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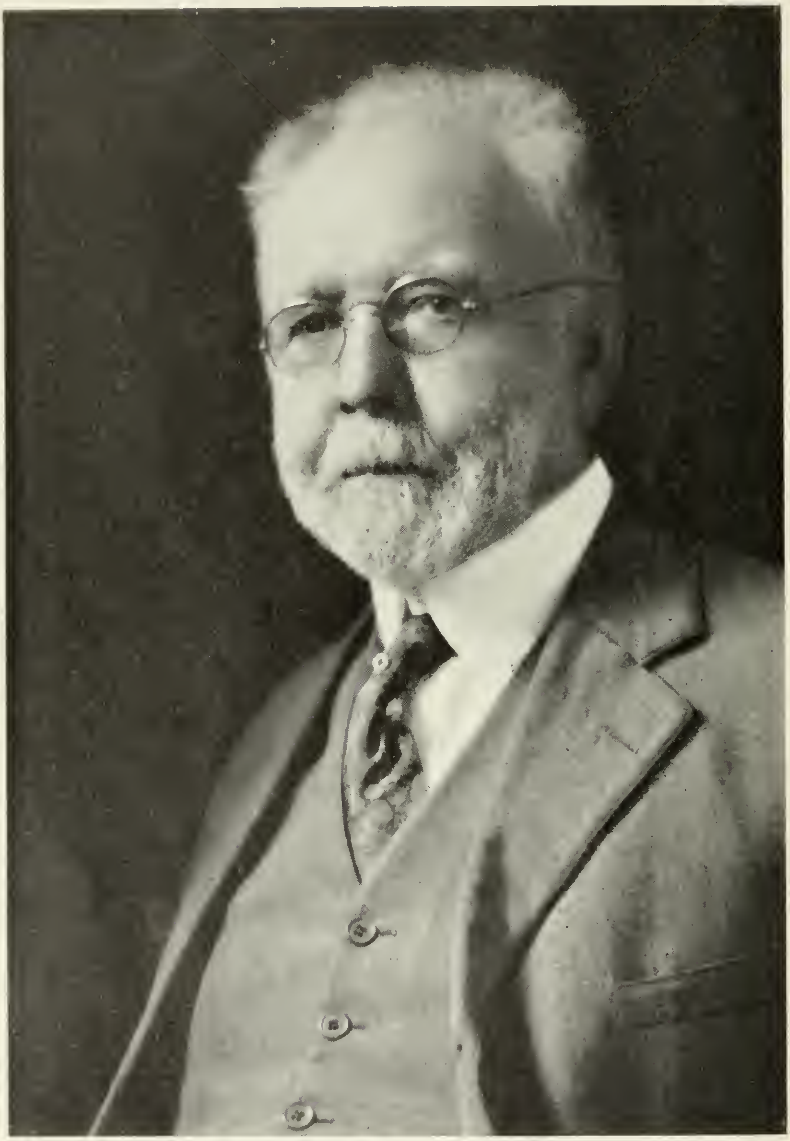

GEORGE PERKINS MERRILL

BORN, MAY 31, 1854. DIED, AUGUST 15, 1929

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COMPOSITION AND STRUCTURE OF METEORITES

BY

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The present work forms No. 149 of the *Bulletin* series.

Alexander Wetmore,
Assistant Secretary, Smithsonian Institution.

Washington, D. C., January 2, 1930.

FOREWORD

The paper here presented was written to form a part of a series to be issued by the Smithsonian Institution, but on completion was adjudged too technical for that particular publication. Rather than attempt its popularization the author withdrew it, substituting in its place a few pages of more easily comprehended generalities. Since then, on considering the matter, and in view of the fact that there is nothing in English covering the same ground, it has been thought advisable to further elaborate and publish as here presented. Students of meteorites in America are at this moment not too abundant, and anything that will excite interest, or be of help, is surely worthy of publication.

That many of the views expressed are the author's own, and perhaps not generally accepted, is recognized. It is thought, however, that this is made sufficiently clear to avoid any misunderstanding.[1]

[Owing to the sudden death of Dr. George P. Merrill in Auburn, Me., on August 15, 1929, while on his summer vacation, he never saw the proof of this bulletin. This fact will serve as an explanation for any scientific errors that may be found in the text, and conspicuously the references to the plates, which would have been more ample, had he seen the reproductions after they had been made.

A copy of his latest photograph has been inserted in this bulletin as a frontispiece.—EDITOR.]

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[1] For a general treatise on the subject the reader is referred to Meteorites, by Dr. O. C. Farrington, Chicago, 1915.

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COMPOSITION AND STRUCTURE OF METEORITES

By George P. Merrill

Head Curator of Geology, United States National Museum

ELEMENTAL COMPOSITION OF METEORITES

A meteorite is a body of more than immediate mineralogical or petrographical interest. It furnishes tangible evidence of the nature of materials existing in remote regions of our solar system and perhaps beyond, and affords, aside from the spectroscope, the only clue to the matter of which celestial bodies are composed and the conditions under which they originated, a fact recognized by Humboldt many years ago. It is, therefore, of interest to compare the materials that are now coming from space, or have come within historic times. with those forming the rocks of the earth's crust.

The most abundant of the meteoric elements are, named in alphabetical order: Aluminum, calcium, carbon, iron, magnesium, nickel, oxygen, phosphorus, silicon, and sulphur. In smaller quantities are found chlorine, chromium, cobalt, copper, hydrogen, iridium, lithium, manganese, nitrogen, palladium, platinum, potassium, ruthenium, sodium, titanium, and vanadium, probably also argon and helium. The presence of antimony, arsenic, gold, lead, strontium, tin, and zinc have from time to time been reported, but recent investigation throws doubt upon the correctness of the determinations.[1] Tests for fluorine have thus far yielded only negative results.

MINERAL COMPOSITION OF METEORITES

Though the elemental matter of meteorites may be the same as in terrestrial rocks, the proportional amounts and forms of combination are at times radically different and of a nature to indicate that they came about under conditions quite unlike those existing on the earth to-day, and particularly so with reference to the presence of free oxygen and moisture. It is for this reason in part that the study of meteorites is so fascinating.

The following list comprises the meteoric minerals which are also constituents of terrestrial rocks: *Olivine;* the orthorhombic pyroxenes *enstatite*, *bronzite*, or *hypersthene;* the monoclinic pyroxenes *diopside*

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[1] Merrill, Geo. P., On the Minor Constituents of Meteorites. Amer. Journal of Science, vol. 35, 1913. p. 509.

and *augite;* the plagioclase feldspars *anorthite, labradorite,* or *oligoclase;* the phosphate *apatite;* the oxides *magnetite, chromite,* and *quartz;* the sulphides *troilite* and *pyrrhotite;* rarely the carbonate *breunnerite* and various forms of carbon including *graphite* and *diamond.* Those meteoric constituents found rarely if ever in terrestrial rocks are the various alloys of nickel and iron, to which the names *kamacite, taenite,* and *plessite* have been given; the nickel and iron phosphide *schreibersite;* the iron and chromium sulphide *daubreelite;* the iron protochloride *lawrencite;* the calcium and titanium or zirconium oxysulphide *osbornite;* the calcium-sodium phosphate *merrillite;* the iron and nickel carbide *cohenite;* the carbon silicide *moissanite;* an isotropic mineral believed to be a re-fused plagioclase and called *maskelynite;* and a form of silica, *asmanite.* These are described in some detail, in alphabetical order below.

Apatite.—The phosphoric acid reported in the numerous analyses of meteoric stones has in times past been considered a constituent of the mineral apatite. As a matter of fact, crystals of this mineral in a meteorite have been actually observed only by Berwerth, in the stony portion of the Kodaikanal, India, siderolite. If occurring at all, it is usually in the form of microscopic granules, though Lacroix has recently described the mineral in the form of microscopic needles in the metal of the Saint Sauveur stone. Late investigations have shown that the prevalent phosphatic mineral is not a normal apatite, but a new mineral—a calcium-sodium phosphate—differing in its crystallographic and optical properties, and to which the name *merrillite* has been applied.[2] (See also p. 7.)

Asmanite.—This name was proposed by Maskelyne [3] for a mineral consisting essentially of silica, occurring in the meteorite of Breitenbach, of which it composed nearly one-third of the siliceous portion. The mineral, when pure, is colorless, with a specific gravity of 2.245, a hardness of 5.5, and is rhombic in crystallization. It is commonly believed to be identical with the tridymite of terrestrial rocks.

Breunnerite.—This is the name given by Haidinger to a ferriferous variety of magnesium carbonate occurring in terrestrial rocks and in a single instance in a meteoric stone, that of Orgueil, France. It is the only instance known of a carbonate compound occurring as an original constituent of meteorites. Its original meteoric nature is perhaps questionable.

Carbon.—Carbon as the gas carbon monoxide (CO) or dioxide (CO_2), or in the amorphous and crystalline form of graphite has been recognized as a constituent of certain meteorites, particularly meteoric irons, for many years. Berzelius recognized a carbon compound in the stone of Alais as early as 1838. Wöhler and Cloez in 1839 found

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[2] Wherry, Edgar T., Amer. Mineralogist, vol. 2, no. 9, 1917.

[3] Philos. Trans. Royal Soc., London, 1871, p. 361.

compounds resembling residue from terrestrial organic substances in the meteoric stone of Cold Bokkeveld, while the French chemist Berthelot thought to have extracted hydrocarbons conformable with the petroleum series from the carbonaceous meteoric stone that fell in Orgueil, France, in 1864.[4] The American chemist, J. Lawrence Smith, and others since have reported repeatedly the presence of carbon in both the amorphous and crystallized forms of graphite in numerous analyses of stone and iron meteorites. Amorphous carbon in the form of coal black spherical masses associated with troilite is a common constituent of meteoric irons, and is often surrounded by a halo of schreibersite as in that of Canon Diablo, Arizona (fig. 1, pl. 2). A nodule of this nature 3 centimeters in diameter was analyzed by Dr. J. E. Whitfield with the following results: Carbon, 38.97; iron, 37.26; sulphur, 20.69; phosphorus, 0.24; recalculated this gives carbon 38.97 per cent; troilite 56.89 per cent, with traces of schreibersite.

Haidinger in 1846, described a cubic form of graphite in the meteoric iron of Arva (Magura), Hungary, as pseudomorphic after pyrite, but which Rose suggested was pseudomorphic after diamond. Fletcher in 1899 gave the name cliftonite to a cubical form of carbon found by him in form of minute crystals in the meteoric iron of Youndegin, Australia, and later in the irons of Cosby Creek, Smithfield, and Toluca. Though at first thought to be a distinct species, this, too, is now commonly regarded as pseudomorphic after the diamond. In 1888 Jerofeieff and Latschinoff found carbon with the hardness and form of the diamond in the Novo-Urei, Russia, meteoric stone. In 1889 was found the first colorless material, thought from its hardness and its burning into carbon dioxide (CO_2) to be diamond in the Arva iron. In 1891 George A. Koenig, of Philadelphia, found a black vitreous substance, of a hardness beyond sapphire and believed to be diamond, in the meteoric iron of Canon Diablo. Material from this source was subsequently examined by O. W. Huntington and found to contain unmistakable minute, colorless, octahedral crystals of diamond.[5] The French chemist Moissan found in this same iron carbon in the amorphous form, as graphite and as black diamond, or carbonado. *Moissanite*, a carbon silicide, perhaps identical with artificial carborundum, was also reported by this chemist in the Canon Diablo iron.[6]

Chromite and *magnetite*.—The oxides of chromium and iron, or of iron alone, are common constituents of terrestrial rocks as well as of

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[4] Doubt as to the correctness of this and other tests for hydrocarbons in meteorites has recently been expressed by P. E. Spielman. Nature, August 23, 1924.

[5] Proc. Amer. Acad., vol. 29, 1894, p. 204.

[6] The fact that meteoric irons are commonly sawn by crushed carborundum raises a doubt as to the actual meteoric source of this material.

meteorites, and need no further mention here other than that they occur as small, usually microscopic disseminated crystals and crystalline grains. Whether or not chromium enters into the composition of the pyroxenes, as in terrestrial rocks, has not, as yet, been determined.

Cohenite.—This mineral was first described by Weinschenk in 1889, having previously been mistaken for schreibersite, which it closely resembles and with which it is very commonly associated. It differs, however, in being soluble in copper ammonium chloride and practically infusible. It occurs in blebs and tabular masses belonging to the isometric system. Chemically it is an iron carbide, of the formula $(FeNiCo)_3C$. Actual analyses of material from the Canon Diablo (I) and Magura (II) irons yielded the results given below:

	I[1]	II[2]	Average
Iron	91.31	89.81	90.56
Nickel	1.77	3.08	2.425
Cobalt	.25	.69	.47
Carbon	6.67	6.42	6.545
	100.00	100.00	100.00

[1] Recalculated after deducting 4.68 per cent schreibersite.
[2] Recalculated after deducting 0.65 per cent schreibersite.

Daubreelite.—In 1876 J. Lawrence Smith gave this name to a black, lustrous, highly crystalline material found by him associated with the troilite in the meteoric irons of Coahuila, Mexico. Incomplete analyses made at the time showed 36.48 per cent of sulphur, some 10 per cent of iron, and a little carbonaceous matter, the undetermined portion being chromium. The true composition he announced as being, probably, sulphur 37.62 per cent; chromium 62.38 per cent.[7] Later he was able to isolate the material in larger quantity and greater degree of purity from the Coahuila iron, and in 1878,[8] he published new analyses and descriptions showing the mineral to have the probable composition: Sulphur, 44.29 per cent; chromium, 36.33 per cent; iron, 19.38 per cent; or the formula $FeS\ Cr_2\ S_3$. Actual analyses, however, showed: Sulphur, 42.69 per cent; chromium, 35.91 per cent; iron, 20.10 per cent; total 98.70 per cent.

Feldspars and maskelynite.—From what is known regarding terrestrial basic igneous rocks, the feldspars of meteorites would naturally be assumed to belong to the more basic varieties, as labradorite and anorthite (fig. 2, pl. 2). Not many actual and complete analyses are available owing to its rare occurrence and the consequent difficulty of securing a sufficient quantity of material in a fair degree of purity. Those quoted below show that in at least two instances the

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[7] Amer. Jour. Sci., vol. 12, 1876, p. 109.
[8] Idem, vol. 16, 1878, p. 270.

feldspar is oligoclase, a form characteristic of rocks of intermediate acidity, as the diorites. The name *maskelynite*, it should be said, was given by Tschermak[9] to an isotropic, colorless mineral abundant in the Shergotty meteorite, and commonly considered a re-fused feldspar. With this most workers agree, regarding it a product of metamorphism.[10] (See pl. 3, fig. 1, also pl. 16, fig. 2.) The mineralogist Groth, on the other hand, was inclined to believe it to be a species allied to leucite. The feldspars are common constituents of meteorites of the basaltic types, such as that of Juvinas, in France, where they occur in elongated polysynthetically twinned forms as in terrestrial rocks. In the chondritic types they occur as scattered granules occupying the interspaces of the olivines and enstatites, and often quite lacking in crystal outlines or twinning bands, in which case their satisfactory determination is a matter of difficulty. In many meteorites of the chondritic type, and in most pallasites, feldspars are wholly lacking.

Analyses of meteoric feldspars

Constituents	Sources			
	Hvittis[1]	Hessie[2]	Shergotty[3]	Johnstown[4]
Silica	63. 5	64. 97	56. 3	43. 72
Alumina	22. 2	22. 06	25. 7	35. 40
Lime	4. 0	3. 01	11. 6	16. 28
Soda	9. 2	9. 96	5. 1	1. 60
Potash	1. 1		1. 3	
	100. 0	100. 00	100. 0	97. 00

[1] Borgstrom, Bull. Comm. Geol. Finlande.
[2] Lindstrom, Ofv. Kongl. Vet. Akad. Forhandl., 1869, p. 723.
[3] Tschermak, Sitz. Akad. Wiss. Wien, vol. 65, 1872, p. 130.
[4] Shannon, Am. Museum Novitates, Nov. 30, 1925.

Gases.—The fact that hydrogen was given off when the Lenarto, Italy, meteoric iron was heated in a vacuum, was first noted by Thomas Graham in 1867. Prof. J. W. Mallet, in 1872, found that the meteoric iron of Augusta County, Va., under similar circumstances yielded not merely hydrogen but also nitrogen, carbon monoxide (CO), and carbon dioxide (CO_2). Prof. A. A. Wright, in 1875 and 1876, showed that in the stony meteorites the gas was chiefly in the form of the dioxide, or carbonic acid (CO_2) as it is commonly called, while in the irons the monoxide (CO) and hydrogen prevailed. Doubts, if such there may have been, concerning these first announcements would seemingly have been completely eliminated by the later work of R. T. Chamberlin[11] from whose paper have been taken bodily the tables following.

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[9] Sitz. Akad. Wiss. Wien, vol. 65, 1872, p. 127

[10] Merrill, Geo. P., On Metamorphism in Meteorites, Bull. Geol. Soc. America, vol. 32, 1921, p. 407.

[11] The Gases in Rocks. Publ. No 106, Carnegie Institution of Washington, 1908.

Gases in stony meteorites

Meteorite	H_2S	CO_2	CO	CH_4	H_2	N_2	Total	Analyst
Guernsey, Ohio		1.80	0.13	0.06	0.95	0.05	2.99	Wright.
Pultusk, Poland		1.06	.06	.06	.52	.04	1.74	Do.
Parnallee, India		2.13	.04	.05	.36	.04	2.62	Do.
Weston, Conn		2.83	.08	.04	.46	.08	3.47	Do.
Iowa County, Iowa		.88	.05		1.45	.12	2.50	Do.
Cold Bokkeveld		23.49	.61	.82	.10	.21	25.23	Do.
Dhurmsala, India		1.59	.03	.10	.72	.03	2.47	Dewar.
Pultusk, Poland		2.34	.19	.27	.64	.09	3.53	Do.
Mocs		1.25	.07	.09	.45	.07	1.93	Do.
Orgueil	{SO_2 48.03}	7.40	1.14	.87		.33	57.77	Do.
Allegan, Mich	Tr.	.21	.19	.01	.08	Tr.	.49	Chamberlin.
Estacado, Tex	Tr.	.24	.25	.03	.31	.01	.84	Do.
Average of 12 analyses	4.00	3.77	.24	.20	.50	.09	8.80	

Gases in iron meteorites

Meteorite	H_2S	CO_2	CO	CH_4	H_2	N_2	Total	Analyst
Lenarto		0.13	0.00		2.44	0.28	2.85	Graham.
Augusta County, Va		.31	1.21		1.14	.51	3.17	Mallet.
Tazewell County, Tenn		.46	1.31		1.35	.05	3.17	Wright.
Shingle Springs, Calif		.13	.12		.67	.05	.97	Do.
Cross Timbers, Tex		.11	.19		.99		1.29	Do.
Dickson County, Tex		.29	.34		1.57		2.20	Do.
Arva, Hungary		5.92	31.91		8.57	.73	47.13	Do.
Cranbourne, Australia		.04	1.13	0.16	1.63	.63	3.59	Flight.
Rowton, Shropshire		.33	.47		4.96	.62	6.38	Do.
Toluca, Mexico	Tr.	.12	1.32	.04	.27	.10	1.85	Chamberlin.
Average		.78	3.80	.02	2.36	.30	7.26	
Average omitting Arva meteorite.		.21	.67	.02	1.67	.24	2.83	

Omitting the high content of sulphur dioxide of the Orgueil stone, which is obviously abnormal, and presumably due to the weathering of the troilite, the total average volume of gas from the stony meteorites is 4.8 times the volume of the material used. In like manner the amount of CO_2 in the Arva iron is abnormal and probably due to oxidation. An average in the irons of 2.83 is therefore considered correct.

Sundry attempts at the determination of the radioactive properties of meteorites have been made by use of photographic plates, but with results by no means satisfactory. Strutt,[12] working by what is known as the Emanation method, was the first to demonstrate the presence of radium in determinable quantity in the stone of Dhurmsala. Later Messrs. T. T. Quirke and L. Finkelstein [13] examined a considerable number of stones and have shown that "the average stony meteorite is considerably less radioactive than the average igneous rock, probably less than one-fourth as radioactive as an average granite, and that the metallic meteorites are almost free from radioactivity." Sixteen meteoric stones were found to have an average radioactivity of 7.39 by 10^{-13} gram of radium to a gram of

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[12] Proc. Roy. Soc., vol. 77, March, 1916, p. 480.

[13] Amer. Journ. Sci., vol. 44, 1917, pp. 237–242.

material. Two stony irons had an average of 6.88 by 10^{-13} gram, while of the seven irons examined but two were sufficiently active for determination, the Toluca iron yielding 2.13 by 10^{-13} grams, and that of Coahuila 7.69 by 10^{-12}.

Lawrencite.—Ferrous chloride. The exudation of drops of ferrous chloride from freshly cut or broken surfaces of meteoric iron was early noted, but it was not until 1855 that J. Lawrence Smith found the material in the condition of a soft solid of a green-brown color in the meteoric iron of Tazewell County, Tenn.[14] In 1877 [15] he also noted the occurrence of the substance in the iron of Rockingham County, N. C. In this same year Daubree thought to note its occurrence in the terrestrial iron of Ovifak, Greenland,[16] and proposed for it the name lawrencite in honor of its first discoverer. The material liquefies on exposure to the atmosphere, the iron passing over quickly to the condition of sesquioxide. It is to this mineral that is due the "sweating" and rapid disintegration of so many irons, and causes the stone meteorites to become rust-brown or freckled with rust-colored spots.

Merrillite.—This mineral, as a common but minor constituent of stony meteorites, was first noted and described by Merrill in 1915 [17] and the name proposed by Dr. E. T. Wherry in 1917.[18] Subsequent more detailed investigations by Larsen and Shannon [19] have shown it to be an entirely new compound of calcium, sodium, and phosphorus with the formula $3CaO, Na_2O, P_2O_3$.

Inasmuch as a description of this mineral is not to be found in the literature in general, it may be given here in full. Occurrence sporadic, without crystal form, colorless and very brittle; cleavage for the most part lacking, though sometimes imperfect and interrupted showing angles of 60° and 120°. Optically uniaxial and negative;[20] birefringence weak, less than 0.005; indices of refraction $\omega = 1.626$, $\epsilon = 1.620$; specific gravity 3.10. (See pl. 3, fig. 2.)

Metallic constituents; nickel-iron alloys.—These are essentially the same in all meteorites. They occur in varying proportions from a fraction of 1 per cent, as in the Bishopville stone, to upward of 90 per cent, as in the so-called iron varieties. In the stones the form is that of disconnected drops or stringers; in the pallasites that of a more or less disconnected mesh or sponge enfolding silicate minerals; and in the metallic forms constituting nearly the entire mass.

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[14] Amer. Journ. Sci., vol. 19, 1855, p. 154.

[15] Idem, vol. 13, 1877, p. 214.

[16] Compt. Rend., vol. 84, 1877, p. 66.

[17] Proc. Nat. Acad. Sci., vol. 1, 1915, p. 302.

[18] Amer. Mineralogist, vol. 2, No. 9, 1917, p. 119.

[19] Amer. Journ. Sci., vol. 9, March, 1925, pp. 250–260.

[20] Wrongly given as biaxial and positive in first publication. Amer. Journ. Sci., vol. 43, 1917, p. 324.

Etching by means of a weak acid, the polished surface of a meteoric iron will in the majority of cases, as already noted, give rise to an interesting series of markings known under the name of Widmanstätten figures, after a German chemist who first brought them to public notice. They are due to the unequal solubility of the three alloys of iron and nickel which make up the mass of the material. Two of these alloys occur in the form of thin plates and are known by the terms *kamacite* and *taenite.* A third alloy, or properly a eutectic known as *plessite,* fills the space formed by the intersection of these plates (pl. 5, fig. 1, *a*, *b*, and *c*). The composition of these, as thus far determined, is somewhat variable owing to the difficulty of separating them one from another, and it is considered probable that the so-called plessite is but a mixture or intergrowth of the other two. Davison gives the composition of the two first named as determined on separations made from the Welland, Canada, iron as follows:

Constituents	Kamacite	Taenite
	Per cent	*Per cent*
Iron	93,09	74.78
Nickel	6.69	24.32
Cobalt	.20	.33
Carbon	.02	.50
	100.00	99.93

In both kamacite and taenite there are variations in the proportionate amounts of iron and nickel, ranging in the first instance from thirteen to eighteen to one, and in the second from one to seven to one. According to Borgstrom,[21] who has given the most recent summary, the kamacite of the octahedrites contains about 7 per cent Ni+Co; the taenite about 38 per cent, and the plessite 14 per cent.

So far as may be judged from chemical analyses there is no essential difference in the metalliferous portions of the stony meteorites and those which are all metal. This is brought out in the selected series of analyses tabulated below.[22]

That in the oxidation of a meteoric iron the first product is not limonite, but a highly lustrous material which crushes down readily to a fine brown magnetic powder, was first noted by the present writer.[23]

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[21] Bull. Soc. Geol. of Finland, vol. 45, 1925.

[22] The frequent reported occurrences of platinum and other rare elements in meteorites and particularly in meteoric irons led the present writer to undertake a series of investigations to determine their correctness. Platinum in traces was found to be a matter of common occurrence; ruthenium and iridium occurred less commonly. No confirmation could be discovered to the reported occurrences of gold, tin, antimony, etc. See particularly A Meteoric Iron from Owens Valley, Calif. Mem. National Academy of Sciences, vol. 19, 1922.

[23] Shannon, E. V., The Oxidation of Meteoric Iron, Proc. U. S. National Museum, vol. 72, Art. 21, Oct. 1927.

IRON METEORITES

Name	Kind	Fe	Ni	Co	Cu	P	S	Mn	Si	Cr	Cl	C	Miscellaneous
Hex River	Hexahedrite	93.59	5.68	0.66	0.04	0.25	0.08			0.02			Insol. res., 0.03.
Canon Diablo	Coarse Octahedrite	93.425	7.335	.51	Trace.	.159	.08	None.	0.032		0.097	0.465	Pt. and Ir., tr.
Casas Grandes	Medium Octahedrite	90.47	4.222	.604	.012	.166	.029	None.	.01	None.	Trace.	.177	
Kokstadt	Medium Octahedrite	91.21	8.01	.63	.02	.22	Trace.			None.	.05	.03	
Ranchito	Medium Octahedrite	85.54	9.40	.98	.02	.12	.02			.01	.02	.01	
Bethany	Fine Octahedrite	91.37	7.97	.50	.02	.03	.02			.04		.05	
Cowra	Finest Octahedrite	85.265	13.23	1.02	.02	.225	.01	Trace.	.01			.025	Pt. and Ir., tr.
Perryville	Finest Octahedrite	89.15	9.66	.545	.025	.365	.002	None.	.003			.015	Pt., Pa., Ir., and Rn. in traces.
Average		90.00	8.19	.68	.019	.192	.03	Trace.	.014	.02	.041	.11	
		98.87											

METAL IN STONY-IRON METEORITES

Name	Kind	Fe	Ni	Co	Cu	P	S	Mn	Si	Cr	Cl	C	Miscellaneous
Brenham	Pallasite	88.49	10.35	0.57	0.03		0.08						
Mount Vernon	Pallasite	82.52	14.044	.949	.104	0.390	.288	0.151	0.808	0.300	Trace.	0.5	Va., traces.
Krasnojarsk	Pallasite	89.90	9.52	.60	None.	.085	None.	None.					
Eagle Station	Pallasite	81.92	16.90	1.12	Trace.	None.	None.						
Crab Orchard	Mesosiderite	87.59	12.09	Trace.	Trace.	None.	None.						
Estherville	Mesosiderite	92.001	7.100	.690	Trace.	.162							
Inca	Mesosiderite	89.77	9.17	.61									
Mincy	Mesosiderite	91.23	7.21	.71									
Breitenbach	Siderophyr	90.426	9.284	.290	Trace.								
Average		88.20	10.63	.615	.022	.212							
		99.44											

METAL IN STONY METEORITES

Name	Kind	Fe	Ni	Co	Cu	P	S	Mn	Si	Cr	Cl	C	Miscellaneous
Allegan	Spherulitic chondrite	91.42	7.87	0.66	0.046								
Cullison	Spherulitic chondrite	89.70	9.207	.507	.04	0.07	Trace.	0.08	0.129	0.16		0.088	
Indarch	Carbonaceous chondrite	90.44	8.26	.18		.08		.04					
Menow	Crystalline chondrite	91.86	7.55	.15	Trace.	Trace.							
New Concord	Intermediate chondrite	87.011	12.36	.42	Trace.	.012	1.08						
Plainview	Spherulitic chondrite	90.63	8.85	.38									
Vernon County	Crystalline chondrite	91.45	7.37	.28	Trace.	Trace.							
Waconda	Spherulitic chondrite	86.18	12.02	.91	.04	.14							
Average		89.84	9.18	.43	.021	.05							
		99.45											

Oldhamite.—This name was given by Story-Maskelyne, in 1862, to a calcium sulphide (CaS) found by him in the meteorite of Busti and described in detail in the Philosophical Transactions of the Royal Society of London for 1870. The mineral is of a pale, chestnut brown color when pure, though often covered on the outer surface by a gypseous oxidation product. It occurs in the form of rounded granules, with cleavages essentially rectangular, imbedded in the pyroxenic constituents. It is optically isotropic and is considered to belong to the cubic or isometric system. Specific gravity 2.58. Boiled in water it is decomposed, yielding a bright yellow solution of calcium polysulphide and an insoluble residue. It readily undergoes alteration into gypsum, hydrous calcium sulphate, which probably accounts for its apparent rarity. As gypsum is itself readily soluble, its possible presence may be determined by boiling the powdered stone in water and then testing the solution for calcium and sulphur.

