 1917, pp. 322-324, and Tests for Fluorine and Tin in Meteorites, with notes on Maskelynite and the Effect of Dry Heat on Meteoric Stones, *Proc. Nat. Acad. Sci.*, vol. 4, no. 6, 1918, p. 176.

³ *Amer. Journ. Sci.*, vol. 45, 1893, p. 64.

⁴ *Wiener Sammlung*, 1895, p. 259.

one of the papers cited by Agafonov.¹ In this the stone is described as composed chiefly of chondrules, entire and fragmental, embedded in a ground of crystals and crystal fragments. The mineral composition is given as olivine, bronzite, augite, maskelynite, nickel-iron, and troilite. Brezina describes it² as having suffered from oxidation to a depth of 1-3 cm. below the original surface, as of a brecciated structure and with strongly developed slicken-sided surfaces (Harnischflächen). He classes it a brecciated chondrite (Cib), though with occasional black chondrules showing a gradation into the brecciated spherulitic chondrites (Ceb). One fragment badly oxidized he seems inclined to class as a crystalline chondrite (Ck). Meunier in his list³ states that while the characteristics are not absolutely identical with those of Tadjera, the composition is the same and the differences not sufficiently marked to justify relegating to a distinct type. Neither says anything of the mineral composition other than is to be inferred from the classification.

The stone is represented in the national collection only by a small oxidized mass weighing 8 grams and a thin slice of the fresh, unaltered stone weighing 14 grams. A thin section cut from this last shows the stone to be of a pronounced chondritic type, the entire mass being composed of chondrules and fragments of chondrules closely compressed and with a minimum amount of fragmental interstitial matter. The mineral composition is nickel-iron, iron sulphide, olivine, an orthorhombic and a monoclinic pyroxene, the last named polysynthetically twinned. In two instances interstitial areas of the phosphate provisionally called "francolite" were noted and there are numerous areas of the black irresoluble matter which Meunier regards as fayalite and of secondary origin.

Judging from what has been written and my own observation, the stone is of a somewhat variable character. From the result of study of this one section I feel disposed to class it as a veined spherulitic chondrite (Cca). (See Fig. 2, Pl. I.)

Farmington, Washington County, Kans.—This stone belongs to the group of black chondrites of Brezina, of which but eight representatives are known. The stone was seen to fall and its history is beyond question. It has been described by several writers among whom only Kunz, Weinschenk,⁴ and Brezina need here be mentioned. Weinschenk, to whom the microscopic descriptions are doubtless due, refers to the occurrence of "the mineral designated by Tschermak as 'monticellite-like' formed in the usual way. This contains rounded, colorless inclusions with bubbles probably of glass." Brezina⁵ says "Auch monticellitartige Chondren kommen vor." I am unable in the five thin sections we have of this stone to find the monticellite-like mineral in chondrules. It occurs rather in irregular cavities, sometimes completely filling them and sometimes merely small, colorless crystalline plates lining their walls. (See Fig. 1, Pl. II.) Naturally there was at once suggested the possibility that these were a phosphate, a possibility made a certainty by treating one of the areas in an uncovered slide with a drop of acid ammonium molybdate, when the mineral was quite dissolved, giving rise to abundant crystals of the phosphomolybdate of ammonium. I have been unable to detect the "asymmetric feldspar," the presence of which was thought to be indicated by the chemical analysis. The structure is, however, very obscure, and it is yet possible that a mineral of this nature may exist and be unrecognizable. Meunier's conclusions relative to the secondary nature of the dark color in the black chondrites are well supported by a comparison of slides of this stone with those from a roasted fragment of Homestead.

Forest City, Winnebago County, Iowa.—The only mineralogical description of this stone that has thus far been given is that of Kunz.⁶ This is incomplete and unsatisfactory, made evidently without recourse to thin sections and a microscope. He describes it as a "typical chondrite, apparently of the type of the Parnallite group of Meunier A broken surface shows the interior color to be gray, spotted with brown, black, and white, containing small

¹ Rev. des Sciences Naturelle, St. Petersburg, no. 1, 1891, p. 41.

² Die Meteoriten Sammlung, 1895, p. 249.

³ Revision des Pierres Meteorique, 1894, p. 413.

⁴ Min. u. Pet. Mittheil. vol. 12, 1891, pp. 177-182, and Amer. Journ. Sci., vol. 43, 1892, pp. 65-67.

⁵ Weiner Sammlung, 1895, p. 253.

⁶ Amer. Journ. Sci., vol. 40, 1890, pp. 318-320.

FIG. 2.

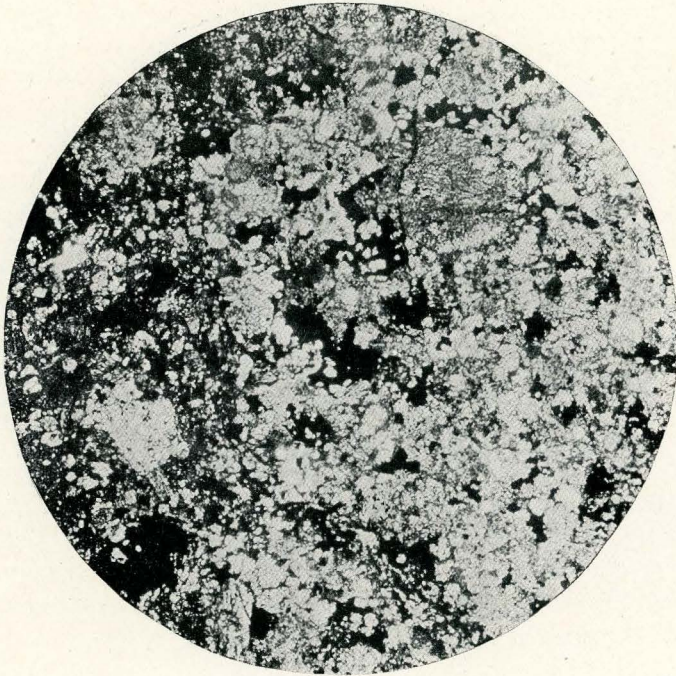
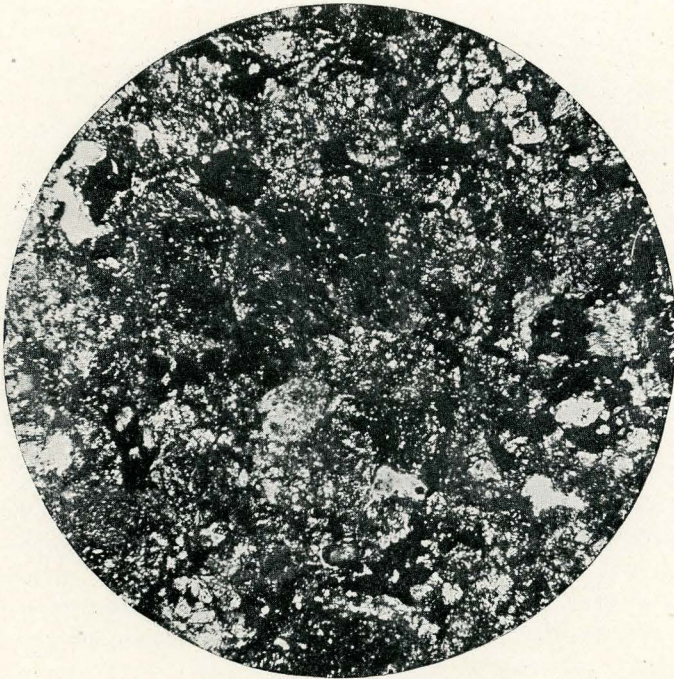


