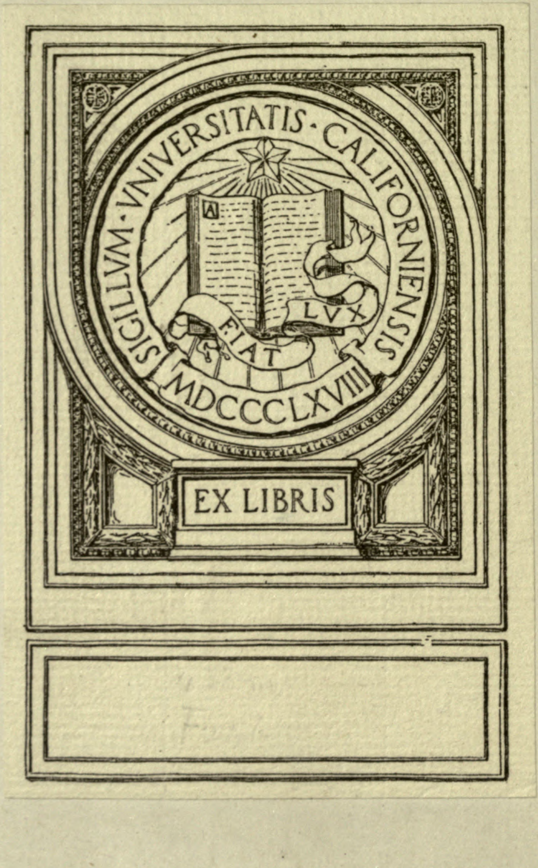
METEORITES

FARRINGTON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Ed. Bernardo
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The Bacubirito, Mexico, meteorite. One of the largest meteorites known. Weight about 27 tons.

METEORITES

THEIR STRUCTURE, COMPOSITION, AND TERRESTRIAL RELATIONS

BY

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PREFACE

Three reasons may be assigned for ascribing peculiar interest to the study of meteorites:

First. They are our only tangible sources of knowledge regarding the universe beyond us.

Second. They are portions of extra-terrestrial bodies.

Third. They are a part of the economy of Nature. No survey of Nature can be considered complete which does not include an account of them.

For these and other reasons the writer has long experienced a fascination and delight in the study of these bodies. In seeking works for his guidance, however, he has found a lamentable lack of any which treated the subject comprehensively. While some phases of the subject and the characteristics of many individual falls have been investigated with admirable thoroughness, the subject as a whole has not received extensive treatment. The admirable Meteoritenkunde of Cohen would have left little to be desired had its author been permitted to carry out his broadly conceived plan, but this privilege was unfortunately denied him. Meunier's Météorites has not been revised in recent years and Fletcher's Introduction, while a model of its kind, is limited in its scope. That the present writer has been greatly assisted by the above works and many others in the preparation of this one needs hardly to be stated. Detailed references to these works, however, were deemed to be impracticable except where it was thought that a fuller treatment of certain subjects might be desired by some readers. In such cases references have been given.

Much assistance in the preparation of illustrations for this work was given the writer by the late Prof. Henry A. Ward. Mr. D. M. Barringer generously furnished photographs of Meteor Crater, Arizona, and the writer is indebted to the *Journal of Geology* through its editor, Prof. T. C. Chamberlin, for the loan of several cuts.

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METEORITES

CHAPTER I

GENERAL CHARACTERS AND NOMENCLATURE

Meteorites are solid bodies which come to the earth from space. Their dimensions range from microscopic to many cubic feet. Their fall to the earth is usually marked by peculiar phenomena of sound and light. The masses observed to fall are for the most part of a stony nature, granular, of a grayish color, and covered with a thin, black crust. As a rule, they contain particles of metal scattered through their substance. In the material of some falls the metal more largely predominates and still others are made up wholly of metal. The nature of this metal is essentially similar in all meteorites, being iron alloyed with from five to twenty-five per cent of nickel.

According to their prevailing substance meteorites may be divided into the two classes of stone and iron meteorites. It is convenient also at times to distinguish an intermediate class which may be designated as iron-stone meteorites.

Most stone meteorites, as has been said, have the appearance of a grayish mass covered with a black, more or less shining crust. Occasionally the mass of the stone may be so dark as to be practically black or it may be brownish. Again it may be nearly white. Further, the crust does not always differ in color from the interior, especially in the case of brown or black meteorites. Scattered metallic grains usually characterize the substance of stone meteorites. The coherence of the stone meteorites is usually such that they do not break easily under the blow of a hammer and they take a fair polish. Some can, however, be crumbled in the fingers.

The iron-stone meteorites differ chiefly from the stone meteorites in their abundance in metal. Instead of occurring as minute, scattered grains forming but a small percentage of the mass of the meteorite, the metal makes up about half the mass and is often continuous. Single nodules of the metal may reach a diameter of one inch or more. Further, the metal may be so abundant as to form a matrix of a sponge-like character in the pores of which silicates are held. Thus by gradation the iron-stone meteorites pass to meteorites made up entirely of metal or iron meteorites.

The metal of the iron meteorites is, when fresh, of a silver-white to grayish-white color and usually malleable. It is made up, as has been said, chiefly of iron alloyed with from five to twenty-five per cent of nickel. When found immediately upon falling, meteorites of this composition usually exhibit a blackish or bluish crust through which the silvery appearing interior gleams here and there, but any continued exposure usually causes the entire surface of such meteorites to become of a rusty-brown color.

No single criterion can be given for distinguishing meteorites from masses of terrestrial origin. Only by combining several features can the positive determination of a meteorite be made. A pitted and fused surface is an important character of meteorites, yet on the one hand this may not be present and the body be meteoric, and on the other hand very similar pittings, though not often produced by fusion, may be observed on terrestrial rocks. The presence of metallic grains is generally a distinctive feature of stone meteorites, but these grains are lacking in some meteorites, and a somewhat similar appearance through the presence of scattered grains of pyrite or other mineral of metallic luster, may be seen in terrestrial rocks. The true chondritic structure when observed under the microscope may be considered a decisive mark of a meteorite, yet a few meteorites do not have this structure.

So far as the iron meteorites are concerned the presence of nickel is essential. No iron meteorites are known without nickel. Yet this alone does not prove meteoric origin since terrestrial nickel-irons are known. Terrestrial nickel-irons, however, have a percentage of nickel either lower (3 per cent) or higher (35 per cent) than that of meteorites, so that a percentage of nickel between 8 per cent and 20 per cent is a pretty sure indication of meteoric origin. The exhibition of octahedral figures on etching is a character confined to iron meteorites, yet a metallic mass may be a meteorite and not give these figures. A pitted surface is characteristic of iron as well as of stone meteorites, but this may be destroyed by weathering; so that its absence is not a sure indication of terrestrial origin. To recapitulate: Stone meteorites usually show a pitted and fused surface, differing in color from the interior and the interior usually contains scattered metallic grains. Iron meteorites always contain nickel, usually exhibit a pitted surface, and frequently show octahedral bands on an etched surface. A convenient test for nickel in a mass whose meteoric origin is suspected may be made by dissolving a fragment of the substance to be tested in nitric acid, adding ammonia till the acid is neutralized, boiling, adding a little more ammonia to make sure that all the iron has been precipitated and filtering off this precipitate (ferric hydroxide). If the filtrate shows a bluish tinge the presence of nickel is indicated, but as small amounts of nickel might not be indicated in this way a few drops of yellow ammonium sulphide should be added to the cold, clear filtrate. If nickel is present, a black precipitate of nickel sulphide will be obtained. In order to test this further, the liquid should be filtered and the precipitate tested with a borax bead. If nickel is present a violet bead will be obtained in the oxidizing flame, changing to reddish brown on cooling. Another test for nickel in the presence of iron consists of dissolving the substance to be investigated in hydrochloric acid, boiling for a moment with a few drops of nitric acid to oxidize the iron, adding a little citric or tartaric acid to prevent precipitation of the iron, neutralizing the solution with ammonia and adding a few drops of a solution of di-methyl gloxine in alcohol. If nickel is present a blood-red color will be given the solution; if not, no change of color will occur.

Owing to the characters above described actual observation of the fall of a meteorite is no longer necessary in order to establish its meteoric origin. In fact, the internal characters of a meteorite furnish at the present time much more reliable evidence of its origin than does as a rule the testimony of human witnesses. Of about seven hundred meteorites now recognized, only about one-half were actually seen to fall. It has been more or less customary to designate meteorites seen to fall as "falls," while those determined from internal characters were called "finds." Since all true meteorites fell at some time, however, the distinction seems superfluous. In the present work all meteorites are referred to as falls, the distinctions of separate falls being based on separate occurrence in time or place, or both.

As between stone and iron meteorites, it may be remarked that a far larger number of stone than iron meteorites has been observed to fall. Of about 350 observed falls only 10 have been of iron meteorites. On the other hand, among meteorite "finds," the iron meteorites largely predominate. This is chiefly for the reason, doubtless, that the iron meteorites by their relatively great weight, metallic resonance and internal silvery appearance attract the attention of the ordinary observer much more quickly than the stone meteorites. The latter show to the casual observer no striking differences from terrestrial rocks, and are thus usually overlooked.

In order to facilitate the comparison, collection, and study of different falls it was long ago found desirable to give each fall a name. Various methods of choosing such names have been adopted: First, and most commonly, that of the province or region where the fall occurred has been used. Second, the name of the discoverer has been applied. Third, the meteorite has been named from some peculiarity of its shape or size. Illustrations of the first class are the names Mexico, Colorado, Texas, which have been given to meteoric falls; of the second class, Gibbs, Lea, Pallas, Humboldt; and of the third class, Signet, Moon, Woman. Of these methods of naming the fall, that of employing the name of the place has been found most satisfactory and has come to be generally adopted, but even this method has passed through some modifications. When but few meteorites were known it was sufficient to designate one as Mexico, another as Colorado, etc., but after two or more meteorites came to be known from the same state or country this method of nomenclature was obviously inadequate. A modification of this method which gained some adoption was that of giving successive meteorites from the same state or province serial numbers, such as Colorado 1, 2, 3, etc., but this was long since abandoned.

For the most part, names of persons or descriptive names that have been applied to meteorites are now also changed to names which show localities. Thus the Pallas meteorite is now known as Krasnojarsk, the Ainsa meteorite as Tucson, the Lea meteorite as Cleveland, etc.

Some authorities, such as Berwerth* have urged that the law of priority should govern the naming of meteorites as it does that of some other objects. This would require, however, giving a number of meteorites the same name and destroy in many cases the very great advantage arising from having the name of a meteorite express the locality of its fall.

Accordingly at the present time in the naming of a meteorite the plan is almost universally followed of designating it by the name of the town or locality of prominence nearest to which it fell. Thus the name Castine, for instance, is used to designate the meteorite which fell at Castine, Maine, May 20, 1848.

For the science which has for its field the study of meteorites, several names have been proposed, but none have as yet received general adoption. Shepard suggested "astrolithology," meaning lithology of the stars, but meteorites are now considered to be quite distinct from the stars. Maskelyne proposed "aërolitics," but the term refers to but a single group of meteorites according to a distinction made by Maskelyne himself. By using the term "meteoritics" the objection mentioned may be overcome and this name may in time gain adoption. The science of meteoritics obviously looks to many other sciences for its

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* Verzeichnis der Meteoriten, 1902, Ann. d. K. K. Naturhist. Hof Mus., Wien, Bd. xviii, pp. 2–3.

data and growth. The science of astronomy throws light on the relations of meteorites to the other heavenly bodies; the sciences of geology, petrology, and mineralogy elucidate the relations of meteorites to the earth and its rocks and minerals, and the sciences of physics and chemistry afford means for the analysis of the structure and composition, spectroscopic characters, etc., which distinguish meteorites from other bodies.

CHAPTER II

PHENOMENA OF FALL

The fall of a meteorite is usually accompanied, as has already been noted, by phenomena of light and sound. These phenomena may be of a startling and violent character or scarcely perceptible. Their nature and extent obviously vary with the distance of the observer from the place of passage of the meteor or from its place of fall, and with the time of fall. Occasionally the passage of a meteor producing meteorites may be observed over an area of thousands of square miles. Falls occurring during the daytime may present no visible phenomena of light and occasionally no sound may be heard, but usually light or sound is observed. Brief descriptions of the phenomena which have accompanied the fall of meteorites at different periods and over various parts of the earth's surface are given following.

At the fall of Tabory, Perm, Russia (Fig. 1), which took place at 12:30 P. M., August 30, 1847, a fiery mass appeared in a clear sky and moved in an almost horizontal direction toward the northeast. It spread sparks in its way which left a bright, smoky trace after them, and some observers saw an illuminated stripe remaining after the mass had passed. The fiery mass remained in view only two or three seconds. Two or three minutes later, sounds like the firing of many cannon were heard. In several villages of the region, black, warm stones weighing from two to twenty pounds fell to the earth.

At the fall of Mocs, Hungary, which occurred February 3, 1882, at 3:45 P.M., an intensely brilliant meteor was seen in a cloudless sky, then a rolling noise and violent detonations were heard. At the spot where the light was first observed, a white, cirrus-like cloud extended in the form of a white stripe from west to east. About a thousand stones fell at this time, the largest of which weighed 70 kilos (154 pounds).

The fall which took place at Sokobanja, Servia, about 2:00 P. M., October 13, 1877, was introduced by two explosions like salvos of artillery, accompanied by a brilliant display of light such as attends the bursting of shells. A dense, black smoke was observed at a considerable altitude, and this broke up into three columns which gradually changed to a white smoke. The noise lasted for some time and resembled the firing of musketry. Soon after the first sound a number of meteorites fell over an area a mile and a half in length and a half-mile in breadth. The largest of these weighed 38 kilos (84 pounds).

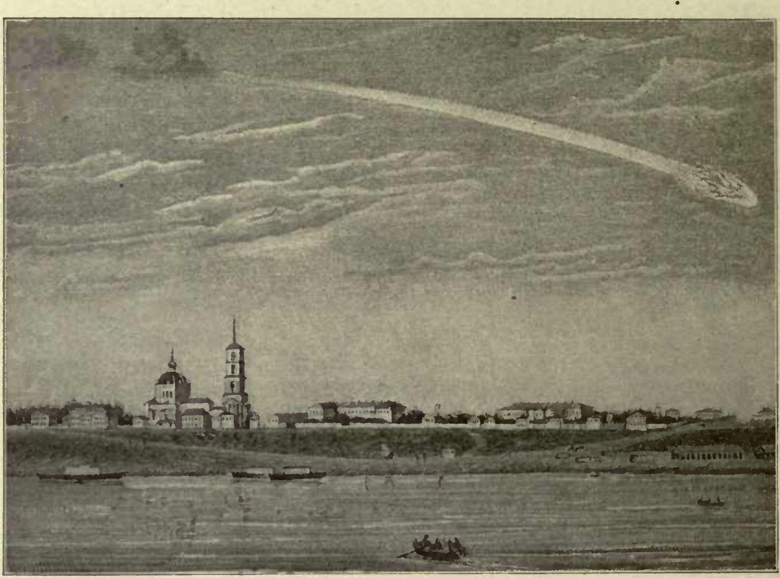

FIG. 1.— Fall of the Tabory, Russia, meteorite, 12:30 P. M., August 30, 1847.

At Sauguis, France, at 2:30 A. M., September 7, 1868, a meteor emitting a pale green light traversed the sky and broke up, leaving a faint, whitish cloud which lasted for some time. The disappearance of this cloud was succeeded by a noise as of thunder, followed by three or four loud detonations, which were heard over a wide area. The inhabitants of Sauguis heard in addition to these noises a sound like that produced by quenching hot iron in water and a dull thud. A stone weighing about 4 pounds was found to have fallen in the bed of a small stream where it was broken to fragments.

The fall of Khairpur, India, which took place September 23, 1873, at 5:00 A. M., was introduced by the appearance of a cluster of meteors in the west. Each member of the cluster is described as having exceeded in brightness a star of the first magnitude and the meteors left behind them a train from 3° to 5° in breadth. The first thought of one observer was that he was gazing at a rocket, but this opinion was soon dispelled as the object rapidly increased in brightness and came toward him leaving a train behind. The motion was not rapid but steady and by the time the mass had come to within about 10° of the meridian, which it passed south of the zenith, it assumed an exceedingly brilliant appearance, the larger fragments, glowing with intense white light with perhaps a shade of green, taking the lead in the cluster, surrounded and followed by a great number of smaller ones, each drawing a train after it which, blending together, formed a broad belt of a brilliant, fiery red color. This light illuminated the whole country like an electric light. The meteor proceeded in this way till it reached a point nearly due east, paling again as it drew near the horizon and about 20° above the horizon appeared to go out. The train continued very bright for some time and was distinctly traceable for three-quarters of an hour after. At first it changed to a dull red, then, as the morning broke, to a line of silvery gray clouds that divided into several portions and floated away on the wind. After the disappearance of the meteor and while the train still attracted attention, there was an interval of perfect silence, then a loud report, followed by a long reverberation that gradually died away as a roll of distant thunder. A number of stones fell from this meteor, over an area 16 miles long by 3 miles wide. The largest stone found weighed about 10 pounds.

The fall which took place at Orvinio, Italy, August 31, 1872, was ushered in by the appearance of what seemed to be a large star of a red color traversing the sky in a northerly direction. This increased in brilliance as it drew on and left a white train in its wake. At a certain point it became brilliantly white and vanished, leaving a luminous cloud which continued to be visible for a quarter of an hour. After the lapse of two or three minutes two reports were heard, the first like that of a cannon, the second like a series of from three to six guns fired in rapid succession. A stone weighing about 7 pounds fell at Orvinio and some fragments were thought to have been carried further northward.

The fall at Hessle, Sweden, which occurred January 1, 1869, at 12:20 P. M., was accompanied by a sound resembling heavy peals of thunder, followed by a rattling noise as of wagons at a gallop and ending with a sound at first like an organ tone and later like that of hissing. Many small stones fell in this shower. One struck ice close to where a man was fishing and rebounded. He picked it up and found it warm.

Witnesses of the fall of the meteorite of Hraschina (Agram) in Croatia, May 26, 1751, state that about 6:00 P. M., as the sun was going down, a fiery ball appeared in the sky, which after dividing into two parts with a report like the sound of artillery, scattered more so that it appeared like a fiery chain falling from heaven. After it trailed a dark smoke which exhibited different colors. Two iron masses, one weighing 80 pounds and the other 16 pounds, were found to have fallen in a field. The accompanying view (Fig. 2) drawn by Haidinger from the accounts of witnesses represents the large and small masses, and A the cloud from which they came.

At Lancé, France, a fall which occurred July 23, 1872 at, 5:20 P. M., was first observed as a sudden increase of light during full sunshine. A brilliant double meteor of a rose-orange color was then seen traversing the heavens with enormous velocity toward the northeast. It separated into two luminous globes, which are said to have had the appearance of two candle flames proceeding horizontally. These passed out of sight at a very low elevation, their disappearance being followed by a sharp sound without echo. The inhabitants of villages to the north saw a small cloud of smoke and heard a tremendous explosion so severe that it caused houses to shake. A large stone weighing 103 pounds which penetrated the soil to a depth of four feet was found at Lancé and a smaller one about six miles distant. The trajectory of this meteorite seems to have been remarkably flat. Its velocity was calculated to have been 2200 feet per second.

FIG. 2.— Fall of the Agram, Croatia, meteorite, about 6:00 P. M., May 26, 1751. At the left the sun is represented as shining.

The meteor which preceded the fall which took place at Weston, Connecticut, at 6:30 A. M., December 26, 1807, was first seen as a globe of fire about one-half the diameter of the moon, rising into the sky from the north. The progress of the meteor is described as not so rapid as that of ordinary meteors or shooting stars. As the morning was cloudy the meteor passed in its course behind the clouds at intervals. The dark clouds nearly obscured it but it shone through the thinner clouds and in the clear sky it flashed with a vivid light like that of heat lightning. In the clear sky a brisk scintillation was also observed about the body of the meteor, like that of a burning fire-brand carried against the wind. A conical train of light was also seen to attend it, waving, and in length about 10 or 12 diameters of the body. The meteor disappeared about 15° short of the zenith. It did not vanish instantaneously but grew fainter and fainter "as a red-hot cannon ball would do if rapidly cooled." The whole period between the first appearance and the total extinction was estimated as about 30 seconds. About 30 or 40 seconds after this disappearance, three loud and distinct reports like those of a small cannon near at hand were heard. Then followed a rapid succession of duller reports, running into each other and producing a continued rumbling like that of a cannon ball rolling over a floor with a varying intensity of sound. Some observers compared the sound to that of a wagon running rapidly down a long and stony hill, and others to a volley of musketry protracted into what is called a running fire. This sound died away in the direction from which the meteor came. Stones fell from this meteor at three different places in the line of movement over an area about 10 miles long. The largest and last to fall weighed about 200 pounds. Especial interest attaches to the circumstances of this fall on account of the fact that the possibility of such an occurrence was at that time scarcely believed and the general opinion was expressed by the President of the United States, Thomas Jefferson, in the remark that it was easier to believe that Yankee professors would lie than to believe that stones would fall from heaven. Subsequent evidence has, however, left no doubt that the Yankee professors (Profs. Silliman and Kingsley of Yale), as well as other historians of the fall, were describing a real occurrence.

The meteorite which fell at Warrenton, Missouri, about sunrise January 3, 1877, first indicated its coming by a sound described by some observers as like the whistle of a locomotive and by others as like the passage of a cannon ball through the air. To four observers the sound became louder and louder and a stone struck a tree near them, breaking off the limbs and coming to the ground with a crash. The snow was melted and the frozen ground thawed near where the stone fell, but the pieces though warm were easily handled. The stone was broken by the fall but the fragments aggregated nearly 100 pounds in weight. No explosion was heard nor were any luminous phenomena noted.

The meteoritic shower which occurred near New Concord, Ohio, about 12:30 P. M., May 1, 1860, was introduced by a strange and terrible report in the heavens, which shook the houses for many miles about. The first report was immediately overhead and after an interval of a few seconds was followed by similar reports with such increasing rapidity that after reaching the number of twenty-two they were no longer distinct but became continuous and died away like distant thunder. Three men working in a field heard, after the first terrible report, a buzzing noise overhead and soon observed a large body descend and strike the earth at a distance of about one hundred yards. This body proved to be a large stone which buried itself about two feet beneath the surface and when obtained was quite warm. The day was cool and the sky covered at the time with light clouds. At Cambridge, Ohio, eight miles west, three or four distinct explosions were heard like the firing of heavy cannon, with an interval of a second or two between each report. This was followed by sounds like the firing of musketry in quick succession which ended with a rumbling noise like distant thunder.

The Cabin Creek, Arkansas, meteorite, one of the few irons and the largest iron ever seen to fall, fell at 3:00 P. M., March 27, 1886. It gave the first indication of its approach to the party who was nearest it, a lady in a house 75 yards away, by a very loud report which caused "the dishes in the closet to rattle and was louder than thunder." Running out of the house the lady saw limbs falling from the top of a tall pine tree, 107 feet high. Three hours later a hole was found near the tree in which an iron meteorite had buried itself to the depth of three feet. The ground was warm and the iron as hot as men could well handle. The loud report which startled the first mentioned observer was heard as far as 75 miles away and was there followed by a hissing sound as if metal had come in contact with water. No luminous phenomena were reported.