Olivine.—A magnesium and iron silicate of the formula (MgFe) SiO_2; relative proportions of magnesia and iron are, however, somewhat variable, as shown in the following analyses.[24]

Locality	SiO_2	MgO	FeO
1. Krasnojarsk, Siberia	40.24	47.41	11.80
2. Kiowa County, Kansas	40.70	48.02	10.79
3. Brahin, Russia	39.61	48.29	11.88
4. Atacama, Chile	36.92	43.16	17.21

The mineral rarely occurs in good crystal form except in the porphyritic chondrules, though in the pallasites of Krasnojarsk and Lodran, blebs with determinable crystal faces have been found. It is of all meteoric minerals perhaps the most abundant and widespread, sometimes, as in those of Warrenton, Mo., and Chassigny, France, composing a very large proportion (75 per cent) of the mass of stone. It is rarely, if ever, wholly absent, even the iron meteorites showing in most cases included granules. It is also a common and widespread constituent of terrestrial igneous rocks. Its appearance is easily determinable by the unaided eye in the pallasites and its meteoric characteristics shown in the illustrations of chondritic structures (pls. 22 and 23). The statement frequently made—first I believe by Daubree—to the effect that meteoric olivines differ from their terrestrial prototype in containing no nickel, needs confirmation. Indeed many careful analyses could be quoted showing the direct opposite.

Osbornite.—This name is also one of Maskelyne's proposal. The mineral occurs in golden yellow microscopic octahedra associated with the oldhamite in the Busti meteorite only, so far as now known.

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[24] Tscherwinsky gives the average composition of the olivine of pallasites as follows: SiO_2, 39.35; FeO, 14.39; MgO, 45.93; MnO, 0.08; NiO, 0.02; CaO, 0.03; Na_2O, 0.02; Al_2O_3, 0.09; Fe_2O_3, 0.06; Sp. Gr. 3.38.

Crystals are brittle and insoluble in acids, even resisting the fluxes potassium and sodium carbonates. Its composition is uncertain, but it is commonly regarded as a titanium or zirconium oxychloride.[25]

Pyroxenes.—Pyroxene is common in meteorites in both orthorhombic and monoclinic forms.

1. Orthorhombic pyroxenes: enstatite, bronzite, and hypersthene. These minerals, next to the olivines, are the most common of the meteoric silicate minerals. The composition is somewhat variable, owing to the varying proportions of iron and magnesia, as in the olivines. A typical enstatite corresponds to the formula $MgSiO_3$, but through the assumption of iron this passes over into the bronzite variety $(MgFe) SiO_3$. So far as known, the highly pleochroic hypersthene rarely occurs in meteorites, though in at least one instance—that of Shalka, India—the percentage of iron is fully as high as in the strongly pleochroic terrestrial mineral. The name clino-enstatite has been proposed by Wahl [26] for a monoclinic variety with a smaller extinction angle on clinopinacoidal sections than normal monoclinic pyroxenes, and which is characterized further by a marked tendency toward polysnythetic twinning. The varying composition of enstatite and bronzite from some of the best known meteorites is given below:

Meteorite	SiO_2	MgO	FeO	Na_2O	K_2O	CaO	Al_2O_3
Bishopville [1]	59.97	39.34	0.40	--------	--------	--------	--------
Busti [2]	58.44	38.94	1.18	0.36	0.33	1.68	--------
Lodhran [3]	55.35	32.85	12.13	--------	--------	.58	0.60
Breitenbach [4]	56.05	30.85	13.44	--------	--------	--------	--------
Hainholz [5]	53.05	25.40	15.63	--------	--------	2.73	3.19
Hvittis [6]	59.05	37.10	.90	.68	.47	.98	1.09
Goalpara [7]	59.92	38.00	--------	--------	--------	2.11	--------
Molina [8]	57.80	39.22	.91	--------	--------	--------	2.07
Shalka [9]	55.55	27.73	16.53	.92	--------	.09	--------
Rittersgrün [10]	57.49	25.78	10.59	1.45	--------	2.12	2.08
Johnstown [11]	52.16	27.60	13.39	--------	--------	1.97	[12] 3.91

[1] Smith, J. L., Amer. Journ. Sci., vol. 38, 1864, p. 225.
[2] Maskelyne, Philos. Trans. Roy. Soc. London, vol. 160, 1870, p. 206.
[3] Tschermak, Sitz. Akad. Wiss. Wien, vol. 61, 1870, p. 467.
[4] Maskelyne, Philos. Trans. Roy. Soc. London, vol. 161, 1871, p. 359.
[5] Rammelsburg, Monatsber. Akad. Berlin, 1870, p. 314.
[6] Borgstrom, Bull. Comm. Geol. Finlande, No. 14, 1903.
[7] Teclu, Rammelsburg's Mineralchemie, 1875, p. 382.
[8] Meunier, Ann. Chem. Phys., vol. 17, 1869, p. 12.
[9] Rammelsburg, Monatsber. Akad. Berlin, 1870, p. 319.
[10] Winkler, Cohen's Meteoritenkunde, Heft 1, 1894, p. 281.
[11] Shannon, Amer. Museum Novitates, Nov. 30, 1925.
[12] Also 0.69 Cr_2O_3 and 0.56 MnO.

As with olivine the mineral rarely occurs in good crystal form excepting in the porphyritic chondrules. A more common form, as noted later, is in that of radiating and cryptocrystalline "kugels." (See pl. 22.)

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[25] The fact seems not generally recognized that the oldhamite and osbornite occur only in that portion of the Busti stone which is plainly an inclusion, and further that osbornite has as yet not been identified in any other stone, although oldhamite is comparatively common.

[26] Tschermak's Min. u. Pet. Mitteilungen, vol. 26, 1907.

Berwerth has described [27] under the name of "Netzbronzit" a fibrous form of bronzite occupying the interstices of porphyritic olivines in the Zavid stone, the fibers standing at right angles to the olivine surfaces. These he considers due to a partial fusion and recrystallization of the fine bronzite material in a chondritic tuff.

2. Monoclinic pyroxenes: Augite, diopside, and diallage. These forms of pyroxene are, on the whole, less common in meteorites than are the orthorhombic forms, though it is possible that they are in reality more abundant than is generally supposed, their close resemblance in all but optical properties (which, owing to the small size and poorly developed crystallization, can not always readily be determined) rendering a sure discrimination somewhat difficult. The composition is, presumably, fully as variable as that of the enstatites, but few actual analyses of pure materials have been made, owing to the difficulty in separating them from the associated minerals. Of the following analyses, No. I is by Maskelyne [28] and II by Tschermak.[29]

Constituents	Source	
	I Busti	II Shergotty
Silica (SiO_2)	55.49	52.34
Alumina (Al_2O_3)	---------	.25
Ferric oxide (Fe_2O_3)	.55	---------
Ferrous oxide (FeO)	---------	23.19
Magnesia (MgO)	23.33	14.29
Lime (CaO)	19.98	10.49
Soda (Na_2O)	.55	---------
	99.90	100.56
Sp. Gr.	---------	3.466

As with other silicate constituents, the monoclinic pyroxenes are but poorly developed crystallographically, with irregular and very imperfect cleavage, and are nearly colorless, though the diopside is often of a bright green in tinge as in the iron of Four Corners, N. Mex. (See pl. 9.) They are often intergrown with enstatites and are rarely appreciably pleochroic. The so-called *peckhamite* of J. L. Smith is but an altered bronzite.[30]

Radium.—See under gases, p. 6.

Schreibersite (and *Rhabdite*).—This mineral, first described and named by Haidinger in 1847 as a constituent of the Magura iron and since found one of the commonest of the accessory meteoric constituents, is a phosphide of nickel iron and cobalt, corresponding approximately to the formula $(FeNiCo)_3P$. It occurs commonly in thin,

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[27] Wissenschafr. Mittheil. aus Bosnianu. der Hercegovina, vol. 7, 1901.

[28] Philosophical Transactions, vol. 160, 1870.

[29] Sitz. des k. Akad. des Wiss., vol. 65, 1872.

[30] See Merrill, Proc. U. S. Nat. Mus., vol. 58, 1920, p. 634.

angular plates of a tin white color, either lying parallel with the taenite-kamacite plates, or in angular, jagged masses as in the Tombigbee iron (see pl. 5, fig. 3), and sometimes in dendritic forms as in the iron of Arispe (see fig. 2 of the same plate). In the pallasites it occurs in thin plates lying between the olivines and metallic mesh. It is brittle, magnetic, and difficulty soluble in acids, but fuses readily. The name rhabdite was given by Rose in 1863 to a phosphide found in the Braunau, Seelasgen, and Misteca irons, occurring in the form of minute prisms of the tetragonal system and commonly considered identical with schreibersite. The following analyses are selected from a large number available:

	I	II	III	IV
Iron	70.07	61.78	50.52	54.43
Nickel	14.57	21.93	33.90	29.36
Cobalt	.43	.38	.62	.67
Copper	.03	.21	.22	.34
Phosphorus	15.80	15.70	15.68	15.45
	100.90	100.00	100.94	100.25

I. Schreibersite from the Sao Juliao de Moreira iron. Fahrenhorst, analyst.
II. Schreibersite from the Kendall County iron. Scher, analyst.
III. Schreibersite from the Magura iron. Fahrenhorst, analyst.
IV, Schreibersite from the Cosby Creek iron. Fahrenhorst, anaylst.

While the formula $(FeNiCo)_3P$ for this mineral is that commonly accepted, a considerable list of analyses by reliable chemists could be quoted from which formulas ranging from the above to $(FeNiCO)_4P$, $(FeNiCO)_5P$, and $(FeNiCo)_7P$ could be calculated. Cohen would account for these discrepancies on the ground of impure or small quantities of material utilized.

The mineral has not been found in well-developed crystals. Some small distorted and imperfect forms obtained by the writer from the Ruff's Mountain iron were submitted to Dr. E. T. Wherry for examination, who reported as follows:[31]

> 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 to 10 minutes, unquestionable tetragonal symmetry being exhibited by the angular relations. The forms observed are: c(001), a(100), m(110), o(111), 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.

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[31] Amer. Mineralogist, vol. 2, 1917, pp. 80–81; vol. 3, 1918, p. 184.

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

[Tetragonal, c=0.346 0.001]

No.	Letter	Symbol	Crystals	Measurements	Angles measured		Angles calculated	
					ϕ	ρ	ϕ	ρ
0	c	001	1	1	----------------	0° 00′	----------	0° 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′

The fact that the mineral never occurs in good crystal form, lends color to the suggestion made elsewhere [32] to the effect that the schreibersite is not a true mineral species but a solid solution of rhabdite in varying proportions of nickel-iron.

Silica.—Silica in the form of quartz was doubtfully identified by Wöhler in the meteoric stone of Hainholz and by Klein in that of St. Marks. All doubts concerning the latter are set at rest by the finding, by Merrill, of well-defined crystal particles as shown in Figure 3 on Plate 11. It is to be noted that the crystals are imbedded in the metallic portion. Silica in the form of tridymite (asmanite) constitutes some 8.527 per cent of the pallasite of Steinbach, and Berwerth has described both quartz and tridymite occurring imbedded in the augite of the stones (eukrites) of Juvinas, Stannern, Jonzac, and Peramiho. This he suggests may be a form of pyrometamorphism due to heat when the meteor stream of which they formed a part came near the sun. Nearly every detailed analysis of metallic meteorites shows traces of silica, which, if reliance can be placed on the examination of the "insoluble" residues of these irons, occurs in the form of crystalline granules and distinct crystals. The manner in which these residues are obtained, it must be confessed, throws a doubt on some of the determinations, but the occurrence of the mineral noted above imbedded in the metallic portion of the St. Marks stone at least insures the possibility.

Troilite.—This name was given by Haidinger [33] to a monosulphide of iron first found in nodular masses in the meteorite of Albareto and since shown to be an almost universal constituent of meteorites (see fig. 1, pl. 21). The theoretical composition as demanded by the formula FeS, is iron (Fe) 63.64; sulphur (S) 36.36. Actual analyses nearly always show traces of nickel and sometimes copper. The mineral was named in honor of Domenico Troili, one of the early enthusiastic defenders of the possibility of meteorite falls. Meunier and some others have been inclined to regard the mineral as identical with pyrrhotite. Rose suggested the possibility that the sulphide in stony meteorites might be in the form of

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[32] Mem. Nat. Acad. Sci., vol. 19, 1922, p. 6, footnote.

[33] Sitz. Akad. Wiss. Wien, vol. 47, 1863, p. 283.

pyrrhotite and in the metallic as troilite. The form assumed is somewhat variable. In the irons it most commonly occurs in globular, spherical masses in sizes up to two or three centimeters or more in diameter; sometimes in greatly elongated, conical forms, as in the Santa Rosa iron. These may be wholly of sulphide, or of sulphide admixed with amorphous carbon. Such nodules are often surrounded by a shell of schreibersite. In the stony meteorites the sulphide occurs in much smaller masses, rarely over two or three millimeters in diameter, scattered through the ground or closely associated with the metallic particles. In the stone of Holbrook, Ariz., the sulphide occurs in such size and form as to be separable from the matrix. Material thus obtained was found to be nonmagnetic and yielded on analysis: Iron, 63.62 per cent; sulphur, 36.50 per cent; with no nickel, cobalt, nor copper. The mineral in this case is, therefore, evidently the monosulphide troilite. Ramsay and Borgström arrived at similar conclusions in their investigation of sulphide in the Bjurbole meteorite. The idea advanced by Allen [34] to the effect that the mineral is not to be considered a true species but rather as the end member of the pyrrhotite series of iron-sulphur compounds is doubtless correct. The name is, however, retained as a convenient term to distinguish the monosulphide so characteristic of meteorites.[35]

CHEMICAL COMPOSITION OF METEORITES

Since meteorites are aggregates in varying proportions of the minerals described it must necessarily follow that they are somewhat variable in ultimate chemical composition. The average of a selected number of analyses of wholly metallic forms has been given in the table on page 9.

Whether or no the all iron meteorites are to be considered independent of the stony forms, and perhaps even from different sources,[36] is an open question, though the presence of transitional forms like the mesosiderites and pallasites, especially those of the Brenham and Estherville type (pls. 13, 14, and 15) suggests that they may be but residual segregations in large masses from which all of the siliceous portions have been eliminated. The size of some of these metallic masses, as that of Cape York or Bacubirito, to be sure, puts a considerable strain upon one's imagination, but there is nothing impossible, or improbable about it, and those who argue in favor of a metallic nucleus for our own earth should certainly find no difficulty in accepting the idea.

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[34] Amer. Jour. Sci., vol. 33, 1912.

[35] Until recently this form of iron sulphide was regarded as of purely meteoric origin. It has of late, however, been discovered in considerable quantity in a copper mine in Del Norte County, Calif. See Amer. Mineralogist, May 1922, p. 77.

[36] Pickering, it will be recalled (Popular Astronomy, No. 165), regarded the cometary origin of iron meteorites as plausible, but not so the stones which he felt were of terrestrial origin.

As may be readily understood, the determination of the chemical mass composition of a stony iron is a matter of difficulty. To overcome this so far as relates to the pallasites, Professor Tscherwinsky[37] resorted to detailed measurements to determine the relative proportions of the two essential minerals (olivine and metal), and from the known composition of each, has calculated the average *bulk* composition of the bodies of which they form the essential part. The percentage by weight of the *olivines* in the pallasites examined he gives as follows: Admire, 49.69; Ahumada, 46.22; Brahin, 37.18; Brenham, 38.71; Eagle Station, 48.29; Finmarken, 61.22; Ilimaes, 43.68; Imilac, 49.25; Krasnojarsk, 52.19; Little Miami, 49.07; Lipovsky, 46.49; Marjahlati, 49.88; Molong, 58.16; Mount Dyrring, 75.11; Mount Vernon, 58.94; Pavlodar, 62.49; South Bend, 41.40. The average chemical composition of the pallasites as a whole calculated as stated is:

	Per cent
Silica (SiO_2)	20. 08
Ferrous oxide (FeO)	7. 42
Magnesia (MgO)	23. 41
Iron (Fe)	43. 33
Nickel (Ni)	4. 91
Cobalt (Co)	. 27
Total	99. 42

The stony meteorites are likewise variable, particularly in their metal content. They are of a very basic nature as a rule—that is, are low in silica. Those highest in this constituent are the achondritic varieties consisting largely of pyroxenes and feldspars like that of Cumberland Falls, Ky. The more basic are among the kugel chondrites like those of Felix, Ala., and Jerome, Kans.

Below are given two analyses illustrative of extremes in basicity and acidity and in the table following an average of 63 analyses of the highest grade obtainable.[38]

	Felix, Ala., extreme basic type	Cumberland Falls, Ky., extreme acidic type		Felix, Ala., extreme basic type	Cumberland Falls, Ky., extreme acidic type
SiO_2	33. 57	55. 172	Na_2O	0. 62	0. 157
Al_2O_3	3. 24	. 382	K_2O	. 14	. 150
Cr_2O_3	. 80	. 062	S	1. 73	. 784
Fe	5. 61	. 888	P	----------	. 034
Mn	----------	. 005	Cl	----------	. 028
Ni	. 36	. 059	C	. 36	. 164
Co	. 08	. 004	Ign	. 16	. 167
Cu	. 01	. 003			
NiO	1. 01	. 123		99. 78	101. 530
FeO	26. 22	2. 916	Less O. for Cl, S, and P	----------	. 569
CaO	5. 45	1. 586			
MgO	19. 74	38. 734		----------	100. 961
MnO	. 68	. 112			

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[37] Bull. Inst. Polytech. Don. Novocherkassk, 1918.

[38] For methods of analysis, see p. 57.

Average composition of stony meteorites

Constituent:	Per cent
Silica (SiO^2)	38.41
Titanic oxide (TiO_2)	.16
Tin oxide (SnO_2)	
Zirconium oxide (ZrO_2)	
Alumina (Al_2O_3)	2.86
Ferric oxide (Fe_2O_3)	.92
Chromic oxide (Cr_2O_3)	.40
Vanadium oxide (V_2O_3)	
Metallic iron (Fe)	12.35
Metallic nickel (Ni)	1.09
Metallic cobalt (Co)	.10
Ferrous oxide (FeO)	13.60
Nickel oxide (NiO)	.40
Cobalt oxide (CoO)	.06
Lime (CaO)	1.88
Barium oxide (BaO)	
Magnesia (MgO)	23.66
Manganous oxide (MnO)	.23
Strontium oxide (SrO)	
Soda (Na_2O)	.82
Potash (K_2O)	.16
Lithia (Li_2O)	
Ignition (H_2O)	.47
Phosphoric acid (P_2O_5)	.34
Sulphur (S)	1.89
Copper (Cu)	.01
Carbon (C)	.16
Chlorine (Cl)	.03
	100.00

EXTERNAL AND INTERNAL FEATURES OF METEORITES

There are certain external features characteristic of nearly all meteorites, both stones and irons, which may well be considered before entering upon a detailed discussion of internal structures.

Apparently there is no necessary limit to the size of meteorites, though the largest actually known is the giant brought by Commander Peary from Cape York, in Greenland, which weighed 37½ tons. The smallest stone, constituting all that is known of the fall is that of Mulau, Austria, which weighed but 5 grams. It is now pretty generally conceded that meteorites, of whatever type or size, are fragments at the time they enter our atmosphere, and that as a rule a further fragmentation and reduction in size takes place owing to the atmospheric pressure induced by the enormous speed at which the body may be traveling. Iron being tougher and more resistant than stone, it would naturally follow that among the metallic forms giants, if such there are, would prevail. This idea is fully borne out in fact, and attention need but be called to the frequent occurrence of stone "showers" and their rarity among irons. The form and size of meteorites are therefore both largely controlled by the speed of travel. In either case sufficient heat is generated for the fusion and burning away of the immediate surface, the fused material being stripped off nearly as fast as formed, and but a thin coating of material quickly cooled during the last moment of the flight remains, producing the black crust so characteristic of stones or the thin layer of oxide on the irons. The burning does not always take place evenly over the entire surface, the foremost point of the body naturally being most affected, the result being a smooth rounded nose, or "brustseite," from which radiate in all directions furrows or flutings (piezoglyphs) sometimes developed to a remarkable degree of perfection, as in the stone of Bath Furnace, Ky. (pl. 1). Inequalities in composition, as the presence of troilite nodules or other causes are often productive of deep flutings in the irons, or holes which may extend entirely through the mass, as in the Tucson iron or several of those of Canon Diablo, Ariz. In this connection it should be said that the flattened, sharply edged, and irregular form of the smaller individuals of the Canon Diablo fall are not original, but due to a weathering, which has been productive of the "shale balls" of Barringer and other writers. That this is correct is shown not merely by their shape—edges unrounded by fusion—but by the occasional finding of a mass with a still unaltered nucleus of metal lying like an oyster in its shell. Once broken, such usually undergo a further rapid oxidation and fall to pieces.

The black crust coating the surface of freshly fallen meteoric stones is, as noted, due to the final hasty cooling of the fused material of the meteorite. This is, on the immediate surface, a more or less perfect glass, which is interspersed below the immediate surface with unfused silicate and metallic particles. It is rarely more than a few millimeters thick, as in the case of the Allegan stone shown in Figure 1, Plate 1, and Figure 1, Plate 28. Should the stone hold the same relative position in the air for any appreciable distance, the fused material stripped from the nose may accumulate to a greater thickness at the rear; it is, however, but a few millimeters thick at best.

Many meteorites are found traversed by a series of black thread-like veins, which are probably but lines of fracture produced by the shock of impact on entering the atmosphere, as noted later (pl. 29).

The meteorite differs from terrestrial rocks not more in external characteristics and chemical and mineralogical composition than in the manner in which its various constituents are arranged in relation one to another. While there are certain features, as the presence of metal, that are sufficiently pronounced to enable one at all experienced in such matters to decide almost at a glance upon the meteoric nature of any object, even though not seen to fall, it is nevertheless on a study of the thin sections and surfaces both polished and etched that chief reliance must be placed. As with terrestrial rocks, it would be very difficult to give by written description alone a clear impression of some of the curious features as revealed by this method, and the reader is advised to consult carefully the numerous illustrations which are reproductions from photographs made in part through the microscope.

1. ALL-METAL METEORITES: SIDERITES

The structural peculiarities of the all-metal meteorites have been well described and beautifully illustrated photographically by Cohen and Brezina in their work Die Struktur und Zusammensetzung der Meteoreisen (Stuttgart, 1906). As, however, this work is quite inaccessible to the majority of students, space may well be given here to a description of a few of the more typical forms.[39]

Metallic meteorites, as has been said, are composed almost wholly of iron with small and variable percentages of nickel and cobalt. In the main, these metals are combined to form the two alloys named, respectively, kamacite and taenite as already described. Each of these alloys in the large majority of cases occurs in the form of thin plates with intervening areas of a third alloy or properly eutectic called plessite which fills the interstices. A characteristic feature of the kamacite and taenite is a tendency to arrange themselves in the form of thin plates lying parallel to the faces of a possible octahedron. To reveal this structure clearly, as shown in Figure 1, Plate 5 and Plate 7, it is necessary to polish a flat surface and etch it with dilute acid.[40] Owing to the differential solubility of the three alloys mentioned, they will be acted upon unequally and stand out each with its own relief. Such markings are called Widmanstätten figures, after their discoverer. In thickness the plates vary from the fraction of one to several millimeters, which fact forms the basis of separation into *fine octahedrites* (Of), *medium octahedrites* (Om), and *coarse octahedrites* (Og), etc. The kamacite presents several varietal forms, dependent upon position and internal peculiarities brought out by magnification. In the octahedral irons the bands are often swollen in the middle and constricted at the ends, as shown in Plate 7. In the pallasites a band of white kamacite a few millimeters in diameter often incloses the silicates and is known as swathing or "wickel" kamacite. (See upper figure of pl. 7.) A thin band of taenite may or may not lie parallel with this and between it and the

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[39] The all-metal meteorites furnish a problem for the metallurgist which needs scarcely be touched upon here, and the reader is referred to standard treatises on the subject. See especially Osmond and Cartaud in the Metallurgist, vol. 4, 1891, and also the Comptes Rendus, vol. 137, 1903, p. 1057; Stahl u. Meteoreisen by F. Berwerth, Metallurgie, vol. 4, 1907, p. 722, reprinted under the title Steel and Meteoric Iron in the Iron and Steel Institute, September, 1907, Ein Naturlisches System der Eisen Meteoriten, Sitz d. Kais. Akad. der Wiss, vol. 123, Abt. 1914, p. 1047; and finally Borgström's paper: On the Composition of the Nickel Iron Alloys and on Magnetic Lines on Sections of Meteoric Irons, Fennia, Helsingfors, vol. 45, No. 2, 1925, pp. 1–18.

[40] Details of the etching process are given by Farrington in his Meteorites, pp. 127–130.

accompanying metal. At times the kamacite plates assume broad and irregular forms as in the iron of Ainsworth and New Baltimore (lower figure, pl. 10; upper figure, pl. 29), predominating over all other constituents; in such octahedral structure is wholly undiscernible except on large surfaces.[41] In some instances taenite and plessite are almost wholly lacking, the entire mass of the iron being composed of the coarse kamacite granules. An interesting varietal phase of octahedral structure is shown in Plate 6 from an iron found in Dungannon, Va.,[42] some years ago. It will be noticed that this has undergone the partial granulation described though traces of the original octahedral structure are still discernible. The dark areas are of graphite with metallic inclosures.

Not all irons are octahedral. In some the metal occurs in the form of granules so fine as to escape easy notice, and thus to appear of a noncrystalline structure or amorphous. These irons will often show on etching certain faint parallel lines traversing the etched surface, which are due, according to Neuman of Vienna, after whom they are named, to the union of crystals in definite opposed relations technically known as twinning, and in this case parallel with the faces of a cube. (Uppeı figure, pl. 8.) Still other irons are distinctly granular throughout, a structure which as shown later, may be secondary and due to the action of heat (lower figure of the same plate). The systematic regularity of arrangement of the taenite and kamacite plates which form the chief constituents of an octahedral iron is often interrupted by the presence in minor quantities of various accessory minerals as cohenite, schreibersite, and troilite or carbon nodules which last are as a rule distributed without order or, it may be, lying parallel with the kamacite bands.

Nearly all irons carry varying, though minute quantities of olivine and other silicates, quartz, and occasionally diamonds in quantities so small as to be detected only in the residues left when the metal is dissolved away by dilute acid. Graphite when present is left as a black amorphous mud. The ubiquitous lawrencite makes its presence known through exudation of greenish drops on a polished surface which quickly absorbs moisture and oxidizes to a rusty red color. It is this mineral which brings about the rapid destruction of many an iron meteorite and which perhaps explains the fact that no meteorites are found in any but the most recent of formations.

Closely related to the wholly metallic forms are those of a somewhat limited group represented to advantage in Plate 9 by a cross section of a mass found near the bounding corners of Arizona, Colorado, New Mexico, and Utah in the United States and hence known as the

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[41] Farrington's tabulations of analyses seems to show that the texture varies with the nickel content, the finest crystallization being found in irons richest in nickel. The ratio is, however, by no means constant. Field Museum publication, No. 120, 1907.

[42] Proc. U. S. Nat. Mus., vol. 62, 1923, art. 18.

Four Corners meteorite. This is described[43] as "a granular mass of octahedral iron with silicate inclosures" which in this case are mainly pyroxenic. It is to be noted that each granule of the metal has its own crystallographic orientation, the structure as a whole resembling very much that of a coarsely crystalline aggregate of calcite or feldspar. The pyroxenic portions (dark in the figure) are finely granular and sometimes in the condition of a fine sand. The closest analogue to this peculiar iron is thought to be that of Copiapo (Dheesa), Chile, as described by various authorities.

A second type which might well be mentioned here is that of Persimmon Creek in Cherokee County, N. C. (Lower figure, pl. 9.) This peculiar mass is described[44] as "a granular octahedrite" but might better be designated as an agglomerate of masses of metal and troilite (A and B in the plate), and occasional dark masses consisting of a dense aggregate of graphite, troilite and olivine (C in the plate). The metallic portions are composed of granules each with its own crystallographic orientation and an octahedral structure as in the iron of Four Corners.

2. STONY-IRON METEORITES: SIDEROLITES

The stony-iron meteorites are classified as (1) *Lodranites*, crystalline granular aggregates of olivine and bronzite in a fine network of metal. But one of this type is known—that of Lodran, India, which fell in 1868 and of which but 970 grams are known to exist. (2) *Mesosiderites*, or grahamites, aggregates of olivine, bronzite, plagioclase, and augite, sometimes chondritic or with a crystalline structure in a continuous net of metal. (3) *Siderophyres* consisting of bronzite and nickel-iron with accessory asmanite (tridymite). But a single meteorite of this type also is known—that of Steinbach (Breitenbach) Saxony, which was not seen to fall but was found in 1751. (4) *Pallasites* consisting of olivine in a continuous network or sponge of metal. With the stony irons are also included by some authorities breccia-like masses of nickel-iron with crystalline chondrites like that of Copiapo and the octahedral iron with crystalline chondrites of Netschäevo.