FIG. 1.



specks of meteoric iron, from 1 to 2 millimeters across. Troilite is also present in small rounded masses of about the same size. On one broken surface was a very thin scum of black substance, evidently graphite, soft enough to mark white paper; a feldspar (anorthite) was likewise observed, and enstatite was also present." Further on, in discussing the analyses by L. G. Eakins he remarks that "it is of course probable that the Cr_2O_3 represents chromite, and possible that the alkalis and alumina with a little lime represent a soda-lime feldspar." Nothing is said as to the presence of olivine, though its presence is to be inferred from the 36.04 per cent soluble in hydrochloric acid.

Under the microscope I find the structure very obscure, confused, and, as is so often the case with meteorites of this class, baffling all efforts at satisfactory descriptions. Few of the constituent minerals are crystallographically well developed, though occasional small forms in the midst of the chondrules present recognizable crystal faces. The recognized constituents, aside from the nickel iron and iron sulphide, are olivine and two pyroxenes, one orthorhombic in crystallization and one monoclinic, the latter polysynthetically twinned. The calcium phosphate is common in the usual interstitial forms. A black carbonaceous matter in veins and coating slicken-sided surfaces is not uncommon. Nothing resembling a feldspar is to be seen in any of the sections examined. (Fig. 2, Pl. II.)

Gargantillo (Tomatlan), Jalisco, Mexico.—This stone was described by Shepard,¹ who seems to have secured 511 grams out of the total known weight of 780 grams. The mineral composition as given by him was as follows:

	Per cent.
Chrysolite.....	80.00
Chladnite (?).....	10.00
Nickeliferous iron.....	7.00
Troilite.....	} 3.00
Chromite.....	
Peroxide of iron.....	
Total.....	100.00

Specific gravity, 3.47 to 3.48.

He noted as a "striking peculiarity . . . the prevalence everywhere of octahedral crystals of nickeliferous iron," which were "so distinct as to be recognizable with the naked eye, the brilliant equilateral, triangular faces coming into view by every change of position of the specimen." No chemical analysis appears to have been made, nor has it apparently been studied further except by Brezina, who classes it in his catalogue² as a "kugelchenchondrit" (Cc) and refers to it as having a very loose and friable ground mass, thick crust, large chondrules, many brown flecks, like Sarbanovas, and the iron abundant with many crystalline faces.

A little more may well be added to this description. The stone is so friable and the abundant chondrules so loosely embedded that it is practically impossible to get a satisfactory section without sacrificing a larger amount of material than is warranted. The microscope shows an indistinct and confused, fine, granular ground of olivine, enstatite, and occasional grains of a monoclinic pyroxene, in addition to the metallic constituents and the sulphide. (See Fig. 1, Pl. III.) The fine powder treated on the slide with a drop of ammonium molybdate yields characteristic globules and crystals of phosphomolybdate of ammonium. No feldspars, even of the maskelynite type, were detected.

A vial of fragments too small for other purposes, found in the Shepard collection, was sacrificed for the purposes of analysis, with the following results:

	Per cent.
Mineral.....	93.54
Metal.....	6.46

The metal amounted to 0.41 grains and consisted of:

	Per cent.
Nickel.....	10.12
Cobalt.....	1.02
Iron (by difference).....	88.86

¹ Amer. Journ. Sci., vol. 30, 1885, pp. 105-108.

² Die Meteoritensammlung, etc., 1896, p. 256.

The mineral portion amounted to 5.94 grains and consisted of:

	Per cent.
Silica SiO_2	41.16
Alumina Al_2O_3	3.97
Ferrous oxide FeO	18.48
Manganous oxide MnO	0.39
Chromic oxide Cr_2O_3	0.20
Phosphoric acid P_2O_5	0.30
Sulphuric anhydride SO_3	5.56
Lime CaO	1.92
Magnesia MgO	26.88
Soda Na_2O	1.14
Potash K_2O	0.06
Total.....	100.06

A recalculation of these figures gives the following, representing the composition of the stone as a whole:

	Per cent.
SiO_2	38.50
Al_2O_3	3.71
Cr_2O_3	0.18
FeO	17.28
MnO	0.36
MgO	25.14
CaO	1.79
Na_2O	1.06
K_2O	0.05
P_2O_5	0.28
SO_3	5.20
Fe	5.74
Ni	0.66
Co	0.06
Total.....	100.01

These figures fall well within the range of chondritic stones. No barium strontium or other alkaline earths than those mentioned could be detected. No calcium in a water solution, hence no oldhamite. The mineral composition is olivine, monoclinic and orthorhombic pyroxene, calcium phosphate (merrillite of Wherry), chromite, nickel-iron, and troilite.

Hartford (Marion), Linn County, Iowa.—The first descriptions of this stone are by Shepard.¹ His determination of its lithological nature is excusable only in consideration of the times and the means at his command. He wrote: "It appears to contain but a single mineral species of this (i. e., 'earthy') description, and this one which . . . has until now escaped a separate recognition." For this mineral he proposed the name *howardite* and gave the complete mineral composition of the stone as howardite, 83 per cent; nickel-iron, 10.44 per cent; magnetic pyrite, 5 per cent; olivine and anorthite, traces. Some twenty and odd years later Rammeisberg² reviewed Shepard's work and showed the stone to consist of 10.54 per cent nickel-iron; 6.37 per cent troilite; 41.58 per cent soluble silicate, and 41.24 per cent insoluble, the soluble portion being identified as olivine; the insoluble, which was analyzed, being "almost exactly a bisilicate," but which he does not name.