The fall of the iron meteorite of Mazapil, Mexico, which occurred about 9 P. M., November 27, 1885, was indicated to the nearest observer by a loud, sizzling noise as though something red-hot was being plunged into cold water, and almost instantly there followed a somewhat loud thud. The air was at once filled with a phosphorescent light with small luminous sparks suspended in it. Horses in the vicinity were much frightened. The luminous air soon disappeared and there remained on the ground a light such as is made when a match is rubbed. After the observers had recovered from their surprise they saw a hole in the ground and in it a ball of light. They feared this ball would explode and retired for a time, but returning found in the hole what looked like a stone which was too hot to handle. This the next day they found to be an iron weighing about 10 pounds. The hole was about one foot deep.

At the fall of the iron meteorite of Braunau, Bohemia, which took place July 14, 1847, at 3:45 A. M., the people of Braunau were wakened from sleep by two violent sounds like cannon shots followed by a whistling and rushing sound which lasted several minutes. Those who hastened into the open air saw to the northwest in a sky in which some stars were yet visible, a small, black cloud. This cloud glowed and emitted tongues of light, two of which flashed to the earth. About the fiery cloud was seen one of ash-gray color which finally disappeared in the direction in which the wind was blowing. An iron meteorite weighing 48 pounds was found in a hole three feet deep, and this six hours after the fall was so hot as to burn the hands of those who touched it. About a mile away to the southeast a mass weighing 35 pounds fell through the roof of a house and near a bed where three children were sleeping.

At the fall of the Rowton, England, meteorite, which took place at 3:40 P. M., April 20, 1876, a strange, rumbling noise was heard, followed almost instantaneously by a startling explosion resembling a discharge of heavy artillery. About an hour later a hole was found in the ground and at a depth of 18 inches in this hole there reposed an iron meteorite weighing 7¾ pounds.

At Quenggouk, India, a meteor burst into view at about half-past three A. M., December 27, 1857. It was in the western quarter of the sky. It sped across the sky in an almost due easterly direction seeming "three times as large as the full moon" and with a blinding brilliancy of light. Far behind its brilliant forward point there trailed a great, luminous, variegated nebulous cloud. A terrific explosion was heard, followed by lesser ones and a protracted rumbling. Three small stones were found to have struck the ground.

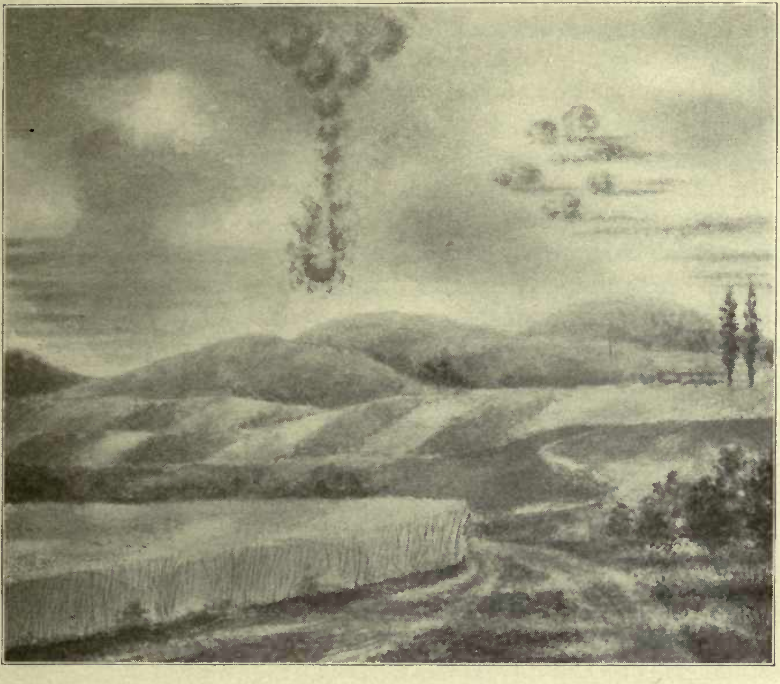

FIG. 3.— Fall of the Knyahinya, Hungary, meteorite, 5.00 P. M., January 9, 1866.

At the fall of Knyahinya, Hungary (Fig. 3), which took place about 5:00 P. M., January 9, 1866, those nearest the point of fall heard sounds like cannon-shots followed by a noise like the boiling of water and a long roll. At the same time a cloud of smoke appeared in the sky from which stones fell. These observers saw no light, but those at a distance of 10 or 12 miles saw a fire ball of the color of white-hot iron with edges of ultramarine blue. Some saw this divide in two. About 1000 stones, ranging in size from 2 grams to 300 kilograms, were precipitated over an area about 9 miles long by 3 miles wide. The stones picked up immediately after the fall were described as being lukewarm or warm. The largest stone found penetrated the soil to a depth of 11 feet, entering in an oblique direction. From subsequent measurements it was calculated that the meteor first appeared at a height of 7¾ miles and dropped almost directly downward.

Phenomena of especial impressiveness seem to have attended the fall of Homestead, Iowa, which took place February 12, 1875, about 10 P. M. A meteor was seen moving north and east and from the first the light of the meteor could hardly be tolerated by the naked eye turned full upon it. Several observers who were facing south at the first flash, say that upon looking full at the meteor it appeared to them round, and almost motionless in the air, and as bright as the sun. Its light was not steady, but sparkled and quivered like the exaggerated twinklings of a large fixed star, with now and then a vivid flash. To these observers, all of whom stood near the meteor's line of flight, its size seemed gradually to increase, also its motion, until it reached a point almost overhead, or in a direction to the east or west of the zenith, when it seemed to start suddenly, and dart away on its course with lightning-like rapidity. The observers who stood near to the line of the meteor's flight were quite overcome with fear, as it seemed to come down upon them with a rapid increase of size and brilliancy, many of them wishing for a place of safety but not having time to seek one. In this fright animals took part, horses shying, rearing, and plunging to get away, and dogs retreating and barking with signs of fear. The meteor gave out marked flashes in its course, one more noticeable than the rest, when it had completed about two-thirds of its visible flight. All observers who stood within twelve miles of the meteor's path say that from the time they first saw it, to its end, the meteor threw down "coals" and "sparks."

Thin clouds of smoke or vapor followed in the track of the meteor and seemed to overtake it at times, and then were lost. These clouds or masses of smoke gave evidence of a rush of air with great velocity into the space behind the meteoric mass. The vapor would seem to burst out from the body of the meteor like puffs of steam from the funnel of a locomotive, or smoke from a cannon's mouth, and then as suddenly be drawn into the space behind it. The light of the meteor's train was principally white, edged with yellowish green throughout the greater part of its length, but near to the body of the meteor the light had a strong red tinge. The length of the train was variously estimated, but was, probably, about 9°, or from seven to twelve miles, as seen from Iowa City. The light about the head of the meteor at the forward part of it, was a bright, deep red, with flashes of green, yellow, and other prismatic colors. The deep red blended with and shaded off into the colors of the train at the part following; but the whole head was enclosed in a pear-shaped mass of vivid white light next to the body of the meteor, and the red light fringed the white light on the edges of the figure, and blended with it on the side presented to the eye.

From three to five minutes after the meteor had flashed out of sight, observers near the south end of its path heard an intensely loud and crashing explosion that seemed to come from the point in the sky where they first saw it.

This deafening explosion was mingled with, and followed by, a rushing, rumbling, and crashing sound that seemed to follow up the meteor's path, and at intervals, as it rolled away northward, was varied by the sounds of distinct explosions, the volume of which was much greater than the general roar and rattle of the continuous sounds. This commotion of sounds grew fainter as it continued, until it died away in three to five explosions much fainter than the rest.

From one and a half to two minutes after the dazzling, terrifying, and swiftly moving mass of light had extinguished itself in five sharp flashes, five quickly recurring reports were heard. The volume of sound was so great that the reverberations seemed to shake the earth to its foundations, buildings quaked and rattled, and the furniture that they contained jarred about as if shaken by an earthquake; in fact, many believed that an earthquake was in progress. Quickly succeeding, and in fact blended with the explosions, came hollow bellowings, and rattling sounds, mingled with a clang, and clash, and roar that rolled slowly southward as if a tornado of fearful power was retreating upon the meteor's path.

The phenomena observed in the fall of a meteorite are due chiefly to the resistance of the air, some of the effects of which may be considered in a general way as follows:

A body in moving through any medium such as air or water experiences a certain resistance; for the moving body sets in motion those parts of the medium with which it is in contact, and thereby loses an equivalent amount of its own motion.

This resistance increases with the surface of the moving body; thus a soap-bubble or a snowflake falls more slowly than a drop of water of the same weight. It also increases with the density of the medium; in rarefied air it is less than in air under the ordinary pressure; and in this again it is less than in water.

The resistance also increases with the velocity of the moving body, and for moderate velocities is proportional to the square; for, supposing the velocities of a body made twice as great, it must displace twice as much matter, and must also impart to the displaced particles twice the velocity. For high velocities the resistance in a medium increases in a more rapid ratio than that of the square, for some of the medium is carried along with the moving body, and this, by its friction against the other portions of the medium, causes a loss of velocity.

Light bodies fall more slowly in air than heavy ones of the same surface, for the moving force is smaller compared with the resistance. The resistance to a falling body may ultimately equal its weight; it then moves uniformly forward with the velocity which it has acquired. Thus, a raindrop falling from a height of 3000 feet should, when near the ground, have a velocity of nearly 440 feet per second, or that of a musket-shot; owing, however, to the resistance of the air, its actual velocity is probably not more than 30 feet per second.

The slowing down by the resistance of the air, of a body having the velocity of a moving meteorite, has been calculated for a number of special cases by Schiaparelli. He found that a ball 1½ inches in diameter with a specific gravity of 3.5 and having an initial velocity of 9 miles per second would have its velocity reduced to ⅓ of a mile per second on arriving at the point where the barometric pressure is 1/66 that at the earth's surface. If the ball had an initial velocity of 40 miles per second the reduction of velocity in the early stages of its fall would be much greater, and on arriving at the point where the atmospheric pressure is 1/66 that at the earth's surface it would be reduced nearly to that of the ball which started with a velocity of 9 miles per second.

The changes are shown in full in the following table:

Initial velocity 72,000 meters (40 miles) per second		Initial velocity 16,000 meters (9 miles) per second	
Remaining velocity, in meters	Atmospheric pressure in mm.	Remaining velocity, in meters	Atmospheric pressure in mm.
72,000	0.0000	16,000	0.0000
60,000	0.0005	14,000	0.0064
48,000	0.0013	12,000	0.0162
36,000	0.0031	10,000	0.0322
24,000	0.0082	8,000	0.0620
12,000	0.0358	6,000	0.1280
8,000	0.0816	4,000	0.3055
4,000	0.3151	2,000	1.2293
2,000	1.2489	1,000	4.2986
1,000	4.3182	500	11.6192
500	11.6388		

The same author has calculated that for a body to reach the earth with a velocity of 500 meters (⅓ mile) per second it must, if of the specific gravity of a stone meteorite, have a diameter of 2.61 meters (8 feet), and if an iron meteorite, 1.17 meters (3 feet).

Niessl* has calculated for several observed meteoric falls the height above the earth at which their initial velocity

*Sitzb. Wien Akad., 1884, 89, 2, 283–293.

was overcome and from which they fell under the influence of the earth's gravity alone. These heights were:

Homestead	3.7 km.
Krähenberg	8.2 km.
Mocs	8.4 km.
Weston	11.1 km.
Knyahinya	11.9 km.
Braunau	14.8 km.
Orgueil	23.0 km.
Pultusk	41.5 km.
Hraschina	46.7 km.

The slowing up of a meteorite by the resistance of the air exerts a powerful disruptive force upon it, since the rear of the meteorite tends to travel with a planetary velocity while the forward part is being checked. Thus Hauser calculated that a meteorite having a volume of a cubic meter and being a square meter in section would, if moving at a velocity of 30 miles per second, develop an internal disruptive force of nearly 3 billion kilogram-meters on arriving within 16 miles of the earth's surface. That this force would tend to burst the meteorite there can be no doubt.

The enormous heat developed by such a checking of velocity or the conversion of its motion into heat, should also be considered. Thus a body weighing one pound, and moving 25 miles a second, has momentum sufficient to raise $(25 \times 5280)^2 \div 2g = 271,500,000$ pounds one foot. By Joule's equivalent, the raising of 772 pounds one foot corresponds to the heat necessary to raise one pound of water one degree Fahrenheit. If the capacity of the meteoric substance for heat is 0.2 (that of iron is 0.12), the loss of a velocity of 25 miles would be equivalent to heating $(271,500,000 \div 0.2) \div 772 =$ 1,760,000 pounds of the substance one degree Fahrenheit, if the whole of the motion was transformed into heat.

The sounds like thunder usually accompanying the fall of a meteorite, are doubtless due, as in the case of lightning, to the explosive shock given to the surrounding air by the sudden heating of the air in the vicinity of the passing meteorite. The pressure thus produced is, according to Thomson* in the case of lightning, equal to ten atmospheres

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* Science, Dec. 17, 1909.

and is probably not less in the fall of the average meteorite. The prolonged and varying rolling sound is also due as in the case of lightning to irregular movements of the meteorite in its course through the air. The first sound heard comes from the part of the path nearest the observer and then follows that derived back along the meteor's path. Any twistings and bendings of the course of the meteorite will cause blendings and separations of the sound waves which will give varying effects.

The effect of the impact of a meteorite upon the earth depends among other factors upon the velocity of the meteorite and the nature of the surface upon which it falls. So far as the velocity of the meteorite is concerned, all evidence indicates, as already noted, that the meteorite loses its planetary speed in the upper layers of the atmosphere and falls during the latter part of its course like any free falling body.

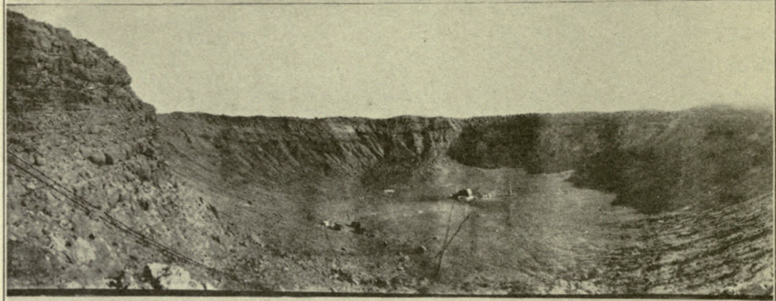
Thus the velocity of the Middlesbrough meteorite on striking the ground was calculated by Herschel to have been 412 feet a second. Borgström reckoned the velocity of the Hvittis meteorite from the depth of the hole which it made in a stiff loam to have been 584 feet a second; that of the St. Michel meteorite (Fig. 4) from similar observations to have been between 563 and 710 feet a second, and that of the Shelburne meteorite to have been 515 feet per second. The depth to which a meteorite will penetrate obviously depends much upon the nature of the soil. A meteorite striking upon a ledge of rock as did that of Long Island, will, if it is a stone meteorite, itself be shattered. On the other hand, when striking soil meteorites may enter it to a considerable depth. The Hvittis and St. Michel meteorites above mentioned passed the one into stiff clay and the other into morainic material to a depth of about two feet each. The largest stone of the Estherville shower, weighing 437 pounds, penetrated stiff clay to a depth of eight feet, and the next smaller stone, weighing 170 pounds, embedded itself in similar material to a depth of five feet. These were, however, stones of higher specific gravity than those previously mentioned. The Farmington meteorite weighing 180 pounds went into hard clay to a depth of four feet. The Kilbourn meteorite, a stone about the size and shape of a man's fist, passed in succession through a barn roof composed of three thicknesses of shingles, a hemlock board an inch thick, and another hemlock board of the same thickness about four

Fig. 4.— Hole in ground made by fall of the St. Michel meteorite. After Borgström.

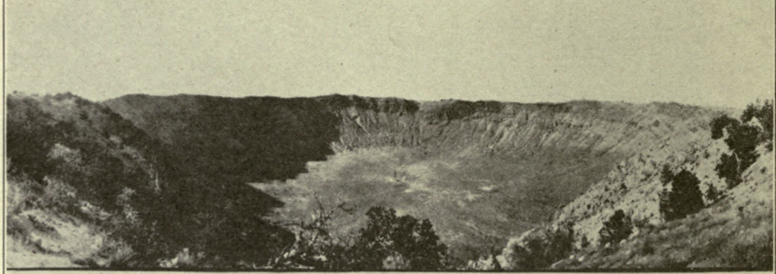
feet below this. The direction of penetration of a meteorite is not always vertical, since the direction of motion of the meteorite is sometimes tangential. Thus the largest stone of the Knyahinya fall, a stone which weighed 660 pounds, reached a depth in the earth of eleven feet, but in a direction inclined about 27° from the vertical so that a stake driven down in the center of the hole which it made failed to strike it. Motion in a direction much inclined from the vertical may account for the apparent lack of forceful impact observed in the fall of many large iron meteorites. These masses with their weight of many tons should seemingly reach to great depths on striking the earth, but little evidence of such penetration has yet been secured. As a rule these masses are found near the surface.

The most extensive terrestrial effect which has ever been ascribed as possibly due to meteoritic impact is to be seen at Canyon Diablo, Arizona, at the point of fall of the Canyon Diablo meteorites. The immediate locality of the fall is known as Coon Butte or Meteor Crater. Here a circular depression about 4000 feet in diameter and 570 feet deep occurs in the surface of an otherwise comparatively level plain. (Fig. 5). The walls of this "crater," as it has been called, are composed of limestone and sandstone and the layers of these rocks dip away from the center of the crater at varying angles. Along the southern wall the limestone and sandstone have been lifted vertically more than 100 feet. At its highest point the crater rim is 160 feet above the outlying plain, and at its lowest 120 feet. The mass of the crater rim is composed of loose, unconsolidated material varying in size from microscopic dust to blocks weighing hundreds of tons. The floor of the crater is comparatively level but has probably been built up by inwash from the sides. Special significance is attached by investigators of the region to the presence of a gray or white sandstone, much of it in the form of a rock flour which is found in the floor of the crater and about its rim. This sandstone is regarded, on account of its structure, as showing signs of metamorphism by heat. Mixed with this material are particles of nickel-iron. At a depth of 820 feet below the floor

METEOR CRATER – COCONINO COUNTY – ARIZONA.



INTERIOR VIEW OF CRATER LOOKING S.S.E.



INTERIOR VIEW OF CRATER LOOKING N.N.W.

VIEW OF CRATER FROM W.N.W. AT DISTANCE OF SEVERAL MILES.

FIG. 5.— Meteor Crater, Arizona. It is about this area that the Canyon Diablo meteorites are found.

of the crater undisturbed strata of red and yellow sandstone are found. Scattered about over the floor of the plain iron meteorites have been found in numbers reaching thousands, and in weight aggregating several tons. Within the crater itself only a few small meteorites have been found. The peculiar topographic form and the associated meteorites lend considerable plausibility to a hypothesis which has been urged by several observers but especially by D. M. Barringer.* This hypothesis ascribes the formation of the crater to the impact of a huge meteorite which was wholly or in part metallic. The dimensions of this meteorite were calculated by Barringer and Tilghman from the size of the crater to have been about 500 feet in diameter.

Complete proof of the correctness of the hypothesis would be obtained by finding within the crater above the undisturbed sandstone a meteoric mass or many of them which would together approximate the size mentioned. Although a number of borings have been made in search of such a mass or masses, none has as yet been found. Search for such a mass with magnetic instruments has likewise given negative results. It has been suggested that the enormous force of impact might have rent the mass of the impinging body into minute fragments, some of which are represented by the nickeliferous particles found in the white sand, and hence no large mass now exists. No certain conclusion can as yet be drawn in regard to this view. An alternative to the hypothesis of meteoritic origin is to assume that the crater originated from some terrestrial force, and that the occurrence of such meteorites as have been found here is purely coincidental. This was the conclusion of G. K. Gilbert, who ascribed the formation of the crater to a steam explosion of volcanic origin. The opponents of this view, however, state that there are no known volcanoes or hot springs near the region to afford the heat necessary for such an action. It seems as yet therefore impossible to give final decision as to the origin of the "crater."

The resemblance of this topographic feature to that of the so-called volcanoes of the moon has often been re-

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*Meteor Crater: Philadelphia 1909. Published by the author.

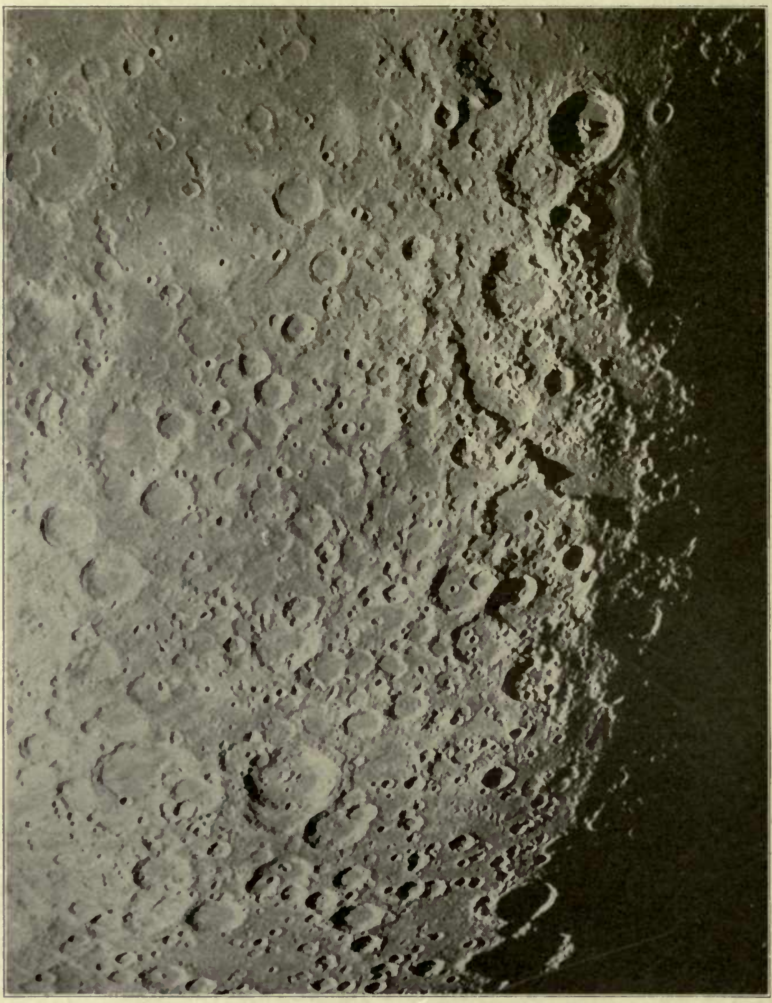

FIG. 6.— Craters of the moon. They resemble Meteor Crater, Arizona, in form and by some have been thought to be formed by the impact of meteorites.

marked and it has been suggested that the moon craters are in reality impact pits caused by the striking of large meteorites upon the moon's surface (Fig. 6). Those who urge this view find cause for the greater effect of such impact upon the moon as compared with the earth in the absence of an atmosphere from the moon. There is thus nothing upon the moon to burn up falling bodies before they reach its surface. There can be no doubt that the earth's atmosphere affords an immense protection to its inhabitants in burning up bodies which would otherwise reach the earth's surface but that meteorites sufficiently large to make the great craters on the moon's surface have ever fallen on that body seems somewhat questionable.