Meteorites of the mesosiderite or grahamite group are well represented by the finds of Crab Orchard (Rockwood), Morristown, Hainholz, and Vaca Muerta. The fall of Estherville though commonly here classed is really of a somewhat different type. The common structure, as shown in Plate 12, is that of a dense net or sponge of metal the interstices of which are filled by silicate minerals in the form of small, single and angular particles and aggregates it may be two or more centimeters in diameter. The metal is rarely segregated in blebs a centimeter in diameter which yield Widmanstätten figures

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[43] Proc. Nat. Acad. of Sciences, vol. 10, 1924, p. 312.

[44] Proc. U. S. Nat. Mus., vol. 27, 1904, p. 955.

when etched. The silicates in the Crab Orchard meteorite were adjudged on chemical grounds to be enstatite and anorthite.[45] Vaca Muerta and Hainholz are in so close agreement as to need no further notice here.

Thin sections of the stony portions of the Morristown mesosiderite show it to be holocrystalline granular, sometimes strongly cataclastic. The latter structure is particularly conspicuous in those portions rich in metallic iron, where the feldspars are often enclosed in the form of sharply angular fragments in the iron or in its numerous embayments. The appearance is not, however, that of a clastic rock, but rather that of a crystalline mass which has been subjected to dynamic agencies. The structure as a whole is quite irregular, and sometimes porphyritic through the presence of large pyroxenic masses which may be 5 to 8 mm. in diameter.

The groundmass of the stone is composed mainly of granules of pyroxenes and plagioclase of such size as to render their determination a matter of considerable ease, but which are interspersed with innumerable rounded and irregular granular forms so minute and so lacking in crystal outlines as to obscure their true mineralogical nature.

The feldspars are in angular fragments showing polysynthetic twinning and numerous cavities and enclosures. Partial analyses on a minute quantity indicate it to be anorthite. A very small amount of olivine is present.

The remarkable meteorite of Estherville, Iowa, is, however, as noted above, of a different type, though how far this difference is original, and how far due to metamorphism remains yet to be shown. The stone has been the subject of much discussion, a general summary of which, up to 1915, is given by Farrington.[46] As shown in Plate 13 it consists of disconnected and irregular blebs of metal distributed throughout the silicates and often with irregular cavities intervening. The silicate components are enstatite, diallage, olivine and anorthite. The enstatite occurs in two forms, a green and highly lustrous variety and a yellow-brown opalescent filled with minute glass cavities. It is to the last that Smith gave the name "peckhamite." Subsequent studies [47] have shown this to be but an altered phase of the green mineral, a change evidently brought about through the agency of heat. Both the pyroxenes and olivine occur at times in globular pebblelike forms. The groundmass is holocrystalline anorthite, often showing signs of incipient fusions and other indications of metamorphism. (See p. 40).

Pallasites.—Meteorites of this group—with the exception of Brezina's rökickites—differ in that the prevailing silicate (olivine) occurs in such forms as to seemingly show its crystal development

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[45] Amer. Journ. Sci., vol. 34, 1887, p. 387.

[46] Mem. Nat. Acad. Sciences, vol. 13.

[47] Proc. U. S. Nat. Mus., vol. 58, pp. 363–370.

out of a metallic magma; a condition difficult to realize. Both Rose and Kokscharow have measured and determined crystal facets on the olivines in the Krasnojarsk pallasite.[48] That, however, the olivines did not crystallize in all cases in the position they now occupy is shown in the lower figure, Plate 13, where the silicate is in sharply fragmental form, a condition thought by Brezina[49] to be brought about by movement in the plastic metal in which the olivines are embedded.

Plate 14 is from a pallasite found some years ago at a locality known as Brenham, Kans. The light, net-like portion is composed of nickel-iron alloys identical in composition, so far as now ascertained, with those of the all-metal meteorites. The dark areas are silicate minerals—in this case olivine (peridot). The structure has been compared, not inaptly, to that of a sponge in which the original sponge material is metal, the silicates filling the meshes. Meteorites of this type are somewhat rare, only about 20 now being known. It is to be noted that the metal, wherever surfaces of sufficient size are exposed, shows a tripartite structure and is never granular. Further, that the kamacite bands often surround the olivines in a form known as "swathing" kamacite (pl. 7) or white iron, on account of the color and brilliant reflection. Between the kamacite and plessite is often a thin band of taenite as in the all-metal forms.

3. STONY METEORITES, OR AEROLITES[50]

The structure of many stony meteorites is of so confused and heterogeneous a character as to be at times almost indescribable in words, and one must refer to the illustrations. In their study the same devices are employed as are commonly used for terrestrial rocks. The figures shown in the accompanying plates are from photomicrographs made from the thin sections prepared in the customary manner.

The one great difficulty in the determination and description of meteoric minerals and structures lies in the imperfect crystal development of the individual constituents, their shattered condition and discoloration caused by oxidation of the lawrencite. This is particularly the case in the chondritic varieties which often present in the section but a confused aggregate of polarizing points so charged with secondary iron oxides as to render indeterminable any but the two or three prevailing constituents, and uncertain the true nature

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[48] It is still a question if these faces may not be due to compression by interference in process of crystallization of a granular olivine aggregate before the introduction of the metal. See, Concerning the Origin of the Metal in Meteorites, Proc. U. S. Nat. Mus., vol. 73, 1928, no. 2742, pp. 1–7. Also, Calcite Oolites with Pentagonal and dodecahedral form, by E. V. Shannon, Journ. Washington Acad. of Sci., October 4, 1927.

[49] Die Meteoriten Sammlungen, 1895. See also Merrill, Concerning the Origin of the Metal in Meteorites, Proc. U. S. Nat. Mus., vol. 73, art. 21, 1928, p. 4.

[50] A most excellent series of photomicrographs showing structures of meteoric stones, with descriptive matter, is given in Tschermak's Die Mikroskopische Beschaffenheit der Meteoriten, Stuttgart, 1885. Unfortunately this work is not generally available.

of the original structure, whether crystalline, glassy, or fragmental. This feature has caused a great diversion of opinion among students. As will be observed, the present writer bases his conclusions as to the original clastic (fragmental) nature of the chondritic varieties not on structure alone, but on the presence in close association of one and the same mineral under varietal forms of crystal development such as are seemingly impossible products of direct cooling from a molten magma.

Few meteoric stones, probably not over a score of those now known, show the crystalline structure characteristic of terrestrial igneous rocks, either basalts or peridotites. In the prevailing system of classification they are divided into two general groups. I, Calcium-aluminum-rich stones nearly free of nickel iron and without chondrules, and II, magnesium-rich stones likewise nearly free of nickel iron and nearly or completely free of chondrules. Group I is again subdivided into (1) the *angrites*—of which but a single representative is known, which consists mainly of a dark brownish augite and a little olivine iron sulphide and with a crystalline granular structure; (2) the *eukrites*, which consist essentially of augite and anorthite with iron sulphide and also a crystalline granular structure like many dolerites; (3) the *shergottites* of which there is also but a single representative known, which consists of augite and the isotropic feldspar maskelynite and a little magnetite, with likewise a crystalline granular structure; and (4) the *howardites*, consisting of augite, anorthite, bronzite, and olivine in a tuffaceous ground with sometimes eukritic segregations.

Group II is likewise subdivided on mineralogical and structural grounds into (1) the *bustites*, of which but a single representative is known, which consists essentially of diopside and bronzite with smaller quantities of oldhamite, plagioclase, nickel iron, and osbornite, with a nearly crystalline structure; (2) the *chassignites* consisting of an iron-rich olivine and small quantities of chromite and with a crystalline granular structure, of which type but a single stone is known; (3) the *chladnites*, consisting of a crystalline granular aggregate of a rhombic pyroxene; and (4) the *amphoterites* consisting of olivine and bronzite with smaller quantities of sulphide and nickel iron. The structure is sometimes granular and sometimes chondritic.

The microstructure of the eukrites and howardites has been described in detail by various writers, including Tschermak, Wahl, Berwerth, and others, all of which have been the subject of review by Lacroix[51] to whose work the reader is referred for details. The Bereba eukrite is described as a breccia of doleritic fragments cemented by recrystallized finely pulverulent material of the same mineral nature. The essential constituents are pyroxene and anorthite with

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[51] Arch. du Museum D'Historie Naturelle, vol. 1, ser. 6, 1926.

secondary magnetite, pyrrhotite, and quartz in minor quantities. The pyroxene of the unaltered fragments is of a brownish color and filled with inclosures; that of the fine granular recrystallized ground is of a yellowish color and free of inclosures. The howardites, of which that of Teilleul is considered typical, is described as constituted almost exclusively of angular fragments of bronzite with ferruginous inclusions; a "diopside-bronzite prive d'inclusions ferruginous" and anorthite, with some chromite. The group would seem really to consist of the same materials as the cataclastic, pulverulent interstitial portions of the eukrites.

The stone of Juvinas consisting of a colorless anorthite and gray to brownish augite shows under the microscope a holocrystalline structure not unlike that of many basic terrestrial rocks and like them containing minute geode-like cavities. That of Shergotty (fig. 2, pl. 16) differs in showing broad plates of brown augite with interspaces occupied by a clear, colorless, and transparent feldspathic mineral which is optically quite isotropic and to which the name maskelynite has been applied. Stones of the Nakhla type (fig. 1, pl. 16), of which but one example is known, consist of an even, granular aggregate of green pyroxene (diopside) with olivine and occasionally a plagioclase feldspar and a little magnetite. It might well pass for a terrestrial pyroxenite. The chassignites, as represented by the single occurrence in Chassigny, are fine crystalline granular aggregates of olivine not greatly dissimilar to some terrestrial dunites. The chladnites as represented by the Bishopville stone consist of a rather coarse crystalline granular aggregate of nearly white enstatite with small amounts of a plagioclase feldspar and occasional troilite granules. The stone is remarkable for its poverty in metal, analyses showing less than 1 per cent of this constituent.[52]

In many meteorites (both chondritic and otherwise) a brecciated structure is plainly evident even to the unaided eye. This may be due to a commingling of rock fragments from diverse sources, or from crushing in mass, or perhaps from both, as shown in the meteoric stone which fell in Kentucky in 1919 (pl. 17). Here are plainly commingled two types of stone which have been compressed sufficiently to produce incipient twinning in the enstatite particles after a manner well known to petrologists. The manner in which the metal is disseminated throughout this stone is of interest and will be referred to later.

Other stones, like those of Supuhee, India, or Rose City, Mich., are plainly agglomerates of pebble-like bodies embedded in finer material of the same mineral nature. In the St. Michel, Finland,

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[52] It is well to remark here that metal in the stony meteorites is present in appreciable quantities only in those the fragmental and tuffaceous origin of which is readily apparent and is almost completely absent in the crystalline or achondritic varieties.

stone described by Borgstrom [53] the fragments are more angular, the stone partaking of the nature of a breccia (pl. 17).

Fully 90 per cent of the stony meteorites are characterized by the presence of small spherical bodies embedded in a fragmental or crystalline ground of the same mineral nature. Mineralogically speaking, the bodies are of pyroxene or olivine, rarely feldspar, though sometimes glassy and without the development of determinable mineral species. In sizes they vary from too small to be visible to the unaided eye to rarely a centimeter in diameter. These are called *chondrules* from a Greek word meaning a grain and are of exceptional interest on account of their unique form and probable origin. A discussion of these features must, however, be left until later.

The chondritic meteorites, or *chondrites*, as they are called, form a group quite variable in types of structure as shown in the several plates here devoted to the subject. They are at times so friable as to crumble easily in the thumb and fingers, or again are very hard and tough, this feature being imparted by metamorphism. In the first instance the chondrules may fall away entire. In the second they may be so firmly embedded as to break with the matrix. All intermediate stages occur. A description of the internal structure—the manner in which the various minerals are disposed relative to one another in a chondritic meteorite—is a matter of no small difficulty. As a whole, the group may be said to consist of a heterogeneous aggregate of minerals largely olivine and pyroxenes, mainly in a fragmental condition, with varying amounts of interstitial metal and metallic sulphides throughout which the chondrules are scattered in varying proportions. It is only when we consider the crystalline chondrites that a satisfactory verbal description can be given.

The chondrites are described by Wülfing (Meteoriten in Sammlungen, pp. 449–454) as magnesia-rich stones consisting essentially of olivine, bronzite, nickel iron, and iron sulphide, and with the exception of Novo-Urei plainly chondritic and tuffaceous. They are divided into:

1. *Howarditic chondrites*, comprising transition members from the howardites into the true chondrites.
2. *White chondrites*, yellowish white tuffaceous stones with chondrules for the most part of the same color.
3. *Intermediate chondrites*, transition forms into the gray chondrites.
4. *Gray chondrites*, yellowish to blue gray tuffaceous stones with variously colored chondrules firmly embedded in the ground mass.
5. *Black chondrites*, firm, dark gray to black stones in which the color is due in part to carbonaceous matter and in part to pyrrhotite. The chondrules are mostly of a lighter color. Meunier has shown that in some instances the blackening has been produced by heat.

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[53] Bull. Com. Geologique de Finland, No. 34, 1912.

6. *Kugelchen chondrites.* This large group consists of very numerous well-developed chondrules embedded in (1) a tuffaceous ground which is almost wholly of chondrules and (2) one in which the ground is so loose and friable that the chondrules are readily broken away. There are transitional forms into the next.

7. *Crystalline chondrites,* consisting of a crystalline ground in which the hard chondrules are firmly embedded.

8. *Carbonaceous chondrites,* consisting of black ground due to carbonaceous matter, and carrying but little metal; hence noted for lack of density. The Orvinites differ in showing a fluidal structure, the crystal Tadjerites are part glassy ground and the Ureilite crystals are black, sometimes chondritic, sometimes granular masses consisting mainly of olivine and showing transitional forms into the group classed under nickel-iron with silicates.

Obviously such a system of classification permits of no sharp discriminations. That of Prior, given below, has much to recommend it in this regard. In this the chondrites are separated according to the true character of their prevailing pyroxenic constituent as follows:

(*a*) Enstatite-chondrites.
(*b*) Bronzite-chondrites.
(*c*) Hypersthene-chondrites.

To the members of each of these groups are applied the qualifications according to color (white, intermediate, gray, black); structure (crystalline, spherical, brecciated, veined); and composition (carbonaceous, etc.), used in the Tschermak-Brezina classification.

As illustrative of a pronounced type of a spherulitic or kugelchen chondrite reference may be made to the stones of Allegan, Michigan; Selma, Alabama; and Bjurbole, Finland, Figures 1 and 2, Plate 18, also Plate 25. These stones are very friable, so friable indeed that thin sections can be prepared only with difficulty. Under the microscope they show in a marked degree the tuffaceous structure characteristic of their class. Three or more types of chondrules are not infrequently present in the same stone, (1) the ordinary enstatite chondrule showing in a section a fan-shaped radiating structure; (2) others composed of olivines, sometimes quite idiomorphic developed in a black glass; and (3) dense structureless forms consisting evidently of enstatite. These are all sharply differentiated from the ground and break away from it readily. The groundmass is itself a confused admixture of olivine and enstatite particles with interspersed metal, metallic sulphide and chromic iron, the silicates being almost universally of a fragmental nature. Much of the interstitial material is so fine and dustlike that it is practically impossible to determine its nature in the section, but when isolated it is found to consist of fresh and sharply angular splinters of olivine and other silicates.

Many of the enstatite chondrules are beautifully perfect spheres and others oval and elongated. They occur also in all stages of fragmentation as described in the numerous publications. Irregular porphyritic forms occur; such the author regards as fragmental forms due to trituration and designated as "chondroids." Many stones, like those of Mezö Madaras, Russia; Selma, Alabama; and Cedar, Texas (pl. 18), are made up in almost their entirety of chondrules and chondritic fragments, the "chondrulites" of Chamberlin.[54] (See further under Chondrule, its Nature and Origin, p. 29.)

From stones of this type there is a constant gradation to the crystalline chondrites of which the stones of Bluff, Estacado, or Hendersonville may serve for purposes of illustration. These are compact, dense stones showing a polished surface thickly studded with gray chondrules of a few millimeters in diameter which are sharply differentiated from the ground, sometimes breaking with it and sometimes falling away leaving the surface studded with little saucer-shaped pits. Some of the chondrules are of the radiating enstatite type; others barred and porphyritic. The groundmass consists of a closely intergrown aggregate of olivines and pyroxenes interspersed with metallic particles and granules of iron sulphide. Under as high a power as the thickness of the section will permit the use, the interstitial matter polarizes faintly and shows a granular to fibrous structure. As a whole the structure is not that of minerals crystallizing freely from a molten magma but is suggestive of a partial recrystallization of fine detrital material as seen in many metamorphic schists (pl. 19).

Continual variations of this are found in the same and other types of chondritic stones, but it is to be noted that as the stones partake more and more of the nature of crystalline rocks the included chondrules grow less and less perfect, merging finally into the groundmass until they quite disappear.

The dark color of the so-called black chondrites as shown by Meunier [55] and subsequently by the present writer [56] is due mainly to heating though it may be in some cases in part to the presence of carbonaceous matter. The coloring material in some cases is interstitial, or again where the heating has been prolonged penetrating the cleavage and fracture lines of the silicates. In the case of the stone of Sevrukof, Russia, the heat has been sufficient to produce a partial fusion now manifested by the presence of a little interstitial brownish glass.[57] Daubree, as quoted by Eberhard,[58] thought this heating

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[54] The Two Solar Families.

[55] Comptes Rendus, vol. 6, p. 178.

[56] Proc. Nat. Acad. Sci., vol. 4, 1918, pp. 178–180.

[57] The writer will here say that he has never found in any meteorite what he considered an original, residual glass such as is characteristic of many terrestrial igneous rocks. Such glass as may exist is secondary, as in the case above. This, of course, does not apply to other chondrules, which are often more or less vitreous.

[58] Arch. f. d. Naturkunde Liv. Est. u. Kurlands, ser. 1, vol. 9, 1882.

to have taken place during the passage of the stone through the atmosphere.

The stone of Indarch, Russia (fig. 1, pl. 20), is microscopically of a dark greenish gray color, firm and compact, admitting of a polish, and on the polished surface thickly studded with small, dark, almost black chondrules and nodular masses of metal and troilite, the largest of which are rarely over 1 millimeter in diameter. Under a pocket lens the chondrules are mostly of a greenish color, though some are nearly black. They break with the matrix in which they are embedded. In thin sections and under the microscope the structure is quite obscure. Owing to the prevalence of graphite, with which it is everywhere impregnated it presents a dense black irresolvable ground throughout which are scattered the iron and iron sulphide, together with abundant sharp splinters of pyroxene and numerous more or less fragmentary chondrules of the same mineral in both porphyritic and radiating forms. All of the well crystallized forms, both in isolated particles and in the chondrules, belong to the polysynthetically twinned clinoenstatite type. Calcium sulphide, oldhamite, occurs in this stone in the form of irregular areas, sometimes interstitial and sometimes inclosed in the enstatite. It is of a yellow brown color, sometimes greenish, completely isotropic, and with well developed cubic cleavage.

The metal in stones of the chondritic class occurs as small irregular particles, sometimes almost chondrule-like, as does also the troilite. More commonly the two minerals are closely associated, the sulphide in irregular form being completely surrounded by a border of metal (upper figure, pl. 21) which penetrates into the interstices of the silicates enacting the part of a binding constituent. Or again, the metal may occur simply capping the sulphide, or as a collar completely surrounding a silicate particle as in Figure 2, Plate 20 (Cullison). In many instances it occurs in the form of thin filaments traversing the interstices and completely enfolding the silicates and penetrating into fracture crevices as in the stone of Cumberland Falls, Ky., all of which points to its origin as a secondary product from some preexisting form, perhaps a chloride.[59] (Lower figure, pl. 21.) As elsewhere noted the metal is most abundant in stones of a pronounced chondritic type.

CHONDRULE: ITS NATURE AND ORIGIN[60]

The term "chondrit," from the Greek χονδρος, a grain, was first used, so far as I am aware, by Gustav Rose to designate a class of stony meteorites characterized by the occurrence of small granules or "*kugeln*."

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[59] See Concerning the Origin of the Metal in Meteorites, by this author, Proc. U. S. Nat. Mus., vol. 73, art. 21, pp. 1-7, 1928.

[60] See On Chondrules and Chondritic Structures in Meteorites, by George P. Merrill, Proc. Nat. Acad. of Sciences, vol. 6, no. 8, 1920, pp. 449-472.

. . . "Sie ist durch kleine Kugeln ausgezeichnet die aus einem noch nicht bestimmten Magnesia-Silicate bestehen, und in einem fein kornigen Gemenge eingemengt sind," etc. The word, with the addition of the terminal *e*, as Chondrite, has been very generally adopted, with its original meaning, by English and American writers. Unfortunately, as it would seem, a further modification of the word as *chondros, chondrule, chondrus, or chondrum* has been introduced, at first apparently synonymous in meaning with "kugel" as used by Rose though it is to be noted that he did not define the word quite as clearly as might be desired. He wrote: "* * * in Bruche erscheinen sie *theils uneben theils fasrig*, im letzern Fall jedoch stets nur sehr feinfasrig, indessen doch immer bestimmt erkennbar fasrig, besonders unter der Lupe * * * nie radial, sondern immer excentrisch fasrig. . . .

No further reference is made to those of "*uneben* Bruche" and one is left only to surmise that they may have been of a granular or porphyritic rather than fibrous structure. The fact that Rose's work was written before the day of thin sections doubtless accounts for the undetermined character of the magnesian silicate.

Tschermak in his *Mikroskopische Beschaffenheit* (1885) was little more explicit in his use of terms than was Rose. He wrote: "Kugelchen und *überhaupt rundliche Körper*, welche bald aus einem einzigen krystallindividuum, bald aus mehreren bestehen, öfters auch aus verschiedenen Gemengtheilen zusammengestzt sind, bilden das Gestein fast allein (Borkut) oder sie lagern unverletzt, öfters auch zersplittert in einer lockeren bis festen Tuffmasse." Elsewhere he includes all the rounded forms under the term "chondren," though in his plate legends and descriptions he designates both as kugelchen, thus using the two terms synonymously.

A perusal of the literature shows that by English and American writers, the terms "chondrule," "chondrus," "chondrum" or "chondros" are now and have for some years been applied to the rounded and oval granules presenting a considerable range in mineral composition and still wider range in internal structure, thus making the terms synonymous with kugel or kugelchen as used by Tschermak above. Of later years and as illustrated in the generally adopted scheme of classification [61] there has seemed a disposition to use the term kugel in a descriptive adjective sense, as "kugelchen chondrit," under which name are included stones containing chondrules (or chondri) having a radiate structure—the spherulitic [62] chondrites of American writers. There has thus apparently arisen in the minds of many a confusion which, as it seems to the writer, has been in part at least responsible for the diverse views expressed concerning the

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[61] See Farrington's Meteorites, p. 200.

[62] Or "globular," see Proc. Amer. Philos. Soc., vol. 43, 1904 (p. 238).

origin of these peculiar bodies. In other words, there has been a failure to recognize or discriminate between the kugelchen with radiate structure and the often polysomatic forms with the irregular fracture.

The following pages represent an attempt on the part of the author to make this discrimination and to show how far proposed theories may apply to the various forms presented.

At the outset and for the purpose of making clear what is to follow, it will be well to figure and describe a few characteristic forms of the individual chondrules. This notwithstanding the previous most excellent and comprehensive work of Tschermak and Cohen.[63] (See pls. 18, 22–25.)

Mineralogically, the chondrules, using the word in its broadest and most comprehensive sense, in nearly all meteorites are composed chiefly of the minerals olivine or pyroxene, the latter in either orthorhombic or monoclinic forms, or both. Some are largely of an undifferentiated glass. Feldspars occur but rarely except in the form known as maskelynite. In addition are occasional inclosures of metal or metallic sulphides, chromite or other minor constituents. The metallic iron sometimes occurs in rounded chondritelike blebs, though it is doubtful if this should be referred to under that name. Structurally, the chondrules in the same meteorite may vary from densely cryptocrystalline, almost amorphous, to those that are part glassy and porphyritic or even holocrystalline.

1. *Glassy, cryptocrystalline, and radiated forms.*—In Figures 1 and 2, Plate 22, are shown examples of cryptocrystalline forms from the stones of Barratta, Australia, and Cullison, Kans. That of Figure 1 is of a peculiar brownish translucency and very dense, resembling the "felsitic" structure of the early petrologist. In the Cullison stone, Figure 2, the chondrules, also of a brownish color, are not completely isotropic but between crossed nicols break up into several ill defined areas over which the dark cloud sweeps faintly and irregularly as the stage revolves. The material seems to be a partially devitrified glass in a condition of optical stress as from sudden cooling. Chondrules of this type and those next to be described more nearly resemble the spherulites of the terrestrial rocks than any others which have come under the writer's notice. Their outlines are at times as sharply demarked from the matrix in which they are embedded as are the spherulites in the rhyolitic obsidians of the Yellowstone National Park.

Chondrules of the radiating type are shown in Figures 3, 4, and 5, from the meteorites of Elm Creek, Hessle, and Parnallee. The mineral in all cases is enstatite[64] and the outline of the spherule as

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[63] See particularly, Die Mikroscophische Beschaffenheit der Meteoritenkunde, respectively.

[64] No attempt in these pages has been made to distinguish between enstatite and the ferruginous varieties bronzite and hypersthene.

sharp and clean as though it had been turned on a lathe. In the Elm Creek example crystallization evidently began at one point on the surface of the spherule and extended inward throughout, but the cooling proceeded too rapidly for the production of an optically perfect crystal. In the Hessle stone (fig. 4), there were evidently several initial points of crystallization. Forms like these grade imperceptibly into such as are shown in Figure 5, in which the radiating bars have unmistakably the crystallographic properties of enstatite.

2. *Half glassy, barred and porphyritic forms.*—Porphyritic forms are characteristics of both olivine and enstatite chondrules, while the barred forms, such as are shown in the upper figures of Plate 23, are limited mainly, if not wholly, to monosomatic forms composed of olivine. In Figure 1, from the Beaver Creek stone, the white portions are olivine which extinguish practically as a single unit; the black portions are glass. It is to be noted that the outlines of the chondrule though sharp are not smooth as in those described above, but have projecting particles extending out into the ground; also that this border portion often contains enclosures. In Figure 2 from the Cullison stone, the bars are bent and curved and do not all extinguish simultaneously, as the stage is revolved, the dark cloud sweeping over it irregularly, indicating a condition of stress. Here, as in the last, the border is not sharply demarked from the ground and it is often impossible to say if a certain crystal particle belongs to one portion or the other. It should be noted that this stone is a crystalline spherulitic chondrite. According to Tschermak, in chrondrules of this nature the olivine bars are sometimes interlaminated with plagioclase (as for example, in the Dhurmsala stone). In the porphyritic form shown in Figure 2, Plate 24, from the Tennasilm stone, the granular ground abuts sharply against the black glass of the chondrule with only on one side a manifested tendency to penetrate into and beyond the border. It is to be noted that the enstatite phenocrysts within the chondrule and near the border are often cut off sharply as though the sphere, originally much larger, had been uniformly reduced by abrasion. This will be referred to later.

Holocrystalline chondrules.—As would naturally be expected, these porphyritic forms, through a reduction of the proportional amount of glass, pass gradually into those which are almost or quite holocrystalline and polysomatic as shown in Figures 1 and 3, Plate 22, from the Barratta and Elm Creek stones, respectively. Of peculiar interest are those of the polysynthetically twinned pyroxene (fig. 3). For some unexplained reason, these rarely grade into the half glassy porphyritic forms, the entire chondrule consisting of the closely crowded pyroxenes with comparatively little, if any, interstitial glass.

In Figure 1, Plate 24, from the Parnallee stone, it will be noted that the crystals are in some instances slightly curved, their vertical axes lying approximately parallel with the circumference of the circle which forms the border of the section. The appearance is as if the chondrules had been molded by external forces after the crystals had formed but while yet in a more or less plastic condition. Again, the pyroxene crystals abut sharply against the border and are cut off at the margin as in the half glassy, porphyritic forms mentioned above, and as shown in the figures. Occasional forms are met with which have all the appearance of fragments, slightly rounded, of holocrystalline granular rocks, which as noted later, they are believed to be.

Secondary borders about chondrules.—A not uncommon feature of the chondrule is the narrow border or rind about the circumference. These borders as a rule, are of lighter color than the interior, of a clear, more pellucid nature, though it may be including portions of the minerals characteristic of the matrix in which they are embedded. This is well shown in the olivine chondrule, Figure 1, Plate 23. This border has an appearance at once suggestive of the secondary intergrowth or enlargement often seen in feldspars and other minerals of terrestrial rocks. The later portions sometimes, though not always, have the same optical orientation as the interior.[65] In some instances the chondrules are surrounded by an irregular border of metal or metallic sulphide.