An examination of thin sections from fragments in the Museum collection shows the essential constituents to be olivine and enstatite, with the usual interstitial calcium phosphate, nickel-iron, and troilite. The structure is not strongly chondritic. (Fig. 2, Pl. III.) No polysynthetically twinned pyroxenes were noted. The phosphatic mineral was evident to the naked eye in two instances as small white spots, perhaps 2 mm. in diameter, on a broken surface of the stone. These were so soft and friable as to fall down to almost dustlike particles when touched with a needle point. It is doubtless this brittle property of the mineral, causing it to break away in the process of grinding the section, that has prevented its earlier detection. It

¹ Amer. Journ. Sci., vol. 4, 1847, p. 288, and vol. 6, 1848, p. 403.

² Mon.-Ber. Berlin Akad., 1870, pp. 457-459.

should be stated that a particle tested by the immersion method showed an index of refraction of 1.625. Far more abundant than the phosphate is a limpid, colorless mineral, likewise occurring interstitially, but locally so abundant as to form almost the base in which the other silicates are embedded. The mode of occurrence and appearance are in every way characteristic of the so-called maskelynite, but that in many instances the area between crossed nicols breaks up into granular aggregates which are plainly biaxial and give distinct polarizations in light and dark, rarely yellowish colors in the thicker sections. The dark cloud, as a rule, sweeps over the face of the crystal in a manner indicating conditions of strain, and in no case have I been able to find a satisfactory section showing the emergence of an optic axis, or other indications of its optical properties than the indistinct black brushes sweeping across it as the stage is revolved. It is apparently positive. There are no signs of cleavage, but in a few instances faint lines were observed traversing the section. In these cases I was able to measure extinction angles against these lines, of 8° and 10° . But for its very evident doubly refracting properties the mineral would have been set down at once as maskelynite. As it was, additional tests seemed necessary. Two determinations of its refractive index by the immersion method gave 1.54 and 1.545, which is higher than that of a similar appearing mineral to which I have frequently referred in other publications. All further doubts as to the nature of the substance are, however, in this particular case set at rest by the finding of occasional granules still retaining residual traces of the characteristic twinning bands of a plagioclase feldspar.

Homestead, Iowa.—The Homestead meteoric stone fell on February 12, 1875, and is now represented by 124,492 grams scattered among 62 collections throughout the world. It has been the subject of numerous papers, concerning which a reference to Wülfing's bibliography is here sufficient. The stone is classed by Brezina as a brecciated gray chondrite (Ceb), and by Meunier as a limerickite. Wadsworth, who examined the stone in thin section, states it to consist of "crystals and grains of olivine, enstatite, pyrrhotite, iron, and base," and quotes Lasaulx as stating that it carries plagioclase. Several chemical analyses have been made, none of which show the presence of any unusual constituents. This is little to be wondered at when one considers that in the case of Gumbel but 1.5 grams of material were at his disposal. Much of the interest that is attached to the stone is due to A. W. Wright's work on the gaseous contents of meteorites.

My own attention was first drawn to this stone when studying the occurrence of the calcium phosphate concerning which I have of late written several papers, and which, incidentally, I find here in abundant characteristic forms. I do not find the plagioclase feldspar referred to by Lasaulx, but do find in some of the chondrules a polysynthetically twinned monoclinic pyroxene which seems to have been wholly overlooked by previous observers. The immediate cause of the present note is, however, the occurrence in each of two slides examined of a minute, bright red-brown, scarcely translucent, isotropic mineral embedded in enstatite, as shown in the drawing reproduced here. (Fig. 2.) An attempt at a definite determination of its mineral nature was a partial failure. Finding it insoluble in ordinary acids, one of the slides was sacrificed, painting around the object as closely as possible with vaseline and then covering the exposed portion with a large drop of fluorhydric acid. The silicates were all decomposed badly, but amidst the gelatinous mass of decomposition products I was still able to detect the red granule apparently untouched. In an attempt to remove the granule for further tests and observation, it became hopelessly lost. I can only surmise from its apparent insolubility, subtranslucency, color, isotropic nature, and a suggestion of octahedral form, that it may be a spinel. That it is osbornite does not seem probable. The second slide, from which the accompanying figure was drawn, has been covered and preserved. I may add that eight other small sections, cut from fragments of the stone in the Barker bequest, gave no new occurrences of the mineral. This is probably the same mineral noted by Gumbel¹ but thought to be garnet. The decidedly octahedral termination on the form figured in the present paper seems to warrant its being considered a spinel.

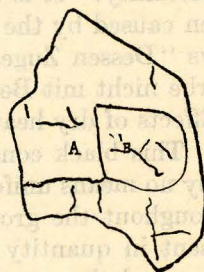


FIG. 2.

¹ Sitz. der Math.-phys. Classe, der K. bayrischen Akad. zu München Dec. 1875, p. 323.

McKinney, Collin County, Tex.—It is remarkable that this interesting stone, which has been known since 1895, should have been allowed so long to remain unstudied, the bibliography consisting only of a brief statement by von Hauer¹ regarding the acquisition by the Vienna museum of upward of 40 kilograms of the material, a description of the stone by Brezina,² based evidently only on an examination by the naked eye, aided perhaps by a pocket lens, a brief note by Meunier³ calling attention to the evidence it afforded of the introduction of the metal and sulphide after consolidation, and lastly an analysis by Whitfield given in my paper on the minor constituents of meteorites⁴ the last named made with particular reference to the possible occurrence of barium, strontium, zirconium, or other of the rare elements.

Macroscopically the stone is fine-grained, compact, dull brownish gray, almost black, looking on a broken surface very much like a piece of hard shale, showing here and there a minute fleck of metal, and with chondrules quite inconspicuous except where it is polished. The texture is firm and the chondrules break with the stone. On the polished surface they are of greenish color, suggestive of a serpentinous alteration, which, however, microscopic examination shows not to have taken place.

In the thin section the microscope reveals, in addition to the iron and iron sulphide, three varieties of pyroxene, one occurring in broad plates with wide (25°–30°) extinction angles, a polysynthetically twinned variety and normal enstatite, in addition to olivine and the calcium phosphate, while the whole mass is here and there so impregnated with a coal black compound as to give it the dark color referred to.

The chondrules are varied and interesting. They consist of enstatite in the common radiating and cryptocrystalline forms as well as in good, well developed phenocrysts in a glassy or fibrous base. Sometimes the entire chondrule is composed of small, closely compacted forms with little or no interstitial base. Others are formed wholly of the polysynthetically twinned monoclinic forms. These twinned pyroxenes occur also scattered throughout the groundmass and under such condition with relation to their associated minerals as to suggest a dynamic action, a crowding and crushing, and sometimes even raising the question if the twin structure may not itself be due to this same cause. The occurrence of the twinned forms in the chondrules where there are no signs of strain forbids, however, the universal application of any such theory of origin. Still other chondrules are wholly of olivine. The calcium phosphate occurs in the usual irregular, interstitial, colorless forms with low relief. The groundmass is everywhere so obscured by the black matter that it is impossible to make out a structure for a certainty. It is apparently fragmental, though if we accept Meunier's views, it may have been caused by the reheating to which he ascribes this black color. In this connection Brezina says "Dessen Zugehörigkeit zu den Cs insoferne nicht ganz sichergestellt ist, als die schwarze Farbe nicht mit Bestimmtheit auf einen Kohlegehalt Zurückgeführt ist". (See further under "Effects of dry heat on meteoric stones," Proc. Nat. Acad. Sci., vol. 4, 1918, p. 178.)