Meteorites show little warmth when they arrive upon the earth. The stone meteorites at any rate are almost always spoken of as being "milk warm" or "barely warm" by those who pick them up immediately after their fall to the earth. Neither are there any indications of any heating effect where meteorites have struck the earth. No baking of the soil or charring of vegetation can be observed. Meteorites have also fallen in haystacks, within barns or in other places where a little heat might start a fire but have never produced any incendiary effects so far as known. This lack of heat is contrary to the general belief, the common opinion being that meteorites are intensely hot when they reach the earth. This opinion is evidently based on the brilliant light emitted by meteors in their course in the atmosphere. A little consideration of the matter, however, will convince one that no heating phenomena should be expected for three reasons:

1. The substance of stone meteorites is a poor conductor of heat.

2. The period in which they might acquire heat is extremely short, but a few seconds at most.

3. Any portion of their surface sufficiently heated to become in a condition even approaching viscosity is immediately removed by the pressure of the surrounding air. With the iron meteorites the case is somewhat different since they are much better conductors of heat than stone

meteorites. They, therefore, generally possess considerable warmth when picked up immediately after their fall. The Cabin Creek meteorite is described as being "as warm as could be handled" after being dug from a hole three feet deep. The Mazapil meteorite was so warm that it could be "barely handled" on removal. The heat emitted even in these cases, however, was not great. Any accounts, therefore, of intense heat being displayed by meteorites can usually be assumed to be false, the observer's previously formed opinion probably coloring his testimony if his testimony is sincere.

FIG. 7.—Old drawing perhaps representing a fall of meteorites.

No meteorite fall has ever positively been known to have been destructive to human life. Accounts purporting to describe such catastrophes prove on investigation to have come either from times or countries so remote that they cannot be verified. Many accounts of such an occurrence come to us from earlier times, and the scene here pictured (Fig. 7) probably illustrates destruction believed by the early artist to have been caused by meteoric stones falling from the skies. But no well authenticated occurrence of the sort is known. Perhaps the most narrow escape which has ever been experienced was that of three children in Braunau at the time of fall of that meteorite in 1847. This meteorite, an iron weighing nearly 40 pounds, fell in a room where these children were sleeping and covered them with debris, but they suffered no serious injury. Other meteorites have fallen near human beings but never have struck them so far as credible information goes. That personal injury or death might be caused by the fall of a meteorite is entirely possible, in fact is likely to occur at some time. It is remarkable that some falls, such for instance as the showers in Iowa which occurred in fairly thickly settled communities, should not have caused serious injury to the inhabitants.

Injury to animals from falling stones has perhaps occurred in a few instances. Cattle were said to have been struck by falling stones in the shower of Macao, Brazil, in 1836, and a dog was reported to have been killed by a meteoric stone in Nakhla, Egypt, in 1911. The evidence in regard to these occurrences is not, however, altogether satisfactory. Buildings have several times been struck by meteorites and usually have been penetrated by them. Besides the building mentioned above as struck by the Braunau meteorite, a 12-pound individual of the Pillistfer fall fell through a tile roof and a floor of a building, and the Kilbourn meteorite penetrated a barn. Buildings were also penetrated by the Aussun, Barbotan, Benares, and Mässing meteorites.

The following recommendations to observers on occasions of the falls of meteorites, describing the points of information most desirable to be recorded regarding their characters and appearance, were published by a committee of the British Association in 1878:*

"In recording observations on the passage of a meteor across the sky, the points which it is most desirable to arrive at are: such data as will allow of our definitely noting the direction of its path and its point of extinction, the duration of the luminous phenomenon, and of individual phases of it, the apparent magnitude of the meteor, the luminosity as compared with other brilliant objects and the changes which it may itself exhibit in this respect during the transit, the duration of the train (or 'streak'), and the changes it may undergo before extinction (whether it fade away simultaneously along the entire length, or break up into a chain of luminous fragments); also, in cases where the streak is one of great persistence, the manner of its final disappearance; again, when the meteor has been observed near the time of sunrise, or sunset, what change it wrought in the appearance of the visible train by the increasing or waning light of the sky. The sound attending its passage, if any, and the character of the sound, as regards intensity and dura-

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* Rept. Brit. Assn. Adv. Sci., 1878, pp. 375-377.

tion, whether single and well defined, or a series of minor explosions closely following one another should be noted and finally, the time of appearance, and that of the interval before the explosion is heard.

"While it is hardly possible for one observer to record all the data referred to, he should not fail to note such of them as may have come clearly within his observation. Other spectators may have remarked what he may have missed, and their joint observations may enable us to arrive at a complete physical history of the meteor in question.

"It is desirable to determine two points of the track of the meteor, as far asunder as possible — the points of appearance and extinction are to be preferred — and to indicate the former by reference to some star or constellation which it overlies, and the latter by some object on the horizon against which it is projected. In cases where the meteor is seen in daytime, the data to be arrived at are the points of appearance and its angular altitude. The former may be estimated by noticing what conspicuous object lies vertically below it on the horizon; a village or a mountain peak. The more distant the object is from the spectator, the more accurate will be the determination of this element of the observation. If objects to which reference can be made should be wanting, the direction may be temporarily noted, and subsequently determined by the aid of a compass-needle. To learn an angular altitude we dare not trust general conclusions, however carefully arrived at; even experienced observers may be misled in such cases. If a vertical object, say the roof of a house, or the top of a tree, happens to lie in the direction under consideration, the observer should approach it till the line of sight of the origin of the course of the meteor skirts the summit of the terrestrial object. The observer has now to determine how far he is removed from the object selected, its vertical height above the plain on which both are situated, and the distance above the ground of his own eye, in order to be in a position to determine the angular elevation of the point of appearance of the meteor, the position of which he desires to ascertain.

"The apparent path of the meteor is often represented by a line like a bow; in other words, the meteor apparently ascends, culminates, and then takes a downward course. This motion is, however, for the most part apparent only; and is a consequence of the varying inclination which a straight line appears to form with the horizon at different points along its course. The observer should endeavor to determine as accurately as possible the apparent inclination at those points of the meteor's arc, or line of flight, which can be most readily identified, such as the beginning and the end of the track, or those where a break in the luminous train occurs, as well as that portion which lies parallel to the horizon. The point of extinction should especially be noted, and this is the more readily accomplished from the fact that the attention has been steadily directed to observing the luminous phenomena preceding it. In regard to the point of appearance, it is of importance to determine whether the impression made on the observer was that he had witnessed the blazing forth of the meteor in the sky, or whether the meteor had entered his field of vision, and a portion of its luminous track had not been seen by him.

"It is, moreover, of importance to arrive at a knowledge of the length of time occupied by the meteor in traversing the sky; this may sometimes be learned by counting the ticks of a watch, or by advancing in the direction of the object at a uniform rate, and counting the paces taken during the observation. It should also be noted whether the meteor moves onward with an accelerating or diminishing velocity.

"The brilliancy of a meteor larger than the fixed stars of different magnitudes can most conveniently be compared with the light of Venus or Jupiter; and in the case of the largest meteors, with the apparent brilliancy and magnitude of the moon in her several phases. The colour exhibited by the meteor should also be carefully observed, and any change of hue along any part of the path should be recorded. The luminous train left after the disappearance of the meteor is sometimes very persistent, and often terminates in a cloud, faintly visible. Any peculiar structure exhibited by the train, or cloud, should be sketched on paper.

"The sound attending the flight of the meteor usually consists either of several distinct explosions, or a crackling, rolling detonation. The closest attention should be given after the extinction of the meteor, for the arrival of the sound and the length of the interval should be carefully noted with the watch.

"Of the many points which, as has been shown, it is desirable that a record should be made, an individual observer can obviously determine but a few; all those of them, however, to the accuracy of which he can certify, are of value since other observers may supply the missing data, and the whole may be collected.

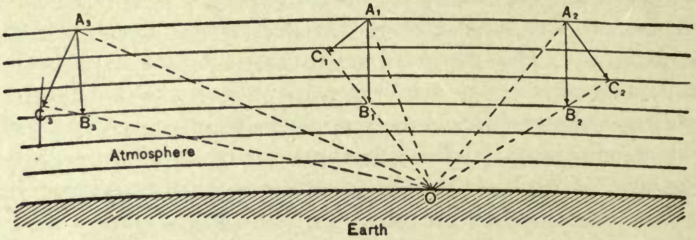

FIG. 8.— Diagram showing effect of position of observer on the apparent paths of meteors. The actual paths are $\overline{AB}$, but the apparent paths as seen at O are $\overline{AC}$. After Moulton.

"If a meteorite has fallen, visit the spot where it struck the ground, and examine the hole which it formed. Determine the depth, and especially notice the direction of the cavity in respect to the points of the compass. Ascertain whether the meteorite was removed from the ground soon after its descent, and whether any observations had been made at the time respecting its temperature. Make a note of the material forming the surface layer, and state whether it was moist or dry. Further inquiries in the neighborhood may lead to the discovery of other meteorites which had fallen at the same time, and at points not unfrequently miles distant. They may vary greatly in size; and stones as small as a pea or bean may be sought for."

To these suggestions may be added in the case of a meteoritic shower the recommendation that the distribution of the meteorites with respect to their size should be observed and the extent and dimensions of the area over which they have fallen should be determined as far as possible. Also an effective means of measuring the height of a meteor has been suggested by Sir Robert Ball. This method requires that two observers situated a number of miles apart should note the meteor and its direction from them. Then on a map of any convenient scale a straight wire should be raised from the position of each observer in the direction in which he saw the meteor. The point of intersection of the wires will show the true position of the meteor and a perpendicular let fall from this point will show its height expressed in the scale of the map.

Further, the effect of the position of the observer on the apparent paths of meteors should be considered. Thus in the accompanying figure (Fig. 8), there are represented the paths of three meteors which are parallel, AB, but their apparent paths as seen by an observer at O will vary in direction, being the lines AC. It is by continuing the lines backward on the celestial sphere that the point from which the meteors came can be determined.

CHAPTER III

GEOGRAPHICAL DISTRIBUTION OF METEORITES

Broadly speaking, we know no fundamental reason why meteorites should be any more numerous upon one part of the earth's surface than upon another.

Compared with the vast area of space in which meteorites wander, our earth is but a point, and moreover a rotating and wabbling point, ever presenting new surfaces to the portions of space in which it is traveling. The marksman who displays his skill by shooting glass balls thrown into the air would have the difficulty of his task enormously increased if he should endeavor to strike successively the same point upon the ball, especially if it had in addition to its forward motion one of rapid rotation about a wabbling axis. Yet this is what a falling meteorite must do if it is to reach any particular point on the earth's surface. These considerations make it difficult to believe that any particular portion of the earth's surface is more likely than another to receive meteorite falls. However, knowledge of falls requires observers or finders and they must be persons of sufficient intelligence to recognize the nature of their finds. Hence a map of the localities from which meteorites are known shows by far the larger part of them in civilized countries and the falls apparently the more abundant the greater the population. Of 634 known meteorites, 256 have been found in Europe and 177 in the United States. Thus more than two-thirds of the known number are from less than one-eighth of the land surface. We have no reason to suppose that these regions actually receive more meteorites than others less intelligently populated and any apparent excess or lack of meteorites in any given locality must be considered in the light of these facts. Taking these facts into consideration, however, there seem to be certain inequalities of distribution of meteorites which may be of some significance. Meteorites seem to be somewhat more abundant in mountainous or elevated regions than in those of an opposite character. Thus they seem to be more abundant near the Himalayas in India, near the Alps in Europe, and about the high peaks of the southern Appalachians in the United States. The largest iron meteorites of North America are nearly all found in the Cordilleras. Whether such regions exert a greater gravitational force or whether they present an actual physical obstacle to the passage of a meteorite is uncertain, but it is probable that if either agency is operative it is the obstructive one. Another seeming difference in distribution may be noted if the meteorites of the two hemispheres of the world be compared: Thus of 256 meteorites known from the western hemisphere, 182 are irons and only 74 stones; while from the eastern hemisphere, of 378 known, 299 are stones and only 79 are irons. Berwerth has sought to account for the excess of irons in the New World by the suggestion that the dry air of the desert areas which abound in this hemisphere has preserved meteorites fallen in long distant periods while those of a similar age in the other hemisphere have been exposed to a moist climate and have for the most part been decomposed. It is true that many of the iron meteorites known from the western hemisphere occur upon the Mexican and Chilean deserts, but quite as many come from the southern Appalachians, where a comparatively moist climate prevails. There are also numerous desert areas in the Old World perhaps as fully explored as those of the New, so that on the whole the above explanation seems inadequate.

Other remarkable groupings of meteorites with regard to their geographical distribution may be noted when areas smaller than hemispheres are compared. Thus of a total of nine meteorites belonging to the class of howardites, five have fallen in Russia. Of the nine meteorites known belonging to the class of carbonaceous meteorites, three have fallen in France and two in Russia.

Again small areas of equal extent and equally well populated vary curiously in their number of meteorite falls. Within the state of Illinois, for instance, no meteorite is known ever to have fallen, while in the state of Iowa, which has about the same area, but a smaller population, four falls have been noted, and from the state of Kansas, which has a larger area than Illinois, but a smaller and less uniformly distributed population, twelve meteorites are known.

CHAPTER IV

TIMES OF FALL

Considering meteorite falls by years it should be remembered that previous to the nineteenth century little reliable record of such falls is available. Single falls are known for the years 1492, 1668, 1715, 1723, 1751, 1766, 1773, 1785, 1787, 1790, 1794, 1795, and 1796, and two falls each for the years 1753, 1768, and 1798. Moreover, for the early part of the nineteenth century the record is not very complete, since during that period the possibility of meteorite falls was yet much doubted. But from 1800 to 1910, 331 falls may be accepted as well authenticated as to their month and year. During this period eleven years show no falls whatever. These years are, 1800, 1801, 1809, 1816, 1817 1832, 1839, 1888, 1906, 1908, and 1909. Of these the years of the last decade will probably have falls to their credit after a time, since the record of falls usually lags somewhat behind their occurrence. The largest number of falls shown in any year during the period is 11 in 1868. The years 1865, 1877, and 1886 show 7 each. All the other years show from 1 to 6 falls each. The full record by years beginning with 1800 is as follows:

1800	0	1817	0	1834	2	1851	2
1801	0	1818	3	1835	3	1852	4
1802	1	1819	2	1836	3	1853	3
1803	3	1820	1	1837	1	1854	1
1804	2	1821	1	1838	5	1855	4
1805	2	1822	5	1839	0	1856	3
1806	1	1823	2	1840	3	1857	6
1807	2	1824	3	1841	3	1858	4
1808	3	1825	2	1842	3	1859	5
1809	0	1826	2	1843	5	1860	5
1810	2	1827	3	1844	3	1861	3
1811	2	1828	1	1845	3	1862	2
1812	4	1829	3	1846	4	1863	6
1813	2	1830	2	1847	2	1864	3
1814	2	1831	2	1848	3	1865	7
1815	2	1832	0	1849	1	1866	6
1816	0	1833	1	1850	2	1867	2

1868	11	1879	6	1890	6	1901	3
1869	6	1880	3	1891	2	1902	5
1870	3	1881	2	1892	3	1903	3
1871	3	1882	4	1893	4	1904	1
1872	4	1883	3	1894	3	1905	3
1873	3	1884	3	1895	3	1906	0
1874	5	1885	4	1896	4	1907	1
1875	5	1886	7	1897	6	1908	0
1876	5	1887	6	1898	3	1909	0
1877	7	1888	0	1899	5		
1878	5	1889	5	1900	3		350

This record on the whole seems to indicate a comparatively uniform supply of meteorites, which is the more remarkable when one considers the various chances affecting the observation of their fall. The record seems to afford no evidence of cycles or periodicity. As already remarked, a large allowance for unrecorded meteorites must be kept in mind. Yet that those recorded are probably typical of the whole seems to be indicated by the fact that while opportunities for observation of meteorite falls have probably continually increased since 1800, the record by decades shows the decade from 1860 to 1870 to considerably exceed in number of falls either of the two succeeding ones.

Passing from the falls by years, the falls by months may be examined. Such an examination should have an especial significance in showing the relations which meteorites may have to well-known star showers. Two of the best known of these showers occur in August and November. If meteorites are related to these, these months should show a larger fall than others. If meteorites are not related to these, no special increase for these months should be shown.

On compiling the results it is found that the months of May and June exhibit the greatest number of falls. The number for November falls below the average and that for August rises only slightly above. The evidence from this record is therefore that meteorites are not related to the best known star showers. It is fair to presume that the record by months will be somewhat influenced by the times that observers are most abroad. Most of the observations of meteorite falls are made in the northern hemisphere and in this hemisphere observers are more likely to be out of doors and hence more likely to observe the fall of meteorites in the summer than in the winter months. The record shows that as a whole the number of falls recorded *is* less for the winter than the summer months, yet the number of falls cannot be influenced by that alone since the high record for May and June drops to nearly half that number in July. Further the months of August, September, and October are equally favorable as regards weather for observations of meteorite falls with those of April, May, and June, yet the latter period much excels in number of falls. The excess of falls in May and June must, therefore, be due to other causes than favorable conditions of observation and seems to indicate that in the portion of the earth's orbit passed through in these months there is an unusual number of meteorites. The full table up to 1910 for the different months is as follows:

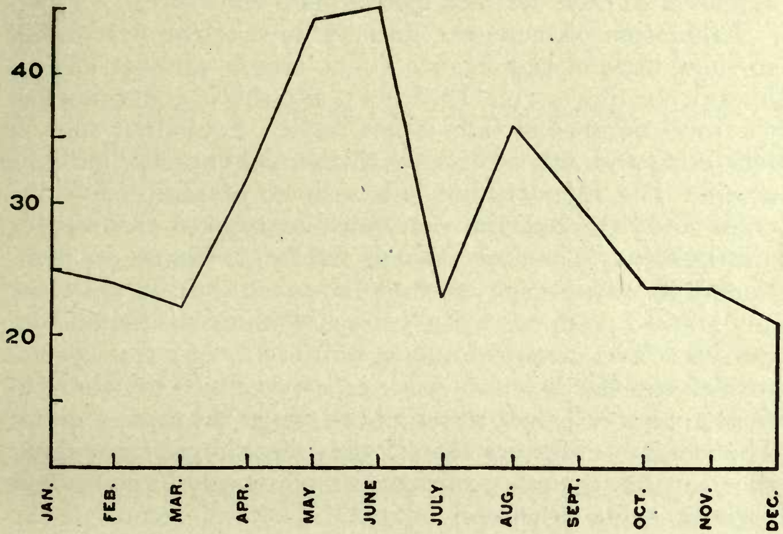

FIG. 9.— Curve of meteorite falls by months.

Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
25	24	22	32	44	45	23	36	30	24	24	21=350

This record is shown graphically in the accompanying diagram (Fig. 9).

Comparison of the falls of meteorites by months as here given, with those of falling stars and fireballs as given by

W. H. Pickering,* shows a marked difference of distribution. According to Pickering's list the falling stars and fireballs are much more uniformly distributed through the year than are meteorites, and their period of greatest number is from July to November. In May and June their number is at its minimum. Hence the record seems to show a difference in character between meteors and meteorites and furnishes *per se* a ground for questioning the gradation that has been supposed to exist between meteors and meteorites.

Tabulation of meteorite falls by days of the year seems to show little of significance. The largest number of falls for any one day is 5 on October 13, and this is a month when the total number of falls is not large. Four days show 4 falls each, and 158, or nearly half the total number, no falls at all. The days without falls seem to be scattered indiscriminately through the year, without marked grouping or arrangement. The days showing falls aside from those mentioned, have from one to three falls each, but do not show any marked grouping. Such a record seems also to indicate that to refer a meteorite falling on the day of a star shower to such showers is unsafe practice, especially if the observations are not sufficient to assign the two to the same radiant. The meteorite falls are so uniformly distributed throughout the year that the two occurrences might easily be coincident without being otherwise related. The full record of the falls by days up to 1910 is as follows:

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1.....	2	..	..	1	1	..	1	3	..	2	..	1
2.....	..	1	..	..	1	2	..	1	1	..	..	2
3.....	2	2	..	1	..	3	..	..	1	2	..	..
4.....	..	..	1	1	..	2	2	1	1	..	..	1
5.....	..	..	..	1	1	..	..	4	4	2	1	1
6.....	..	..	2	2	..	2	..	..	1	1	..	1
7.....	..	..	..	2	..	2	..	2	2	1	..	1
8.....	1	..	..	..	3	..	1	1	..	1	..	..
9.....	..	1	..	2	2	2	..	..	2	..	..	1
10.....	..	3	..	3	1	..	1	2	1	..	1	1
11.....	..	..	..	1	2	1	1	3	..	1	1	..
12.....	1	2	3	1	1	4	1	1	..	..	2	..
13.....	..	2	..	2	2	2	..	1	3	5	..	3
14.....	..	..	..	..	3	2	3	2	1	1	..	1
15.....	1	2	1	2	1	2	1	..	1	..	2	..
16.....	1	3	1	..	..	2	..	2	1	..	1	..

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* Popular Astronomy, 1909, 17, 277.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
17	..	..	1	1	3	1	2	..	..	..	1	..
18	..	3	..	1	..	2	1	1	..	1	..	..
19	2	1	2	1	3	1	..	..	1	..	2	1
20	1	..	1	1	3	2	1	..	..	..	1	..
21	1	..	..	..	1	2	..	..	1	2	..	1
22	..	..	1	..	3	1	1	1	3	1	..	2
23	3	..	..	..	1	..	1	..	1	..	1	..
24	..	..	1	1	2	..	2	..	..	1	1	..
25	2	1	3	..	1	1	1	2	..	..	1	1
26	..	..	..	3	2	1	..	..	1	1	1	..
27	1	..	1	1	2	..	1	..	1	..	3	2
28	1	1	2	..	1	3	..	..	1	..	..	..
29	1	1	..	1	..	1	..	3	..	1	..	..
30	1	..	..	..	1	1	..	1	..	..	4	..
31	2	..	1	..	..	..	..	1	..	1	..	..
	23	23	21	29	41	42	21	32	28	24	23	203=27

Of all times of fall of meteorites the most satisfactory for study are probably the hours of fall, since the ratio of number of falls to number of hours is larger than that to days, months, or years. While the hour of fall is not known of as many meteorites as is the year and month, yet of 273 sufficiently satisfactory records are available. Of these 273 falls, 184 occurred in the time from noon to midnight, and 89 from midnight to noon. The record in full is as follows, the total number being less by seven than that recorded for forenoon and afternoon, since of these seven the hour is not known:

Hours	12	1	2	3	4	5	6	7	8	9	10	11		Total
A. M.	1	2	3	2	6	7	7	18	12	10	9	12	=	89
P. M.	24	13	19	33	21	15	11	8	16	7	9	3	=	176

This record is shown graphically in the accompanying diagram (Fig. 10).

As in the case of the months and the years, it is quite likely that here also considerable allowance should be made for conditions of observation. It is reasonable to expect that the number of falls recorded in the early morning hours would be less than that for other times, since mankind is generally asleep then. That some such allowance must be made is indicated by the records, for the number of falls from midnight to 6 A. M. is only 21, while from 6 A. M. to noon it is 68. From noon to 6 P. M. it is 124 and from 6 P. M. to midnight 60.