Double or compound chondrules.—Occasional forms are met with in which a large crystal of olivine or pyroxene is inclosed by a border of finer crystals of the same mineral but suggestive of a later generation. Of greater interest is the occasional occurrence of a chondrule within the mass of a second or larger form, as figured by Tschermak, on Figure 1, Plate 8, of his Beschaffenheit.

Theories of origin.—In this review it will perhaps not be necessary to go back much beyond the time of the introduction of the microscope and thin sections into the study of rock structures since obviously little that was accurate could be told of them by the naked eye alone.

A brief glance at the literature is sufficient to suggest that many of the opinions expressed have been based upon examinations of but a limited number of occurrences which quite failed to yield the information necessary for building satisfactory hypotheses or conclusions.

Reichenbach, as early as 1860 wrote:[66] "Aus allerdem wird es klar, das die Einschlusse in dem Meteoriten, als die Trümmer und

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[65] I am not certain if this border is of a like nature to that described by Tschermak about some of the chondrules of the Grosnaja stone and which he considered of secondary origin.

[66] Pogg. Ann., vol. 3, 1860, p. 384. See also Chamberlin's The Two Solar Families.

die geshicbartigen Knollen und Kugeln darin, keine einfach nachen Bestantheile, sondern nichte anderes sind als auch wie die Meteoriten. Meteoriten nur von anderer Anordung ein und derselben naturn Bestandtheile." And again: "Es sind also die Einschlusse theils kleine meteoriten, theils Trümmer von meteoriten von hohenen Alter als diejenigen meteoriten es sind, in welche sie eingeschlossen vorkommen; es sind altere kleinere meteoriten in jungerern grossern meteoriten." In brief, and in plain English, he believed each particle as now found to represent a minute but independent meteorite derived from the breaking up of some older preexisting stone and now included as a constituent part of one new formed.

In discussing the microscopic structure of meteoric stones, H. C. Sorby, in 1864 [67] wrote:

> It would, therefore, appear that after the material of the meteorites was melted, a considerable portion was broken up into small fragments subsequently collected together, and more or less consolidated by mechanical and chemical action. * * * Apparently this breaking up occurred in some cases when the melted matter had become crystalline, but in others the form of the particles lead me to conclude that it was broken up into detached globules while still melted. This seems to have been the origin of some of the round grains met with in meteorites; for they occasionally still contain a considerable amount of glass, and the crystals which have been found in it are arranged in groups radiating from one or more points on the external surface in such a manner as to indicate that they were developed after the fragments had acquired their present spheroidal shape.

In continuation of this same idea in 1877,[68] Sorby wrote:

> As is well known, glassy particles are sometimes given off from terrestrial volcanoes, but on entering the atmosphere they are immediately solidified and remain as mere fibers, like Pele's hair, or as more or less irregular laminae, like pumice dust. The nearest approach to the globules in meteorites is met with in some artificial products. By directing a strong blast of hot air or steam into melted glassy furnace slag, it is blown into a spray, and usually gives rise to pear-shaped globules, each having a long, hair-like tail, which is formed because the surrounding air is too cold to retain the slag in a state of perfect fluidity. Very often the fibers are of the chief product. I have never observed any such fibers in meteorites. The formation of such alone could not apparently occur unless the spray were blown into an atmosphere heated up to near the point of fusion, so that the glass might remain fluid until collected into globules. The retention of a true vitreous condition in such fused stony material would depend on both the chemical composition and the rate of cooling, and its permanent retention would in any case be impossible if the original glassy globule were afterwards kept for a long time at a temperature somewhat under that of fusion. The combination of all these conditions may very well be looked upon as unusual, and we may thus explain why grains containing the glass are comparatively very rare; but though rare they point out what was the origin of many others. In by far the greater number of cases the general basis has been completely devitrified, and the larger crystals are surrounded by a fine-grained stony mass.

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[67] Proc. Royal Soc., June, 1864.

[68] Nature, London, April 5, 1877, p. 296.

> Other grains occur with a fan-shaped arrangement of crystalline needles, which an uncautious, nonmicroscopical observer might counfound with simple concretions. They have, however, a structure entirely different from any concretions met with in terrestrial rocks, as for example, that of oolitic grains. In them we often see a well-marked nucleus, on which radiating crystals have been deposited equally on all sides, and the external form is manifestly due to the growth of these crystals. On the contrary the grains in meteorites now under consideration have an external form independent of the crystals which do not radiate from the center, but from one or more places on the surface. They have, indeed, a structure absolutely identical with that of some artificial blowpipe beads which become crystalline on cooling. With a little care these can be made to crystallize from one point, and then the crystals shoot out from that point in a fan-shaped bundle, until the whole bead is altered.
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> In this case we clearly see that the form of the bead was due to fusion, and existed prior to the formation of the crystals. The general structure of both of these and the previously described spherical grains also show that their rounded shape was not due to mechanical wearing. Moreover, melted globules with well defined outline could not be formed in a mass of rock pressing them on all sides, and I, therefore, argue that some at least of the constituent particles of meteorites were originally detached glassy globules, like drops of fiery rain.[69]

In this Sorby would appear to have had reference only to "kugels" with radiate, internal structure.

Tschermak, who together with Haidinger, was one of the first to pronounce on the tuff-like character of the chondritic meteorites, announced in 1874[70] the opinion that the individual chondrules (kugelchen) were but rock particles which became simply rounded under conditions similar to such as might exist in the throat of a terrestrial volcano.

> Ich wiederhole hier nur das Eine, dass Ich die Chondrite fur Zerreibungs-Tufe, und die Kugelchen derselben fur solche Gesteinspartikelchen halte, welche wegen ihrer Zähigkeit bei dem Zerreiben des Gesteines nicht in Splitter aufgelöst, sondern, abgerundet wurden.

And again in 1875:[71]

> Man kann sich allenfalls vorstellen dass die Steinmassen, welche der Zerreibung ausgesetzt waren, ziemlich weich gewesen seien und würde sich dadurch der Vorstellung Daubrees nähern, welcher an ein Gestein denkt, welches in einer Gasmasse wirbelnd erstarrte; doch ist es sicher, dass die Kugelchen das Resultat einer Zerreibung sind.

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[69] Sorby's idea, as it seems to the author, may be visualized and made probable by a consideration of a meteorological phenomenon common during the winter months in cold latitudes. It not infrequently happens that on the occasion of a cold winter storm, owing to meteorological conditions, the snow (condensed water vapor) falls not in the customary form of flakes, but in that of hard, icy pellets of approximate pin-head size, comparable with a chondrule. In a cold, dry atmosphere and with a high, intermittent wind, these particles are driven at a great speed in all directions through the air, constantly colliding with one another and ultimately reaching the ground, where, under the same influences they are drifted over the surface, still colliding with one another and the various obstructions, until an ever variable proportion of them are shattered or disintegrated—finally coming to rest to be compacted in a more or less solid mass comparable with that of the more friable chondritic meteorite stones. The theory, it will be observed, thus accounts for the origin of the chondrule as well as that of the stone itself.

[70] Die Trümmerstructur d. meteoriten, etc., Sitz. k. Acad. Wiss., Wien., vol. 70, 1874, (4).

[71] Idem, vol. 71, 1875.

In both of these quoted expressions Tschermak seems to have had in mind only the granular and porphyritic polysomatic forms, and the fragmental "kugelchen."

Three years later[72] after a consideration of the depressions and excrescences occurring in and on the chondrules of the Tieschitz meteorite, he came to a partial agreement with Sorby conceiving that

> Die Kügelchen sind nach wie vor wegen der tuffartigen Beschaffenheit der Meteorsteine als Resultate vulcanischer Eruptionen und Explosionen anzusehen, aber ihre Form dürfte doch eher von einem plastischen Zustande, als von der Zerreibung starrer Partikel abzuleiten sein.

And again, after another four years[73] he announced:

> Ich hatte * * * zu der Ansicht gefuhrt wurde, dass die Kügelchen der Chondrite als erstarrte Tropfen anzusehen sind, während die aus Splittern bestehende Grundmasse nach wie vor als vulkanischer Detritus zu betrachten wären.

Daubrée[74] seems also to have held the opinion that the majority of chondrules were simply débris particles rounded by attrition. He wrote:

> J'ai montré que la structure globulaire telle qu'elle se présente dans certains types * * * a été imitée artificiellement et s'explique par une sorte de granulation operée au moment où la substance se solidifie. Mais le plus souvent les globules des météorites paraissent être des simples débris arrondis par frottement.

F. Rinne,[75] by means of a simple electric device, was able to fuse the silicate constituents of meteorites and by abrupt alterations of the strength of the current produce a "spratzen" of the melt resulting in the projection from the crucible of small drops which quickly cooled in the form of "kugels." To some such action he would ascribe the formation of meteoric chondrules. Later, by the aid of an oxygen blast and a Linnemann burner he was able to produce enstatite beads evidently in every way comparable with meteoric chondrules.[76] These, it will be observed, are really synthetic demonstrations of the possible correctness of Sorby's views. Berwerth in 1901[77] announced his conviction that the chondritic stones were tuffs more or less completely metamorphosed by heat, and seemed to regard the individual chondrules as portions of the melt that cooled in globular form. Borgstrom[78] in his description of the Hvittis stone (1903) (a crystalline chondrite), says that the chondrules are always so firmly intergrown with the ground that it is often impossible to determine where the one leaves off and the other

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[72] Denk. Math. Natur. Classe kaiser. Akad. Wiss., vol. 39, 1878.

[73] Sitz. k. k. Akad. Wiss., Wien, vol. 95, 1882, p. 205.

[74] Géologie Expérimentale, 1879, p. 530.

[75] Neues Jahrbuch Min. Pet., vol. 2, 1895, pp. 229–246.

[76] Idem, 1897, pp. 259–261.

[77] Centralblatt Min., etc., No. 21, pp. 641–647, 1901.

[78] Die Meteoriten von Hvittis u. Marjalatti, Helsingfors, 1903.

begins. In many instances, the enstatites of a chondrule extend out into the ground mass with which they are intergrown. As noted, the Hvittis stone is a crystalline chondrite; this might suggest either a crystallization of the chondrule *in situ* or a case of secondary enlargement. In writing of the Shelburne stone, a gray chondrite, however, he says,[79]

> Each individual chondrule represents a structure of cooling and crystallization from a molten state, and as their structure shows an intimate relation to the boundary of the chondrule it must be supposed that each, at the time of its solidification, was a separate unit. Because chondrules of the same chemical composition have a different structure, they must have been formed under different physical conditions. Since such a variety of conditions can not have existed in the narrow space in which the different structures now are met with, the chondrules must have accumulated after solidification.

Such a condition is well shown in Figure 2, Plate 18, from the stone of Cedar, Tex. Meunier [80] basing an opinion apparently upon the theoretic work of M. Faye, suggests the probability of the chondrules resulting from the sudden condensation of a cyclonic vapor.

> Il parait difficile de ne pas admettre que les chondres sont aux roches de precipitation gazeuse ce que les dragées de Carlsbad et le fer en grains sont aux roches de précipitant aqueus * * * Conformement à la terminologie dont font usage les paleontologistes à propos du vent fossile, du soleil fossile, de la pluie fossile, on serait tenté de les qualifier de *cyclones photosphériques fossiles*.

This is conceivable, to the present writer, only in the case of radiate enstatite or monosomatic forms.

Brezina, to whom is so largely due the building up of the magnificent collection at Vienna, concludes a review [81] of the subject with the statement:

> Durch die vorangefuhrten Beobachtungen können wohl die alteren Anschauungsweisen als beseitigt betrachtet werden, und wir können wohl mit Bestimmtheit die Meteoriten als gestore über hastete Krystallbildungen in einem einzigen gemengten Magma bezeichen.

This apparently includes both the ground mass and its chondrules.

Hussak, basing an opinion on experimental work by himself and Dolter [82] suggests that chondritic meteorites, like that of Uberaba, Brazil (a crystalline chondrite), originate through the long continued immersion of meteoric stones in a nickel-iron magma, and are to be regarded as true volcanic ejectmenta,

> Ich möchte demnach die Meteorsteine durch ultrabasische Eruptivgesteine vergleichen und die Bildung der Chondren wie der Trümmerstructur und der schwarzen Adern als eine magmatische Eirnwirkung vor der Ejerktion ansehen.

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[79] Trans. Royal Astr. Soc., Canada, 1904.

[80] C. R. Paris Acad. Sci., vol. 96, 1883, p. 868.

[81] Die Meteoritensammlung, etc., 1885.

[82] Neues Jahrb. fur Min., etc., vol. 1, 1884, pp. 18-43. They immersed fragments of an "olivinefels" for many hours in a slowly cooling melt of nephelin basalt. The stone was strongly attacked and the outer portions, in close contact with the melt, shattered and corroded, the olivine granules becoming filled with embayments and enclosures of a secondary colorless glass, all strongly suggestive of meteoric chondrules.

> Daher die vollstandigen Ubergange in Siderite und die Deutlichen Korrosionserscheinungen an den grossen Olivinkristallen der Pallasite.

C. Klein, in 1906 [83] evidently basing an opinion largely on figures of chondrules in the works of Hahn and Tschermak, affirmed that there occur many ideally perfect forms that lack the eccentric radiating structure, but are "radial strahlig" from a center, equally in all directions and are true spherulites. Those not having this perfection of structure are considered fragments. It may be well to note before going further, that Klein apparently stands alone in holding these views though they may be correct for certain forms.

Wahl [84] would explain the formation of the chondrule as due to the cooling of a silicate melt in a heated atmosphere, the resultant drop crystallizing from the surface inward.

> Die Entstehung der Chondren lässt sich also ganz allemein als durch Zerstäubung von Silikatschmelz fluss innerhalb einer heissen Atmosphäre und Kristallization der hierdurch enstandenen Tropfen von aussen nach innen zu erklaren.

This again would seem to refer only to the cryptocrystalline, radiating enstatite, and the barred and monosomatic olivine chondrules.

Finally in 1913, Fermor [85] of the India Survey, suggested that the chondrules are remelted garnets.

The views of the present writer have been set forth elsewhere [86] and need not be repeated here in their entirety. It suffices to say that struck by the discordant character of the views expressed he studied the forms not merely as shown in the thin sections, but in their complete forms as freed from the matrix of some of the more friable stones. (See pl. 25.) It was found (1) that the most perfectly spherical and oval forms occurred in those stones the tuffaceous nature of which was beyond question. These show a cryptocrystalline or radiating internal structure and are mineralogically of pyroxene. (Fig. 5, pl. 22, and fig. 1, pl. 25.) They often show excrescences or saucer-shaped depressions, as through shrinkage or interference during solidification. (2) Other forms, more irregular in shape (fig. 2 of plate 25) show a rougher surface, and interiorly are of a polysomatic nature—composed of phenocrysts of olivine or pyroxene in a more or less glassy base or of an almost holocrystalline aggregate of one or more minerals. His conclusions were then to the effect that:

1. Only the chondrules of glass and cryptocrystalline or radiating enstatites (kugelchen) present the rounded or oval form with smooth rindlike crust and surfaces, with often one or more saucerlike depressions or excrescences such as are consistent with a theory of origin as fused drops of "fiery rain." (Sorby.)

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[83] Studien uber Meteoriten, p. 35.

[84] Zeitschrift Anorg. Chem., vol. 69, 1910, pp. 52-96.

[85] Records Geol. Survey India, vol. 43, 1913, p. 45.

[86] Proc. Nat. Acad. Sci., vol. 6, 1920, p. 449.

2. Chondrules of a compound, holocrystalline nature, and those porphyritic through the development of olivine or pyroxene phenocrysts in a more or less glassy base are lacking in smooth exteriors and though often quite spherical in outline, are as a rule more or less irregular and in many instances show unmistakable evidences of an origin of form through mechanical attrition. These last should be designated chondroidal forms, rather than true chondrules. These distinctions are well shown in Figures 3 and 5, Plate 22, and in the general view from a thin section of the stone of Cedar, Tex. (fig. 2, pl. 18).

ORIGIN OF OTHER TYPES OF STRUCTURE IN METEORIC STONES

The question of the origin of the various types of texture and internal structure of stony meteorites has been, as has that of the chondrules themselves, a much disputed one, as already noted. By many, including such authorities as Brezina, Link, Renard, and the American Wadsworth, the obscure and confused structures shown by stones of the chondritic group are due merely to hasty crystallization succeeded in some cases by crushing. To others, including Tschermak, Sorby, Berwerth, Wahl, and the writer, they are for the most part due to a tuffaceous origin, accompanied in many instances by metamorphism. That is, they are comparable with more or less compacted and altered masses of volcanic ash or tuff. Certain stones, like those of El Nakhla, Juvinas, and Shergotty, are apparently products of direct cooling from a molten magma and their clastic structure, when present, due to mechanical causes. Others, as those of Allegan, Hessle, and Quenggouk are so plainly tuffaceous as to seemingly be beyond argument. There yet remain certain abundant types, however, belonging to what are classed as the *crystalline*, *crystalline-chondrite*, and *white*, *gray*, and *intermediate chondrite* groups, the structures of which are obscure and which, though commonly regarded as metamorphosed tuffs, yet furnish grounds for reasonable doubt as to their origin.

The writer, however, in a recent summary, regards the tuffaceous nature of the stones classed as spherulitic chondrites as no longer open to argument. The crystalline types mentioned he considers products of metamorphism, in this agreeing with the other workers quoted. The grounds for this belief are summarized as below. [87]

The most perfect chondrules and chondroidal forms are found in those stones the fragmental nature of which is most pronounced, and become less perfect, more highly altered, often merging imperceptibly into the groundmass as the stones pass from fragmental into crystalline forms (pls. 19 and 20) as those of Estacado and Bluff and Indarch.

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[87] On Metamorphism in Meteorites, Bull. Geol. Soc. Amer., vol. 32, 1921, pp. 395–416.

It is therefore suggested, though not insisted upon, that the mere presence of a chondrule in a meteorite, whatever its condition, is indicative of a tuffaceous origin. The clear, limpid interstitial "glass" sometimes quite isotropic and sometimes doubly refracting, known as maskelynite, is shown to have been, together with the phosphate merrillite among the last of the constituents to solidify, and probably a product of a reheating and cooling too abrupt for crystallization. The dark, glassy interstitial material sometimes surrounding a chondrule (fig. 1, pl. 27) and the pellucid borders presented by some of the feldspars in the Estherville stony iron, are considered of like origin. It is shown further that the occasional crushing of the individual constituent, while productive of a cataclase structure, is a very minor feature and without necessary bearing on the question of the original nature of the stone (figs. 3, 4, 5, pl. 27). Lacroix also holds to this view. This condition, it is variously conceived, may have been produced by compression within the mass, by the shock of a collision, or too abrupt and extreme changes in temperature, as when a comet approaches the sun and then flies off again into the cold of space. It is possible that all three may have operated at various times and under various conditions. It is also conceivable that it may be in part due to impact with the earth's atmosphere. (See further under Metamorphism).

METAMORPHISM IN METEORITES

Not all of the phenomena of structure and composition noted can be considered original. Some are unquestionably of secondary origin—a result of accident or changed conditions, and may in part be designated metamorphic, as with terrestrial rocks.

With the possible exception of the chondrules, no meteoric constituent, it may be stated, presents a more interesting puzzle than the metallic portion. As has been noted, this is not a simple but a compound body consisting of three more or less definite alloys of a composition, and an arrangement among themselves not found in terrestrial irons, artificial or otherwise.[88] Indeed the octahedral arrangement of the plates, when such exists, is considered sufficiently characteristic to insure the meteoric nature of any iron in which it may be found, whether or not seen to fall. The conditions under which such an arrangement could take place are not as yet quite understood and need not be considered here. The feature that now concerns us is its lack of stability, its susceptibility to change, under changed conditions. It has been shown that if an octahedral iron like that of Toluca, Mexico, an etched slice of which is shown in Figure 1, Plate 26, be heated for a few hours at a temperature below

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[88] Artificial alloys comparable with the meteoric irons have been formed. (See Benedict, Neues Jahr., 1912, vol. 1, p. 44). While, however, these show an octahedral structure the clearly marked separation into alternating plates of kamacite and taenite is lacking.

redness, it gradually assumes the granular structure shown in Figure 2. If the heat be continued for a sufficient period, the octahedral structure will entirely disappear and the iron show only the granular structure. This feature has has been noted and described by Berwerth [89] of the Vienna Museum, who applied to it the name *metabolism*, and to irons in which the change had taken place that of *metabolites*.[90] Some irons, like that of Roeburne, Australia, which, so far as known, have not been heated since reaching the earth, show a combination of the two structures, and others are wholly granular. Are these octahedral irons which, in their wanderings have become highly heated, perhaps by too close proximity to the sun, and become thus metamorphosed? Who shall say? It is at least something worth thinking about.

The ultimate source of the metal has likewise been a matter of speculation. By Daubree and some others it has been thought to have been derived, by a process of reduction, from some iron-rich silicate such as olivine. This is, however, extremely improbable since nowhere are there evident signs of the process in its incomplete stage. Moreover, the olivine fragments in such iron-rich forms as that of Admire, Kans., are all perfectly fresh and sharp as so many fragments of broken glass. That the iron was never in a molten condition is shown not only by the uncorroded condition of the silicates, but by the physical condition of the metal itself, which is not that of a metal cooling from fusion, like ordinary "cast iron," but is rather that of the soft, malleable material commonly known as "wrought iron" which may be smelted from its ores at a comparatively low temperature. It seems, therefore, altogether probable that the metal results from reduction from the chloride form and that the small amount of this material now found as lawrencite is but a residue, as was suggested by Meunier several years ago.[91]

That it plainly was not a portion of the molten magma from which the other constituents crystallized out is shown further by the position it often occupies relative to the silicate constituents as shown in Plates 20 and 21, where it is found as a mere film enwrapping chondrules and crystal fragments indicating an extreme degree of fluidity. It is possible to conceive of this having been brought about through the percolation into the interstices of the porous tuff of a gaseous or liquid chloride, afterwards to be reduced.[92] Such a reduction, as

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[89] Sitz. der Kais. Akad. der Wiss., vol. 114, May 1908.

[90] That the granular structure might be secondary was first suggested by Sorby in 1887. He did not prove definitely that it might be produced artificially by heating.

[91] See Concerning the Origin of the Metal in Meteorites, by George P. Merrill, Proc. U. S. Nat. Mus., vol. 73, Art. 21, pp. 1–7, pls. 1–3, 1928.

[92] The Estherville meteorite offers a strong argument in favor of the origin of the metal through chloride reduction. This meteorite is a metamorphosed conglomerate, quite slaglike in portions, and the metal often occurs only partially filling the cavities as would naturally be the case did not the supply of material continue throughout the reducing process, the chloride consisting of but 44.1 per cent of iron and 55.9 per cent chlorine.

noted by Nordenskiold [93] and others, must have taken place outside of our atmosphere and in one deficient in oxygen. Perhaps attention need be called to the fact that metal occurs in quantity only in stones which are plainly of a fragmental nature. In achondritic types of an original crystalline structure it is almost entirely lacking. It may be noted, incidentally, that the average amount of metallic iron in stony meteorites is 11.98 per cent, which is equivalent to 16.55 per cent of magnetite or 27.16 per cent of purely ferrous lawrencite.

The sharply angular, uncorroded condition of the silicates in pallasites of the röckiky group has been noted as indicative of low temperature reduction of the metal. The question may well arise, however, could not this structure be produced by a shearing pressure on a pallasite of normal structure in the same manner as foliated and schistose rocks are derived from massive terrestrial forms? It seems at least possible.

Since very early in the study of meteorites, there have been held radically different opinions among students as to the causes of the clastic structure so pronounced a feature of many stones and particularly those of the chondritic types. This has been referred to elsewhere (p. 39) but it will be well to enlarge upon the matter here. Attention has been called to the fact that the most perfect chondrules like that shown in Figure 3, Plate 22, occur only in those rocks concerning the tuffaceous nature of which there could be little doubt. And further, that in those stones which are approximately crystalline, the chondrules, where such have existed, are more or less distorted and sometimes obliterated as in Plate 23. Further than this there are often evident signs of compression in the mass such as has led to fragmentation of certain constituents, as shown in Plate 27.[94] It is true that a portion of this fragmentation may be due, as has been contended, to abrupt changes in temperature as when a meteorite approaches the sun and then rushes off once more into the cold of space, or to the shock of a collision; but in any case they are secondary and have little to do with the original structure of the stone.

Evidences of metamorphism in which heat is the primary factor are afforded by the Bereba eukrite described by Lacroix [95] and in the chondritic breccia of St. Michel described by Borgström [96] who says distinctly:

> Die Grundmasse is kein Verfestigungsprodukt, sonder das Resultat einer unvolständigen Metamorphose eines Trümmergesteins, das aus Kornchen und Splitterchen derselben Mineralien die auch jetzt den Stein aufbauen bestanden hat.

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[93] Zeits. d geol. Gesell., 1881, p. 25.

[94] Merrill, George P.: On Metamorphism in Meteorites, Bull. Geol. Soc. Amer., vol. 32, 1921, pp. 395-416.

[95] Archiv. du Mus. d'hist. Nat., ser. 6, vol. 1, 1926, p. 35.

[96] Bull. Com. Geol. de Finland, No. 34, 1912, p. 36.

In like manner the groundmass of the Hendersonville stone is described as not at all that of minerals crystallizing freely from a molten magma, but suggestive, rather, of a partial recrystallization of fine detrital material as seen in metamorphic schists.[97] Instances in which the direct action of heat alone is more evident is afforded by Figure 1, Plate 24, which is that of a chondrule in the stone of Parnallee, India. That the chondrule is foreign to the ground in which it is embedded is obvious. The present interest in it lies in the dark, glassy border by which it is surrounded and which is considered due to the action of heat on the fine, dust-like material in which it was embedded. That it is not an original residual glass should be evident to any petrographer.

An equally instructive illustration of heat action is shown in the transformation of a normal plagioclase feldspar into the mineral maskelynite, as first noted by Tschermak and since verified by others. This is considered by the writers as indicative of a reelevation of temperature sufficient to change its character even if not completely fuse it, and, on sudden cooling, leave it in the form of a feldspathic glass. As stated elsewhere, the mineral is not always isotropic but shows frequent transition stages to the normal mineral. In the Mocs meteorite the feldspar occurs, according to Tschermak, as plagioclase in the mass of the stone and as maskelynite in the crust.

The possibility of a refusion and crystallization of the feldspar without the formation of maskelynite has been shown by the writer in the case of the Estherville meteorite which is regarded as a metamorphosed agglomerate, the finer portions of which (fig. 2, pl. 2) show a structure not unlike that of some partially altered crystalline schists in which the feldspars fluxed without altering the fragmental structure of the pyroxenes. A striking feature of this meteorite which has not before been mentioned is the presence in it of boulderlike masses of a different structural nature than the mass of the material (pl. 13). It is to be noted that while around the border the silicate material seems to merge into the general ground of the main mass, the interior while evidently of the same mineral nature is of a more regular texture and the metal is in very fine threads which at times completely surround, or enfold the silicate particles as is often the case in ordinary chondritic stones. The percentage amount of metal, it should be said, is plainly much less than in the main mass. The question arises, Is the nodule a pebble or a portion of the original ground of the agglomerate which has escaped the metamorphic changes of the rest of the mass? In either case the metamorphic nature of the meteorite seems fully substantiated. Lacroix[98] has noted the recrys-

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[97] Merrill: Proc. U.S. Nat. Mus., vol. 32, 1907, p. 80.

[98] Archiv. du mus. d'hist. Nat., ser. 6, vol. 1, 1926, p. 35.

tallization of the finely granular interstitial silicates in stones of the eukrite and howardite groups.

Many of the stony meteorites are traversed by small, black, thread-like veins, at most but a few millimeters in diameter (fig. 2, pl. 29) which are plainly due to a fracturing of the stone, though whether or not prior to entrance into the earth's atmosphere is a question. A greatly enlarged section of one of these from the Bluff, Fayette County, Tex., meteorite is shown in Figure 2, Plate 28. The filling material of the vein is of a nearly coal black color, opaque, and of an undetermined nature, inclosing white and gray particles of the minerals composing the body of the stone. Occasionally a slight movement between the walls of these veins has developed a structure known as slickensides in terrestrial rocks. In the illustration shown, no such movement has taken place, and it will be noted that the coloring material penetrates into the walls in the form of small veinlets on either hand. Much discussion has taken place concerning the origin of these veins and a great divergence of opinion manifested, a part of which is evidently due to mistaken ideas regarding the nature of the filling material, often referred to as "metallic." As a matter of fact, the material is metal in comparatively few cases, but is apparently identical both in composition and origin with that forming the base of the so-called black chondrites, and can best be accounted for through a slight modification of the idea expressed by Wahl, the shock from a collision producing the fracture, along which is immediately propagated a heat wave sufficient to produce the result. In this way the minute ramifications (spirts) of the vein matter into either wall, as shown in the figure, would be readily accounted for. The occasional presence of metal, or metallic sulphide, as an apparent filling constituent, can be best explained as has Farrington [99] on the assumption that either constituent occurred in the form of more or less connected filaments. Fracturing would naturally take place along these lines rather than across them. That heat could have melted the metal without affecting the silicates is impossible, and that the filling matter is not of the same nature as the crust (that is, a glass) is almost self-evident.