This black constituent, which is sufficiently abundant to give the stone a uniform color, is by no means uniformly distributed, but, as shown in the thin section and figures, is injected throughout the ground and along cleavage and fracture lines of the various minerals, being absent in quantity from the chondrules, forming a dense black, opaque ground from which these and the scattered, often fragmental silicates stand out sharply. An attempt was made to determine the possible presence of a hydrocarbon, but the facilities at command did not enable me to arrive at a satisfactory result. One hundred grams of the pulverized stone were digested for 48 hours, first in ether and next in carbon disulphide. Although care was taken to use the purest chemicals obtainable, and the filters were first washed in ether, the slight, colorless extract obtained in the first instance, and the single small drop of a greenish, oil-like matter in the second, were both felt to be perhaps in part due to impurities. Any hydrocarbon, if present at all, is certainly there in very small quantities. The apparent introduction (or perhaps better *production*) of the coloring matter at a late period in the history of the

¹ Ann. Hof-Mus., vol. 10, 1895, p. 34.

² Idem, pp. 252, 253.

³ Revision des Pierres Meteorique, etc., p. 412.

⁴ Mem. Nat. Acad. Sci., vol. 14, 1916, p. 19.



FIG. 1.

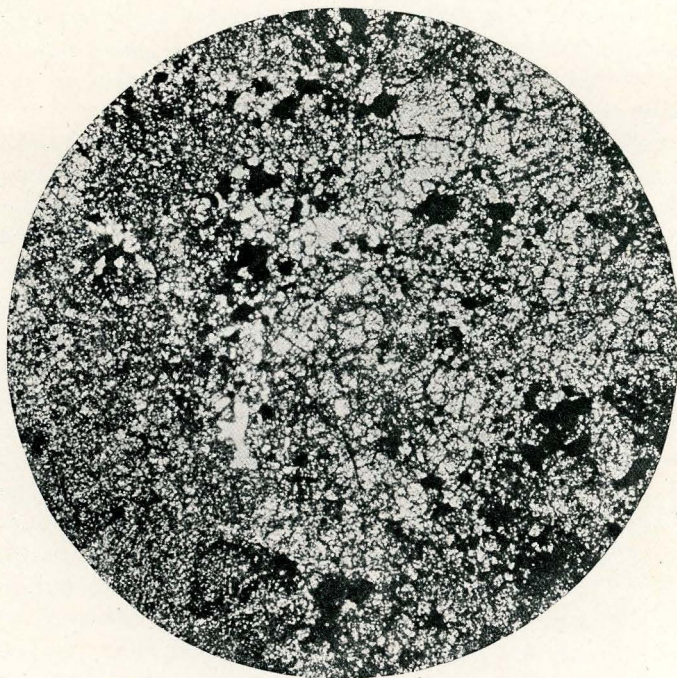


FIG. 2.

stone is beautifully shown in some of the pyroxene sections where the cleavage and fracture lines have become so filled as to form a black network between the threads of which the colorless pyroxenic material stands out sharply and in all its original freshness.

Naturally these observations recalled Meunier's views on the origin of the meteorites of his tadjerite group through a preterrestrial heating of aumalites, and the matter seemed of sufficient interest to warrant a partial repetition of his experiments. The results, I have given on page 178 of the Proceedings of the Academy as noted above.

Ness County, Kans.—This is a holocrystalline chondritic stone, of firm texture, the chondrules breaking with the matrix. Thin sections show, where not too badly stained by iron oxides, a granular aggregate of olivine and bronzite with the usual scattering blebs and granules of nickel-iron and iron sulphide. The chondritic structure is very obscure and the chondrules themselves present little variation. (Fig. 2, Pl. IV.) The structure is in places decidedly cataclastic. Aside from the minerals mentioned, I find, rarely, clusters of minute, polysynthetically twinned pyroxenes and numerous limpid, completely colorless interstitial areas, without crystal outlines or determinable cleavage, polarizing only in light and dark colors, often showing conditions of strain, and giving occasionally biaxial interference figures. It is evidently of the nature of the so-called maskelynite.

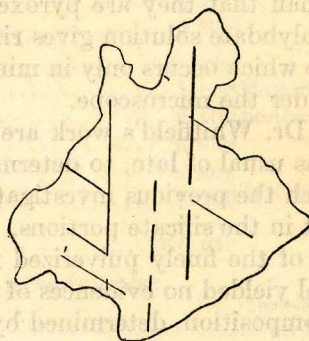


FIG. 3.

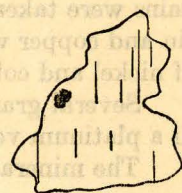


FIG. 4.

By careful work with a needle point on an uncovered section the edge of one of these areas was sufficiently exposed to permit testing by the immersion method, and found to have an index of refraction of between 1.55 and 1.56, or that of andesine as given by Iddings. In addition, two of the sections show a completely colorless mineral, one of which is isotropic and shows two lines of cleavage cutting at angles of about 56° and 124° , and the other showing extinctions parallel with a single series of cleavage lines and giving a uniaxial interference figure strongly suggestive of the mineral apatite¹ (see Figs. 3 and 4).

Although sought for most carefully, this mineral could not be found in any of the six other sections examined, and a more exact determination is impossible. It is perhaps the same mineral referred to by Farrington² and which he also failed to determine.

Ochansk, Siberia.—Through an oversight on my part, this stone in my Handbook and Catalogue³ was stated not to have been analyzed as a whole. Since the issue of that publication, my attention has been called to the paper of Tichomirow and Petrow⁴ in which is given the analysis quoted below.

My excuse for taking the matter up once more lies in the somewhat unusually high ratio of nickel to iron⁵ (1-3.5) which, so far as I now recall, is equalled only by that of the Middleborough stone. They also report 0.52 per cent of copper and tin. A quantity of fragments of not over a gram or so each in weight, the residues from the Ward collection, formed abundant opportunity for further investigation, which after sundry qualitative tests by myself, was undertaken in detail by Dr. Whitfield.

As is well known, the stone belongs to the brecciated spherulitic chondrules of Brezina or canellites of Meunier. The texture seems to be somewhat variable. In a sample received from De Kroutschoff in 1887, the texture is firm enough to receive a smooth surface and a rather low-grade polish. The samples in the Ward collection, on the other hand, which are fresh and unoxidized, are quite friable. Otherwise, however, both in structure and mineral com-

¹ A similar mineral described by me in the Mocs meteorite (see Fig. 5, p. 305, Proc. Nat. Acad. Sci., vol. 1, May, 1915) was found to be soluble in acid and to give solutions reacting for phosphorus and calcium.