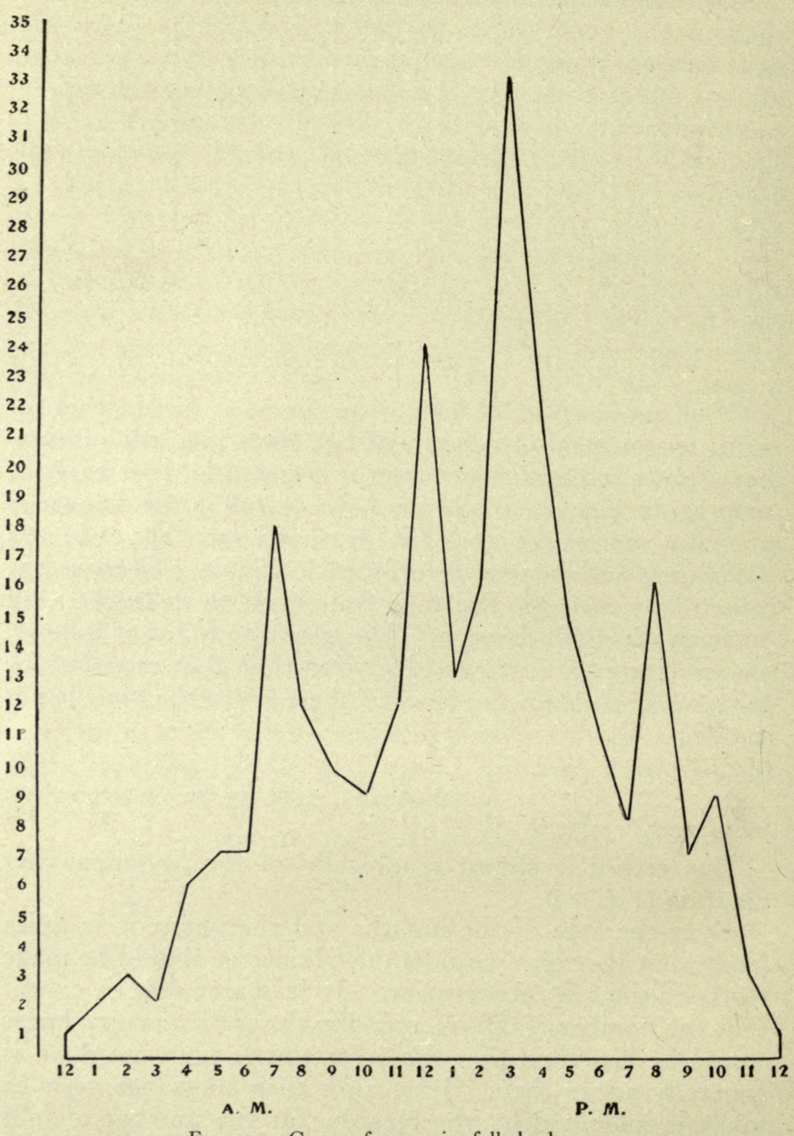

FIG. 10.— Curve of meteorite falls by hours.

The hours of fall are chiefly significant, however, in indicating the direction of movement of meteorites. It will be seen from the accompanying diagram (Fig. 11) that all meteorites reaching the earth between noon and midnight must be moving in the same direction as the earth in its orbit. These are said to have direct motion. Those reaching the earth between midnight and noon however, must be moving in a direction opposite to that of the earth or so slowly that they are overtaken by it. Those moving opposite to the earth are said to have retrograde motion. It will be seen that meteorites with direct motion must reach the earth by overtaking it (or being overtaken by it) while those with retrograde motion meet the earth.

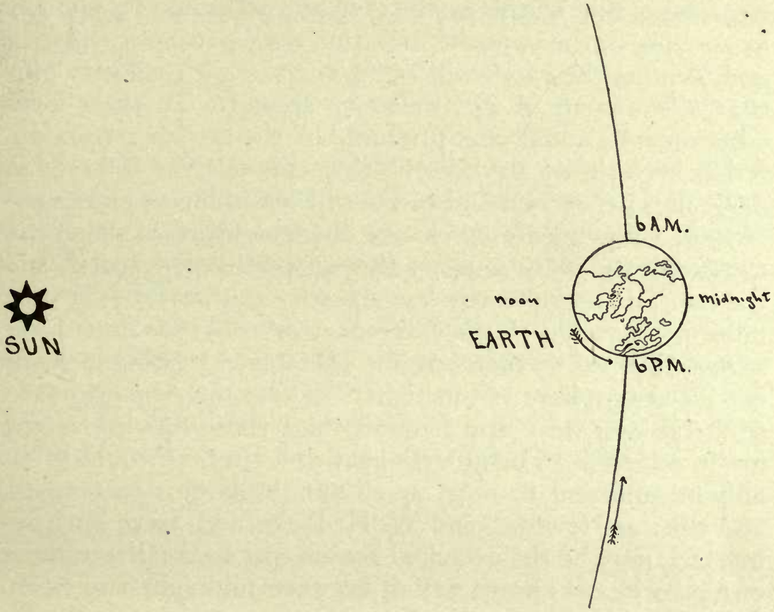

Fig. 11.—Diagram showing relation of time of day and direction of earth motion to velocities of meteorites.

These differences in direction of motion must produce great differences in the velocity with which meteorites strike the earth, since those overtaking the earth have the earth's velocity subtracted, while those meeting the earth have the earth's velocity added to theirs. The earth's velocity about the sun is 18.5 miles per second. All meteorites which move in orbits which are parabolic about the sun have a velocity of 26.16 miles per second. If, therefore, a meteorite having this velocity overtakes the earth it will strike with a velocity of only 7.7 miles per second, its velocity minus that of the earth. On the other hand a meteorite moving in the opposite direction with parabolic velocity and meeting the earth will strike with its own velocity plus that of the earth, or 44.7 miles per second. To these velocities must be added that produced by the earth's attraction. It has been shown by Lowell* that this may be as great as 2.66 miles per second and can not be less than 0.53 miles per second. The greatest velocity then at which a meteorite can strike the earth is $44.7+2.7=47.4$ miles per second, and the least, if the meteorite has direct motion, is $7.7+0.5=8.2$ miles per second. Such differences in velocities must have a marked effect on meteorites. Meteorites passing into the earth's atmosphere at the higher velocity must be subjected to far greater heat and friction than those moving at the lower velocity. The greater heat and friction would probably be sufficient to burn up all but the largest meteorites, and this, as Newton† and W. H. Pickering‡ have both remarked, may be the principal reason why so small a number of meteorites is known to fall between midnight and noon. According to the records above given more than twice as many meteorites fall from noon to midnight as from midnight to noon. This would indicate that most meteorites are moving in their orbits in the same direction as the earth, but taking into consideration the lack of favorable opportunity for observation of meteorites with retrograde motion on account of the time of their fall and taking into consideration the greater liability that they will be burned up on account of their greater velocity, it is possible that the difference in quantity of meteorites of the two classes is not as great as appears at first sight.

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*Science, N. S., 1909, 30, 339.

†Am. Jour. Sci., 1888, 3, 36, 10.

‡Popular Astronomy, 1910, 18, 264.

A study of the table shows that the falls are much more numerous at some hours than others. They are most numerous at 3 P. M., but are also abundant about noon and about 7 A. M. Haidinger in 1867* gave the hours of 178 meteorite falls which may serve for comparison with the above table. Omitting from Haidinger's table about 40 falls which are now known to be unreliable, his results are as follows:

	12	1	2	3	4	5	6	7	8	9	10	11	Total
A. M.	1	1	1	2	3	3	4	10	5	5	5	17	= 57
P. M.	7	9	9	16	15	7	5	7	3	0	0	3	= 81

Here likewise the afternoon falls are seen to be more numerous than the morning falls, and the number is greater at 7 A. M., 11 A. M., and 3 P. M. Thus the numbers of falls at different hours seem to retain about the same proportion when different yearly periods are compared.

On the whole the study of the times of fall of meteorites seems to show (1) that they differ considerably from meteors in times of fall, (2) that they are not noticeably related to any of the well known star showers, and (3) that the rate of their supply to the earth is remarkably uniform.

*Sitzb. Akad. der Wiss., Wien, Bd. 55.

CHAPTER V

METEORITE SHOWERS

A striking feature of some meteorite falls (striking in more ways than one), is the fact that a large number of individuals, sometimes thousands, fall at one time and place. Such occurrences are called meteoritic showers, and present phenomena of much interest. These showers have taken place on various parts of the globe and at various times without any seeming regularity or relation.

Three of the largest showers, those of Estherville, Forest, and Homestead, took place within the boundaries of the State of Iowa, and three others, Knyahinya, Mocs, and Pultusk, fell in Hungary or the neighboring Poland. The phenomena of violent sounds and brilliant light which usually accompany the fall of a meteorite are generally intensified in the case of these showers, though not always to a marked degree. The phenomena attending the shower of Homestead, described on pages 16 to 18 may be considered typical of the more violent form. The distribution of the stones of these showers is usually over an elliptical area with the longest axis of the ellipse in the direction of movement of the meteor (Fig. 12). The greatest distance along which the individuals of a shower have been observed to be distributed in this way is sixteen miles. This was the distribution of the Khairpur shower.

The distribution of this and other showers is as follows.*

Limerick	3	miles	long	
Butsura	3	miles	x 0.6	mile
Holbrook	3	“	x 0.6	“
Pultusk	5	“	x 1	“
Barbotan	6	“	long	
Homestead	7	“	x 4	miles
L'Aigle	7½	“	x 2½	“
Stannern	8	“	x 3	“
Estherville	8	“	x 1¼	“
Pillistfer	8	“	x 2¼	“
Mocs	9	“	x 2	“
Knyahinya	9	miles	x 3	miles
Weston	10	“	long	
Hessle	10	“	x 3	“
New Concord	10	“	x 3	“
Castalia	10	“	x 3	“
Macao	14	“	long	
Cold Bokkeveld	16	“	x 1	mile
Khairpur	16	“	x 3	miles

*Chiefly from Fletcher, Min. Mag., 1889, 8, 225.

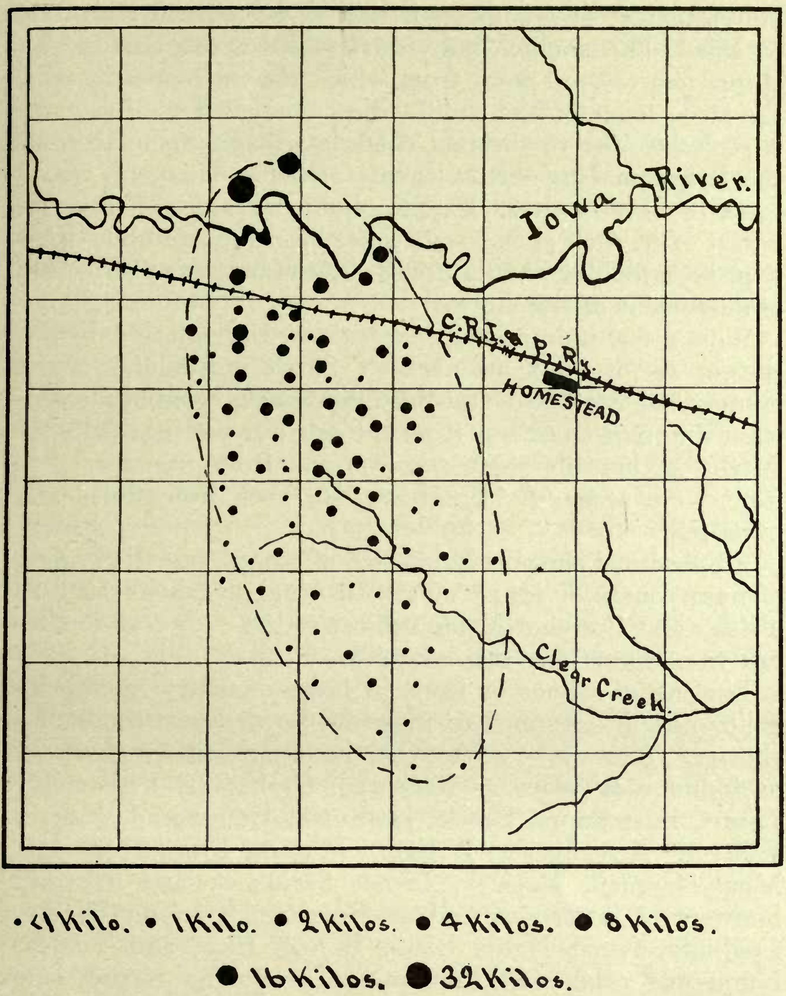

FIG. 12.— Distribution of the individuals of the Homestead, Iowa, meteorite shower. The shower moved from south to north, the larger individuals being carried farther by their greater momentum. The squares in the diagram represent a square mile each.

Another feature to be noted in the distribution of the individuals of such showers is that of assortment according to size. The smaller individuals fall at the end of the ellipse nearest the point from which the movement comes, the larger ones at the end farthest away. This difference is probably due to the fact that the greater momentum of the larger masses carries them farther. This rule would seem to be of universal application and any apparent reversal of it, such as has sometimes been reported, may perhaps be explained as a failure to determine the true direction of movement of the meteor.

With a few unimportant exceptions, the individuals of a shower are of the same nature. Single individuals of the Homestead, Stannern, and Pultusk showers were of a somewhat different character from the rest but not markedly so. In the Estherville shower gradations from iron-stones to irons were seen. At Brenham also both iron-stones and irons fell.

All observed showers have been of stones, but the finding of numerous individuals of iron in single localities such as Toluca and Canyon Diablo indicates that showers of meteoric irons sometimes take place also.

Finding of stones or irons in large quantity at any locality may be assumed to show the former occurrence of a shower. Showers of stones that have either been observed or found took place at Barbotan, Cronstadt, Estherville, Forest, Futtehpore, Hessle, Holbrook, Homestead, Jonzac, Killeter, Knyahinya, L'Aigle, Macao, Mezö-Madarasz, Mocs, Orgueil, Pultusk, Siena, Stannern, and Weston. Showers of irons occurred at Brenham, Canyon Diablo, Coahuila, Great Nama Land, Imilac, Inca, and Toluca. Numerous other falls, while not producing a sufficient number of individuals to constitute a shower, yet afforded many stones. Thus many stones fell at Admire, Agen, Aleppo, Borgo San Donino, Cold Bokkeveld, Dhurmsala, Kesen, Khairpur, Madrid, Manbhoom, Modoc, Monte Milone, Ness County, Nulles, Ochansk, Sokobanja, Tomatlan and Toulouse. At Chail, Grazac, Khetree, Jelica, New Concord, Ploschkowitz, and Segowlee from 20 to 40 stones fell; at Zsadany 16, at Ställdalen 11, at Blansko 8, at Bandong and Lancé 6, at Barratta, Bremervörde, Butsura, and Drake Creek 5, at Harrison County, Marion and Lissa 5, and at numerous other localities 2 to 3 stones. Of irons, about 15 individuals are known from Glorieta; 4 to 6 from Smithville, Staunton, Steinbach, Trenton, and Youndegin: 3 from Arispe, Bischtübe, and Crab Orchard; and 2 from Braunau, Chupaderos, Cosby Creek, Hraschina, Losttown, and Tucson.

It is highly probable that at many of the above localities not all the individuals which fell were found, so that the numbers would be increased if the full complement were known.

The number of stones falling in some of these showers is remarkable. In each of the showers of Pultusk and Mocs more than 100,000 stones fell. In the shower of Holbrook 14,000 stones fell, and in that of L'Aigle 2–3,000. The total quantity of meteoric matter falling in a single shower is also often large though not larger than some single stones. In the Knyahinya shower the stones of which were relatively large, over 423 kilos (840 pounds) fell. From Holbrook 218 kilos were obtained and about the same quantity from Pultusk.

The question of the amount of area over which meteorites of a shower may be distributed becomes of considerable importance when considered in relation to meteorites found. If showers can distribute meteorites over areas covering scores or hundreds of miles, meteorites of similar characters found within such areas should be referred to one fall instead of many. This is an especially important consideration in regard to the iron meteorites of the class of medium octahedrites, since many of them are separated in point of fall by less than a hundred miles and yet are regarded of distinct origin. Earlier writers were inclined to group into one fall all similar meteorites, even though separated by thousands of miles of distance, but later observations have failed to confirm this view. Until an observed shower can be seen to disperse meteorites for great distances we seem compelled to allow but slight dispersion by a shower. Two important meteoric finds, however, seem to be exceptions to this rule. These are Coahuila and Great Nama Land.

In the state of Coahuila, Mexico, numbers of meteoric irons of the rare class of hexahedrites are found one or two hundred miles apart. It hardly seems likely that separate falls of these rare meteorites would occur within such a limited area, and the only alternative seem to be to ascribe them to a shower or to assign their distribution to human agency. Fletcher after an exhaustive study concluded that it was highly probable that the usefulness of these masses of iron for anvils and other artificial purposes caused their wide distribution by man. The irons of Great Nama Land are also of a peculiar class, being fine octahedrites. They have been found in various places over an area whose farthest limits are about fifty miles apart. Here again it seems highly probable that distribution by man has taken place.

Opinions differ as to whether the individuals of a shower are separated before striking the earth's atmosphere or come from a single mass broken up in its passage through the atmosphere. Some breaking up of individuals is known to take place in the atmosphere, because individuals show various stages of crust formation on different surfaces. This crust varies from a deep alteration to a mere smoking, and such differences could only arise from successive fractures and successively shorter periods of exposure. But the majority of individuals of a shower are thoroughly encrusted on arrival at the earth and are often oriented (Fig. 13). Hence they must have had a nearly uniform period of flight through the atmosphere. As Cohen suggests,* this could only be the case if the breaking up took place simultaneously and very soon after the entrance of the mass into the atmosphere. Now, if conditions favor such a breaking up at the beginning of the atmospheric course, it is not easy to see why meteoric showers are not more abundant, since meteoric stones do not differ greatly in structure and composition. A breaking up of the soft, carbonaceous meteorites would be especially probable. Moreover, while the breaking up of stones in the atmosphere can be con-

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* Meteoritenkunde, Heft II, 186.

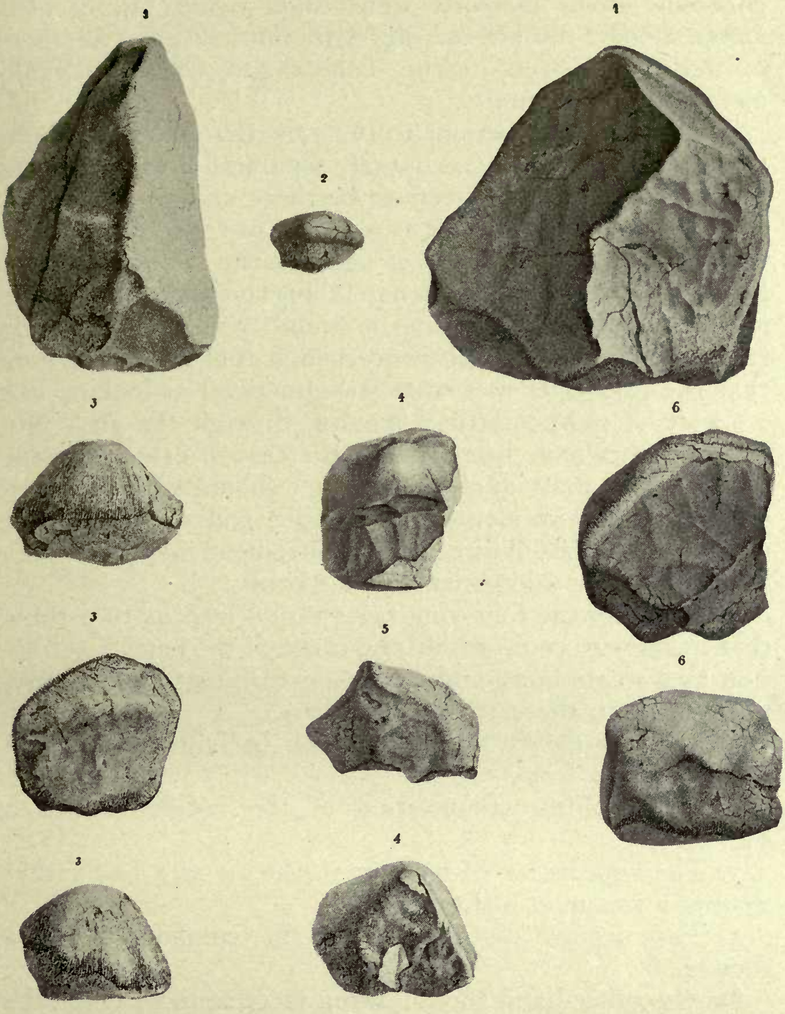

Fig. 13.— Various individuals of the Orgueil, France, shower. Similar numbers indicate the same stone in different positions. Somewhat reduced. After Daubrée.

ceived, it is hard to understand how masses so tough and coherent as the meteoric irons could readily be divided except along a few pre-existing clefts into the great numbers of individuals seen in the Toluca and Canyon Diablo meteorites for example.

The principal objections to the view that the individuals of a meteoritic shower are largely separated before reaching the earth's atmosphere seem to be those urged by Daubrée, that if the meteorites exist as a swarm in space they should be seen moving as a swarm of lights in the atmosphere, and further that their distribution in falling should be much more irregular and extensive than is found to be the case. So far as the first objection is concerned, it is of interest to note that the Rochester meteorite was described as looking like a "flock of red-hot birds" moving through the air. Numerous lights have been seen in the case of other showers. But that the individuals of a shower should be distributed over so narrow an area is remarkable, and shows to what a high degree a fixed direction of movement may have been imparted to the components of a swarm.

To sum up, the following facts would lead us to assume that meteorites come within the range of the earth's attraction as a single body and that their disintegration, if any, takes place in the earth's atmosphere:

1. The angularity of most of the individuals of stone showers.
2. The uniform composition of the individuals of a shower.
3. The appearance of meteors in the air as a ball rather than as a swarm of bodies.
4. The narrow distribution of the components of a shower.

On the other hand the following facts seem to favor the assumption that meteorites which fall as showers existed as a swarm in space:

1. The complete encrusting of most individuals of a shower.
2. The small number of showers.
3. The regular form of the area over which a shower dis-

tributes itself and the regular distribution of the individuals over it.