That collisions among meteorites are not limited to the stony forms is strikingly shown in Figure 1, Plate 29, from a polished slice of an iron meteorite found a few years ago in Somerset County, Pa. It will be noted that the iron is traversed by a fine, thread-like fissure along which has taken place a movement for a distance of something like a centimeter. In short, it is like a fault in terrestrial rocks. As the iron is soft and malleable, we are apparently justified in the

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[99] Amer. Journ. Sci., vol. 11, 1901, p. 59.

assumption that the shock producing the fracture took place somewhere in space where the metal had become so cold as to be brittle.

The black coating on the surface of the stony meteorites is, as already noted, a more or less perfect glass, due to the fusion of the various constituents from the heat generated during the passage of the stone through the atmosphere. This, as shown in thin section (see pl. 28, fig. 1) is never of more than a few millimeters in thickness. It consists, in the case of the Allegan stone figured, of a black glass interspersed with numerous residuary particles of metal and unfused silicates, which passes gradually into the unaltered granular stone. Sections of the thick, blebby glass from the lower surface show air vesicles and numerous crystallites imperfectly secreted from the glassy base, and too small to be seen in the figure, together with the residuary unfused particles of the original minerals.

The so-called "black chondrites" are considered by Meunier and others as chondrites of the ordinary white, gray, or *kugeln type* which have been heated to a temperature considerably short of that of fusion, as already noted.

METEORITES COMPARED WITH TERRESTRIAL ROCKS

From what has been written it must be evident that, though composed of the same elemental matter, meteorites differ in some very marked respects from terrestrial rocks. Nevertheless there are resemblances, some of which, when one considers the problematic source of these bodies, are of peculiar interest.

All known meteorites are composed of volcanic materials, and none has shown any traces of animal or vegetable life, unless the carbonaceous matter is to be so considered. This, however, is a wholly unnecessary and, indeed, unwarranted assumption. It is true that the German, Otto Hahn, when the possibilities of the microscopic study of rocks were first becoming realized, described as organic (corals and crinoids) what are now known to be but incipient crystallizations of silicate minerals. Nothing in the nature of a terrestrial sedimentary rock, a sandstone, shale, or limestone, or a metamorphic like a schist or gneiss, has yet, so far as known, come to us from space, nothing of a pumiceous nature, and nothing in content of silica, alumina, lime, or alkalies corresponding to the granites (the tektites, if meteoric, would most nearly correspond to this type of terrestrial rock) and nothing of the nature of a true vein rock. Further, and this seems the more singular when theories of earth history are considered, nothing that can with certainty be ascribed to a meteoric origin has been found in terrestrial beds of any geological horizon but the most recent.[1] If such have fallen during earlier periods, they must have been a quite different type, or what is more probable, become so thoroughly decomposed or otherwise altered as to be unrecognizable.

Owing to the presence of abundant oxygen in our atmosphere, the iron in the terrestrial rocks is nearly always in an oxidized condition; its presence as metal is exceptional.

Other minerals noted as found in meteorites in smaller quantities and lacking in terrestrial forms are cohenite,[2] lawrencite, merrillite, osbornite, and schreibersite, elsewhere described. It will be seen, therefore, that the chief chemical and mineralogical differences lie in the presence of unoxidized combinations in the meteorites, and not in elemental composition. Rarely occur forms of crystallization like that shown in Figure 2, Plate 29, which are more nearly allied to the basalts and pyroxenites. The nearest terrestrial approach to this meteorite are the iron-bearing basalts of Greenland and Ober Cassel, in Germany, which shows native metal dispersed throughout a ground of silicate minerals.[3]

The nearest terrestrial equivalent to the stony meteorites as a whole is a comparatively insignificant group of intrusive igneous rocks to which the name *peridotite* is given. These, like the meteorites, are composed essentially of the minerals olivine and pyroxene, and so close is their analogy that an element found in one may be predicated for the other, though not necessarily in the same form of combination. The most pronounced difference is in the commonly fragmental nature of the meteorite and presence of iron in the metallic state. We know of no volcanic (tuffaceous) equivalent of our peridotites unless the diamond-bearing breccias of Arkansas and South Africa be so considered. A singularly striking similarity lies in the presence of diamonds and platinum in certain members of both groups, though in meteorites only in minute quantities.

In the following table is given in I the average results of the analyses of 63 stony meteorites; in II that of 8 peridotites, the group of terrestrial rocks most nearly allied to meteorites; and in III the average composition of the rocks of all kinds composing the earth's crust.[4]

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[1] This fact was noted by Olbers nearly 90 years ago. Ward's statement as to the Pliocene age of the Lujan mesosiderite seems contradicted by its having been found in "an undisturbed Quaternary formation."

[2] Cohenite has been reported by O. Sjoström in the native iron of Greenland.

[3] Chemical analyses show this iron to contain only about 1.90 per cent of nickel. In both cases the metal is secondary and in the case of Ober Cassel derived by reduction from the sulphide pyrrhotite.

[4] Clarke, F. W., Data of Geochemistry. Bull. 491, U S. Geol. Survey, 1911, p. 27. The 63 analyses of stony meteorites include all varieties of which complete and satisfactory analyses were available.

Constituent	I	II	III
Silica (SiO_2)	38.41	37.78	59.93
Titanic oxide (TiO_2)	.16	.58	.74
Tin oxide (SnO_2)	None.	---------	---------
Zirconium oxide (ZrO_2)	None.	---------	.03
Alumina (Al_2O_3)	2.86	3.11	14.97
Ferric oxide (Fe_2O_3)	.92	2.41	2.58
Chromic oxide (Cr_2O_3)	.40	.19	.05
Vanadium oxide (V_2O_3)	Trace.	---------	.02
Metallic iron (Fe)	12.35	---------	---------
Metallic nickel (Ni)	1.09	---------	---------
Metallic cobalt (Co)	.10	---------	---------
Ferrous oxide (FeO)	13.60	18.36	3.42
Nickel oxide (NiO)	.40	.18	.03
Cobalt oxide (CoO)	.06	---------	---------
Lime (CaO)	1.88	3.06	4.78
Barium oxide (BaO)	None.	---------	.11
Magnesia (MgO)	23.66	28.38	3.85
Manganous oxide (MnO)	.23	.31	.10
Strontium oxide (SrO)	None.	---------	.04
Soda (Na_2O)	.82	.68	3.40
Potash (K_2O)	.16	.32	2.99
Lithia (Li_2O)	Trace.	---------	.01
Ignition (H_2O)	.47	3.79	1.94
Phosphoric acid (P_2O_5)	.34	.10	.26
Sulphur (S)	1.89	---------	.11
Copper (Cu)	.01	---------	---------
Carbon (C)	.16	---------	---------
Chlorine (Cl)	.03	---------	.06
Carbonic acid (CO_2)	(?)	.75	.48
Fluorine (F)	(?)	---------	.10
	100.00	100.00	100.00

The most important of the differences brought out by the analyses are (1) the excess of silica (SiO_2) and alumina (Al_2O_3) in the terrestrial rocks; (2) the presence of a considerable amount of free iron and proportionately large quantities of ferrous oxide (FeO) and magnesia (MgO) in the meteorites. The presence of many of the rarer elements tabulated as constituents of the terrestrial igneous rocks has not yet been fully established in those of meteoric origin. As noted, however, many of them have been found in amounts too small to estimate.[5] Here indeed is a striking thought—that throughout all space so far as yet made known to us, there exists so great a uniformity of material yet so individualized that one conversant therewith can tell almost at a glance whether celestial or terrestrial in origin.

TEKTITES

Of late years there has been much discussion relative to the possible meteoric nature of certain glass pebbles of a green or black color with peculiar markings, found on the immediate surface or slightly embedded in Tertiary and Quaternary gravels in Australia, Moldavia, islands of the Malayan Peninsula, and a few other localities. The Australian forms, variously known as "bombs," "obsidian buttons," "australities", etc., are of a dense black glass, rounded, irregularly

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[5] Merrill: The composition of stony meteorites compared with that of terrestrial igneous rocks, and considered with reference to their efficacy in world making; Amer. Journ. Sci., ser. 4, vol. 27, 1909, p. 469. Also: Report on researches on the chemical and mineralogical composition of meteorites, with special reference to their minor constituents. Mem. Nat. Acad. Sci., vol. 14, memoir 1, 1916.

oval forms without distinct surface markings. Those of Moldavia are of a green color, of extremely irregular forms, and gashed and impressed in a manner to suggest they may, in plastic condition, have been subject to mastication like a mass of chewing gum. The forms from the island of Billiton are the most singular and unaccountable of all. Like those of Australia, they are of a dense, opaque glass, their distinguishing character being as in the last case, the peculiar surface markings. Chemically, as shown in the accompanying table, they average a trifle higher in silica, calcium, and ferric oxide than the ordinary obsidian, and are poorer in alkalies. Their resemblance to known meteorities in composition is remote. Each locality yields its own peculiar forms, though all are grouped under the general name of "tektite." In no instance have there as yet been discovered facts relative to their occurrence such as can give a clue to their origin. By some they are firmly believed to be glassy meteorites. How far the difficulty of accounting for them otherwise may have had influence in the formation of such an opinion the writer is not prepared to say.

Analyses of tektites

Constituent	I	II	III	IV
SiO_2	75.87	69.80	76.25	77.96
Al_2O_3	14.35	15.02	11.30	12.20
Fe_2O_3	.22	.40	.35	.14
FeO		4.65	3.88	3.36
MgO	.29	2.47	1.48	1.48
CaO		3.20	2.60	1.94
Na_2O	3.96	1.29	1.23	.61
K_2O	4.65	2.65	1.82	2.70
H_2O+100	.33		.32	
H_2O-100			.02	
TiO_2	Trace.	.80	.65	
MnO		.18	.06	.10
SO_3	.23			
Total	99.90	100.46	99.96	100.49

I. Obsidian pebble. Colombia. Analyst, J. E. Whitfield.
II. Obsidianite. Upper Weld, Tasmania. Analyst, W. F. Hillebrand.
III. Obsidianite. Near Hamilton, Victoria. Analyst, G. Ampl.
IV. Moldavite. Tribitsch, Bohemia.

COMBUSTIBLE METEORITES

The fact that there is so complete a lack of coordination between the periodic meteoric showers and the fall of meteorites has more than once suggested the possibility that the materials of the first mentioned might be of an easily combustible nature, so that they were consumed in their passage through the atmosphere, while only those which were composed chiefly of metal or silicate materials survive, and this only in part. The fact, too, that there is known a group of carbonaceous meteorites (Orgueil, etc.) containing in certain cases as high as 14 per cent of volatile matter, gives the suggestion a certain degree of probability. In this connection, then, it may be well to consider the often-reported occurrences of the fall of combustible matter, even though in several of the instances there seems good reason for doubting their absolute authenticity.

The earliest account to be mentioned is taken from the second American edition of the New Edinburgh Encyclopedia, where it is stated that a meteorite fell near Roa, in Borgus, Spain, in 1438 and was reported to have been of very light material, resembling condensed sea froth. It is also said in the same publication that after the fall of a fire ball in Lusatia in 1795 there was found on the ground a viscous substance having the consistency, color, and odor of brown varnish. This was examined by Chladni, who thought it to be composed mainly of sulphur and carbon. One of the best authenticated reports of this nature is that in connection with the fall of stones near Hessle in 1869. This was accompanied by a quantity of carbonaceous matter of a coffee color, in the form both of powder and in masses as large as the hand. When freed from the metallic substance, it was found to consist of: Carbon, 51.6 per cent; hydrogen, 3.8 per cent; oxygen, 15.7 per cent; silica, 16.7 per cent; ferrous oxide, 8.4 per cent; magnesia, 1.5 per cent; lime, 0.8 per cent; and soda with traces of lithia, 1.5 per cent.

M. Meunier,[6] under the title "Substance singulière recueillie à la suite d'un météore rapporté à la foudre," described a peculiar resinous substance which was represented to him as having been deposited over the suface of various objects during a violent thunder-shower. The material is largely organic, burning with a resinous odor, and differs from ordinary fulgurite in that it is of the same nature regardless of the substance over which it is deposited, showing at once that it is not derived by direct fusion. Meunier expressed a doubt as to whether or not the material is the effect of a thunderbolt.

In the same volume,[7] A. Tracul takes up the matter and claims that the material is really a product of meteoric conditions, and says that during a shower on the 25th of August, 1880, he saw issuing from a black cloud a luminous body, very brilliant, slightly yellowish but almost white, of an elongated form with the two tips in the form of briefly attenuated cones. This body remained visible during the brief time and then it disappeared, reentering the cloud, but as it disappeared, there separated from it a small quantity of material which fell vertically downward, as a heavy body under the influence of gravity. It left behind it a luminous train, the edges of which were manifestly reddish, sparkling globules. These, in the latter part of their course, fell nearly vertically. Although none of this

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[6] Comptes Rendus, vol. 103, 1886, p. 837.

[7] Idem, p. 848.

material was found, the writer (Tracul) regarded it as perhaps identical with that described by Meunier.

The fall of a meteor or fire-ball, witnessed by Professor Dewey, at Amherst, Mass., in August, 1819, is described by a Mr. Rufus Graves.[8] In this case the object was described as being as large as a man's hand, and the conditions of observation were such that there could seemingly be no doubt where it fell. This was in the evening. Early on the ensuing morning there was found at this point "a substance unlike anything before observed by anyone who saw it," and which was regarded as beyond reasonable doubt the residuum of the meteoric body. It was described as of circular form, resembling a sauce or salad dish, bottom upwards, about 8 inches in diameter, something more than an inch in thickness, and of a bright buff color. Interiorly it was of a pulpy consistency like soft soap, with a suffocating and very offensive odor. After brief exposure it changed into a livid color resembling veinous blood. It shortly began to liquefy, and in the course of a few days evaporated, leaving a small, dark colored residuum which, when rubbed between the fingers, produced a fine, ash-colored powder without taste or smell. Nitric and muriatic acid seemed to have no chemical effect upon it, while with sulphuric acid a violent effervescence ensued and nearly the whole substance dissolved.

This would certainly indicate that it was of organic and probably fungoidal nature, and not meteoric.

Again, in the same journal (vol. 16, 1829), is given the translation of an account of a like gelatinous material found in a wet meadow in Germany and under such conditions that it was supposed to be meteoric and was distinguished by the name "sterne-gallerte" (star jelly). Counselor Doctor Schultes considered it as a "tremella nostoc." Buchner thought otherwise because he could discover no organic structure, and maintained that it could be neither plant nor animal, as a whole, but might be a product, like gum or mucus. The writer of the article, Doctor Brandes, regarded the masses as either animal excretions or gelatinous meteors, but he did not think it probable that they were like the manna of the Israelites, as had been suggested. A reference is made to the observations of a Spanish soldier who, while standing on sentinel duty, during cool nights had frequently observed shooting stars and in the morning, in wet places, in spots where he thought the stars had fallen, he would find white, gelatinous masses which soon dissolved. He quotes also the work of a Mr. Schwabe, an apothecary of Dessau, who examined a gelatinous mass found in a wet meadow, and who decided that it was the real "nostoc commune" of Vauch. The writer enters into a somewhat elaborate discussion of the chemical nature and general appearance of

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[8] Amer. Journ. Sci., vol. 2, 1820.

these bodies and suggests that they may have been of the nature of snail spawn jelly, at any rate of organic and terrestrial nature. In a footnote to the article, reference is made to the observations of a Mr. John Treat, who, while with the army of General Washington during the Revolution, saw a shooting star fall within a few yards of him. He immediately went to the spot and found there a gelatinous mass which "if we recollect right was still sparkling." Other similar observations are given. There would seem no question, however, but that these were in all cases of an organic (fungoidal) nature, and of terrestrial origin.

A large share of these reported occurrences are doubtless due to the observers having been mistaken in their identification of the fallen material.

Within but a few months the writer was interviewed by a person who brought a sample of meteoric material "seen to fall" which proved to be but a flat, widespreading fungoidal growth. No amount of argument could convince the finder that he was in error.

Meteorites are not themselves magnetic, but nearly all meteoric irons will acquire strong and permanent magnetism, though this property may be in part, not wholly, destroyed by heat. It may be remarked here, as noted elsewhere[9] that in process of oxidation, meteoric irons assume first a magnetic oxide stage before passing over into the normal nonmagnetic sesquioxide.

CHONDRITIC STRUCTURES IN TERRESTRIAL ROCKS

The question is likely to arise, "Do these chondrules and chondroidal forms have any exact counterpart in terrestrial rocks?" The answer, with the information available to-day, is "No." Nevertheless it will be well to consider a few cases which on first glance at least, so closely resemble the meteoric chondrule as to merit attention. Before entering upon this discussion it will be well, however, to refer back, perhaps repeat in part, the writer's dictum to the effect that only those chondrules with smooth surfaces, often indented and showing internally amorphous, microcrystalline, radiate, or barred structures, may have the origin ascribed to them by Sorby—are cooled drops of molten matter having the chemical composition of enstatite or of olivine. Those of a rough exterior and internally porphyritic or holocyrstalline are products of the mechanical attrition of preexisting cooled rock masses.[10]

A most suggestive example of chondroidal structure in a terrestrial rock is afforded by a "kugelgrünstein" found at Stefanschacht, Schemnitz, Hungary. The stone is quite massive and of a light

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[9] Proc. U. S. Nat. Mus., vol. 24, 1902, p. 910.

[10] Proc. Nat. Acad. Sci., vol. 6, no. 8, 1920 pp. 449–472.

green-gray color, consisting of a dense ground carrying numerous rounded chondrule-like bodies of a more compact texture and internally of a darker color, but which break away readily, often with portions of the ground adhering. (Upper figure, pl. 30.) The ground itself is so fine in texture as to render its mineralogical determination by the unaided eye a matter of difficulty, though studded with small whitish specks suggestive of a feldspar. The "kugels" vary in size from but 2–3 mm. to rarely 20 mm. in diameter. When cut across they show a darker ground than the matrix in which they are embedded and are distinctly porphyritic even to the unaided eye. (Pl. 30, lower figure.) In the thin section they show a normal, though somewhat altered andesitic structure of feldspar and hornblende phenocrysts in a microlitic ground. The kugels separate readily from the matrix but are plainly not inclusions of foreign matter. Even by the naked eye they may be seen on a polished surface to grade into it without sharp lines of demarcation. From an examination of hand specimens only, not having studied the occurrence in the field, one is inclined to accept the conclusions of Szterinyi[11] to the effect that they are magnetic segregations liberated through the propylitic form of decomposition which the stone has undergone. Whatever be their origin their chondritic nature is wholly simulated.

Messrs. Cushing and Weinschenk, in their description of the phonolites of the Hegaus,[12] mention an interesting tuff which in addition to other constituents carries abundant kugel forms which are easily distinguished through their dark color, hardness, and lustrous fracture. These the microscope shows to be of melilite basalt, and plainly are not rolled pebbles.

> Sondern kleine Answürflinge, wie sie überall einen integrirenden Bestandtheil der Basalttuffe bilden und durch häufig zu betrachtende centrische Structur verrathen, dass ihre Form durchaus primär ist.

In their mode of occurrence, form, and structure they are described as comparable with the chondrules of meteorites.

In response to a letter, the late Professor Cushing, then at the Case School of Applied Science in Cleveland, kindly sent one of his original specimens, with permission to use as much as might be necessary for the investigation. This yielded the material from which the accompanying illustrations were prepared. In Figure 1 of Plate 31 a nucleal augite is surrounded by a zone of elongated melilites which in a general way are arrayed with their longer axes lying in the circumference of a circle having the nucleus as a center. This is assumed to be the "centrische" structure of the authors quoted. Be this as it may, the centric structure while suggestive is not quite that of the majority

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[11] Foldtani Kozlony, Budapest, Nos. 12–13, 1882–83, pp. 207–222.

[12] Tschermak's Min. u. Nat. Mitheil., vol. 13, 1892, p. 36.

of chondrules. It is to be noted, however, that they break away from the matrix leaving a smooth concavity simulating the chondrules in the tuffaceous meteorites—spherulitic chondrites.

Among a series of specimens brought from the Hawaiian Islands in 1920 by Dr. H. S. Washington were some loose aggregates of fine volcanic ash labelled "fossil rain" from the Kilauea eruption of 1790. These are often pisolitic, strongly suggestive of the chondritic structure so pronounced in meteorites of the Bjurbole type. The entire mass, however, pisolites and all, quickly falls to pieces when wet, and shows itself to consist of finely comminuted glass and the silicate minerals characteristic of the lavas of this flow. The chondroidal forms are entirely fragmental and the particles show no order in their arrangement. Apparently they have originated in place and are due merely to a haphazard aggregating of the finer particles in the ash through the influence of water falling in the form of fine drops such as would result through the condensation of steam. Such forms are readily imitated in this same dry ash by gently dropping into it small, isolated drops of water, and hence the expression "fossil rain" which, though on many accounts objectionable, is expressive. The pisolites described above are apparently of the same nature as those occurring in ash from the Krakatoa craters and figured by Friedlander.[13] Like forms are to be found in ash from Pompeii. In these last the spherules are somewhat harder and effervesce for a time when treated with a dilute acid, after which they are readily reduced to a mud by crushing between the fingers. Prof. J. A. Udden has described [14] the formation of small pellicles of a somewhat similar nature occurring in a volcanic ash in McPherson County, Kansas. These he ascribes to wave action. However, their resemblance to the meteoric chondrules is purely superficial.

A beautiful illustration of apparent chondritic structure is furnished by the basaltic tuff from the "Anterior Lava Sheet" of Connecticut described by W. G. Foye.[15] The stone is fine grained, dark gray, somewhat laminated, and shows scattered throughout its mass abundant black spherules in varying sizes up to five millimeters. These are a trifle rough on exterior surfaces, but break away easily from the matrix leaving smooth cavities often lined with a portion of the exterior shell of the spherule. In thin section they are plainly fragmental, and show a thin outer zone or border of fine, dark material enclosing the coarser, clastic silicate particles (see fig. 2, pl. 31) which form the general groundmass of the stone. The structure on the whole so closely simulates that of the "fossil rain drops" noted elsewhere, as to suggest a like origin for both. Be this as it may,

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[13] Zeit. fur Vulkanologie, vol. 1, Heft 1, 1914.

[14] American Geologist, vol. 11, 1893, pp. 269–271.

[15] Bull. Geol. Soc. Amer., vol. 15, no. 2, 1924, p. 335.

the chondritic character so evident on casual inspection, is not borne out by close study.

A suggested resemblance to chondritic structure is found in the peculiar drift bowlders found some years ago at Thetford, Vermont. These were described by Dr. E. O. Hovey[16] as resembling conglomerate the most conspicuous feature of which is the numerous rounded masses of granular olivine scattered through it. In addition are numerous rounded pebble-like grayish green pyroxenes sometimes reaching dimensions of several inches. The pebble form of the last is however wholly assumed, the microscope and thin section showing them to be crystalline secretions partially resorbed. The olivine aggregates are, however, true inclusions in a crystalline ground of augite and feldspars like those in the basalts of the Eifel and Rumberg, Bohemia; or the meteorite of Parnallee, India. On a gigantic scale the Bohemian examples do bear a resemblance to the chondroidal forms found in some meteorites as that of Bjurbole. As, however, the groundmass of the basalts is crystalline and glassy there is no real connection.

Another very suggestive example of an imitative form is shown in Plate 32, Figure 2. The rock is a periodtite from a dike 2 miles east of Raton, N. Mex., collected many years ago by Orestes St. John, and with other collections recently turned over to the National Museum by Dr. Frank Springer. Megascopically the rock shows a dense dark greenish gray, nearly black ground thickly studded with dark phenocryst and occasional large spherulitic forms and sizes up to a centimeter in diameter. These are of olivine which sometimes break away in form and manner strikingly simulating the meteoric chondrule.

In thin section the rock is found highly altered but consisting mainly of olivine and a rhombic pyroxene with abundant small octahedra of pleonast and numerous colorless needles with the characteristics of apatite, though their optical properties are wholly obscured by decomposition. An abundant phosphomolybdate reaction is produced when a drop of acid ammonium-molybdate is placed upon the slide. The one time presence of a glass base is indicated, but here too decomposition has gone too far for satisfactory determination. It can only be said that numerous interstitial areas are nearly colorless and wholly isotropic.

The chondritic structure is found to be wholly simulated and is produced by large oval and spherical olivines which have undergone a partial serpentinous and chloritic alteration as shown in the figure. This alteration begins with the formation of a thin coating (border in the section) around the outside and all stages to complete alteration of the granule. Such alteration is common, but rarely as in

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[16] Trans. New York Acad. Sci., vol. 13, 1893-94, p. 161.

this case does the resultant forms so simulate those of chondritic meteorites.

Other descriptive matter suggestive of chondritic structure is found in the literature but the writer has been unable to secure examples of the material upon which the descriptions are based.

Rinne[17] describes chondrule-like forms occurring in a nephelinbasalt tuff from the Hussenberges in Westphalia. He says (p. 243):

> Es liegen eine grosse Anszahl rundlicher Auswürflinge schon in der Ebene eines Dünnschliffes bei einander. Sie zeigen in ihrer braunlichgelben Glasmasse scharfe Einsprenglinge von Olivin und auch monoklinen Augit. Solche Bildungen sind immerhin in ihrer allgemeinen Erscheinung porphyrischen Chondren vergleichbar. Ein Unterschied liegt zwischen beiden darin, dass bei den vorliegenden, iridischen Bildungen das Glas mit vielen Blasenräumen versehen ist. Es fehlt ferner z. B. die strahlige Chondrenstructur die man wohl nur bei auch chemisch und mineralogisch den Chondriten ähnlichen Gesteinen erwarten kann.

The accompanying figure (fig. 1, pl. 32) from Rinne's paper is so similar in structure to the porphyritic kugels (chondroids) in many meteoric stones as to strongly suggest an identity in composition and origin.

Von F. Schalch, in the 19th lieferung of the Beiträge zur Geologischen Karte der Schweiz, pages 103–104, describes what is likewise apparently a chondritic phonolite tuff. He says:

> Die sonst gleichartige Tuffmasse führt an zahlreichen Stellen * * * runde Kugelchen von Erbsen—bis Haselnussgrösse, selben von noch betrachtlicheren Dimensionen, die aus einem festeren und auch öfters etwas verschieden gefärbten Substrate bestehen und dem Gestein eine ausgeprägte Pisolithstructur verleihen.

And again on page 105:

> Man findet dieselben von ganz verschiedener Grösse; gewöhnlich sind sie indess nicht viel über nussgross, seltener faustgross oder von noch bedeutenderen Dimensionen. Meist besitzen sie ziemlich scharfe Kanten und Ecken, bisweilen sind sie aber auch mehr oder weniger abgerundet die grösseren Stücke hie und da zersprungen und deren Theilfragmente wieder durch Tuffmasse mit einander verkittet. Zuweilen findet man sie nur vereinzelt, an anderen Stellen nehmen sie derart an Menge zu, dass sie neben den oben genannten grösseren Krystallfragmenten und Pisolithkugeln geradezu die Hauptmasse des Tuffes bilden.

Gumbel, in his Geognostische Beschreibung des Königreichs Bayern (Abt. III, p. 226), described a "schalstein" which apparently is of like kugel form in structure. He says:

> Bei diesen Abänderungen besteht das Gestein bald mehr, bald weniger vorherrschend aus kleinen und kleinsten Brocken von verschiedenartigem oder doch in verschiedenen Stadien der Umbildung begriffenem Diabas mit vorherrschend abgerundeten Umrissen, welche durch eine Zwischenmasse nach Art des gewöhnlichen Schalsteins, vorherrschend durch die chloripitische Substanz ver-

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[17] Neues Jahrbuch fur Min., etc., vol. 2, 1895, pp. 229–246.

kittet sind. Die Diabasbröckchen, welche sichtlich durch abrollung ihre abgerundete Form erhalten haben, sind meist stark zersetzt, lassen jedoch noch deutlich die Texturverhältnisse des Krystallinisch kornigen Gesteins in der Verschiedenartigkeit des Diabases wahrnehmen. * * * Dazu gesellen sich zuweilen Brocken oder knollenartig rundliche Stückchen mehr oder weniger veränderten Nebengesteins, namentlich Fornfelsähnliche Fragmente und kugelige Ausscheidungen, welche beim Durchschlagen die Zusammensetzung der als Perldiabas beschrieben Varietäten besitzen. Diese enthalten häufig im Centrum grössere Putzen von verändertem Gestein, um welche sich mit nach aussen abnehmender Häufigkeit einzelne kleine Perlen oder Knöllchen der veränderten Substanz in zonen- oder schalenähnlicher Anordnung anlegen. (Berneck.)