² Meteorite Studies I, Field Columbian Museum Publ. 64, Geol. Ser., vol. 1, 1902, p. 300.

³ Bull. 94, 1916, U. S. National Museum.

⁴ Jour. de russ. phys-chem. Ges. 1888, Part 1, pp. 513-518.

⁵ See Prior, on the Genetic Relationship and Classification of Meteorites, Mineralogical Magazine, vol. 18, 1916, no. 83, pp. 29 and 33.

position, the stones seem to be identical and there is apparently no reason for doubting the authenticity of the material now under consideration. A broken surface is light ash gray in color, thickly studded with chondrules, some of which are of a dark color and others very light greenish when broken across. All separate readily from the ground, often in very perfect spherulitic forms. No metal is evident to the unaided eye. In thin sections under the microscope the structure is that of a tufaceous ground carrying the abundant chondrules, entire and fragmental, and scattered crystalline particles with the usual sprinkling of metal and metallic sulphide. It will be recalled that Siemaschko¹ described this last as occurring in pentagondodecahedral forms and, therefore, pyrite. The correctness of this has been questioned (see Cohen, p. 208). The recognizable silicates are olivine and enstatite, though as often the case many of the chondrules are densely crypto-crystalline and their mineralogical nature indeterminable other than that they are pyroxenic. The powdered stone treated with a drop of acid ammonium molybdate solution gives rise to abundant reaction for phosphorus, indicative of a lime phosphate which occurs only in minute interstitial granules quite inconspicuous unless specially sought under the microscope.

The results of Dr. Whitfield's work are given below. It should be stated that particular pains were taken, as usual of late, to determine the presence of the rarer elements particularly tin and copper which the previous investigators had reported, and also the presence or absence of nickel and cobalt in the silicate portions.

Several grams of the finely pulverized material boiled for half an hour in distilled water in a platinum vessel yielded no evidences of the presence of oldhamite.

The mineral composition, determined by the usual methods, was found to be—

	Per cent.
Silicate portion (including a small amount of phosphate).....	76.274
Troilite.....	6.100
Metallic portion.....	16.860
Chromite (calculated).....	0.766
Total.....	100.000

The metallic portion yielded—

	Per cent.
Iron.....	92.092
Nickel.....	7.158
Cobalt.....	0.686
Phosphorus.....	0.064
Total.....	100.000

The silicate portion yielded—

	Per cent.
SiO ₂	44.438
Al ₂ O ₃	9.226
Cr ₂ O ₃	² 0.550
P ₂ O ₅	0.503
FeO.....	13.675
MnO.....	0.376
CaO.....	1.505
MgO.....	27.204
NiO.....	0.678
CoO.....	0.066
Na ₂ O.....	1.186
K ₂ O.....	0.222
SO ₃	0.371
Total.....	100.000

¹ Tschermak's Min. u. petro. Mitt, vol. 11, 1890, p. op.

² Equals 0.766 chromite.

By recalculation the composition as a whole is found to be—

	Per cent.	
SiO ₂	34.235	
Al ₂ O.....	7.107	
Cr ₂ O ₃	0.423	
P ₂ O ₅	0.387	
FeO.....	10.535	
MnO.....	0.289	
CaO.....	1.159	Silicate portion.
MgO.....	20.958	
NiO.....	0.563	
CoO.....	0.058	
Na ₂ O.....	0.913	
K ₂ O.....	0.171	
SO ₃	0.285	
Fe.....	15.526	Metallic portion.
Ni.....	1.196	
Co.....	0.115	
P.....	0.011	
Fe.....	3.880	Troilite.
S.....	2.220	
Total.....	100.031	

The analysis given by Tichomirow and Petrow is as follows:

	Per cent.
SiO ₂	36.36
FeO.....	13.80
MgO.....	18.54
CaO.....	3.00
Fe.....	19.80
Ni.....	5.55
S.....	2.30
P.....	0.05
C.....	0.08
CuSn.....	0.52
Mn, Co, Na.....	Traces.
	100.00

The discordance in these results is altogether too large to be accounted for satisfactorily. That there must have been some error in the percentage of nickel, as suspected, is evident, as Dr. Whitfield's analysis of the metallic portion shows but 7.158 per cent of this constituent, which, when calculated in percentage of the entire stone, amounts to but 1.196 per cent instead of 5.55. The discrepancy in the calcium oxide (1.159 per cent against 3 per cent) is greater than should exist in portions from the same mass, but, singularly enough, the amount of troilite as indicated by the 2.30 per cent of sulphur is about the same and the remaining differences are perhaps not greater than might be expected with the exception of the alkalis, Whitfield reporting 1.084 per cent.

It is to be noted further that Whitfield reports no traces of tin or copper and that the silicate portion freed from all metal by boiling the finely pulverized mineral in mercuric chloride still yields 0.744 nickel and cobalt oxide. It may be recalled that in the table of analyses given in the *Memoirs of the Academy*¹ there are to be found several instances of this character.

To these, at the time, I made no reference in the text, feeling that in some instances at least they might be due to imperfect separation of the metal from the silicate portion. In analyses since made especial care has been taken to guard against any such possibility and there seems no reasonable doubt but that the silicates—olivines or pyroxenes, or both—in meteorites carry small quantities of these constituents, as is the case in terrestrial rocks. Such being the case, it follows that the statement made by Dr. Prior,² together with an explanation by Dr. Wahl³ to the effect that "the ferromagnesium minerals of chondritic stones contain practically no oxide of nickel," is founded upon faulty analyses and insufficient data.

¹ Vol. 14, 1916, pp. 7-27.

² *Min. Mag.* Nov., 1916, p. 39.

³ *Min. u. Petr. Mittheil.*, vol. 26, 1907.

The Ruff's Mountain, South Carolina, meteoric iron, and its included phosphide.—This beautiful iron was first described by Shepard¹ and has since been the subject of numerous other notices, which need reference here only as they bear directly upon the matter in hand. An etched surface shows it to be a medium octahedrite, after Brezina, or a caillite if we follow Meunier. It is chiefly distinguished by the broad fields of plessite and the lack of notable quantities of troilite. The kamacite bands are somewhat swollen and there are occasional rather inconspicuous Reichenbach lamellae. My attention was first drawn to it by the unsatisfactory nature of Shepard's analysis and his supposed discovery of potassium as one of its constituents. A slice weighing a little over 150 grams was therefore submitted to Dr. J. E. Whitfield with the request that he utilize so much as was necessary for an exhaustive analysis. Bulk analysis yields:

	Per cent.
Iron.....	90.654
Copper.....	0.018
Nickel.....	8.550
Phosphorus.....	0.233
Cobalt.....	0.500
Carbon.....	0.025
Sulphur.....	0.020
Silicon.....	None.
Total.....	100.000

with no traces of platinum, palladium, iridium, ruthenium, or the allied elements. Shepard, it may be recalled, reported 96 per cent iron; 3.121 per cent nickel, with chromium, cobalt, magnesium, and sulphur in traces. Later Rammelsburg reported a mean of 8.62 per cent nickel, which is substantially the amount given by Whitfield above. There is nothing of especial note in this composition unless it be its freedom from the rare elements.