4. The difficulty of breaking up iron masses by atmospheric shock.

CHAPTER VI

SIZE OF METEORITES

The largest individual meteorite known is one of the Cape York, Greenland group (Fig. 14). It is an iron meteorite weighing 36½ tons. Its principal dimensions are: Length, 10 feet, 11 inches; height, 6 feet, 9 inches; width, 5 feet, 2 inches. The meteorite had long been known as a mass of iron to the natives of the region where it occurred, but it had not been seen by white men until Lieut. Peary visited it in 1895. It lay on the shores of Melville Bay, 35 miles east of Cape York, Greenland. The Esquimaux had christened it "Ahnighito," meaning the "Tent," in allusion to its shape and size. About four miles away, lay two other large iron meteorites which were undoubtedly individuals

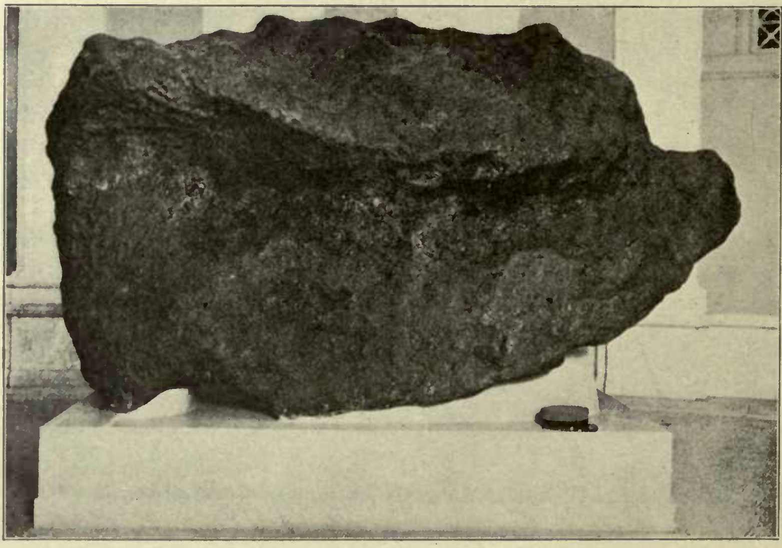

FIG. 14.— Cape York, Greenland, the largest known meteorite. Weight, 36½ tons.

of the same fall. All of these meteorites were brought to New York City by Lieut. Peary in 1895 and 1897.

The next largest meteorite to "Ahnighito" is that of Bacubirito, Mexico (Frontispiece). This is also an iron meteorite. While it has not been weighed, its estimated weight is 27 tons. Its dimensions as given by H. A. Ward, are: Length 13 feet, 1 inch; width, 6 feet, 2 inches; thickness, 5 feet, 4 inches. As its shape is much less compact than that of the large Cape York individual, these dimensions are not of much service in comparing the masses of the two bodies. The existence of this meteorite had perhaps long been known to white men, but it was first brought to scientific notice by Prof. Barcena in 1876. Later the meteorite was visited and described by Prof. H. A. Ward. The mass has never been moved from the locality in the state of Sinaloa, Mexico, where it originally fell.

Two masses of meteoric iron from Chupaderos, Mexico, which together weigh about 26 tons, must be placed next in the scale of size. Although these two masses were found a few hundred feet apart, the character of their surface showed that they were a single mass before falling. The dimensions of this mass were: Length, 12 feet; width, 7 feet. As separated, one of the masses had about twice the weight of the other. These irons were first located by Europeans as early as 1582 and were removed by the Mexican Government to the City of Mexico about 1880.

Following these masses in size comes that of Willamette, Oregon, an iron whose present weight is about 15½ tons but the original weight of which was undoubtedly much larger. The dimensions of the mass are: Length, 10 feet, 3½ inches; breadth, 6 feet, 6 inches; height, 4 feet, 3 inches. The mass is conical in shape and lay for an unknown length of time in a dense forest with its base uppermost. The climate being very moist, conditions were favorable for a rapid oxidation and decomposition of the iron and as a result great cavities (Fig. 15), were formed in the mass which have considerably decreased its original weight. The size of one of these cavities is described by Ward as 3 feet long by 10 to 15 inches across and with an average depth of 16 inches. Many other such cavities of nearly equal size occur. This mass was moved to New York City in 1906.

An iron meteorite of a similar form to Willamette but smaller and little if any affected by decomposition is that of El Morito (San Gregorio), Mexico, the weight of which is about 11 tons (Fig. 16). The dimensions of this meteorite are: Length, 6 feet, 6 inches; height 5 feet, 6 inches; breadth, 4 feet. The existence of this iron was known as early as 1600 and in 1821 a Spanish inscription was cut on it which (translated) read: "Since no one in the world could make it, only God with his power this iron can destroy." About 1880 the meteorite was removed with several others to the City of Mexico.

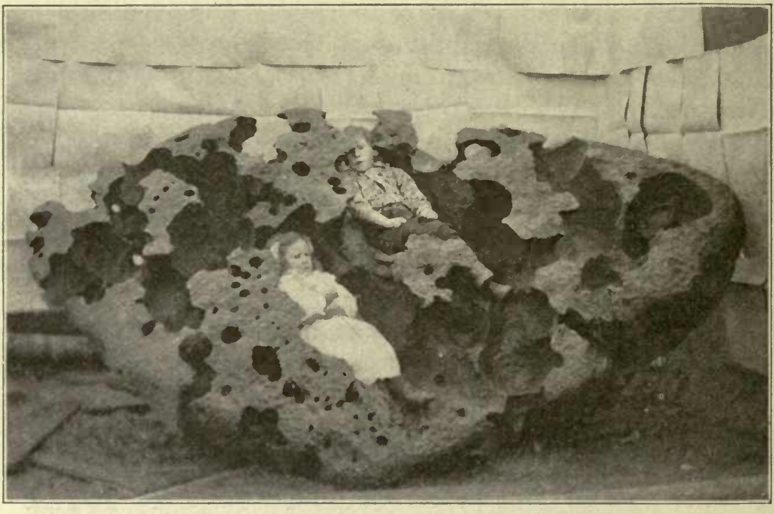

FIG. 15.—The Willamette meteorite showing cavities produced by terrestrial erosion and solution.

Between this and the meteorite next in size a considerable gap in weight intervenes. The Bendego, Brazil, meteorite which comes in this place, weighs only about 5 tons. It is of a flattened, forked shape, its extreme dimensions being: Length, 7 feet; width, 4 feet; thickness, 2 feet. The meteorite is said to have been discovered in 1784 but was not described till 1816. In 1888 it was moved to Rio Janeiro.

The next largest meteorite in size comes from Australia, and is known as Cranbourne. Several masses occur of this fall, of which the largest weighs nearly 4 tons. It is of rounded form and is now in the British Museum.

Next in weight ranks another Mexican iron found not far from those of Chupaderos. This is known as Adargas or Concepcion. It is of flattened form and has the dimensions:

Fig. 16.— El Morito, Mexico, meteorite. Weight, 11 tons.

Length, 3 feet, 10 inches; breadth, 3 feet, 1 inch; thickness, 1 foot, 2 inches. Its weight is about 3 tons. According to an inscription on the iron it was found in the year 1600. It is now in the City of Mexico.

The second largest individual of the Cape York fall ranks next in size. This is of conical form and weighs nearly 3 tons. From its shape it was christened, by the Esquimaux, the "Woman."

Another Mexican meteorite comes next in size. This is the meteorite of Casas Grandes, which was found carefully wrapped in coarse linen in some ancient ruins in the state of Chihuahua. It is of lenticular form and has the dimensions:

Length, 3 feet, 2 inches; width, 2 feet, 5 inches; height, 1 foot, 6 inches. The weight of this meteorite is nearly 2 tons, and it is now in the United States National Museum.

The last of known meteorite individuals whose weight exceeds 1 ton is from Quinn Canyon, Nevada. This is a beautifully oriented, conical iron having the dimensions: Length, 3 feet, 11 inches; breadth, 2 feet, 11 inches; height, 1 foot, 8 inches. Its weight is a little over 1½ tons. It was found in 1908 and is now in the Field Museum of National History, Chicago.

The weights of these masses are shown in kilograms in the following table as well as the cities in which the meteorites are now preserved.

Name	Weight in Kilograms	Where Preserved
Cape York.............	33,113	......New York
Bacubirito.............	27,500	......Mexico
Chupaderos, 2 individuals	20,881	......Mexico
Willamette	14,110	......New York
El Morito	10,000	......Mexico
Bendego	5,370	......Rio Janeiro
Cranbourne............	3,731	......London
Adargas...............	3,325	......Mexico
Cape York	2,727	......New York
Casas Grandes.........	1,545	......Washington
Quinn Canyon.........	1,485	......Chicago

The above are all irons, and except in one case single masses. Other large iron masses known are those of Magura, weighing 1500 kilos, Zacatecas 1000 kilos, Charcas 784 kilos, and Red River 750 kilos. All of these exceed in size the largest stone meteorite, Long Island, which weighs 564 kilos (1200 pounds). Although broken at the time of its fall this undoubtedly fell as a single individual. The largest unbroken stone meteorite individual known is one of the Knyahinya shower, weighing 293 kilograms (600 pounds). The mass of Bjurböle fell as a single stone weighing about 400 kilos (800 pounds) but it was broken by striking the earth. The iron meteorites will be seen from the above statements to far outweigh the stone meteorites in the size of single masses, and this would be expected from the greater resistance to fracture and erosion which their substance is able to exert. None of these large iron masses have been seen to fall. The largest single iron mass seen to fall is that of Cabin Creek, weighing about 100 pounds.

From large masses all gradations of size occur down to material of microscopic dimensions. Some meteoric showers produce large numbers of small stones, others only large ones. In the shower of Holbrook it was estimated that over a thousand individuals of the size of grape seeds fell. Individuals smaller than this are not likely to be found, but it is theoretically certain that they are formed.

CHAPTER VII

FORMS OF METEORITES

The forms of meteorites seem to depend chiefly on the amount of shaping which they undergo in their passage through the earth's atmosphere. This may in turn depend partly on their speed of fall, a lower velocity giving a longer time for shaping. The amount of shaping seems to be independent of the size of the masses, since large and small individuals show similar forms. It is also largely independent of the substance of the meteorites, but there are some forms acquired by iron meteorites which are hardly possible to stone meteorites. Meteorites which break up shortly before reaching the earth present irregular forms such as a rock broken by a hammer might show. A longer course through the atmosphere gives an opportunity for shaping the masses, under the operation of which certain characteristic forms are produced. These forms may be enumerated as follows: Cone-shaped or conoid, shield-shaped or peltoid, shell-shaped or ostracoid, bell-shaped or codonoid, pear-shaped or onchnoid, column-shaped or styloid, ring-shaped or cricoid, and jaw-shaped or gnathoid; while among angular forms may be observed cuboidal, pyramidal, rhombohedral, tetrahedral, etc., forms.

Of the above forms the cone-shaped or conoid is the most common and typical. The cone of such forms is usually low in proportion to its breadth, but its proportions may so vary as to approach the bell shape on the one hand or the shield shape on the other. The form is evidently due to the greater exposure of the forward corners of the falling meteorite to the heat and friction of the atmosphere. These corners, as represented in the accompanying diagram (Fig. 17), are worn away more rapidly than interior portions. From the edges to the center the abrading forces thus gradually lessen in intensity and a sloping surface is produced.

This slope is usually somewhat rounded, and the highest point or apex of the cone is not always situated at the geometric center of the figure. It is probably, however, generally in line with the center of gravity of the mass. While

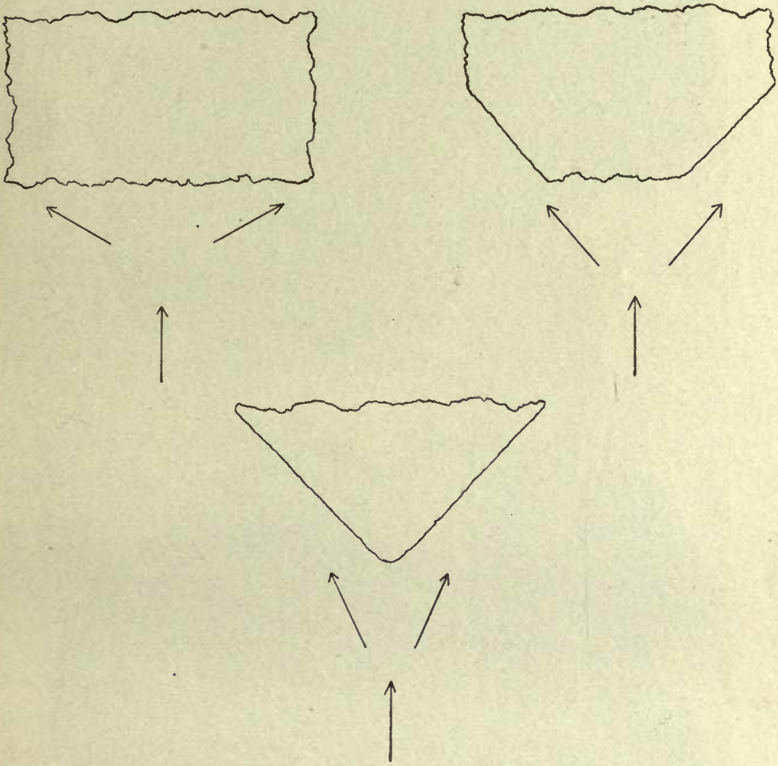

FIG. 17. Diagram showing production of conical form in a meteorite by the greater exposure of its corners.

it is true that this conical form may be largely the result of atmospheric shaping, it is also true that a meteorite originally possessing such a form would be turned by the resistance of the earth's atmosphere, as has been shown mathematically by Schlichter,* with its apex foremost. The subsequent action of the atmosphere would then tend simply to preserve this form.

*Bull. Geol. Soc. Am., 1903, 14, 112–116.

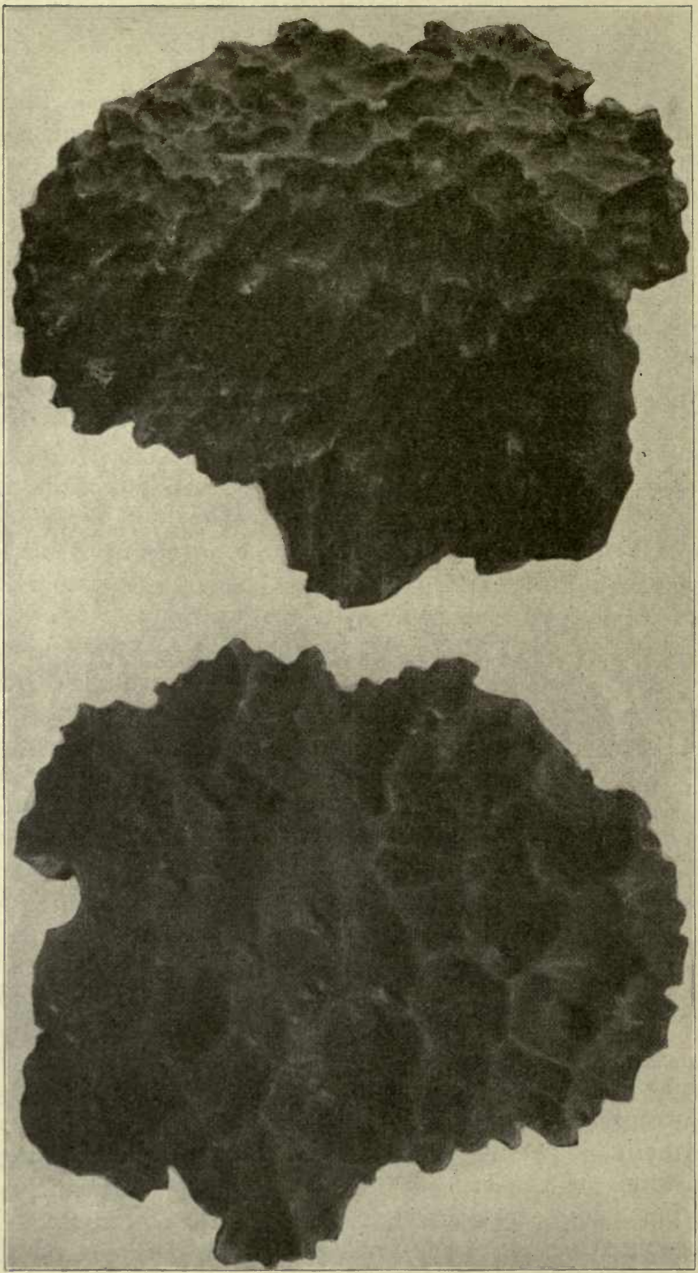

Fig. 18.— Front (upper figure) and rear (lower figure) sides of Cabin Creek meteorite. The contrast in the relief of the two surfaces is typical of well-oriented meteorites.

While the rear side of such a meteorite is much less affected than the front, yet here too some shaping seems to take place, since it is usually more or less concave as compared with the convex front side. A marked difference in the character of the pittings is usually also noticeable between the front and rear sides. Those of the front side are small, deep, and oval in outline, while those of the rear side are broad, shallow, and more or less circular (Fig. 18). The crust of the front side is thin and dark in color; that of the rear side thick, slaggy, and usually of a reddish or brownish hue. The latter feature shows that the rear side has encountered less air, since it indicates less oxidation. Evidence of the passing of currents of air radially from the apex of the cone is to be seen in the arrangement of the pittings on the front side, (Fig. 19). These pits are as a rule elongated, oval, and furrow-like, and broadest on the side toward the edge. The slope of their sides is commonly

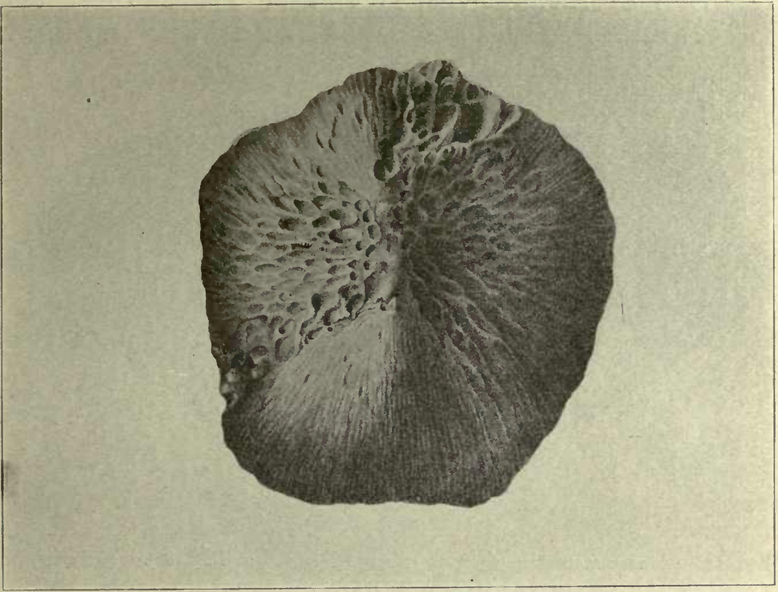

Fig. 19.— Front side of Goalpara meteorite, showing radial arrangement of pittings. After Haidinger.

unequal and the position of the steeper slope is not constant. The pits do not as a rule merge into one another on all sides, but follow lineal and radial courses. In size the pits are usually larger on iron than on stone meteorites, their average range being from one-fourth to one inch in diameter. The pits are not usually to be found on the apex of the cone, the surface there being characteristically smooth. A characteristic feature of the edge where the front and rear surfaces of the meteorite join is a thickening of the crust caused by an accumulation of fused matter (Fig. 20). This crust is also often notably blebby in character. The rear side also often exhibits adhering particles which have the appearance of being fragments of crust. Haidinger regarded these as fragments which accompanied the meteorite from space with a velocity equal to it and fused upon it when its speed was lessened. Rath and Tschermak, however, thought them fragments from the front side of the meteorite which were thrown to the rear and fused upon that surface by hot air streaming into the space behind.

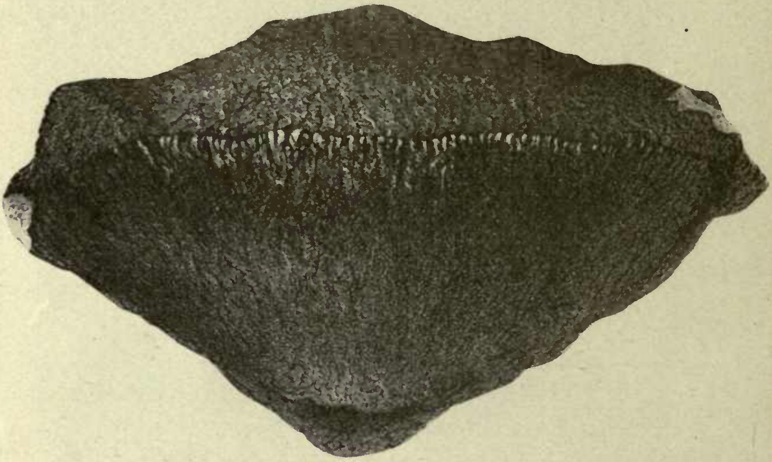

Fig. 20.— Jonzac meteorite, showing lateral edge produced by meeting of currents from front and rear.

Many large meteorites, and especially iron ones, exhibit the conical or conoid form in a high degree. Among such large iron meteorites may be mentioned El Morito, Willamette, (Fig. 21), Quinn Canyon, and Cabin Creek.

The iron meteorite of Cabin Creek weighs about 100 pounds. Its front or apical side is covered with numerous, deep, elongated impressions one-half to one inch in diameter. The apex is free of crust, but from it fused threads of the substance of the meteorite run radially. These threads are hair-like in thickness and from one to four inches long, and may be traced, according to Kunz, on the slope and bottom of the pits. The rear face is relatively flat and shows broader, shallower pits than the front. These pits

FIG. 21.— A conoid or cone-shaped meteorite. Willamette. Weight, about 15 tons.

are from one to two inches in diameter. The rear surface has a rough, scale-like crust about one millimeter thick. Brezina regards the thin, smooth crust of the front side of this meteorite as giving evidence that it was in the state of a thin, mobile liquid, while the thick crust of the rear side shows that it was in a viscid condition and, therefore, must have received less heat.

Other smaller iron meteorites exhibiting a more or less well-marked conoid form are Braunau, Carlton, Cleveland, and Costilla.

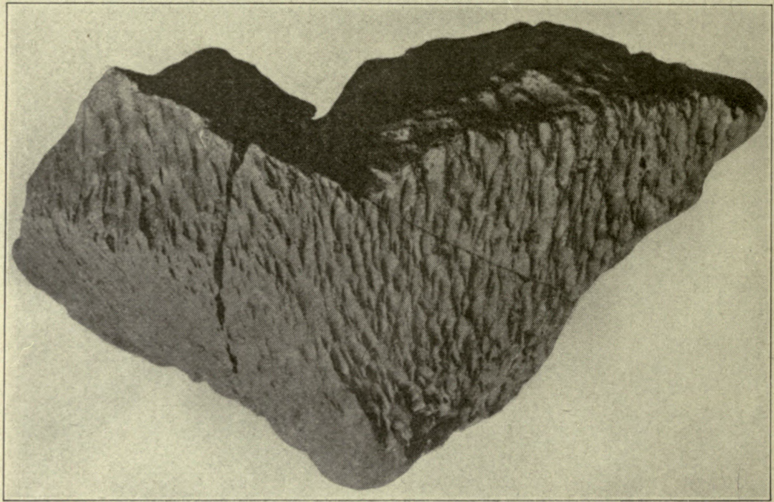

FIG. 22.— A conoid or cone-shaped meteorite. Long Island, Kansas. Stone, weight about 1100 pounds. The symmetrical arrangement of the pittings is noteworthy.

Of stone meteorites the largest known to exhibit the conoid form is Long Island (Fig. 22), the weight of which when entire was about 1400 pounds. Here a smooth apex, deep, radial pitting of the front side, and broad, shallow pitting of the rear side are exhibited. The altitude of the cone of this meteorite is 20 inches, and the greatest diameter of the base 34 inches.