The spherulites of the acid volcanic glasses like those of the Yellowstone National Park, in appearance and mode of occurrence often so closely simulate the kugels of meteorites as to demand attention here. Indeed Klein [18] affirms that those kugels with radiate structure: "Echte spharolithe darstellen." Berwerth, too, it may be recalled compared the kugels in meteorites to the spherules in artificial glasses, an error to which I have elsewhere called attention.[19]

The term spherulite, as now used by the leading petrologists, it may be said, refers to the complex growths of minerals of one or more species, principally miscroscopic quartz and orthoclase with minor quantities of tridymite, colloidal silica, and minute forms of other accessories characteristic of highly siliceous igneous rocks. "The essential character of spherulitic growth is the crystallization of minerals from one or more points with a radiating or divergent arrangement." (Iddings.) In external form they are often beautifully spheroidal, though not necessarily so, and break from the matrix, with which they are practically identical in composition, as freely as do the chondrules from a meteorite of the spherulitic chondrite type. In thin sections between crossed nicols they show a black cross which is due to the elongated form and radial arrangement of the principal constituents. That they originate in place and their formation is but a peculiar phase of magmatic crystallization is unmistakable. The question of their origin throws no light upon that of the granular and porphyritic chondrules, and seemingly none upon those of the eccentric radiating type.

Brief reference should be made to other occurrences of kugellike forms in terrestrial rocks.

The kugels of the spheroidal granites of Donigal, England, Westmoreland, Sweden, Quonochontogue Beach, R. I., and those of Finland, recently described by Sederholm [20] all show a marked concentric structure, rarely if at all simulated by the meteoric chondrule. The nearest approach to these forms that has thus far come under

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[18] Studien über Meteoriten, 1906, p. 35.

[19] Bull. Geol. Soc. Amer., vol. 32, 1921, p. 409.

[20] Bull. Com. Geologique de Finland, No. 83, 1928.

my observation are those described[21] in the stones of Parnallee and Tennasilm. Even here, however, the resemblance is slight, consisting in the case of the latter in an outer zone of crystals surrounding a granular interior. The kugel gabbros as those of Slättmossa, Norway, and Dehesa, Calif., show a variable granular nucleus surrounded by more or less radiating and elongated minerals of the same nature as those in the main rock mass. This holds true also of the kugel diorites of Corsica and Davie County, N. C. The structure and origin of these is so obviously different from those of the true chondrule as to render discussion unnecessary.

A further striking and decisive distinction between the meteoric and terrestrial forms lies in the fact that in the last named the spherules in any rock mass are invariably of a single type only. In meteorites, two or more types, varying in mineral composition and degrees of crystallization usually occur in the same stone and often in close juxtaposition.

Finally, and so far as relates to the kugelchen, or spherulitic chondrites there is a difference in that the meteoric chondrules are in all cases foreign to their hosts. Those of the terrestrial rocks, with the exception of the Thetford conglomerate, are formed in place.

METHODS OF ANALYSES OF STONY METEORITES

The making of satisfactory chemical analyses of stony meteorites is attended with difficulties little appreciated by one accustomed only to ordinary silicate work. This is due to several causes, the chief of which is the presence of iron in its several forms (as metal alloyed with nickel and cobalt, as phosphide, sulphide, and carbide and also in ferrous and ferric combinations in the silicates) and the desirability of determining each of these in its individual percentage amount. On first thought the magnetic separation of the iron might seem in all cases most feasible, but long experience has shown the impossibility of complete separation and many analysts have resorted to the expedient of solvents, as digestion in mercuric chloride. The following actual analysis illustrates the method adopted by Museum chemists in the analysis of the Florence, Tex., stone.[22] It is in substantial agreement with that used by Prior of the British Museum and J. E. Whitfield of Philadelphia.

A piece of the stone weighing 19.08 grams was crushed to pass 80 mesh. The larger particles of metal which would not pass the sieve were pounded flat to free them from silicate as far as possible and reserved. The powdered material was then worked over thor-

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[21] On Chondrules and Chondritic Structure. Proc. Nat. Acad. Sci., vol. 6, 1920.

[22] J. T. Lonsdale, American Mineralogist, Vol. 12, no. 11, November, 1927.

oughly with a hand magnet and all attracted material was removed and added to the metal. This separation gave:

	Grams
Attracted portion	3. 8425
Unattracted portion	15. 2362
	19. 0787

The attracted portion was all digested in aqua regia, evaporated to dryness, taken up in hydrochloric acid and filtered. The undissolved portion was washed thoroughly in hot water, then digested for one hour in hot 10 per cent sodium carbonate solution, filtered, and the then insoluble residue washed thoroughly with hot water, then with dilute hydrochloric acid and again with hot water. The residue was weighed as insoluble silicate. This gave:

	Grams
Dissolved	3. 5501
Insoluble	. 2924
	3. 8425

The alkaline and acid filtrates were combined, evaporated to dryness, taken up in hydrochloric acid, and the silica separated and determined in the usual manner. The solution was then made up to 500 cc. in a calibrated flask at 38° C. and divided into aliquot portions. Portions of 50 cc. (equivalent to 0.35512 gm.) were used for determination of MnO, P, and S; 100 cc. (0.71024 gm.) for the portion used for Fe, FeO, Ni, CO, CaO, Al_2O_3, and MgO, and the remaining 250 cc. (1.7756 gm.) was used for determination of Cu.

The portion for sulphur was evaporated to approximate dryness on the steam bath, an excess of hydrochloric acid and of potassium chloride added and twice again evaporated to approximate dryness with concentrated hydrochloric acid to expel nitrates. The potassium chloride unites with the ferric chloride to form a crystalline double salt, thus facilitating evaporation. The material was then taken up in hydrochloric acid, precipitated with barium chloride and weighed as barium sulphate on a small Gooch crucible.

The portion for manganese was evaporated to dryness several times with strong nitric acid, taken up in nitric acid, diluted and boiled with bromine, precipitate with ammonia. The precipitate was dissolved in nitric acid, thus freeing from chlorides, oxidized with silver nitrate solution and ammonium persulphate, and determined colorimetrically.

The portion for phosphorous was likewise evaporated with nitric acid several times to free from chlorides, precipitated with ammonia, dissolved in nitric acid and precipitated with ammonium molybdate reagent. It was filtered on a small Gooch crucible and weighed as phosphomolybdic anhydride, $24MoO_3.P_2O_5$.

The portion for the main analysis was precipitated twice with ammonia to separate iron and alumina from the other constituents. The nickel was then precipitated in the ammoniacal filtrate with dimethylglyoxime. The filtrate from the dimethylglyoxime precipitate was evaporated to dryness on the steam bath and treated with strong nitric acid to expel ammonium salts and destroy the excess of the dimethylglyoxime reagent. This was necessary before separating cobalt, as the element can not be precipitated as sulphide in the presence of dimethylglyoxime, although this compound does not interfere with the determination of lime as oxalate or magnesia as phosphate in the usual manner. The dry residue from the evaporation was evaporated once more with hydrochloric acid, taken up in dilute hydrochloric acid, made ammoniacal, saturated with hydrogen sulphide and filtered. The filtrate after freeing from H_2S was used for the determination of lime and magnesia. The precipitate of cobalt sulphide, somewhat contaminated with iron and some other impurities was ignited, was digested in acid and precipitated with ammonia, the cobalt passing into the filtrate in very small volume of solution from which it was recovered and weighed as $CoSO_4$.

The remaining acid solution was evaporated to free from nitrates and precipitated with H_2S. The precipitated impure copper sulphide was digested in a porcelain crucible, the solution made ammoniacal and the impurities filtered out. The filtrate was again acidified with hydrochloric acid and again precipitated with H_2S, ignited in a small tared porcelain crucible, digested in the crucible with a few drops of nitric acid, evaporated to dryness, and weighed as CuO. No platinum could be detected in the amount of material used. The results of analysis of this portion were as follows:

	Grams	
Soluble silicate:		
SiO_2	0. 0404	
Al_2O_3	Trace.	
TiO_2	Trace.	
FeO	. 0187	
CaO	Trace.	
MgO	. 0435	
Total		0. 1026
Troilite:		
Fe	. 0151	
S	. 0087	
Total		. 0238

Metal:	Grams	
Fe	3. 0680	
Ni	. 2780	
Co	. 0143	
Cu	. 0003	
P	. 0006	
Total		3. 3612
Grand total		3. 4876

The sulphur is all stated as S and enough Fe deducted to form troilite with all of it. The phosphorous is stated as P and the iron sufficient to form orthosilicate with the excess of Si over MgO is calculated to FeO. The metal then is found to make up 17.62 per cent of the whole meteorite and to have the following composition:

Net composition of metallic portion

	Per cent
Iron (Fe)	91. 277
Nickel (Ni)	8. 270
Cobalt (Co)	. 426
Copper (Cu)	. 009
Phosphorous (P)	. 018
	100. 000

THE SOLUBLE SILICATE

For the analysis of the soluble silicate portion, 2.0000 grams of the unattracted powder were taken and treated in the same manner as the preceding by digestion in aqua regia followed by hydrochloric acid and sodium carbonate solution. The results were:

	Grams
Dissolved	0. 9137
Insoluble	1. 0863

After separation of the silica the acid solution was made up to 250 cc. in a calibrated flask at 38° C. Portions of 50 cc. were taken for Mn, P_2O_5, and S. The remaining 100 cc. was used for FeO, Al_2O_3, CaO, NiO, MgO, etc. The results obtained were as follows:

Composition of soluble silicate portion

	Grams		Grams
SiO_2	0. 2586	P_2O_5	. 0065
TiO_2	Trace.	Fe	. 0784
Al_2O_3	. 0050	NiO	. 0035
FeO	. 1668	S	. 0450
CaO	. 0150		. 9213
MgO	. 3290		
MnO	. 0135		

Per cent, 100.83.

Except for enough to combine with the sulphur to form troilite the iron is calculated as FeO. The Ni is all determined as NiO in this portion and the phosphorus as P_2O_5.

THE INSOLUBLE SILICATE

From the last treatment there remained slightly over 1 gram of clean acid washed insoluble silicate. One-half gram (0.5000) of this was weighed out, fused with sodium carbonate and analyzed by standard methods to give the composition of the insoluble portion. The chromite was undecomposed by the sodium carbonate fusion and was weighed with the silica. It remained in the residue when the silica was treated with hydrofluoric and sulphuric acids. After weighing this residue was again treated in the platinum crucible with hydrofluoric and sulphuric acids, evaporated to sulphuric acid fumes, diluted with water and the chromite filtered out and weighed. It was not in amount sufficient for analysis and, in the summation below it is assumed to have the composition $FeO.Cr_2O_3$. The analysis of the insoluble silicate gave the following results:

Analysis of insoluble silicate portion

	Per cent		Per cent
SiO_2	56. 94	NiO	None.
Al_2O_3	4. 86	Chromite	0. 60
TiO_2	Trace.	Na_2O	. 87
FeO	8. 98	K_2O	1. 28
CaO	4. 56		
MgO	22. 28		100. 37

No trace of nickel could be detected by the dimethylglyoxime method. Alkalies were separatively determined by the J. Lawrence Smith method and all assigned to the insoluble silicate. The direct determination of alkalies in the remnant of the insoluble silicate was considered impractical, since the material had been digested in sodium chloride and might have retained a minute amount of soda. This remainder was therefore used for microscopic examination.

The composition of the portion of the meteorite ground for analysis is then:

	Weight (grams)	Per cent		Weight (grams)	Per cent
SiO_2	6. 8903	36. 115	Co	0. 0143	0. 075
TiO_2	Trace.	Trace.	Cu	. 0003	. 002
Al_2O_3	. 5258	2. 756	S	. 3515	1. 842
FeO	2. 0755	10. 880	P	. 0006	. 003
CaO	. 5308	2. 782	P_2O_5	. 0495	. 259
MgO	4. 4594	23. 370	Cr_2O_3	. 0350	. 183
MnO	. 1028	. 539	K_2O	. 1094	. 573
NiO	. 0267	. 140	Na_2O	. 0742	. 388
Fe	3. 6807	19. 290			
Ni	. 2780	1. 492		19. 2048	100. 689

The unused acid and alkali extracted portion of the insoluble silicate was screened free from fines and the portion between 80 and 200 mesh was passed through a methylene-iodide-bromoform heavy solution in an attempt to isolate grains of feldspars for optical examination. Only an exceedingly small light portion was obtained. This consisted of grains of feldspar containing numerous inclusions of the silicate of higher index, probably pyroxene for which the feldspar forms a matrix. Practically none of the feldspar grains showed twinning and most of them had a refractive index, beta, of about 1.550, varying about 0.002.

The unused portion of the unattracted powder was likewise screened free from fines and passed through heavy solution. The lightest product separated from this likewise consisted of only a few mixed grains consisting of a feldspar with very abundant rounded inclusions of pyroxene and olivine. The feldspar showed no twinning and is optically positive with 2V medium, beta index from 1.550 to 1.553. The feldspar thus appears to be a fairly sodic plagioclase approaching andesine in composition. Occasional grains of the feldspar-bearing material are heavily pigmented with a black substance which is probably largely carbon.

The heavier concentrate from the insoluble silicate consists of a few clear grains which exhibit moderately high bi-refringence. A majority of these were aggregate in structure, greatly dusted with inclusions and gave very little optical data. The clearer grains were biaxial and positive with a beta index of about 1.680. No cleavage was observed and only one or two grains showed recognizable polysynthetic twinning. The optical properties are those of diopside.

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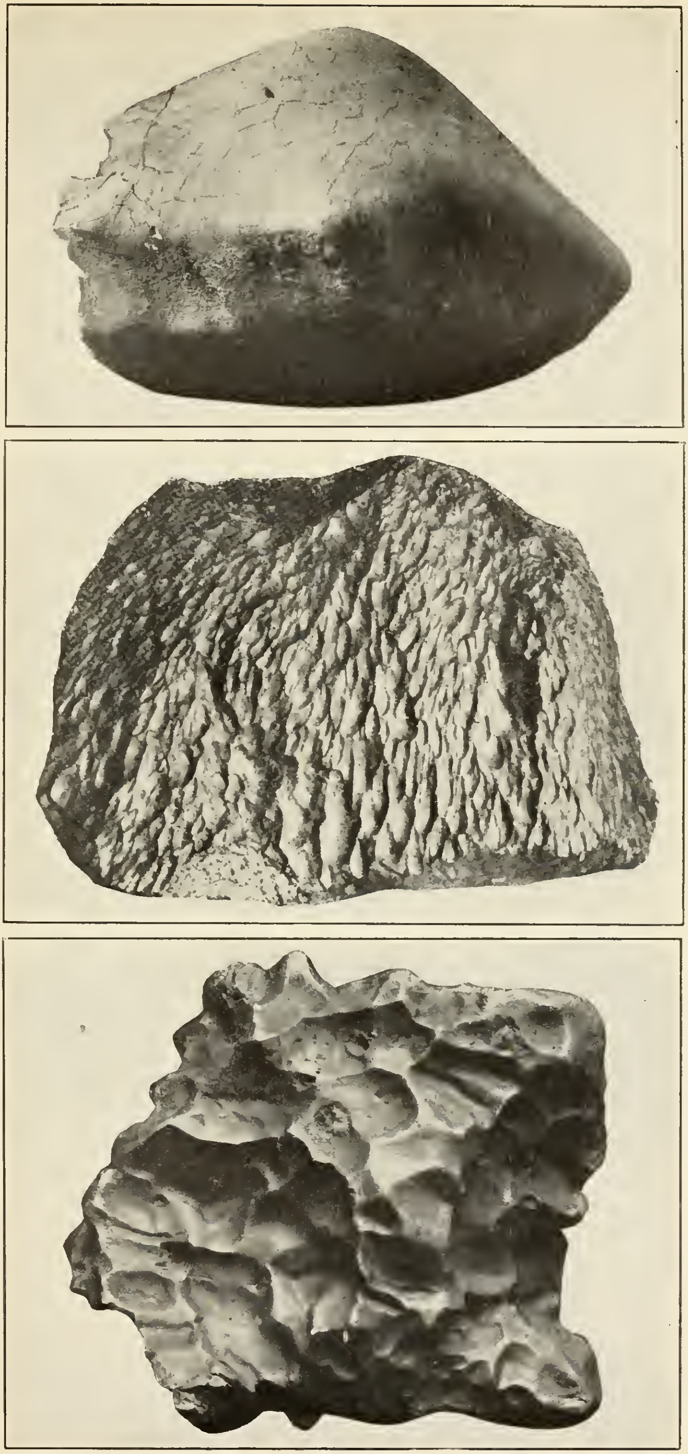
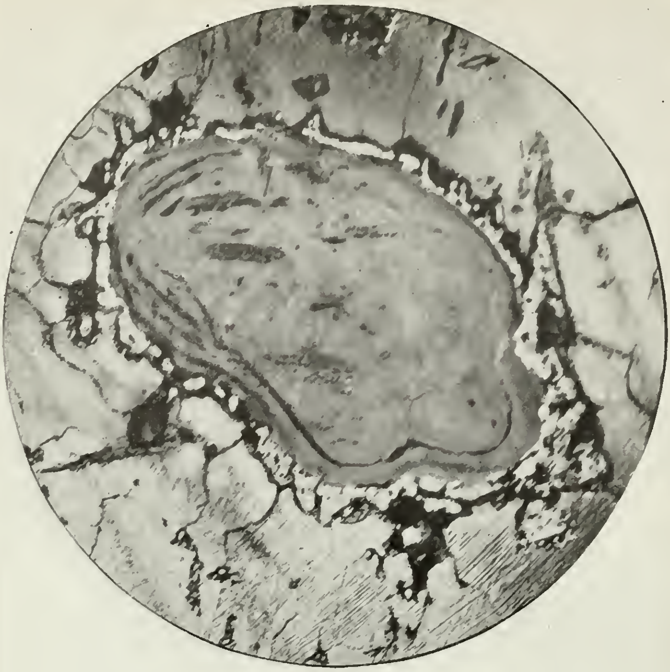


EXTERNAL FORM OF ALLEGAN AND BATH FURNACE STONES; AND OF MAZAPIL IRON

FOR EXPLANATION OF PLATE SEE PAGE 18



1

2

(1). CARBON NODULE IN CANON DIABLO METEORIC IRON; (2). REFUSED FELDSPAR IN ESTHERVILLE METEORIC STONY IRON

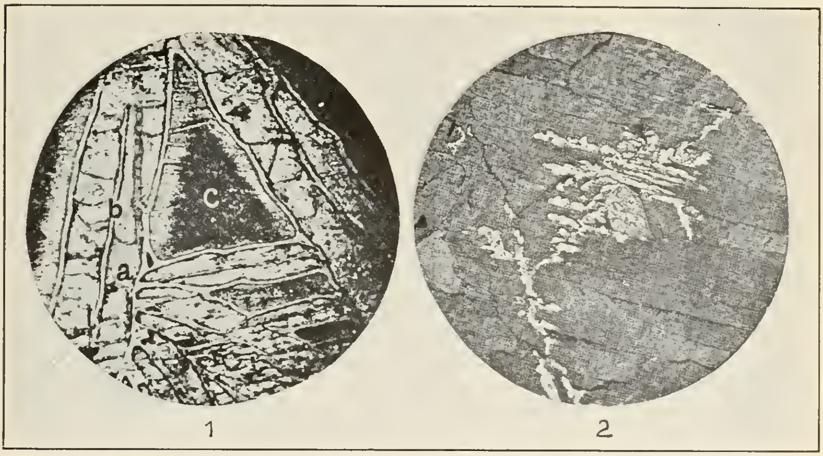
FOR EXPLANATION OF PLATE SEE PAGES 3, 4, AND 43

(1). Maskelynite in Troup Meteoric Stone; (2). Merrillite in New Concord Meteoric Stone

For explanation of plate see pages 5 and 7

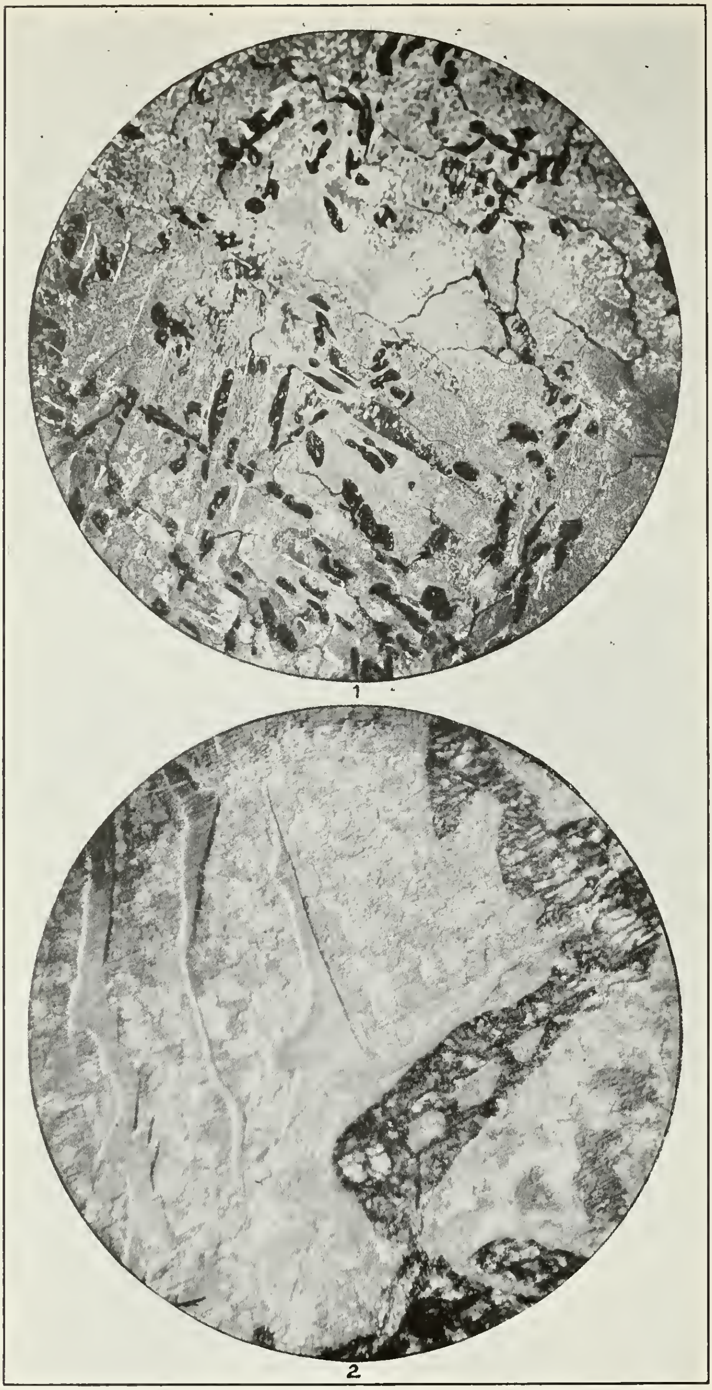
(1), FRAGMENTAL TWINNED PYROXENES IN JOHNSTOWN METEORITE; (2), FRAGMENTAL PYROXENES IN ESTHERVILLE METEORITE

FOR EXPLANATION OF PLATE SEE PAGE 11



(1). Widmanstätten Figures, Enlarged; (2). Schreibersite in Arispe and (Lower) in Tombigbee Irons

For explanation of plate see pages 8, 13, and 19

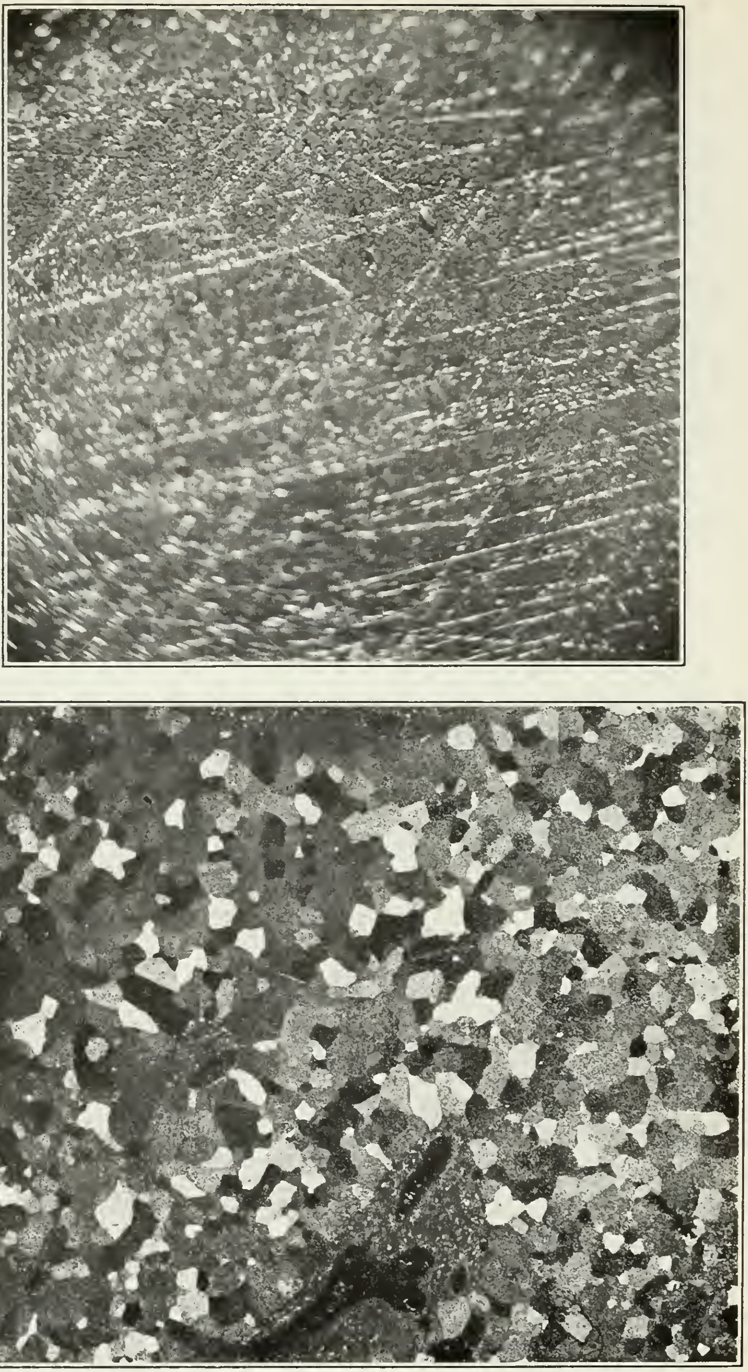


(1). Meteoric Iron From Dunganonn, Va., Showing Partial Granulation; (2). the Same Greatly Enlarged

For explanation of plate see page 20

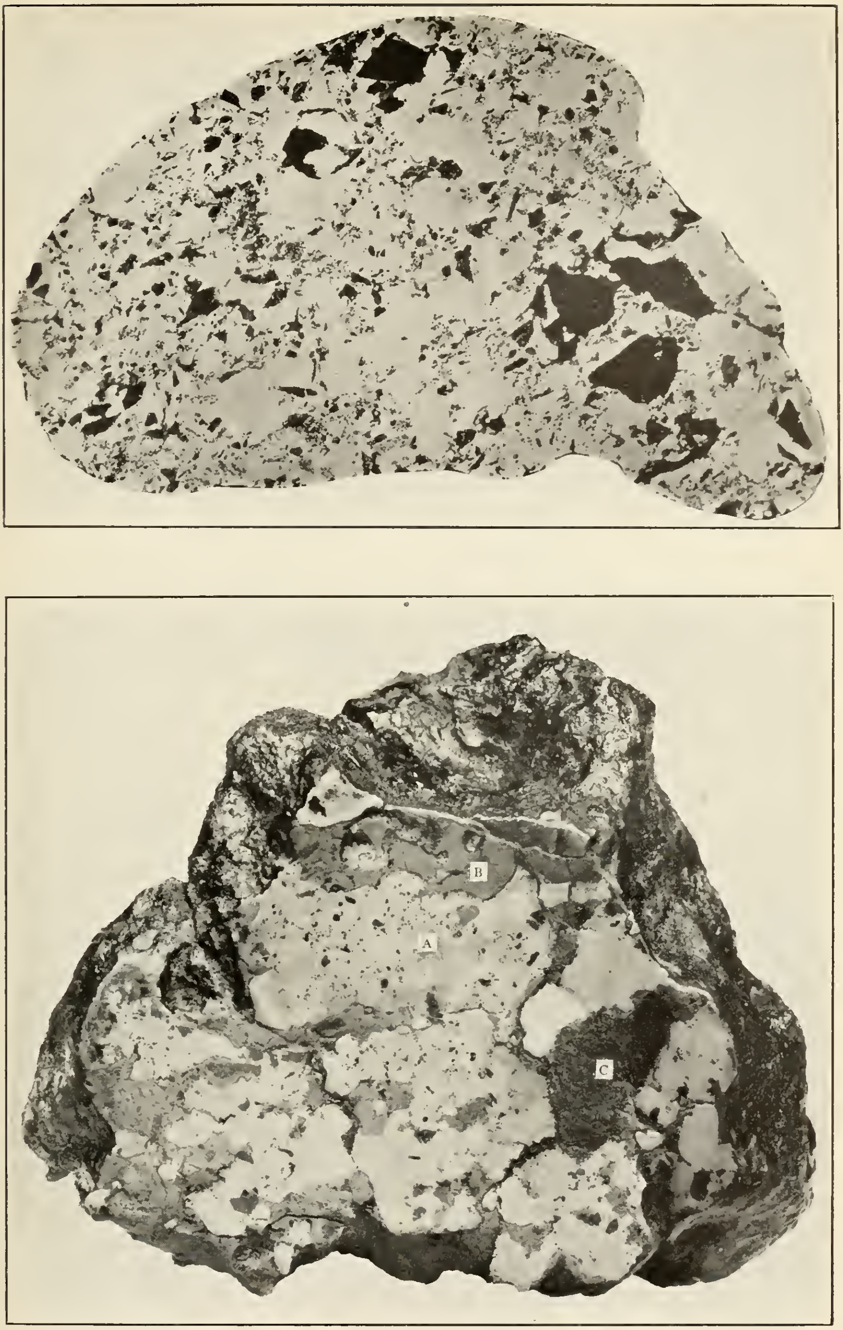
(UPPER). SWATHING KAMACITE IN ADMIRE PALLASITE; (LOWER). OCTAHEDRAL STRUCTURE AND REICHENBACHIAN LINES IN CARLETON IRON

FOR EXPLANATION OF PLATE SEE PAGES 19 AND 23



(Upper). Neuman Lines in Braunau Iron; (Lower). Granular Structure in Mejillones Iron

For explanation of plate see page 20

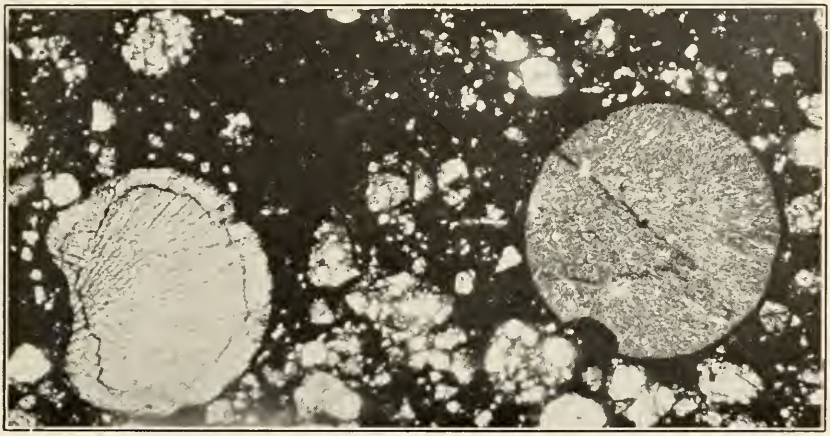


(UPPER). OCTAHEDRAL IRON WITH SILICATE INCLOSURES. FOUR CORNERS. N. MEX.; (LOWER). PERSIMMON CREEK. N. C., IRON

FOR EXPLANATION OF PLATE SEE PAGES 12, 20, AND 21

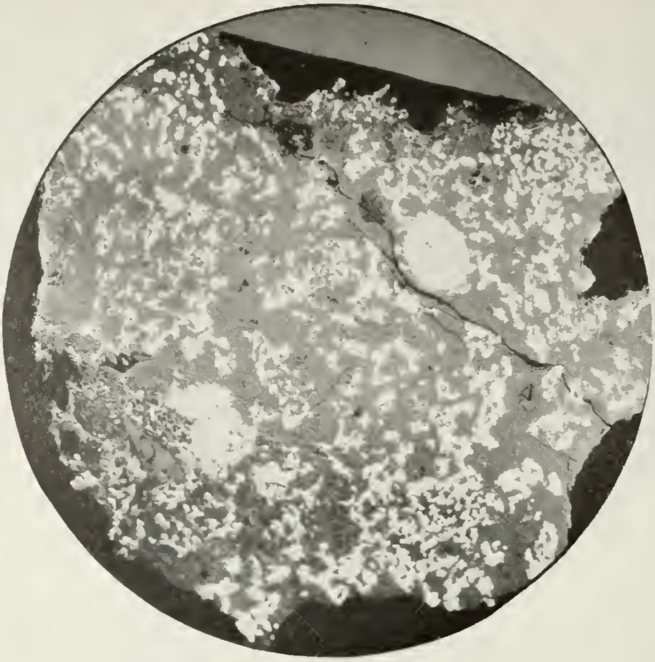
(UPPER), BRECCIATED HEXAHEDRITE, KENDALL COUNTY, TEX.; (LOWER), COARSEST OR KAMACITE OCTAHEDRITE, AINSWORTH, NEBR.