Ninety grams of the iron yielded 1.4843 grams of material insoluble in hydrochloric acid of one-half ordinary strength. This residue when examined under the microscope was found to consist largely of schreibersite particles, among which were a few of sufficiently perfect crystalline form to permit measurements and determination of crystalline system. The material possessed the well-known physical properties of schreibersite (see Cohen, *Meteoritenkunde*, pp. 118-131), including the characteristic habit of breaking up readily into cuboidal forms, and which need not be further discussed.

The particles showing well-developed crystal faces were submitted to Dr. Edgar T. Wherry, then assistant curator in charge of the Mineral Department, who reported as follows:²

The crystals average about one-half millimeter in diameter and are irregularly distorted, some of the faces being cavernous; the system of crystallization is not evident on superficial examination. The faces yield, however, fairly good reflections, the positions of which can be located in many cases within 5-10 minutes, unquestionable tetragonal symmetry being exhibited by the angular relations. The forms observed are: c (001) a (100), m (110), o (111), and x (362). In addition there are rounded or poorly developed faces of other pyramids and prisms. All of the forms are incomplete, but there is hardly sufficient regularity in the suppression of faces to justify the assignment of the crystals to any particular hemihedral class.

Below are given the angles observed, which compare closely with those measured on artificial crystals by Mallard, Hlawatsch, and Spencer.

TABLE 1.—*Measured and calculated angles of iron phosphide.*

Tetragonal, $c=0.346\pm 0.001$.

No.	Letter.	Symbol.	Crystals.	Measurements.	Angles measured.		Angles calculated.	
					ϕ	ρ	ϕ	ρ
0	c	001	1	1	0° 00'	90° 00'	0° 00'	90° 00'
1	a'	010	2	5	0° 00'	90° 00'	0° 00'	90° 00'
2	m	110	2	5	45° 00'±15'	90° 00'	45° 00'	90° 00'
3	o	111	2	5	45° 00'±60'	26° 05'±15'	45° 00'	26° 05'
4	x	362	1	2	26° 00'±60'	49° 00'±60'	26° 34'	49° 15'

¹ Amer. Journ. Sci., vol. 10, 1850 p. 128.

² Amer. Mineralogist, vol. 2, 1917, pp. 80-81; vol. 3, 1198, p. 184.

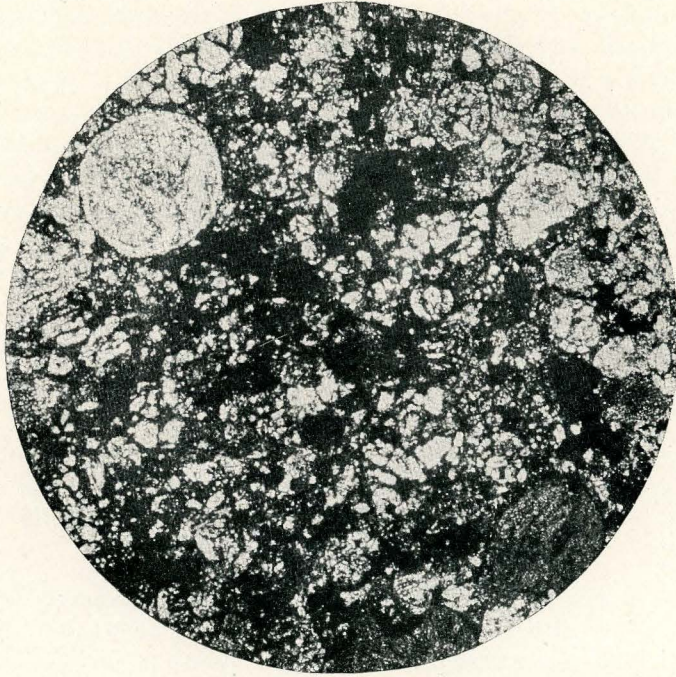


FIG. 1.



FIG. 2.

Several attempts were made at a determination of the chemical composition of this material, but with results so discordant that the matter must be pended awaiting further investigation.

Tennasilm, Estland, Russia.—This stone, which fell on the 28th of June, 1872, was described by G. Baron Schilling some 10 years later.¹ The acquisition of a fragment weighing nearly a kilogram, through Krantz, in Bonn, led me to sacrifice enough for thin sections. An examination of these leads to conclusions relative to its mineral composition somewhat at variance with those of Schilling and is the cause of the present note. It should, however, be stated in advance that Schilling apparently made no use of thin sections, but based his mineralogical determinations wholly upon the results of chemical analysis.

The stone is of a pronounced chondritic type, a veined spherical chondrite (Cca) according to Brezina, or a limerickite if one follows Meunier. Schilling, as a result of analyses which need not be repeated here in their entirety, finds the silicate portion of the stone to consist of 54.45 per cent olivine; 32.27 per cent bronzite, and 13.23 per cent labradorite. Cohen² seems to have accepted these results without question and by a further calculation gives the chemical composition of the labradorite as though it had actually been isolated and analyzed, while as a matter of fact, as noted later, labradorite, or other feldspar, is wholly lacking, at least so far as the Museum material is concerned. Meunier³ apparently accepts this mineralogical determination, placing the stone in his limerickite group, the mineral composition of which is enstatite associated with bronzite and a feldspathic mineral. My observations are based upon a study of four thin sections cut from different portions of the mass mentioned. As described, the stone is of a gray color, plainly chondritic, somewhat soft and friable, the chondrules falling away readily from the matrix when the stone is broken. The metallic constituents are scarcely evident to the unaided eye. Under the microscope the chondritic structure is very pronounced (see Fig. 1, Pl. V). The chondrules are in some cases of beautifully limpid, well developed orthorhombic pyroxenes in a somewhat fibrous base, sometimes of the radiating cryptocrystalline forms, sometimes of polysynthetically twinned monoclinic forms, or again, of olivine. In no case have I been able to find a feldspar, even in the maskelynite condition.

This occurrence offers an interesting illustration of the danger of calculating the mineral composition from chemical analyses, and also the weakness of the quantitative classification when applied to rocks of this type.