Another large stone meteorite exhibiting the same form is the large mass of Bath Furnace (Fig. 23). This is an

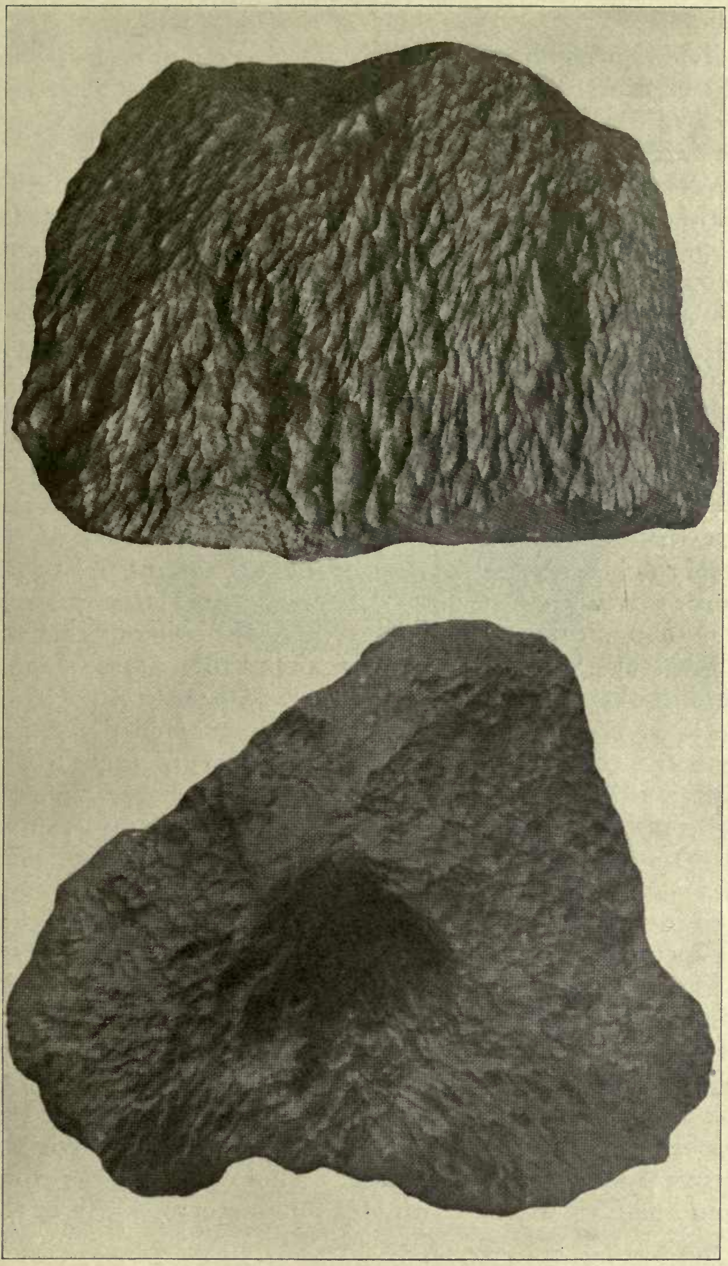

Fig. 23.— Side (upper figure) and front (lower figure) views of the Bath Furnace meteorite. This is a well-oriented stone meteorite weighing about 180 pounds. The symmetrical arrangement of the pittings is well shown.

individual weighing 180 pounds and covered uniformly with a black crust. On the front side appears the usual smooth apex with rows of pittings radiating from it. The rear side is relatively smooth.

Variation of the conical shape produced by a diminution of the altitude of the cone gives, as has been stated, shield-shaped forms. Of this form the N'Goureyma and Algoma meteorites furnish excellent examples. Both of these are iron meteorites. The N'Goureyma meteorite is 22 inches long and 11 inches broad, and its greatest thickness is 3½ inches. Its outline seen broadside is very irregular and the boss of the shield is placed near one end. The front or boss side is convex and marked by small, deep, rounded pits, the walls of which often exhibit smaller pits giving them a pockmarked appearance. Fine, furrow-like depressions also give this surface a scale-like semblance. Contrary to the usual rule, the crust is rougher and darker on the front than on the rear side. The pits of the rear side are large, shallow, smooth, and elongated. Cohen was of the opinion* that the original form was more symmetrical, but that it was strongly modified by the erosion of the air. On account of drift markings seen on both surfaces he also concluded that the meteorite moved through the air at an acute angle to the direction of its motion. Hobbs,† however, urged that the drift markings on the rear side were plainly the result of air currents forced through two holes in the meteorite, since they were found only in the area peripheral to these openings. It is highly probable, therefore, as Hobbs concluded, that the meteorite took the broadside attitude in its flight.

The outline of the Algoma meteorite (Fig. 24), on its broadside is roughly elliptical with axes of 10 and 6 inches. Its thickness varies from about one inch near the geometric center, to knife edges at several points. A few large, shallow pits occur upon the front side, but a more remarkable feature is a complete series of radial furrows extending over the surface from the center outward. These are knife-like edges from one-fifth to one-tenth of a millimeter in width at the

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*Am. Jour. Sci., 1903, 4, 15, 254.

†Bull. Geol. Soc. Am., 1903, 14, 108.

base, separated by furrows from one to two millimeters wide. The ridges are modified somewhat in their course by the structure of the meteorite, but in general pursue a rectilinear direction with a slight curve to the left. On the rear side the surface is concave and a number of broad, shallow pits appear but the ridge-like markings of the front side are entirely absent.

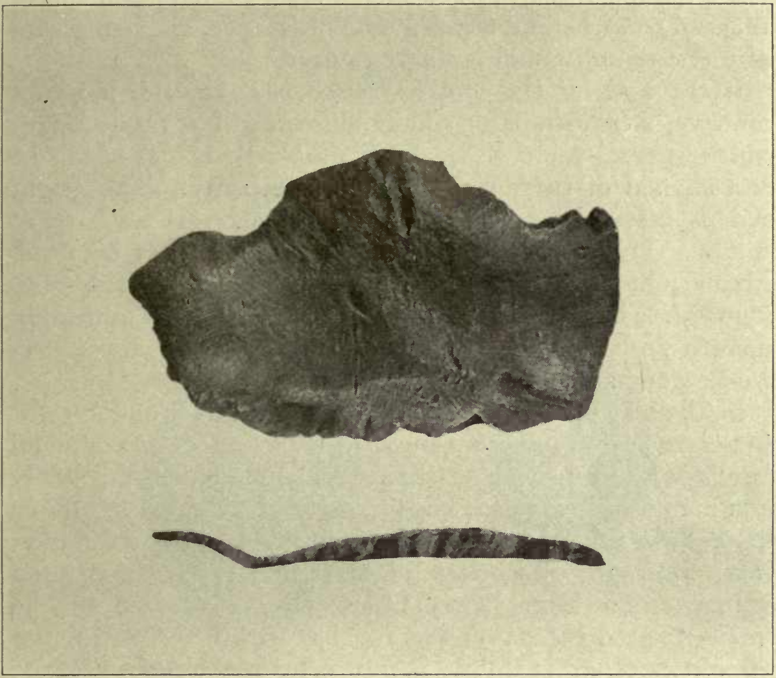

Fig. 24.— Front and side views of Algoma, a peltoid or shield-shaped meteorite. An iron meteorite. Weight, 9 pounds.

Somewhat similar in form to the shield-shaped or peltoid meteorites are the shell-shaped or ostracoid meteorites but the origin of the ostracoid form is probably quite different from that of the peltoid form. Ostracoid meteorites are thin and extended, concave on one side and convex on the other, with much more marked curving than in the peltoid meteorites. Instead of owing their form chiefly to atmospheric shaping, the ostracoid meteorites are probably primarily shaped as a scaling from some larger body. Many of the Canyon Diablo meteorites show this shape to a marked degree. The best illustration among stone meteorites is Butsura, which fell in several pieces which, when put together, made a well-marked shell shape. Such a shape is ill adapted to withstand atmospheric resistance, and hence rupture of the individual is likely to occur.

If the apex of the cone be raised, and the side slope be concave, a bell-shape or codonoid form will be produced, of which several meteorites afford illustrations. One of the best shaped of these is the Durala meteorite. The height of this meteorite is 7 inches; the diameter of its base 10 inches. The outline of the base is triangular rather than circular, but the angles of the triangle are considerably rounded. The surface of this meteorite is almost uniformly smooth and shows little or no contrast in appearance between front and rear sides.

By being elongated still more in the direction at right angles to its circular outline the bell-shaped or codonoid form passes into the pear-shaped or onchnoid form. Only iron meteorites, so far as known, exhibit this shape. Among these Boogaldi and Charlotte furnish excellent examples, (Fig. 25). In meteorites of this shape the orientation changes. The large, heavy, blunt end is now foremost, the small, pointed end at the rear. That such is the position of these meteorites in falling is shown beyond a doubt by the markings on Boogaldi. At the thick, heavy end of this meteorite, well-defined concentric zones of fused oxides may be seen, with transverse furrows running in the direction of the thinner end of the meteorite. The disappearance of both zones and furrows is gradual and in the same direction (Fig. 26). Liversidge* regards these zones of oxides as thrown up by the resistance of the air "just as waves are formed in water or sand by the wind or at the bows of a boat." At the small end of the meteorite longitudinal ridges and furrows may also be seen in a "skin" of fused oxides. These have the same direction as the furrows at

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*Proc. Roy. Soc. N. S. Wales, 1902, 26, 343.

the larger end, and there are remains of drops where the melted material dripped off at the small end. Another indication that the meteorite moved large end foremost, although this evidence is not always conclusive, lies in the fact that it was resting on this end when found. The length of the meteorite is 5 inches and its diameter at the large end

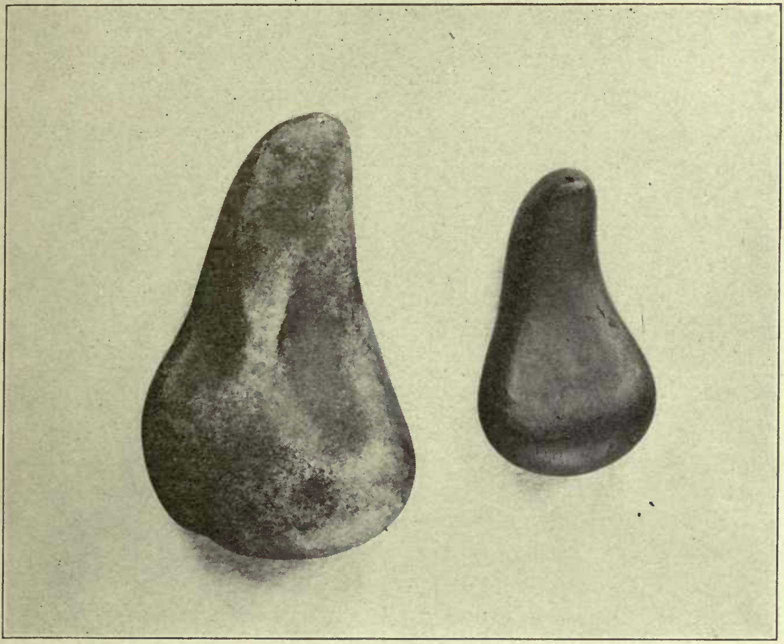

Fig. 25.— Onchnoid or pear-shaped meteorites. Charlotte at the left, Boogaldi (from a cast) at the right. Both are iron meteorites. Charlotte weighed 9 pounds; Boogaldi, 5 pounds.

3 inches. The surface in general is smooth and shows no pittings except for the furrows referred to. The continuity of the etching figures to the edges of the meteorite as seen in section (Fig. 27) shows that the form of the meteorite is due to erosion.

The Charlotte meteorite is about the size and shape of Boogaldi, but somewhat more flattened laterally, and one side is concave. No markings such as those which so dis-

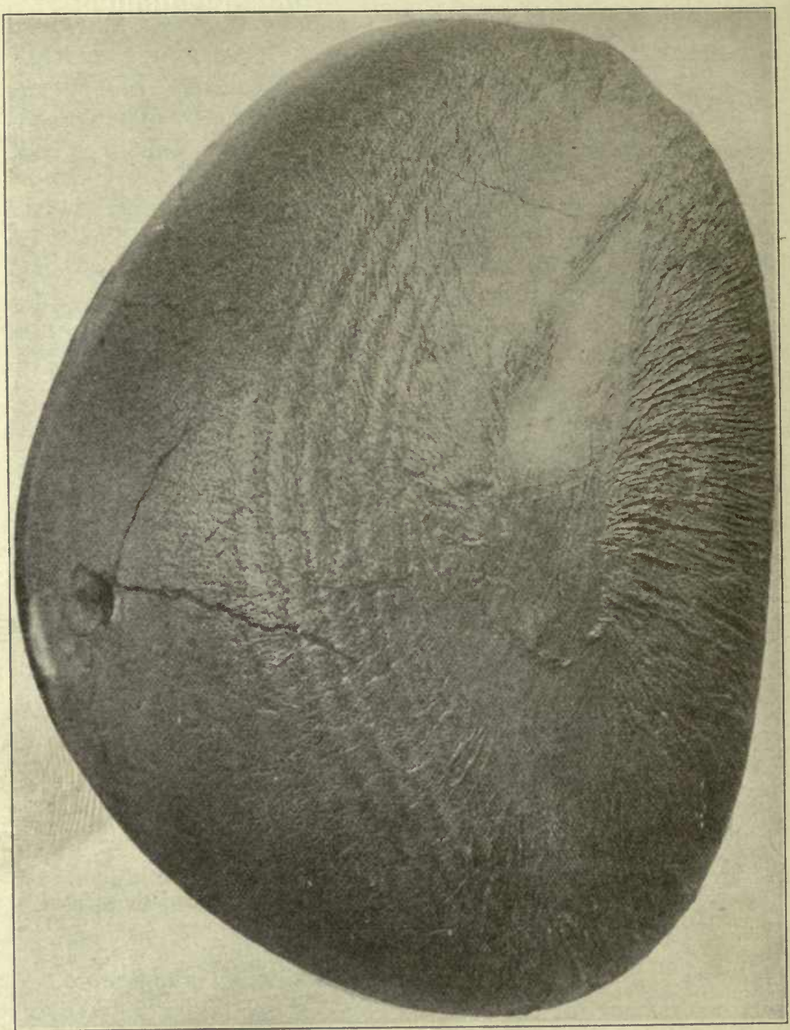

FIG. 26.— Forward end of the Boogaldi meteorite showing waves and ridges formed on its surface by fusion during its fall. Enlarged 1.7 diameters. After Liversidge.

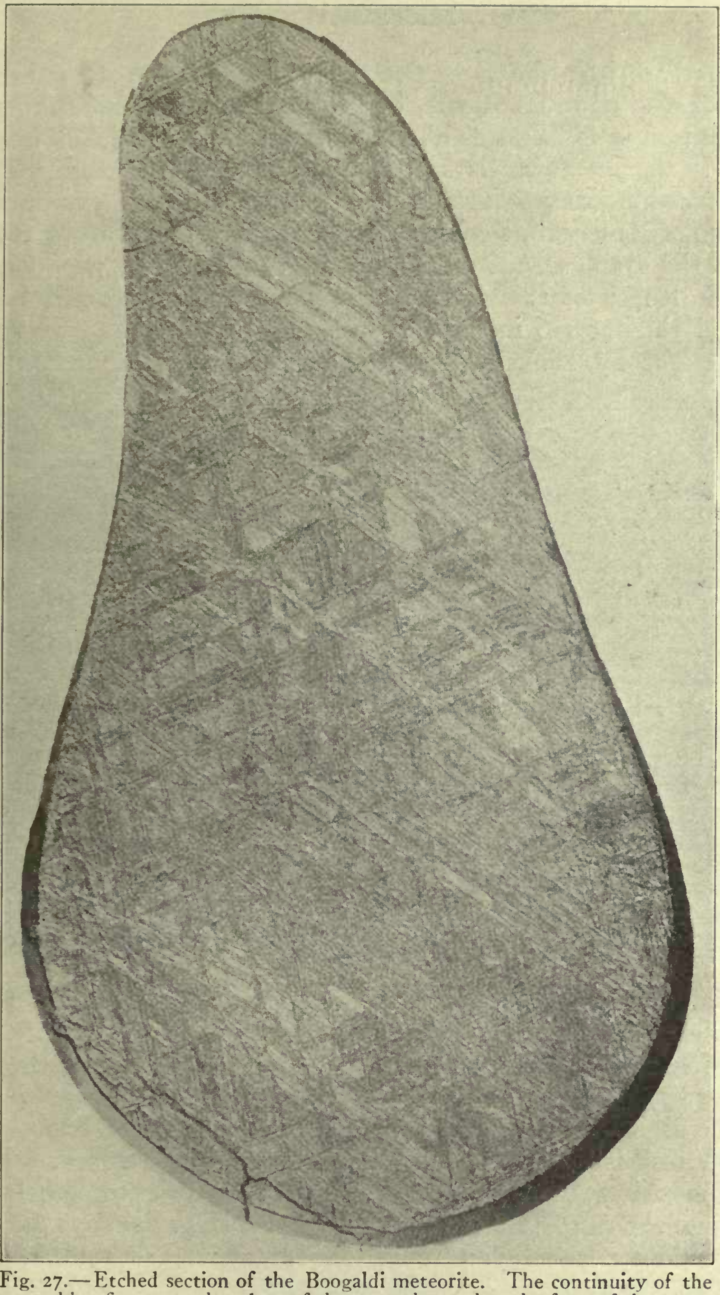

Fig. 27.—Etched section of the Boogaldi meteorite. The continuity of the etching figures to the edges of the mass shows that the form of the meteorite has been produced by erosion. Enlarged 1.3 diameters. After Liversidge.

tinctly orient the Boogaldi meteorite seem to have been observed upon Charlotte, but it is highly probable that its position in falling was likewise with the large end foremost.

If the meteorite is still more elongated and acquires a somewhat convex instead of a concave curve in the direction of its length, a column-shaped or styloid form like that of the Babb's Mill meteorite (Fig. 28) will be produced. The length of this meteorite is 3 feet; breadth 10 inches, and thickness 6 inches. It weighed 290 pounds. It was thought by Blake, who originally described it, that this meteorite was a residual nodule of an irregularly shaped mass from which the irregular portions had been thrown off by terrestrial weathering, but it seems quite as likely that the form was acquired in falling.

FIG. 28.— Babb's Mill. A styloid or column-shaped meteorite. Length, 3 feet. Weight, 290 lbs.

Of ring-shaped or cricoid forms among meteorites but a single example seems to be known, that of Tucson (Fig. 29). This meteorite is in the form of a metallic ring, the exterior diameter of which varies from 49 to 38 inches and the interior diameter from 26½ to 23 inches. The width of the thickest part of the ring is 17½ inches and of its narrowest part 2¾ inches. The greatest thickness at right angles to the plane of the ring is 10 inches. It will thus be seen that the ring is somewhat irregular in form, but a general ring shape is well exhibited. There are no oriented pittings upon the ring. As to the origin of this ring, opinions differ. Haidinger concluded* that the meteorite rotated in its

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*Sitzb. Wien. Akad., 1870, Bd. 61, II, p. 506–511.

descent and that thus a hole was bored through it by the air. Observation of the action of the air upon other meteorites does not confirm this view, however. It is more probable that the ring existed preterrestrially as a portion of an otherwise stony mass and that the stony portion fused or fell away in the passage of the mass to the earth. This view is rendered somewhat more probable by the fact that the iron contains about five per cent of silicates.

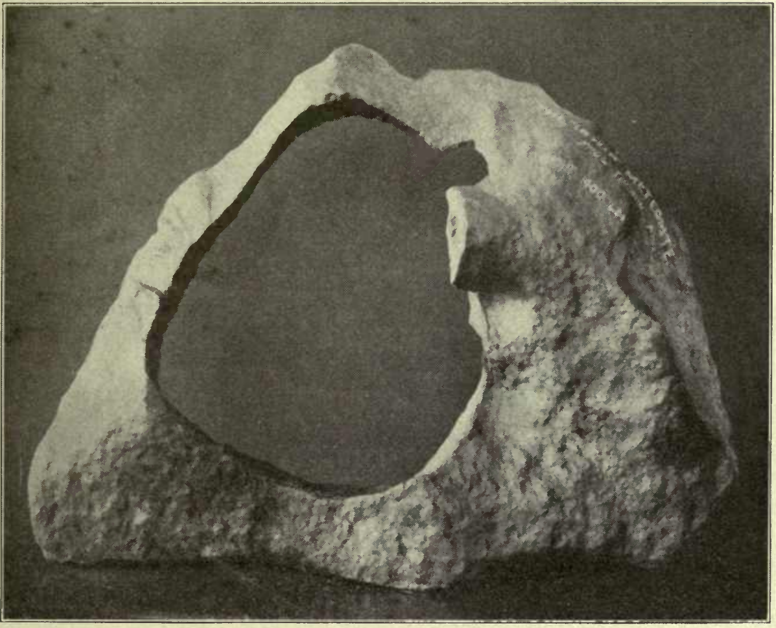

FIG. 29.— A cricoid or ring-shaped meteorite. One of the Tucson, Arizona, fall. It is an iron meteorite and weighs 1514 lbs.

Of jaw-shaped or gnathoid meteorites Kokstad and Hex River (Fig. 30) furnish excellent examples. These are both iron meteorites and of nearly the same size. Kokstad is 26 inches long, 12 inches wide at the angle of the "jaw," and 3 inches thick. Its surface is comparatively smooth except for one large circular depression probably caused by the fusing out of a troilite nodule. Hex River is 20 inches long, 11 inches wide, and 7 inches thick. It is thus somewhat more massive than Kokstad and approximates the pear shape. Unlike Kokstad, it is deeply pitted all over its surface. The pits are broad, shallow depressions of rather uniform size, in part so arranged as to give the impression of furrows passing around the "jaw" at right angles to its length. Nothing in the distribution, size, or shape of the pittings seems to give a clue as to the position of the meteorite in falling. From its resemblance in form to the pear-shaped meteorites, however, it may be surmised that it

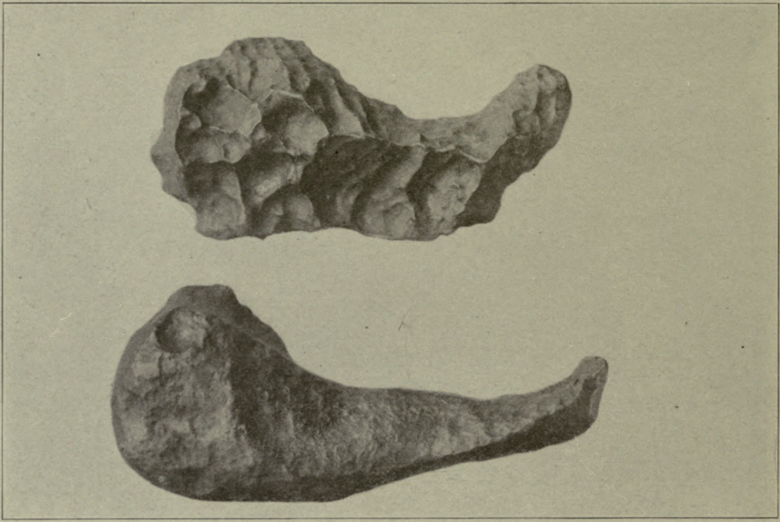

FIG. 30.— Gnathoid or jaw-shaped meteorites. Upper one, Hex River; lower, Kokstad. Both are iron meteorites and weigh about 100 pounds each.

fell with the heavy end foremost. The jaw shape is exhibited in some degree also by the great Bacubirito meteorite, (Frontispiece) although the form is not as well marked as in those previously described. The surface of this meteorite is quite uniformly covered with pittings, regular in size, 2 to 3 inches in diameter, with well-defined walls and quite shallow. No characters seem to afford data for an orientation of the mass. A single, small specimen of Toluca in the Field Museum collection also exhibits a gnathoid shape. It is reasonable to suppose that this shape would be exhibited only by iron meteorites, since stone meteorites if of this form would be likely to be broken up in passing through the earth's atmosphere. The most satisfactory suggestion that seems to have been made regarding the origin of the gnathoid shape is that of Brezina,* who thought that it arose from the breaking apart of a ring like that of Tucson. It is clear that such forms might arise from a dismembered ring, but whether this was the actual origin of those known cannot, of course, be stated positively.