FOR EXPLANATION OF PLATE SEE PAGE 20



(1). Swollen Kamacite in Mesa Verde Iron; (2). Structure of Four Corners Iron, Enlarged; (3). Quartz Crystals in St. Marks Stone; (Lowest). Chondrules in Sharps, Va., Stone

For explanation of plate see page 14



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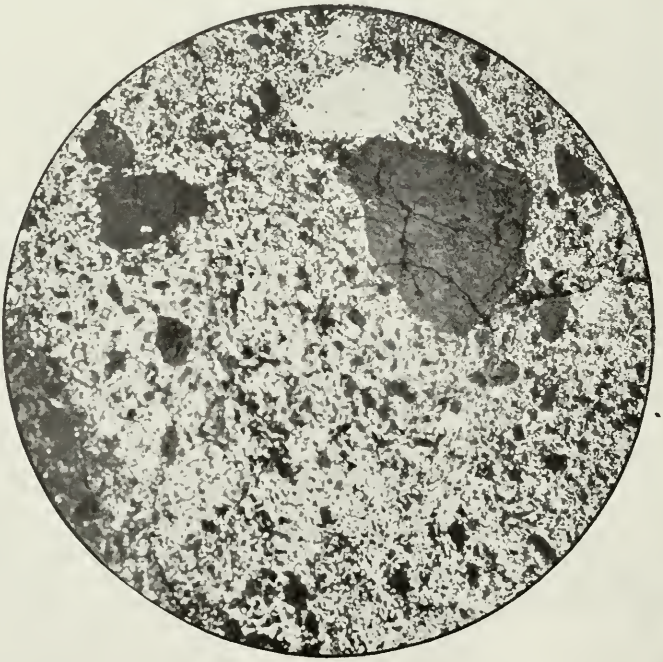
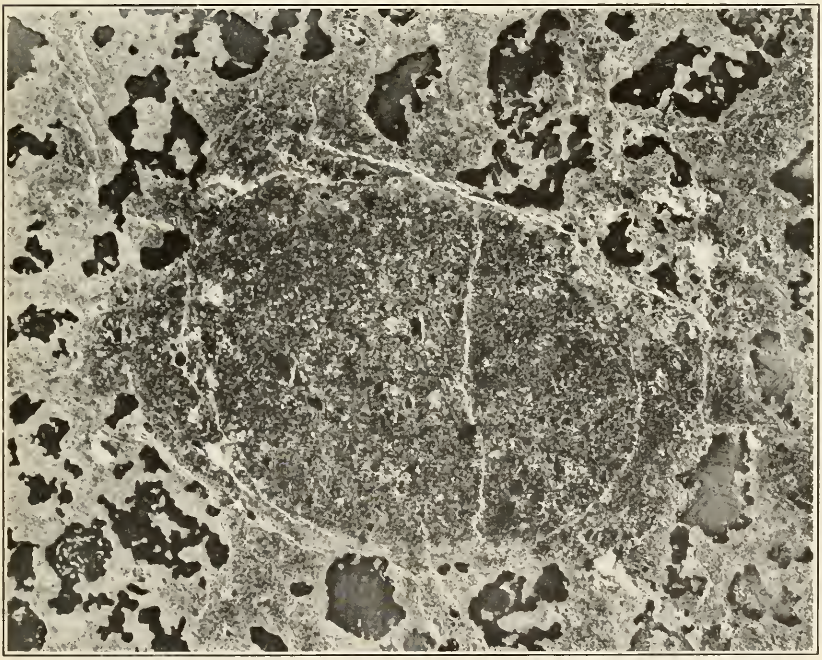


2

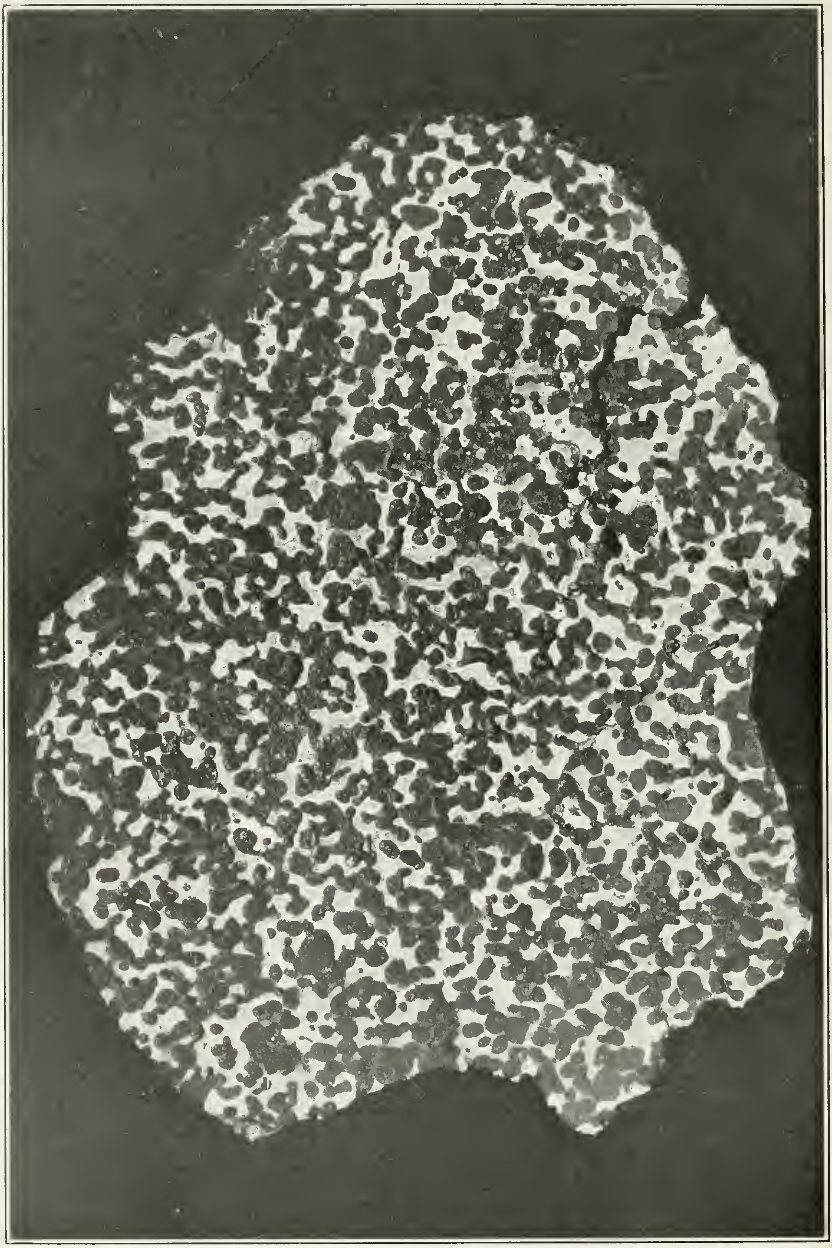
Grahamites from Morristown and Crab Orchard Stony Irons

For explanation of plate see page 21



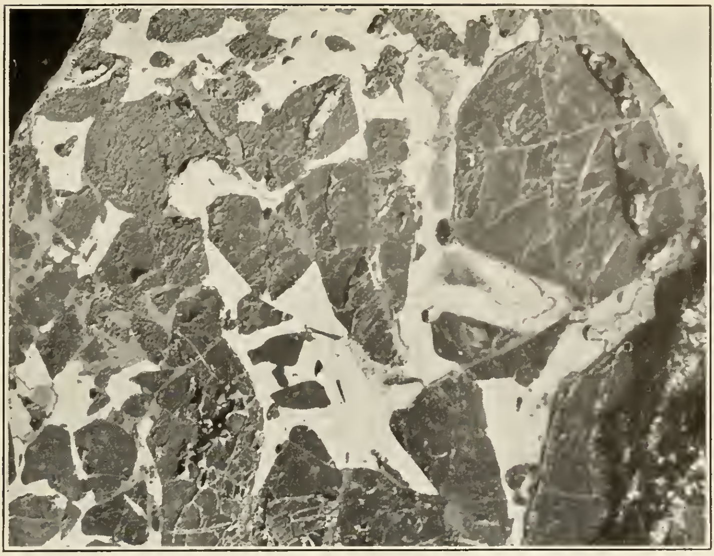
(UPPER). ESTHERVILLE STONY-IRON; (LOWER). SAME WITH INCLOSURE

FOR EXPLANATION OF PLATE SEE PAGES 15, 22, 23, AND 43



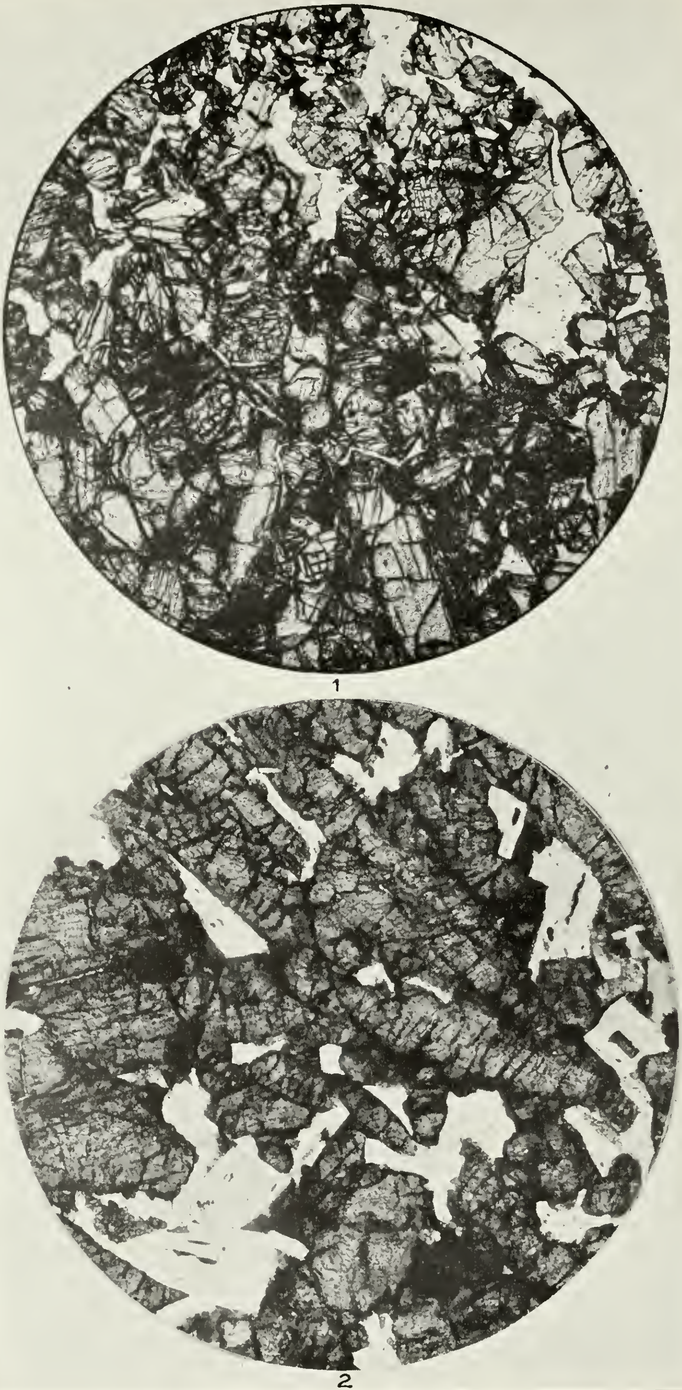
Pallasite from Brenham, Kans.

For explanation of plate see pages 15 and 23



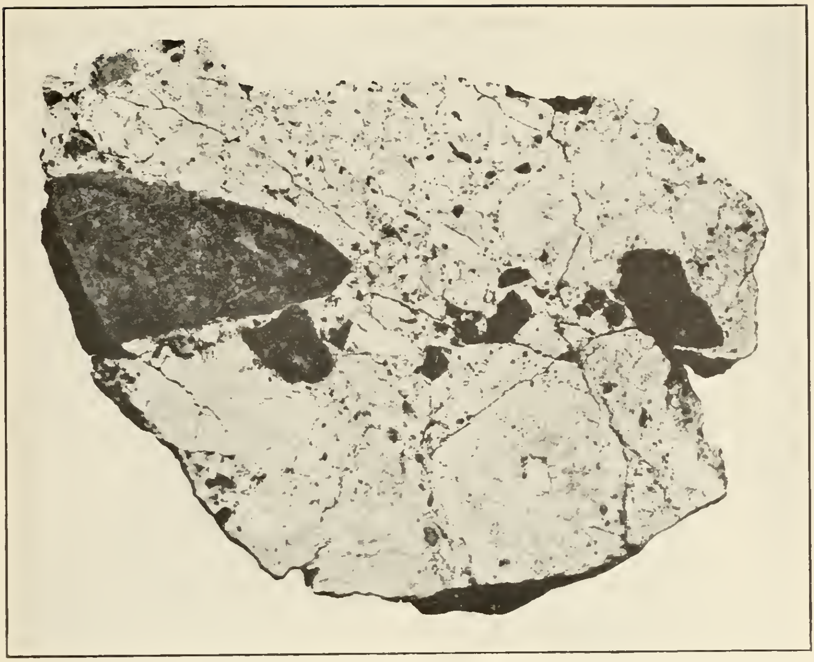
(UPPER), SECTION OF THE ADMIRE PALLASITE; (LOWER), AN IRON-RICH PORTION OF BRENHAM PALLASITE

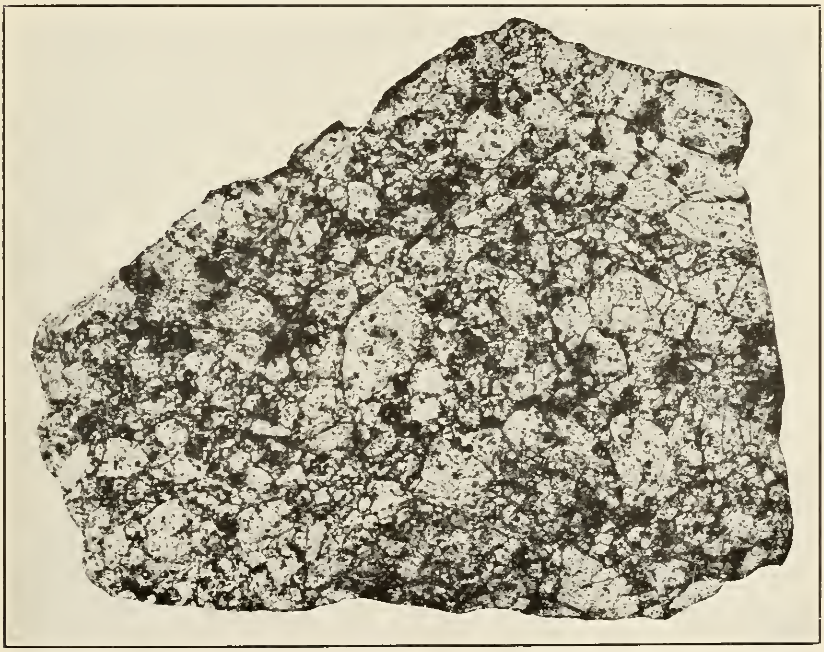
FOR EXPLANATION OF PLATE SEE PAGE 15



Microstructure of, (1), El Nakhla Stone; and (2), of the Shergotty Stone

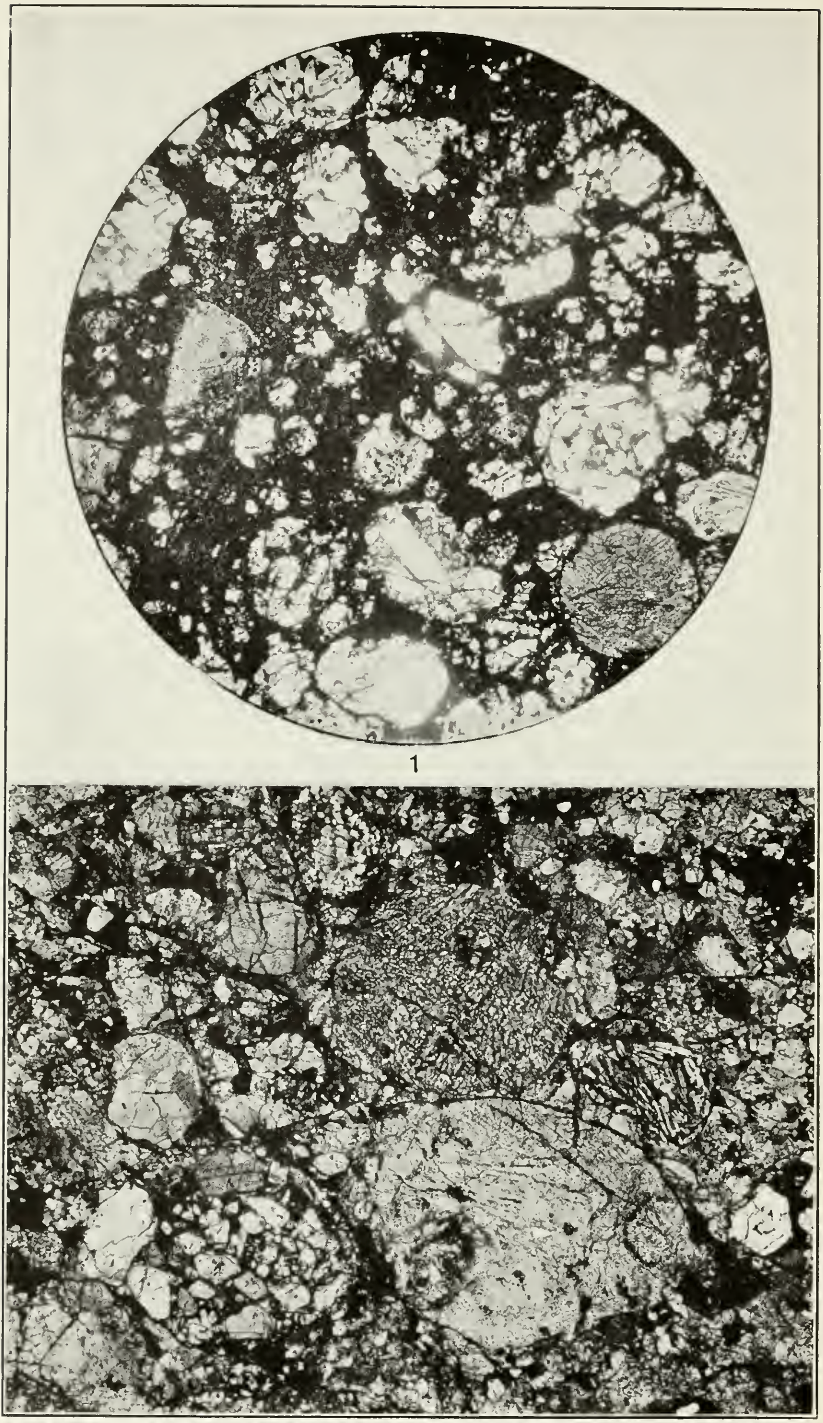
For explanation of plate see pages 5, and 25





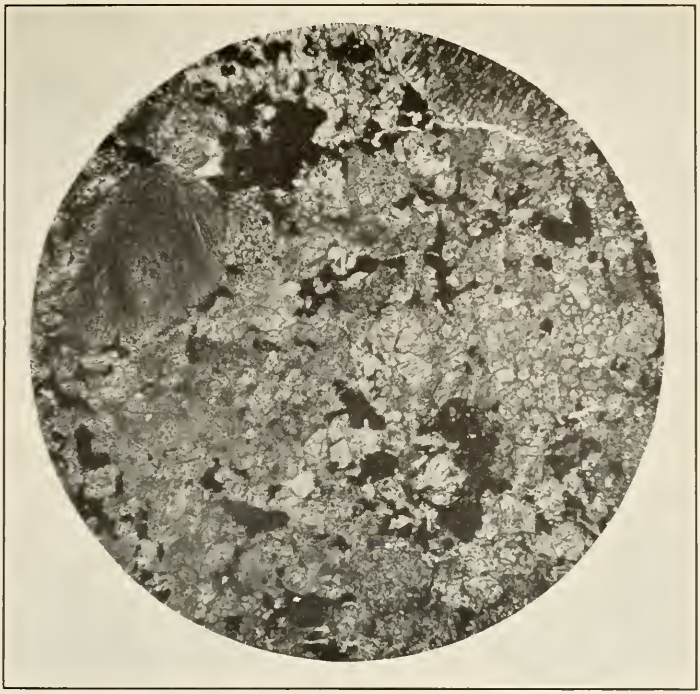
(UPPER). BRECCIATED STRUCTURE OF THE CUMBERLAND FALLS, AND (LOWER). ST. MICHEL STONES

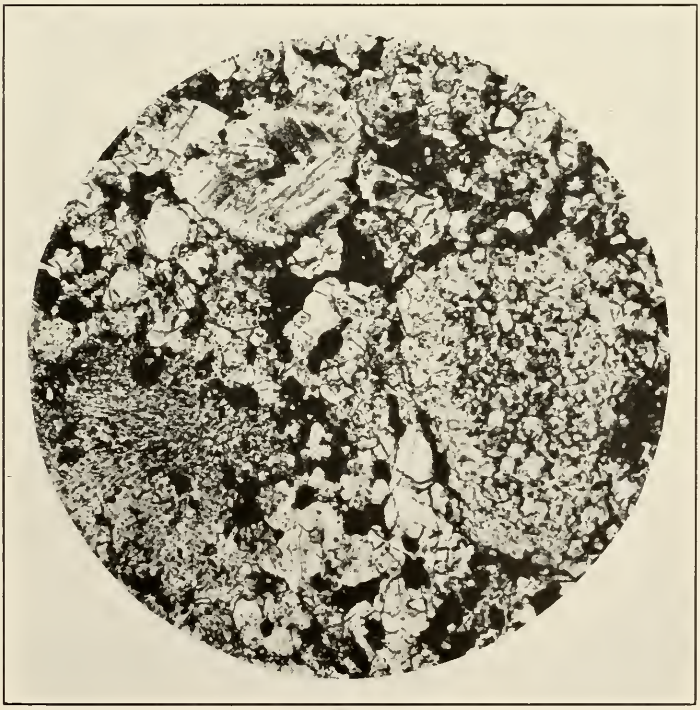
FOR EXPLANATION OF PLATE SEE PAGES 25 AND 26



CHONDRULES AND CHONDRITIC STRUCTURE OF SELMA, ALA., AND CEDAR, TEX., STONES

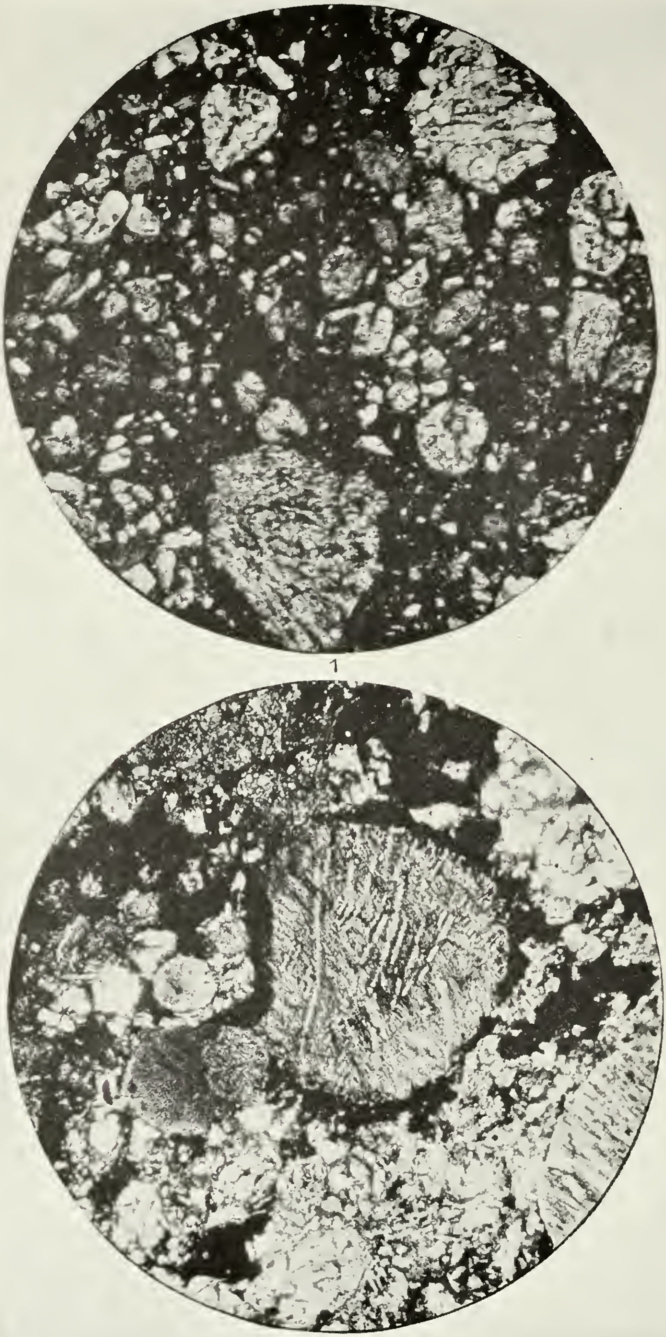
FOR EXPLANATION OF PLATE SEE PAGES 27, 28, 29, 31, 37, AND 39





(UPPER), MICROSTRUCTURE OF THE BLUFF, AND (LOWER), ESTACADO STONES

FOR EXPLANATION OF PLATE SEE PAGES 28 AND 39

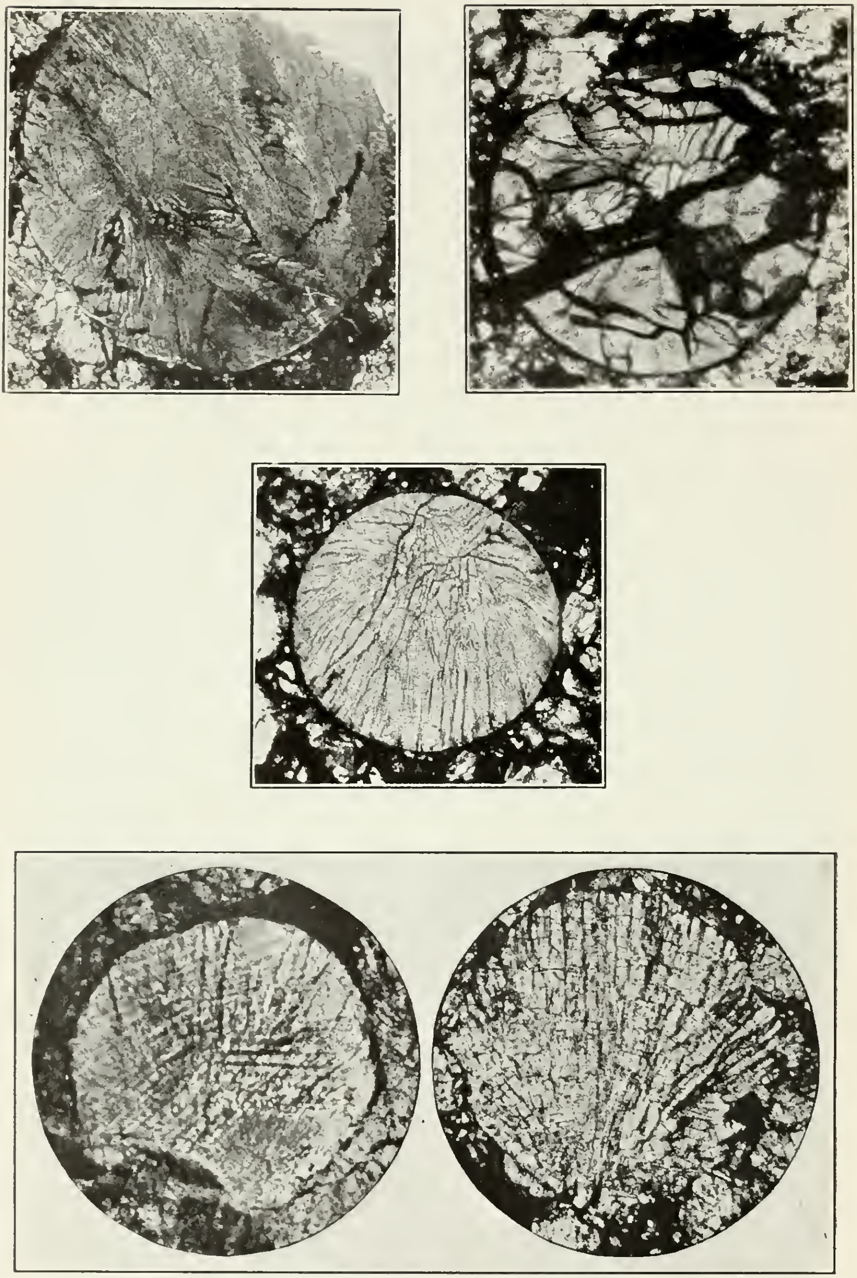


MICROSTRUCTURE OF, (1), INDARCH STONE, AND (2), OF CULLISON STONE, SHOWING A COLLAR OF METAL ABOUT A FRAGMENTAL CHONDRULE