Travis County, Tex.—This stone needs a brief reference for the reason that Wülfing in his catalogue raises the question if it does not belong to the Bluff, Fayette County, fall.

Such a suggestion is wholly unwarranted, and it is safe to say would never have been made by one who had seen and compared the two stones. Indeed, if the question of identity were to be raised it might well be with that of McKinney, in Collin County, which it closely resembles. Like the McKinney stone it is black in color, very firm and compact, and presents on a freshly broken surface little to suggest its meteoric nature. It might well be mistaken for a fine-grained basalt. The chondritic structure is very obscure and metallic particles safely identified only with a microscope or pocket lens. Abundant exudations of lawrencite, made conspicuous by globules of iron oxide, serve as a fairly safe criterion of its celestial nature.

Under the microscope the resemblance to the McKinney stone is further augmented. The ground is everywhere impregnated with a black material, carbonaceous⁴ in part, which permeates into the borders of the chondrules and cleavage and fracture lines of the enstatites, and the olivines have in many cases the same greenish yellow appearance suggestive of a serpentinous or chloritic alteration. The enstatites of the ground are colorless except where injected with the black matter which gives the dark hue to the stone. These are interspersed in a manner difficult of description, with radiating and polysomatic chondrules of both olivine and pyroxenes often so altered as to break up into scaly and fibrous aggregates when

¹ Arch. Naturk. Liv. Est. u. Kurlands, vol. 9, pt. 2, 1882, pp. 95-114.

² Meteoritenkunde, vol. 1, p. 310.

³ Revision des Pierres Meteorique, etc., pp. 393-406.

⁴ Roasted in a closed tube the powdered stone yields moisture and gives a distinct empyreumatic odor.

the stage is revolved between crossed nicols. A monoclinic pyroxene is present in minor quantity, showing indistinct traces of polysynthetic twinning, and there are frequent interstitial, very irregular areas of calcium phosphate. It will be noted from Eakins' analysis that the stone yields 0.41 per cent P_2O_5 , an unusually large amount. I find nothing that I can with safety relegate to a feldspar, even of the maskelynite type. The structure is, however, so obscure that it will not do to pronounce too definitely on this point. The general resemblance to the McKinney stone is very close, but in composition, as shown by the two analyses below, it differs radically in the proportional amounts of alumina and ferrous iron, a difference which can be explained by the presence of an aluminous-monoclinic-pyroxene in the stone of McKinney, while magnesian forms prevail in that of Travis County.

	Travis County.	McKinney.
	<i>Per cent.</i>	<i>Per cent.</i>
Silica (SiO ₂).....	44.75	37.900
Alumina (Si ₂ O ₃).....	2.72	13.290
Chromic oxide (Cr ₂ O ₃).....	.52	1.110
Ferrous oxide (FeO).....	16.04	7.400
Magnesia (MgO).....	27.93	26.690
Lime (CaO).....	2.23	1.650
Manganous oxide (MnO).....	Trace.	.210
Nickel oxide (NiO).....	.52	.440
Potash (K ₂ O).....	.13
Soda (Na ₂ O).....	1.13
Iron (Fe).....	1.83	5.070
Nickel (Ni).....	.22	.920
Cobalt (Co).....	.01	.050
Copper (Cu).....	Trace.	.004
Sulphur (S).....	1.83	26.260
Ignition (H ₂ O).....	.84
Phosphoric acid (P ₂ O ₅).....	.41	.050
Total.....	101.11	100.044
Less O for S.....	.92
Total.....	100.19

¹ Chromite.² FeS.

It is obvious from the above that the Travis County stone is to be classed—following Brezina—as a black chondrite, rather than a Ckb, as is Bluff.

It is greatly to be regretted that so little is known regarding the fall or finding of either of these interesting stones.

Wacanda, Kans.—This stone has been the subject of several papers and briefer references, of which only those of Shepard, Smith, Wadsworth, and Brezina, are important. Neither Shepard nor Smith made use of thin sections, a method then practically unknown, and their determinations of mineral composition were surmises based on chemical analyses. Wadsworth based his brief description evidently on a single section, and there is nothing in Brezina's to indicate that he made use of other means than perhaps a pocket lens.

As thus far described, the stone is a brecciated crystalline chondrite, or aumalite of Meunier, consisting of olivine, enstatite and a monoclinic pyroxene with the usual sprinkling of metallic iron and iron sulphide. Smith's analysis, referred to later, showed it to consist of 3.85 per cent troilite, 5.34 per cent nickel-iron, and 90.81 per cent stony matter. In describing the appearance of the stone he mentioned as occurring "only on one part" of his specimen a mineral "in the form of a white, crystalline mass, not exceeding in weight 20 milligrams," which was soluble in hydrochloric acid, the solution reacting for magnesia and silica. This mineral he thought might occupy "the same place among the unisilicates of the meteorites that the enstatite does among the bisilicates."

In looking over a quantity of fragmental material in the Shepard collection my attention was attracted to a small white area, some 2 mm. in diameter, on one of the fragments, and, recalling Smith's work, I undertook its determination. The results are given below, and, as will be apparent, the investigation was much more extended than at first intended.

In the thin section the stone is at once seen to be composed essentially of olivine and pyroxene with nickel-iron and troilite. The chondritic structure is very evident (Fig. 2, Pl. V), the individual chondrules consisting wholly of pyroxenes or of olivine in the customary forms,

embedded in a crystalline ground of the same constituents, and the metallic components. Where not stained by oxidation the silicates are beautifully clear and pellucid. The pyroxene is in part of the normal enstatite type, though many of the larger forms are monoclinic, showing extinction angles as high as 25° . In almost the first section examined attention was attracted to a minute, irregular, colorless area traversed by numerous fracture lines, with only moderate relief, non-pleochroic, and polarized in faint bluish-gray colors. Its appearance at once suggested the phosphatic mineral described by me in a previous paper.¹ Microscopic examination of a considerable number of slides, accompanied in some instances by microchemical tests, showed the mineral to be a calcium phosphate, and occurring not infrequently. In no instance was the mineral found in the crystalline form characteristic of apatite. Nearly altogether it occurs as an interstitial filling, almost isotropic, and, as in the previous cases which I have described, of lower refractive indices than normal apatite. Indeed, in many instances the mode of occurrence and low relief without cleavage or crystal outline causes it to resemble on casual inspection an interstitial glass, for which doubtless it has heretofore been frequently mistaken. In such cases, it is only by treating a slide with a drop of acid and watching the mineral gradually disappear, then testing the solution, that its true nature can be determined.

Further examination showed the presence of this phosphate in the Waconda stone where it could not be recognized even microscopically. It was found that when the surface of an uncovered slide was treated with a dilute solution of hydrochloric acid and allowed to stand for not more than a quarter of an hour, the solution thus obtained would react for phosphorus and calcium, and the slide when examined be found to contain frequent minute, irregular, interstitial pits where the material had been dissolved away.