The other meteorite forms mentioned, such as cuboidal, pyramidal, tetrahedral, etc., are exhibited by various meteorites and especially those falling in showers. Here the action of the air has frequently not been sufficient to greatly modify the original angular form, and hence such forms as would be found in freshly broken terrestrial rocks occur.

*Verh. der K. K. geolog. Reichsanstalt, Wien, 1887, 289.

CHAPTER VIII

CRUST OF METEORITES

All meteorites are characterized by a more or less smoothed or rounded coating differing in color or texture or both from that of the substance of the meteorite beneath. This superficial skin or coating is known as the "crust" and is a distinguishing character of meteorites. It is obviously the result of fusion of the surface of the meteorite by heat encountered during the passage of the mass through the atmosphere. Being the result of fusion, it varies according to the constitution of the meteorite. If the meteorite is composed of feldspar and augite, for example, which are minerals fusible with comparative ease, a smooth and varnish-like crust flowing in little rivulets over the surface is seen. If, however, the meteorite is composed chiefly of the difficultly fusible minerals, bronzite and chrysolite, as are the majority of stone meteorites, a rough, scoriaceous crust is formed. The color of the crust also varies with the composition of the meteorite. Meteorites containing iron compounds in even small quantity have a black or dark-colored crust on account of the presence of these substances. If, however, iron compounds are lacking, the crust may be nearly colorless as in the meteorite of Bishopville, or yellowish, as in Bustee. Inasmuch as iron or its compounds is a nearly constant component of meteorites, a black or dark crust is to be found on the majority of them. Since iron meteorites consist almost wholly of iron, the crust upon them is usually black when they are freshly fallen. Iron meteorites are, however, not as uniformly or plainly encrusted as are the stone meteorites. The crust of iron meteorites when it can be separated is found to have the composition of magnetite. It is usually very thin (1 mm. and less) and dull or only weakly shining. Its surface may be smooth or rough, shagreened or warty, and occasionally slaggy. Reichenbach called it "iron glass" (Eisenglas), but the term is hardly an apt one, since, as Cohen remarks, the substance is not iron and not glass. In addition to the formation of crust, there is an alteration by heat of the periphery of iron meteorites producing a zone exhibiting a granular structure which may be seen about the edge of the meteorite. It is illustrated in the accompanying figure of a section of the Charlotte meteorite, (Fig. 31). This zone varies in width from an extreme of 10 mm. in Cabin Creek to less than 1 mm. in Prambanan. As a rule, the zone is thinner the greater the weight of the meteorite, although there are some exceptions to this. Such a relation of the width of the zone to the weight of the meteorite is doubtless due to the greater difficulty of heating the larger masses. Since most iron meteorites have not been

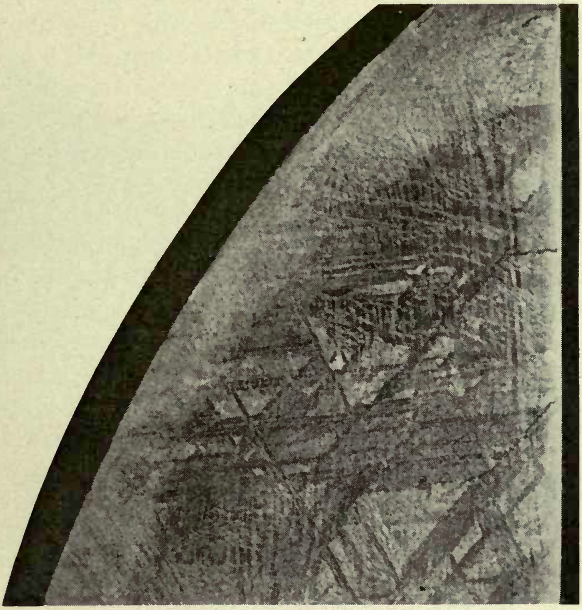

FIG. 31.—Heat crust of Charlotte meteorite. The heating of the surface in the passage of the meteorite to the earth produced the granular edge seen at the left. ×2.5.

found until some time after their fall, they have generally suffered oxidation which has considerably altered if it has not altogether destroyed their fusion crust. In its place one finds, as a rule, an oxidized crust, usually of a reddish brown color and of varying thickness. The rapidity with which it may form is largely dependent on the constitution of the meteorite, those having considerable chlorine oxidizing the most rapidly. Climate is also an important factor in determining the rate of oxidation of iron meteorites. Decomposition takes place much more rapidly in wet than in dry climates.

FIG. 32.— Surface relief of Juncal meteorite produced by terrestrial erosion.

The erosion of dry climates sometimes produces peculiar markings on the surface of iron meteorites. These markings may simply be numerous, small, circular pits independent of one another or they may run together to produce rills like those seen on the surface of the Juncal meteorite (Fig. 32). The position of these rills coincides with the lamellar structure of the meteorite. Such an appearance is especially characteristic of the meteorites which have been obtained from the Chilean desert, but it is also shown on the Australian meteorite of Youndegin.

In both stone and iron meteorites the thickness and other characters of the crust vary in different parts of the meteorite. Many of the characters depend on the position of the meteorite in its flight through the atmosphere and the length of time during which the different surfaces have been exposed. On the side of the meteorite which was in front in its course the crust is thinner and shows more complete fusion than on the side which was behind. Other portions of the meteorite may show a thickened crust from the flow of fused matter to those points. A feature occasionally seen in the crust of some stone meteorites is a marking off by fissures into little angular fields such as are seen on "crackled" earthenware. These are evidently due to contraction in the cooling of the crust. In contrast to the generally rough appearance of the crust of some stone meteorites, there occur in places spots which appear to have been glazed over. These are generally round or oval, from 2 to 10 mm. in diameter, smooth and usually of a yellowish or reddish color as compared with the black crust. They appear to represent the location of exceptionally fusible constituents upon the surface of the meteorite. They are quite characteristic of the stones of Mocs, also are seen in some of those of Modoc, L'Aigle, etc. Where nickel-iron appears upon the surface of stone meteorites it generally projects in rounded forms, especially if the grains are large. This indicates that it is more refractory than the siliceous constituents of the meteorites. In other cases, however, the nickel-iron may oxidize sufficiently to form with the silicates a more fusible compound and cause pits instead of knobs. The thickness of the crust of the stone meteorites depends somewhat upon their texture, a compact stone having a thinner crust than one of more open texture. Upon meteorites of a relatively porous character the crust may reach a thickness of 10 mm., though a lesser thickness is usual. The stones of the meteoric shower of Mocs furnish proof that in the stone meteorites the thickness of the crust does not vary with the size of the stone. Though the stones were of many sizes, the thickness of the crust was invariably ⅓ to ⅔ mm. All of these features indicate that the crust is the result of a sudden, brief heating.

When seen under the microscope in section, the crust of most stone meteorites presents the interesting feature of three, and in some cases four, well-marked zones (Fig. 33).

FIG. 33.— Microscopic section of a Mocs meteorite showing (above) three zones of the crust. × 70.

The outermost of these, called the fusion zone, is thin as compared with the other two, glassy, black and opaque to brown and transparent. Beneath it lies a broader, transparent zone in which the constituents of the meteorite appear little, if any, changed. This was called by Tschermak the absorption zone (Saugzone). Next and last follows a broad zone of black, opaque, spotted appearance. This zone may be so broad as to make up four-fifths of the width of the crust. The constituents of the meteorite appear in this portion of the crust to be in normal condition, but impregnated with black, generally opaque matter. Hence this zone was called by Tschermak the impregnation zone (Imprägnationszone). The relative width of the three zones was found by Ramsay in Bjurböle to be as follows: Outer zone, 0.1 mm.; middle zone, 0.2 mm.; inner zone, 0.3 mm. The relative and total widths of these zones vary in different meteorites, being usually the broadest in the more friable and porous meteorites. In compact meteorites the crust is thinner, and often only the outer, fused zone can be distinguished. In the crust of other meteorites again the middle, transparent zone may be lacking and only the opaque, outer and inner zones be seen. On many of the stones of Mocs, Brezina noted a very thin layer of yellow transparent substance outside of the fusion zone, so that the number of zones was raised to four.

The origin of the three crust zones seems best accounted for by the theory of Tschermak that fused matter from the exterior penetrates through the middle zone and congeals in the inner zone.

In the crust of the St. Michel meteorite Borgström* found a large excess of pyrrhotite in the inner or impregnation zone. As pyrrhotite is the most fusible ingredient of this as well as of all meteorites, he urged that the opacity of the impregnation zone was probably due to the chilling and collecting there of pyrrhotite which had flowed inward from the outer crust in a fused condition. From the fusing temperature of pyrrhotite Prof. Sundell calculated the length of time during which the crust had been exposed to heat, or in other words the time of formation of the crust to be 1.16 seconds.

Between a completely developed crust and no crust at all, various gradations occur according to the length of time during which a meteoritic surface is exposed during the flight of the meteorite through the atmosphere. As meteoritic individuals often break up during their flight to the earth, different surfaces will be exposed for varying lengths of

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*Bull. Com. Geol. de Finlande, 1912, 34, 22.

time. Those which become exposed just before reaching the earth will have no crust at all; those exposed a little longer will appear as if smoked. A little longer exposure may produce a blackening of the entire surface, but without glazing or smoothing, and between this and a well-formed crust all gradations may occur. Such a partial encrusting is often called a secondary crust to distinguish it from the well-formed primary crust. Individuals of a meteoritic shower frequently exhibit several grades of secondary crust, due to successive disruptions in the air.

CHAPTER IX

VEINS OF METEORITES

Many of the stony meteorites are penetrated by black, thread-like veins. These veins may run continuously or with interruptions, and may be close together or scattered. When very numerous they give to the meteorite a brecciated appearance and may be so abundant as to color the whole mass. They seem to be largely confined to the chondritic meteorites, being seen among the achondrites only in Bishopville. So abundant are they among the chondrites that Brezina made the presence of veins a ground of subdivision of all their groups. Of 267 chondrites he reported 145 either veined or breccia-like. The white and intermediate chondrites showed the largest per cent of veining, and the gray chondrites the largest amount of breccia-like structure. In the spherical and crystalline chondrites both features were less frequently observed.

The course of the veins is not as a rule marked by any particular system or direction. It is generally more nearly straight than curved, but there may be much forking and anastomosing. In the Bluff meteorite two systems of veins cross at angles of about 45°. The narrower of these veins is of nearly uniform width and was observed over a plane 4x15 inches. The other vein varies in width and is less extensive. Some veins are so delicate as to appear in section like the finest hair, scarcely 0.01 mm. in thickness. On the average they have a thickness of about 0.1 mm. The thickness as a rule is pretty uniform, but swellings and knottings may appear. Sometimes vein-like masses are seen more than an inch in thickness, and single stones of Pultusk and Mocs seem to be made up wholly of vein material. Other meteorites showing large vein masses are Chantonnay, L'Aigle, Orvinio, and Ställdalen. Another feature allied to veins seen in many meteorites (best disclosed on breaking the stone) is that of smoothed, blackened surfaces passing in various directions. They are termed armored surfaces (Harnischfläche). Such surfaces have been likened to the slickensides of terrestrial rocks, also to stylolites. They pass to veins by insensible gradations.

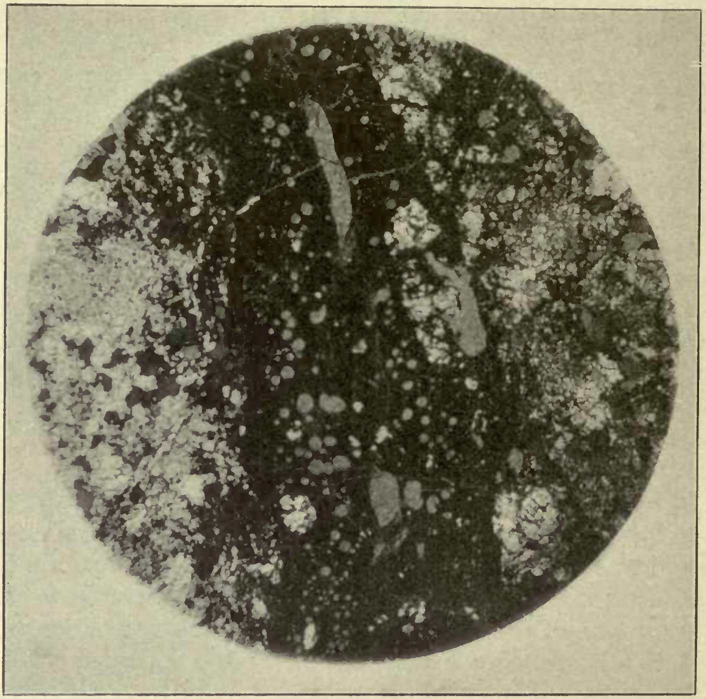

FIG. 34.— Cross section of a vein of one of the Mocs meteorites. The vein mass appears as a broad black band through the center. It is in part intermixed with the adjoining ground mass and in part has well-defined walls. The gray spots are lumps and spheres of nickel-iron illuminated by reflected light. The branching of some of these into clefts, one of which is still open, is of interest. ×20. After Tschermak.

Under the microscope the principal substance of the black veins appears like that of the first and third layers of the crust. It is opaque, dull, half glassy, showing in reflected light fused spheres of nickel-iron and pyrrhotite and grains of nickel-iron branching out into delicate leaves (Fig. 34).

The occurrence of these fine iron veins furnishes the chief distinction between the substance of the crust and that of the black veins. The boundary between the veins and the adjoining stone is at times sharp and again gradual. In the latter case the ground mass seems to be impregnated by a black, half-glassy injection. In the broader veins a distinct flow structure of the substance is evident. The finer veins in their course tend to avoid the chondri and follow the pyrrhotite.

In three meteorites analyses of the normal stone and of the vein substance have been made. These meteorites are Orvinio, Ställdalen, and Bluff. The analysis of the normal stone is shown in the following table in each case under *a*, that of the vein under *b*.

ANALYSES OF VEIN MATERIAL

	1		2		3	
	a	*b*	*a*	*b*	*a*	*b*
SiO_2	38.01	36.82	35.71	38.32	37.70	38.96
Al_2O_3	2.22	2.31	2.11	2.15	2.17	1.89
FeO	6.55	9.41	10.29	9.75	23.82	22.98
MgO	24.11	21.69	23.16	25.01	25.94	7.52
CaO	2.33	2.31	1.61	1.84	2.20	tr.
Na_2O	1.46	0.96	....	....	....	....
K_2O	0.31	0.26	....	....	....	....
MnO	....	....	0.25	1.00	....	....
NiO	....	....	0.20	0.42	....	....
Fe	22.34	22.11	21.10	17.47	4.41	2.30
Ni+Co	2.15	3.04	1.78	1.02	1.75	3.26
S	1.94	2.04	2.27	2.51	1.30	0.26
P_2O_5	....	....	0.30	0.31	....	....
	101.42	100.95	98.78	99.80	99.29	97.17
G=	3.675	3.600	3.733	3.745	3.510	3.585

REFERENCES

1. Orvinio. Sipöcz. Sitzb. Wien Akad, 1874, 70, 1, 464.
2. Ställdalen. Lindström. Geol. Foren. Stockholm, 1878, 4, 53–54.
3. Bluff. Whitfield and Merrill. Am. Jour. Sci., 1888, 3, 36, 119.

These analyses make it evident that the substance of the veins does not differ essentially from that of the meteorite. The vein matter, therefore, has doubtless been formed by alteration in place of the substance of the meteorite and does not represent foreign matter introduced into a fissure, as is the case with most veins in terrestrial rocks. For this reason, therefore, the term veins applied to these formations in meteorites is somewhat misleading, and the lack of analogy to veins in terrestrial rocks should be kept in mind.

The similarity in composition between the vein and the substance of meteorites and the resemblance of the vein matter to the crust seem to make clear the origin of the veins. They are apparently produced by the penetration of heat into the fissures of the meteorite during its passage through the atmosphere. Some have thought that the vein matter was fused matter from the surface which flowed into fissures; but, as Tschermak pointed out, the low temperature of the interior of the meteorite would probably prevent this. In Chantonnay he found several fissures into which the fused matter from the surface had penetrated to a depth of but 6 mm., leaving the fissure open for the remainder of its course. Earlier writers were inclined to regard the veins of preterrestrial origin, but there seems no need to assume this. Reichenbach regarded some veins of cosmic, others of telluric, origin. The cosmic veins, he stated, avoided the larger constituents of the meteorites and characterized the iron-rich, dark, and compact chondrites. The telluric veins passed through the larger constituents and characterized the light, iron-poor chondrites. These distinctions have not been accepted by later observers. That the substance of the chondrites turns black upon heating has been abundantly proved experimentally. Meunier observed that a piece of Pultusk became black upon heating it in a stream of carbonic acid gas. A piece of Tadjera was turned red by heating in a current of air and later black by heating in hydrogen or carbonic acid gas. Cohen, heating pieces of Lançon in a platinum boat to a point at which hard glass softened, obtained only a reddish brown color both in a current of air and in one of hydrogen; but on heating in the flame of a blast lamp in a platinum crucible, a black color appeared. He, therefore, concluded that the amount of heat rather than the presence or absence of oxygen caused the production of the black color.

Besides black veins, metallic veins consisting largely of nickel-iron occur in some meteorites, especially in Farmington and Tabory. The form and distribution of these metallic veins seem to be similar to that of the black veins, and it is the belief of Cohen * that all gradations occur between the two kinds. The broad, black veins often have more or less metallic interiors and an increase of this metallic substance would produce a metallic vein. The present writer, has however,† called attention to the fact that a diminution of the metallic substance of an iron-stone meteorite might equally well produce the veins. Perhaps both methods of origin are possible. In the Farmington meteorite, which is the one in which the metallic veins are best developed, the veins penetrate throughout the mass, and it is not easy to understand how a substance so difficultly fusible as nickel-iron could be so distributed by the penetration of heat into the fissures.

Black veins also occur in iron meteorites, penetrating between the bands and at times crossing their course. Their usual contour has been accurately described by Cohen as like that of a stroke of lightning. The substance of these veins where it has not suffered terrestrial alteration is hard, takes a good polish, and resists acid. It was regarded by Reichenbach and Brezina as magnetite and as probably produced by the penetration of heat and air into the fissures of the meteorite. In the view of the present writer, a fissuring of iron meteorites can take place after their fall by the penetration of slow oxidation inward, which would give a vein-like appearance. The alteration of a magnetite vein to limonite might also produce such an effect. Structures similar to the armor faces of stone meteorites have been noted in the iron meteorites of Quesa and Sacramento.

Probably related to armored surfaces (page 86) are the slickensides seen in some stone meteorites, notably Long Island (Fig. 35). These in Long Island lack the dark color, as if rubbed with graphite, which is common to the average armored surface. They are smooth, shining, somewhat uneven, and striated in the direction of movement. The surfaces may be parallel to each other at different levels and

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*Meteoritenkunde, Heft II, p. 121.

†Am. Jour. Sci., 1901, 4, 11, 60–62.

also run in different directions. In Long Island three of these directions are nearly at right angles to one another. The movement has brightened and elongated the metallic grains, but produced no other changes in the immediately adjoining areas. Cohen has urged that these surfaces are terrestrial in origin, but this seems to the author unlikely. Their coursing in different directions makes it difficult to ascribe them to impact upon the earth, as was done by Cohen, as in such case the movement would be expected to be in a single direction.

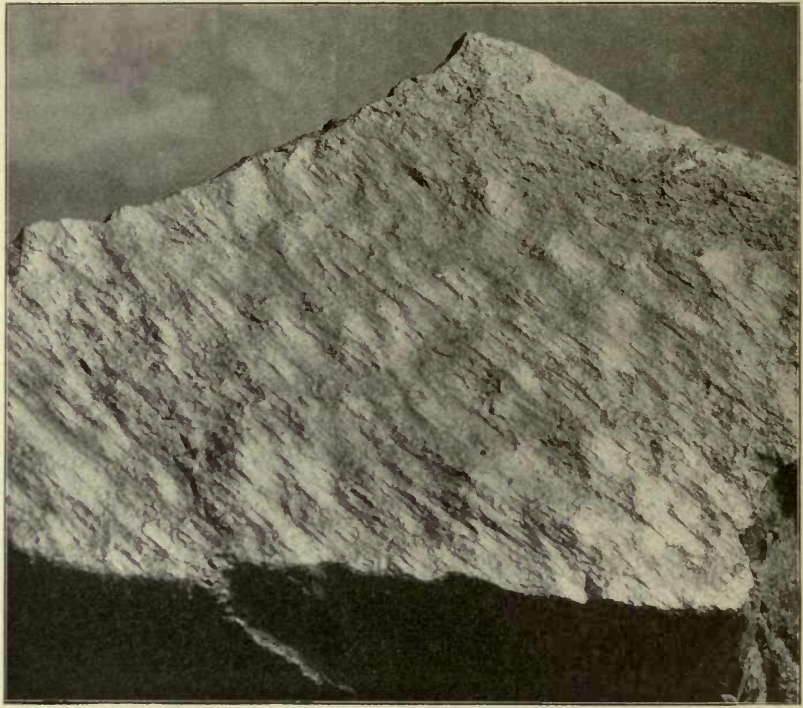

FIG. 35.— Slickensided surface, Long Island meteorite. Natural size.

In iron meteorites evidence of internal movement is afforded by faulting in the etching figures. Bridgewater, Carlton, Descubridora, Magura, and Puquios are meteorites in which such faults have been described. In Puquios dislocation has taken place in several directions. The largest fault extends the entire length of the mass and has a throw of 3 mm. In Descubridora a throw of from 6 to 12 mm. has been noted. The faulting is believed by Brezina to be due to the impact of the meteorite on the earth, though Howell was inclined to ascribe it, in the case of the Puquios meteorite at least, to the passage of the mass near the sun, causing high heating.

Another evidence of movement in iron meteorites is afforded by bent or curved figures such as have been noted in Bacubirito, Carlton, Glorieta, Jamestown, and Toluca. Such figures are usually confined to a small area on a single meteorite and are probably correctly assumed to be produced by the impact of the meteorite on the earth. The writer has produced them by boring or hammering a meteorite.