FOR EXPLANATION OF PLATE SEE PAGES 29, 39, AND 41

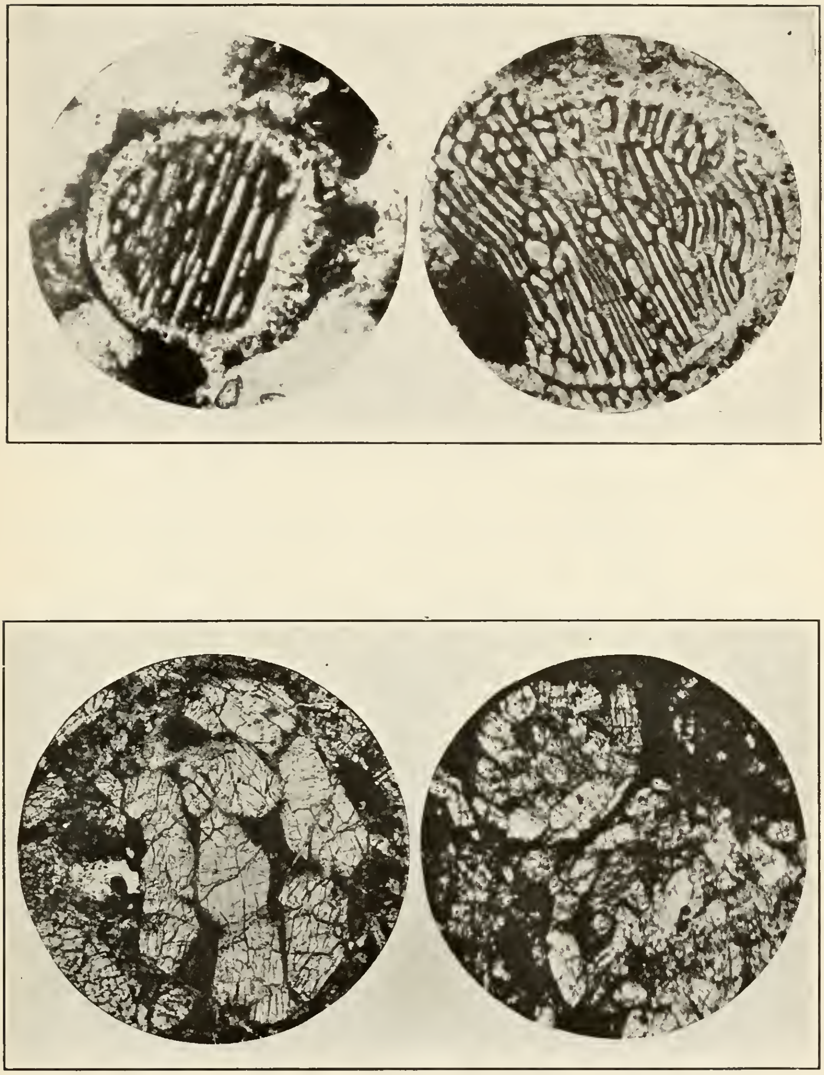
(UPPER). SLICE OF ANTHONY METEORITE SHOWING TROILITE WITH BORDER OF METAL AND (LOWER). SECTION OF DARK INCLOSURE OF CUMBERLAND FALLS STONE SHOWING DISTRIBUTION OF METAL

FOR EXPLANATION OF PLATE SEE PAGES 14, 29, AND 41



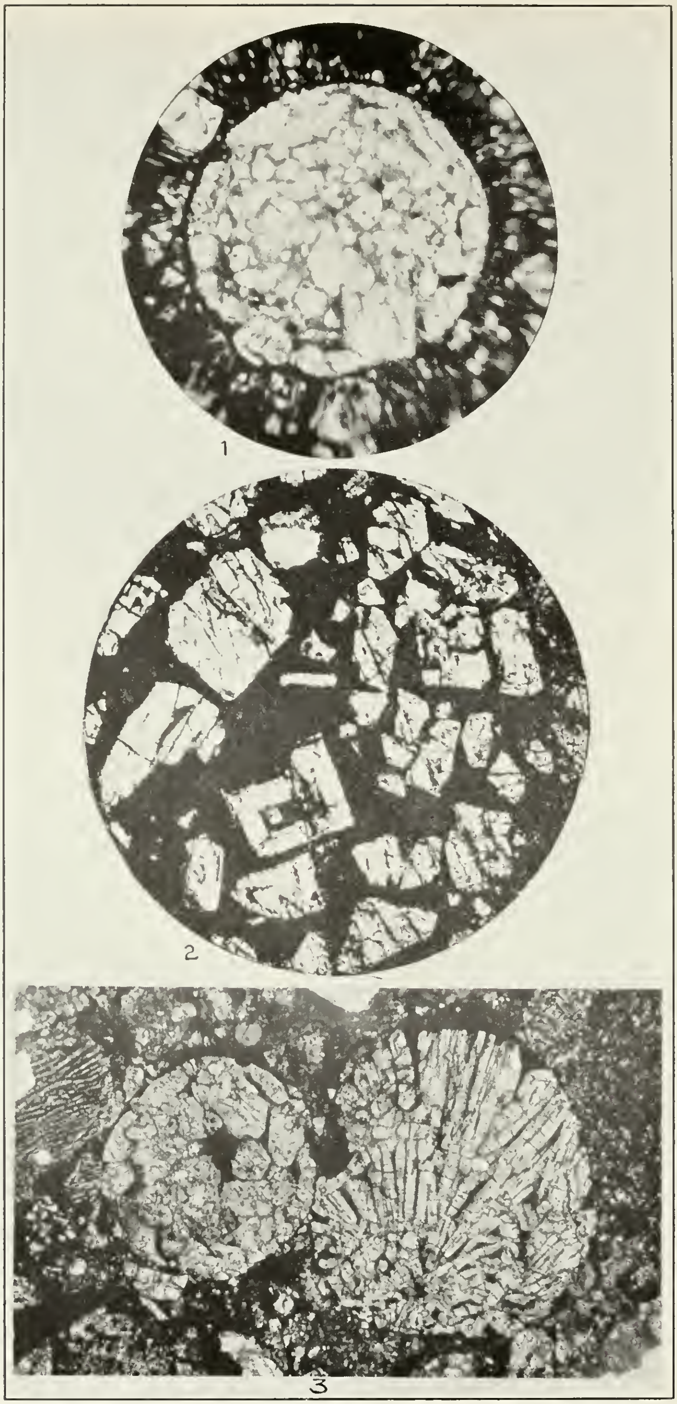
CHONDRULES IN BARRATTA, CULLISON, ELM CREEK, HESSLE, AND PARNALLEE STONES

FOR EXPLANATION OF PLATE SEE PAGES 10, 11, 31, 32, 38, 39, AND 42



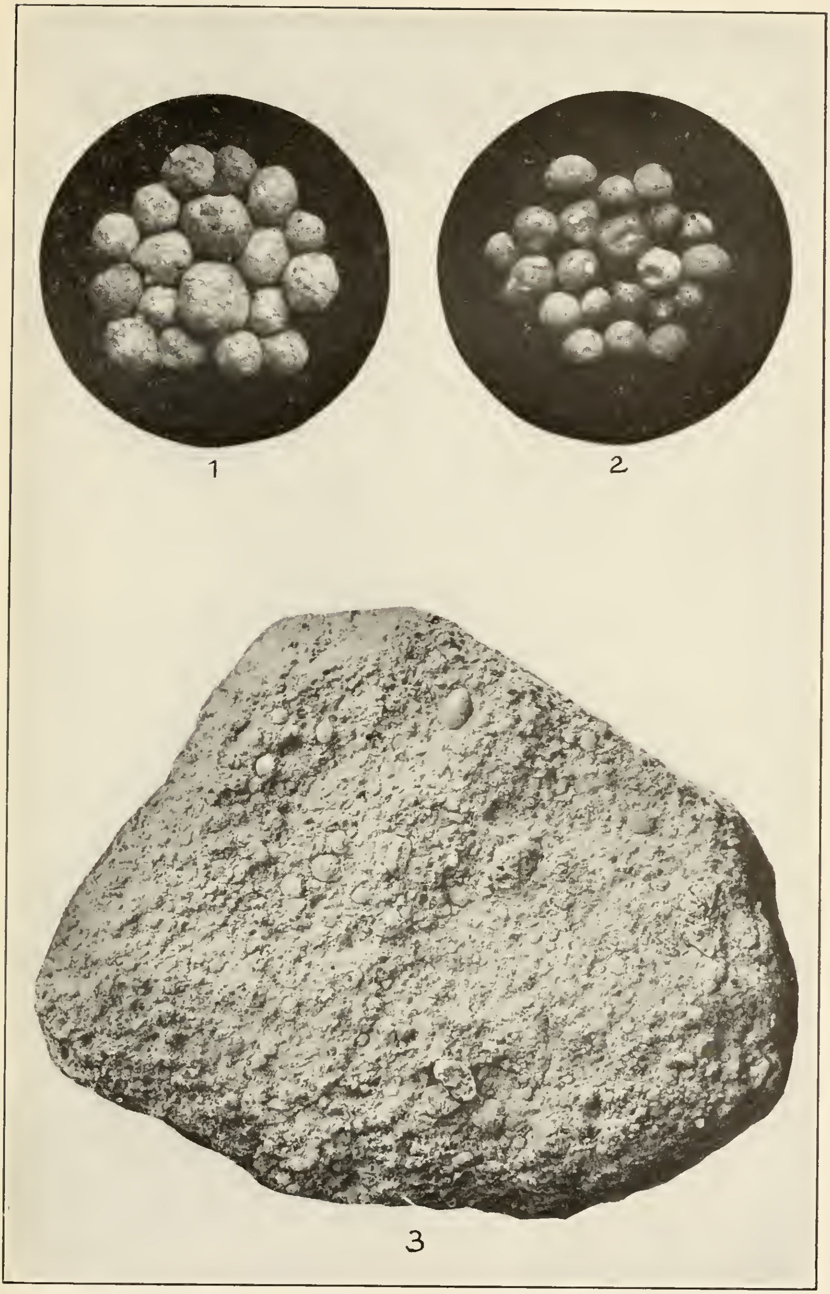
(Upper), Olivine Chondrules in Beaver Creek and Cullison Stones; (Lower Left), Enstatite Chondrule in Cullison: (Lower Right), Twinned Enstatite Chondrules in Parnallee Stone

For explanation of plate see pages 10, 31, 32, 33, and 42



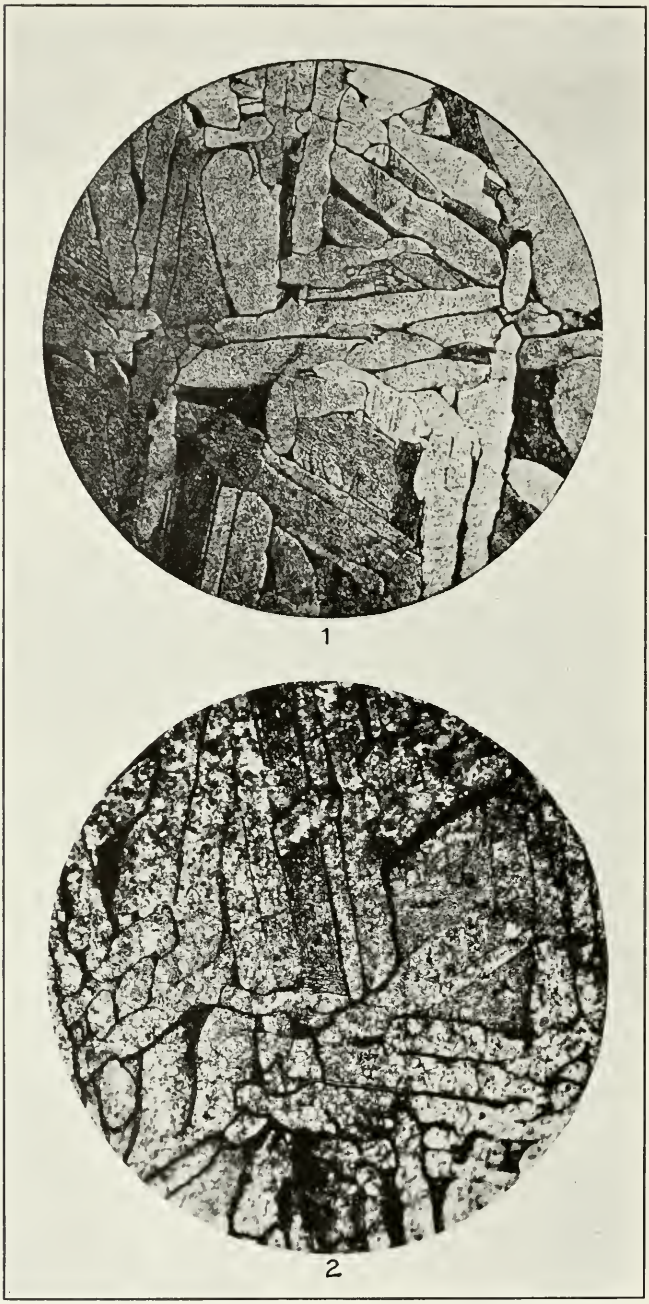
CHONDRULES IN (1) PARNALLEE; (2) TENNASILM; AND (3) ELM CREEK STONES

FOR EXPLANATION OF PLATE SEE PAGES 31, 32, 33, AND 43



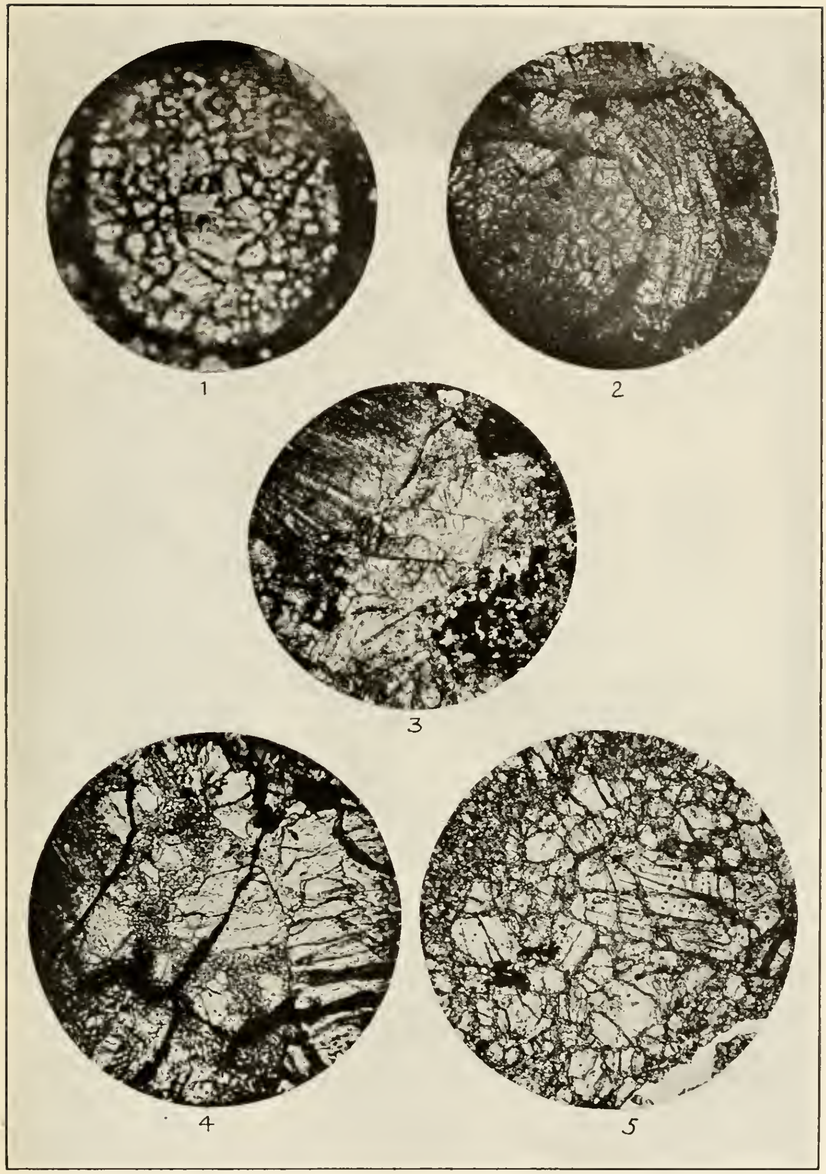
(1 AND 2), CHONDRULES AND CHONDROIDAL FORMS FROM THE BJURBÖLE STONE. (3), BROKEN SURFACE OF BJURBÖLE STONE. ABOUT NATURAL SIZE

FOR EXPLANATION OF PLATE SEE PAGES 27, 31, AND 38



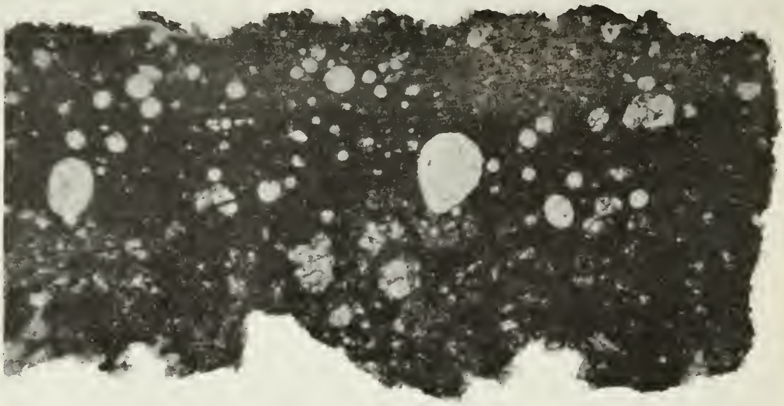
Toluca Iron, (1), Before and, (2), After Roasting

For explanation of plate see pages 40 and 41



(1). Chondrule in Parnallee Stone with Secondary Glass Border; (2). Same Showing Effects of Crushing; (3, 4, and 5). Chondrules from Hendersonville, Troup, and Ensisheim Stones Showing Effects of Crushing

For explanation of plate see pages 40 and 42



1

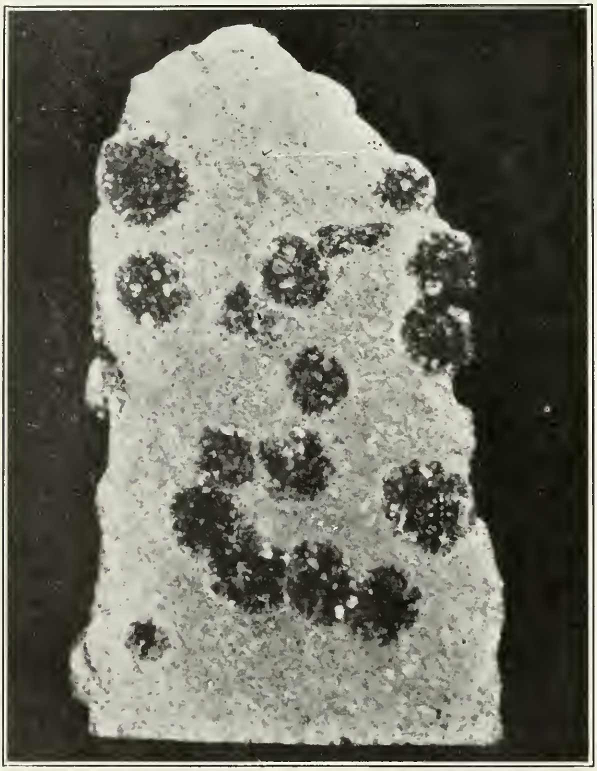
2

(1). Section Through Crust of Allegan Stone; (2). Section Through Black Vein in Bluff Stone

For explanation of plate see pages 18, 44, and 45

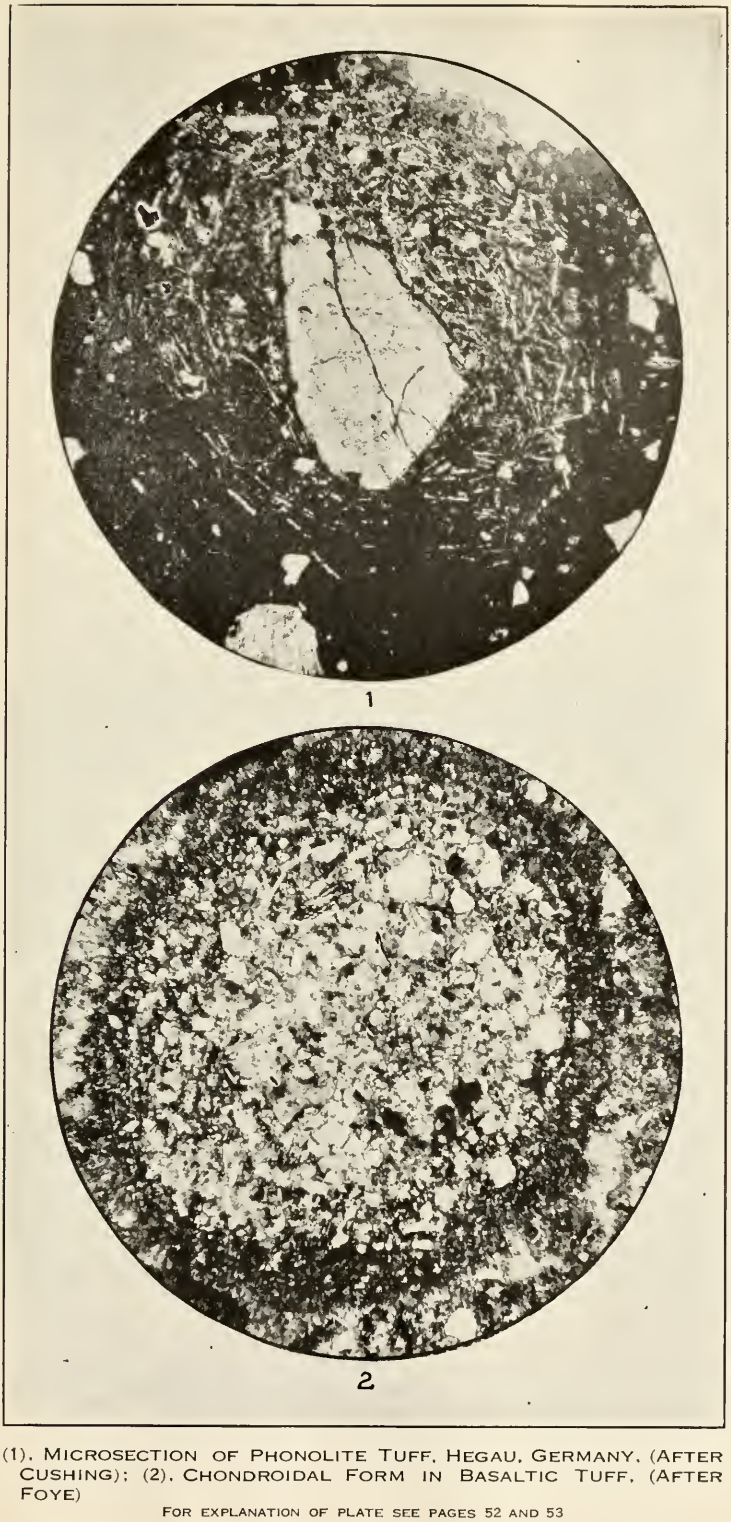
(UPPER), FAULTED METEORIC IRON, NEW BALTIMORE, PA.; (LOWER), SHATTERED STONE FROM CEDAR, FAYETTE COUNTY, TEX.

FOR EXPLANATION OF PLATE SEE PAGES 18, 20, 44, AND 46



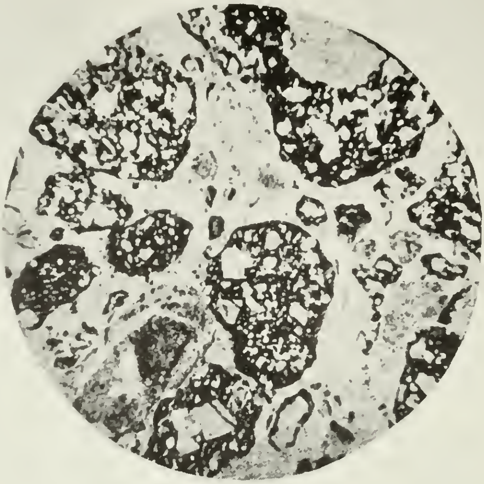
(UPPER). BROKEN SURFACE OF "KUGELNGRÜNSTEIN," SCHEMNITZ, HUNGARY, SHOWING CHONDROIDAL FORMS; (LOWER). CUT AND POLISHED SURFACE OF THE SAME

FOR EXPLANATION OF PLATE SEE PAGE 52



(1). MICROSECTION OF PHONOLITE TUFF, HEGAU, GERMANY. (AFTER CUSHING); (2). CHONDROIDAL FORM IN BASALTIC TUFF. (AFTER FOYE)

FOR EXPLANATION OF PLATE SEE PAGES 52 AND 53



1

2

(1). CHONDROIDAL FORMS IN NEPHELINE BASALT, HUSSENBERGES, WESTPHALIA. (AFTER RINNE); (2). PSEUDOCHONDRITIC FORMS OF OLIVINE IN PERIDOTITE, RATON, N. MEX.

FOR EXPLANATION OF PLATE SEE PAGES 54 AND 55