These determinations naturally suggested the possible phosphatic nature of the white spots before noted. An examination with a pocket lens showed these to be composed of aggregates of minute crystals of a faint yellow-green tint. It being obviously impossible to rely on cutting a thin section including the desired area, recourse was made once more to microchemical tests on minute fragments broken out by a needle point. Reactions for phosphorus and calcium were easily obtained, the mineral being readily soluble in cold nitric acid and less so in hydrochloric acid. Dr. E. S. Larsen kindly determined the indices of refraction by solutions, as follows: $\alpha = 1.627 \pm 0.003$; $\gamma = 1.621 \pm 0.003$. These results are low for normal apatite, agreeing more closely with those obtained by Dr. Wright on material from the Alfanello and Rich Mountain stones, as given in the paper before referred to.

As phosphorus was not determined by J. L. Smith in his analysis of either the metallic or silicate portions of this stone, a second analysis was decided upon. The results as determined by Dr. J. E. Whitfield are given below, Smith's results being also given for purposes of comparison.

Preliminary separations yielded:

	J. E. Whitfield.	J. L. Smith.
	<i>Per cent.</i>	<i>Per cent.</i>
Stony matter.....	87.80	90.81
Nickel-iron.....	5.93	5.34
Troilite.....	6.27	3.85
Total.....	100.00	100.00
Nickel-iron yielded:		
Iron.....	85.50	86.18
Nickel.....	13.78	12.02
Cobalt.....	.71	.91
Copper.....	(?)	.04
Total.....	99.99	99.15

¹ On the monticellite-like mineral in meteorites, and on oldhamite as a meteoric constituent, Proc. Nat. Acad. Sci., vol. 1, 1915, p. 302, and On the calcium phosphate of meteoric stones, Amer. Journ. Sci., vol. 43, 1917, p. 322.

² Not determined.

Phosphorus not determined in either case.

Smith further determined the stony portion to consist of 69 per cent soluble in aqua regia and 41 per cent insoluble, giving analyses of each, from which the bulk analysis given below was calculated.

	J. E. Whitfield.	J. L. Smith. ¹
	<i>Per cent.</i>	<i>Per cent.</i>
SiO ₂	35.05	38.14
FeC.....	16.53	23.44
P ₂ O ₅23	(²)
Al ₂ O ₃	4.94	1.02
CaO.....	2.25	(³)
MgO.....	24.98	26.69
NiO.....	.74	(²)
CoO.....	.04	(²)
MnO.....	.29	.47
SO ₃06	(²)
Na ₂ O.....	.76	1.05
K ₂ O.....	.17	(³)
H ₂ O.....	1.61	(²)
Fe.....	5.07	4.64
Ni.....	.81	.65
Co.....	.04	.05
Fe... } Troilite.....	3.99	3.85
S... }.....	2.28	
Total.....	99.84	100.00

¹ Analyses recalculated by Farrington. Smith reported also traces of lithium and copper.

² Not determined.

³ Trace.

Five grams of the finely pulverized stone were boiled in distilled water for an hour, resulting in a solution yielding 0.062 per cent SO₃ and 0.012 per cent CaO. A portion of the SO₃ probably came from the decomposed troilite, rendering any calculations uncertain, while the amount of lime (CaO) is too small to make the results more than suggestive of the presence of a minute quantity of oldhamite. A second 5 grams were boiled for half an hour in acetic acid of 15 per cent normal strength. The solution yielded 0.08 per cent P₂O₅ and 0.122 per cent CaO. Inasmuch as the bulk analysis shows 0.23 per cent P₂O₅, it is evident that a complete solution of the phosphate was not accomplished by the acetic acid. Be this as it may, the relative proportion of acid to base is such as to render it unsafe to draw definite conclusions.¹

It is difficult to account for all the discrepancies between the two analyses. The difference of some 3 per cent between the amount of stony matter and troilite may perhaps be accounted for on the supposition that Smith worked, as is so often the custom, on very small amounts that did not correctly represent the stone as a whole. (Whitfield had 19 grams of selected material.) The analyses of the metallic portion, it will be noticed, agree fairly well excepting that Whitfield reports no copper. In the bulk analyses, however, we find a difference of 3 per cent (in round numbers) in the total silica, nearly 7 per cent in the ferrous iron, 3.92 per cent in the alumina, and 2.25 per cent in the lime, with minor differences, mainly due to omissions elsewhere. The totals for iron and magnesia do not differ more than might be anticipated from analyses on separate portions, made by even the same analyst. That Smith did not determine the nickel and cobalt in the silicate portion is not strange, it being customary in his day to regard these elements as constituents of the nickel-iron only. The phosphoric acid, amounting to 0.23 per cent, should in this day certainly not be overlooked.

It does not seem in the least probable that the phosphate to which I have referred above as evident to the unaided eye can be the white mineral mentioned by Smith. Nevertheless, a most careful examination of all the material in the Museum and Shepard collections reveals nothing that is even suggestive of his doubtful unisilicate.

¹ Since the above was written, Dr. E. T. Wherry (Amer. Mineralogist, vol. 2, No. 9, 1917) has complimented me by suggesting that the problematic phosphate be given the name *merrillite*. Had I been consulted in the matter I should have suggested a postponement until a more definite statement of its composition could be given. Incidentally, it may be stated, I had considered the use of Shepard's name, *apatoid* (Amer. Journ. Sci., vol. 2, 1846), but abandoned it because of his definite statement that his mineral contained no phosphorus.

Weston, Conn.—Notwithstanding that this is the oldest known of American falls, it is deserving of more detailed study than it has yet received either from a mineralogical or chemical standpoint. The work of Shepard (in 1809, 1846–1848) would naturally at this date be considered faulty. He described the stone as composed principally of howardite and olivinoid, with scattered grains of magnetic pyrites and nickel-iron. Little advance over this seems to have been made by subsequent workers, excepting Meunier, who, in classifying the stone as a limerickite, recognized its chondritic character and mineral composition. Brezina classified it as a spherical chondrite, brecciated, apparently without regard to its composition or microscopic structure. The breccia-like structure is very evident, and is produced by angular pieces of a light gray color embedded in the prevailing dark-gray material. The chondritic structure is equally pronounced in both, and so far as can be determined by the unaided eye or a pocket lens there are no essential differences between the two kinds of fragments other than that of color. The mineral composition I find to be chiefly a pyroxene with a low angle of extinction, about 10° , which therefore relegates it to the clino-enstatite of Wahl, a polysynthetically twinned pyroxene, olivine, "merrillite," nickel-iron, and iron sulphide. No feldspars, even in the form of maskelynite, were observed.