CHAPTER X

STRUCTURE OF METEORITES

STRUCTURE OF IRON METEORITES

Iron meteorites as seen upon a polished surface usually present a homogeneous and uniform structure. Sometimes cleavage planes of considerable dimensions pass through individual masses, and broken fragments of iron meteorites often exhibit a hackly surface or various small cleavage planes. Large structural peculiarities are, however, generally wanting. The nearest approach to them is to be seen in the iron of Mount Joy, which appears to be composed of irregular nodules, some of which are an inch or two in length. These are generally regarded, however, as phases of a crystalline structure on a large scale. But though large structural features are wanting, when examined intimately most iron meteorites exhibit a well-marked minute structure. It is most successfully brought to view by etching a polished surface of the meteorite. Then there appear, on the majority of iron meteorites, figures formed of parallel bands intersecting in two or more directions, (Fig. 36). These are called Widmanstätten * figures after Alois von Widmanstätten of Vienna, who first produced them in 1808 by heating a section of the Agram meteorite. The presence of these figures shows that the iron is in reality made up of a number of laminae or plates lying in parallel and crystalline positions. Wherever the structure appears in this form it is found that the plates are parallel to the four pairs of faces of an octahedron. The structure is therefore octahedral, and such irons are known as octahedral irons. While the structure may be in a general way described as made up of plates parallel to the planes of an octahedron, it is in reality as a rule more complex than this. Generally each plate or lamella is itself made up of many

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*The word is sometimes given the adjective form, Widmanstättian.

smaller plates combined in twin position, arranged according to the positions of twelve faces of the trisoctahedron, 112. These smaller plates or lamellae repeat the structure of the larger lamellae. So far as their coarse structure is concerned, the larger lamellae as seen in section consist of a broad, central band to which Reichenbach gave the name of kamacite, from *κάμαξ*, a shaft, bounded on either side by a thin border to which Reichenbach gave the name taenite, from *ταινία*, a ribbon. Angular interstices between intersecting lamellae may be filled with a homogeneous substance known as plessite or partly with this and partly with structures repeating on a smaller scale those of the larger lamellae. The interstices are usually known as fields.

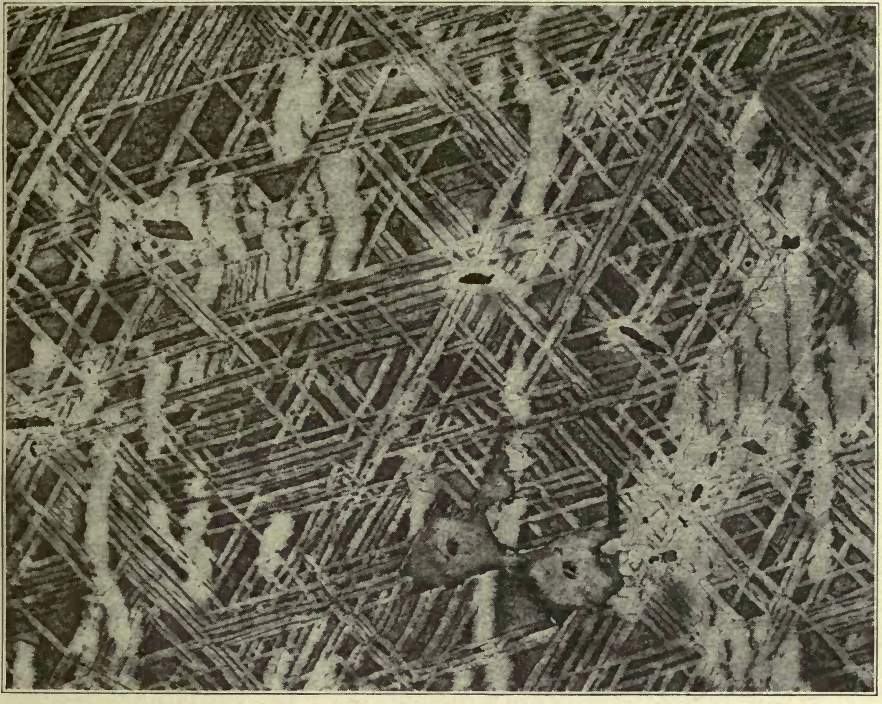

FIG. 36.—Typical octahedrăl etching figures of an iron meteorite. The Red River meteorite.

Various minute structures may be scattered through the fields, most prominent among which are combs (Kämme). These run out from the principal lamellae, but differ from the primary lamellae in their smaller size and also in that the taenite and kamacite in them are fused together. Other inclusions in the fields may be (1) minute flakes of taenite giving a shimmering appearance and (2) slightly indicated small lamellae giving a half-shaded effect. Again small lamellae may lie nearly alone in a field.

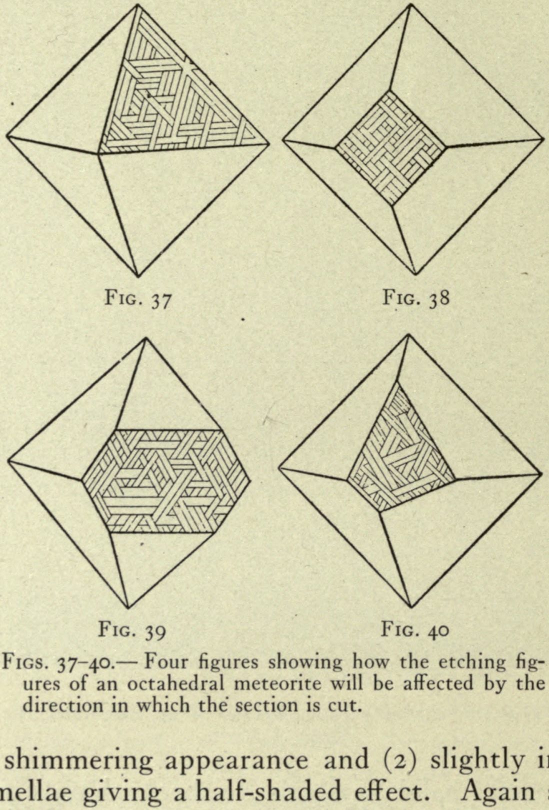

Fig. 37 Fig. 38

Fig. 39 Fig. 40

Figs. 37–40.— Four figures showing how the etching figures of an octahedral meteorite will be affected by the direction in which the section is cut.

Considerable differences in the figures of different meteorites are produced by variations in the grouping, size, and shape of the lamellae. Thus the lamellae may be in parallel groups of nearly equal length or they may be of unequal length, the middle ones in this case usually being the longer. Again the lamellae may be long or short and may be of uniform width or have rounded or irregular outlines. Again, they may vary much in width, extremes of variation being from a fraction of a millimeter to several millimeters. Such variations as are above described do not occur to any large extent on any single meteorite. Almost without exception, the figures are uniform throughout any individual mass and for all the individuals of a single fall. This fact aids in distinguishing meteorites of different falls. The angles at which the lamellae intersect in any given section will depend as shown in the accompanying figures (Figs. 37–40) on the direction of the section with relation to the octahedral structure. Thus if the section should be parallel to an octahedral face (as in Fig. 37) the section will show three systems of bands intersecting at angles of 60°. If it is parallel to a cubic face (Fig. 38) it will show two systems of bands intersecting at angles of 90°. If it is parallel to a dodecahedral face it will show two systems of bands intersecting at angles of 109° 28′, and two others which will bisect this angle (Fig. 39). If it should be made in any other direction, and this is of course most likely, it will show bands running in four directions and intersecting at unequal angles (Fig. 40).

A modification of the octahedral structure observed by Rinne* in a section of the Bethany (Gibeon) iron, showed, as may be seen in the accompanying figure (Fig. 41), in addition to the usual octahedral lamellae, lamellae running parallel to the planes of a cube. To meteorites having this structure Rinne gave the name tesseral-octahedrites. In English, the term tesselated octahedrites is perhaps better. Plates of pyrrhotite found in this iron followed the planes of the dodecahedron in their arrangement.

Another of the Bethany (Mukerop) irons showed a structure which has not been elsewhere observed which seems to be a mass twinning. The meteoritic individual which shows this twinning weighs about 350 pounds. It appears on etching to be made up of three individuals of about equal size. These are separated as seen on an etched plate by two straight clefts which run through the plate in parallel direc-

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*Neues Jahrb., 1910, I, 115–117.

tions. These clefts run parallel to octahedral planes. The clefts divide the etched plate into three nearly equal parts, all of which differ in their etching figures. On two of the parts the usual figures of a fine octahedrite are shown, but they run in different directions, on one as if the section were parallel to an octahedron and on the other as if it were parallel to a hexoctahedron. The third portion exhibits at first sight no octahedral figures, but appears like an ataxite. On close examination, however, indications of octhedral figures can be discerned in this portion also. The best explanation of the peculiar structure seems to be that of Berwerth,* who regards the mass as made up of three individuals twinned according to the spinel law, but one of the individuals suffered some subsequent molecular alteration.

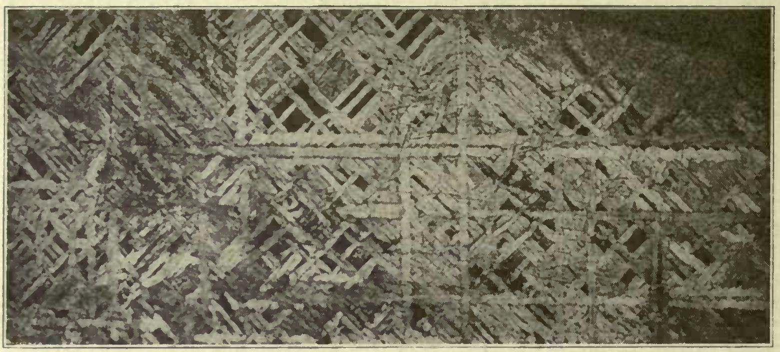

FIG. 41.— Tesselated octahedral figures seen in one of the Bethany meteorites. Some of the lamellae follow the lines of a cube, others those of an octahedron.

Some iron meteorites on etching do not exhibit the broad, lamellar figures which have been described for octahedral meteorites. Their surface appears, except for occasional inclusions, practically uniform and homogeneous. Yet on close examination their surfaces will be found to be crossed here and there and in different directions by long, straight, narrow, slightly depressed lines. Scattered among these are shorter lines, also running in various directions. Such lines were first observed and described in detail by Neumann

*Sitzb. Akad. d. Wiss., Wien., 1902, 111.

and they are therefore generally known as Neumann lines. Meteorites which exhibit them are also found to possess a cubic cleavage which can best be observed by cutting a section of the meteorite partly in two and then breaking the remainder. The fractured surface then presents an appearance like that of broken galena. The Neumann lines always exhibit some definite relation to the cubic structure, by either running as diagonals of faces or to central points of a cubic edge. The appearance of these lines and their relation to a cube are shown in the accompanying figure (Fig. 42) as drawn by Huntington* from a section of Coahuila. The lines are regarded as representing narrow lamellae more easily dissolved by acid than the intervening portions. They lie in twinning relation to the main individual. According to Linck† the twinning plane may be the octahedron or both the twinning plane and the growth plane may be the trisoctahedron, 211. Irons which show the Neumann lines also exhibit an oriented sheen. This is

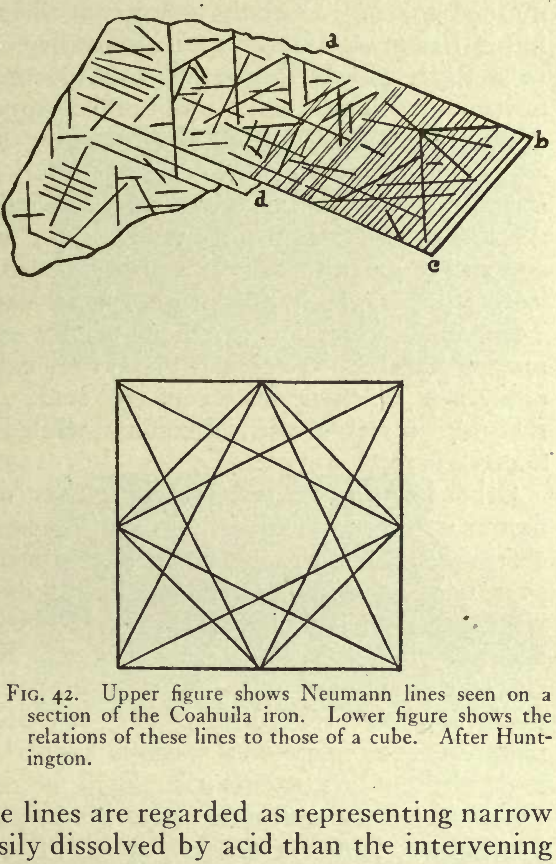

Fig. 42. Upper figure shows Neumann lines seen on a section of the Coahuila iron. Lower figure shows the relations of these lines to those of a cube. After Huntington.

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*Am. Jour. Sci., 3, 32, 284.

†Zeitschr. für Kryst., 1892, 20, 209–215.

believed to be caused by reflection of light (1) from minute, square pits which are negative crystals of a tetrahexahedron and (2) from the Neumann lines. Owing to the various cubic features which characterize irons of this type, they are known as hexahedrites. They form a small but well-marked group. The only member of the group observed to fall is Braunau. Other typical hexahedrites are Coahuila, Hex River, Lick Creek, Murphy, Nenntmannsdorf, and Scottsville. These exhibit an uninterrupted cubic structure and are known as normal hexahedrites. Others which are cubic show a more or less coarse-granular structure and are known as granular hexahedrites. The individual grains on these show Neumann lines which differ in direction. The size and shape of these grains also varies in different meteorites. Bingera, Holland's Store, Indian Valley, Summit, and Tombigbee River are examples of this group. While the normal hexahedrites appear alike, they exhibit considerable difference in their resistance to acid. Some, like Fort Duncan, dissolve with difficulty while Lick Creek and Scottsville etch very easily.

Other iron meteorites on etching show neither octahedral figures nor Neumann lines, and neither octahedral nor cubic cleavage. Some show a fine-granular structure but others even under the microscope exhibit no division into grains which can be detected. They are, therefore, except for accessory minerals, quite structureless. Peculiar streaks or clouds characterize some, but they are neither octahedral or cubic in their arrangement. To this third group of iron meteorites the name of ataxites is applied, the name meaning "without arrangement." Such meteorites, because of their lack of characteristic figures, form a difficult group to distinguish from terrestrial irons. Some of them are regarded by Berwerth as showing traces of octahedral structure and to have been produced by heating of octahedral meteorites.* Such an origin for some ataxites is rendered probable by the fact that heating an octahedral iron destroys the octahedral structure, as shown in the accompanying figure (Fig. 43). The upper figure shows a

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*Sitzb. Wien Akad., 1905, Vol. 114.

section of Toluca exhibiting the usual etching figures of that meteorite, while the lower figure shows the change made in the appearance of the iron by heating it to a temperature of 950° C. for seven hours. The octahedral structure is practically destroyed and an appearance closely resembling that of many of the ataxites is produced. On the other hand not all ataxites can have been produced in this way since some of them have too high a content of nickel to have had octahedral structure. The ataxites fall for the most part as regards composition into two groups, one being high (15 to 20 per cent) in nickel, the other low (5 to 7 per cent). A few are intermediate between these in their nickel content.

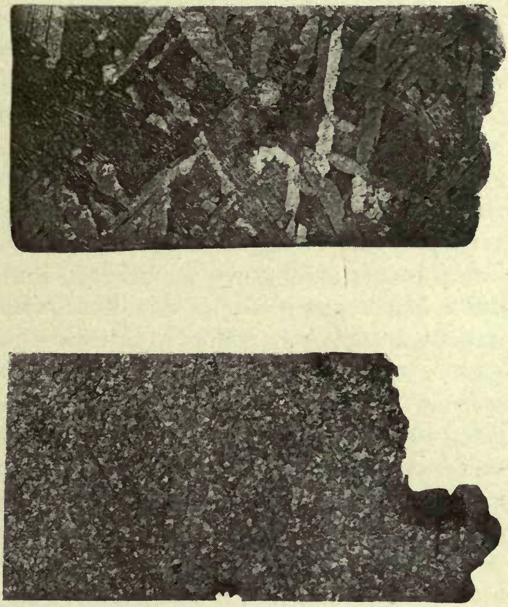

Fig. 43.— Effect of heating a section of the Toluca meteorite for 7 hours at 950° C. Upper figure, before heating. Lower figure, after heating. The heating destroyed the lamellar structure and produced an appearance like that of some ataxites. After Berwerth.

A study by the writer* of the composition of the iron meteorites showed that a definite relation apparently exists between their composition and structure or that their composition apparently controls their structure. Thus the hexahedrites all contain about 6 per cent of nickel, the octahedrites from 7 to 15 per cent and one group of the ataxites a still higher percentage. It appears, therefore, that in cooling from the original magma, a meteoric iron which

*Pubs. Field Mus. Geol. Ser., 1907, 3, 106.

contains 5 to 7 per cent of nickel will crystallize in the cubic form, one containing between 7 and 15 per cent will crystallize in the octahedral form, and one containing a percentage of nickel greater than this will not crystallize at all. Further, among the octahedral irons the percentage of nickel will influence the width of the bands, the bands being narrower as the percentage of nickel increases.

Accessory minerals occur in all the iron meteorites. Their position and form may or may not be independent of the structure of the nickel-iron. Thus in the octahedral irons pyrrhotite may occur in nodules of various shapes and sizes without regular arrangement, or it may occur in plate-like forms arranged parallel to the faces of a cube or dodecahedron. In the latter case the term Reichenbach lamellae is applied to the forms. Schreibersite may likewise be irregularly distributed or it may occur in plate-like forms arranged according to the planes of a dodecahedron. The latter forms are known as Brezina lamellae. Graphite nodules also occur in the octahedral irons but they are always irregularly distributed. They may be individual or intergrown with pyrrhotite or schreibersite. Frequently, inclusions of these minerals are surrounded by a border of kamacite. Within, this follows the outline of the inclusion but on its outer side it is not in accord with the octahedral structure. Cohenite is a common ingredient of the coarse octahedrites, usually in the form of prismatic crystals lying in the bands of kamacite. Among the hexahedrites, schreibersite in the needle-like form known as rhabdite is a common constituent. It is usually regularly distributed in oriented positions. Schreibersite also frequently occurs in the hexahedrites in the form of large inclusions resembling hieroglyphic characters. Pyrrhotite is not as abundant in the hexahedrites as in the octahedrites but may occur in both oriented and non-oriented positions. Daubréelite is common and characteristic of the hexahedrites, usually occurring intergrown with pyrrhotite in parallel plates. Graphite is of rare occurrence in the hexahedrites.

Among the ataxites accessory constituents are usually rare and of small size. When they do occur a zone of slightly different appearance from the rest of the meteorite usually surrounds them in much the same manner as a border of kamacite surrounds accessory minerals in the octahedral irons. Two or three of the ataxites are rich in rhabdite. Other minerals besides those mentioned which sometimes take part in the structure of iron meteorites are chromite, diamond, amorphous carbon, lawrencite, chrysolite, forsterite, and quartz. No marked feature so far as known attends the distribution of these. Brezina* gives the following as the order of cooling or solidification of the constituents of the iron meteorites: Daubréelite, pyrrhotite, graphite, schreibersite, cohenite, chromite, swathing kamacite, band kamacite, taenite, and plessite.

STRUCTURE OF IRON-STONE METEORITES

The iron-stone meteorites pass, as has been said, into the iron meteorites on the one hand and the stone meteorites on the other. Yet within their boundaries they present well-marked characteristics of structure. The pallasites, which most nearly resemble the iron meteorites, consist of a sponge-like mass of nickel-iron, the pores of which are filled with chrysolite. The proportion of metal to silicate in pallasites varies in different falls and in individuals of the same fall. Thus in individuals of Brenham part has the pallasite structure and part the octahedrite structure, and while the majority of the individuals of the fall are pallasites, some are entirely octahedrites. In all pallasites the metal shows octahedral figures on etching. The chrysolite element is usually in the form of rounded or angular grains. Some of the grains attain a diameter of a centimeter or more, but a size of about half a centimeter is more common. Often the grains exhibit crystal planes, but a rounding of the solid angles, as if the surface had been fused, usually obscures the crystal forms. The grains are usually surrounded by a band of kamacite which accommodates itself to their form. This shows that the metal solidified subsequent to the silicate. In the other groups of iron-stone meteorites the sponge-like structure is far less noticeable or if it occurs,

*Denkschr. Wien Akad., 1905, 88, 641.

there is greater irregularity in the size and shape of the pores in which the silicates occur. The metal tends to aggregate in large nodules at times and the silicates do likewise. Again there may be a uniform dotting of metal as seen on a section surface, with similar dotting of silicates interspersed. By the gradual diminution of the amount of metal, these iron-stone meteorites of which Mincy and Crab Orchard are good illustrations, pass over to the structure of the stone meteorites.

STRUCTURE OF STONE METEORITES

Chondritic Structure

A structure peculiar to about 90 per cent of all stone meteorites consists in their being made up of rounded grains or spherules. These grains or spherules are named chondri, (dim. chondrules) from the Greek χόνδρος, a grain, and meteorites largely or partly made up of them are known as chondrites. In size chondri vary from that of a walnut to a dust-like minuteness. The larger number are about the size of millet seeds. The form of chondri is generally spheroidal, but varies from essentially spherical to mere irregular fragments. Some chondri are flattened or oval and others show apparent deformation subsequent to their origin. In the latter, depressions or projections occur which often look as if a hard chondrus had pressed against another soft one during the process of formation. The deformed chondri pass by every gradation into those which appear to be rock fragments with rounded angles. The surface of the chondrus is rarely smooth, being usually rough or knobbed. From many friable meteorites individual chondri can easily be isolated, but if the meteorite is at all coherent the chondri break with the rest of the mass. The color of chondri is usually white or gray, but some are brown to black. As they are often of the same substance as the groundmass in which they are imbedded they may differ little in color from it. On this account and on account of an ill-defined contour they may be overlooked and a crystal may be considered porphyritic, which is really part of a chondrus. Usually, however, the chondri are plainly marked on a polished section by differences in color and contour. In structure chondri may themselves be granular, porphyritic or coarsely or finely fibrous. They may consist of a single crystal individual, in which case they are said to be monosomatic, or of several individuals, when they are said to be polysomatic. True monosomatic chondri are confined almost exclusively to the mineral chrysolite. They may be known by their simultaneous extinction in polarized light. Polysomatic chondri may be made up of different minerals as well as different individuals and may show more than one kind of structure, i. e., a chondrus may be granular in one portion and fibrous in another. The following minerals are noted by Tschermak as forming chondri, their relative abundance being in the order named: Chrysolite, bronzite, augite, plagioclase, glass, and nickel-iron. Chrysolite chondri usually contain large quantities of glass of a dark brown color. This may be arranged (*a*) in the form of alternate layers, in which case a marked rod-like or lamelliform appearance is produced, (*b*) forming a base in which the mineral is developed porphyritically, (*c*) occurring in the center of a crystal, or (*d*) forming a net-work. Polysomatic chondri of the latter sort are especially liable to be mistaken for those of enstatite since they simulate the fibrous appearance of the latter. Occasionally the crystallization may have proceeded only far enough to produce skeletal or branching growths of the mineral among glass. Both monosomatic and polysomatic chrysolite chondri may have the arrangement of a well-marked rim about a spherical interior. This rim may, in the polysomatic chondri, be composed of many individuals. Such a rim is often dark from a content of iron and pyrrhotite. Chromite, either in minute grains or in dust-like aggregations, also forms a common inclusion usually near the surface of the chondrus. The quantity of opaque inclusions may be so great as to give the chondrus a black color. Such chondri associated with those of light color are to be found in the stones of Knyahinya, Mezö-Madaras, and others. The constituent minerals of such chondri are chiefly chrysolite and enstatite. Enstatite chondri are usually of a finely fibrous character. The fibers instead of radiating from a center as do those of spherulites usually diverge from an eccentric point (Fig. 44). This eccentric arrangement constitutes one of the most marked features of these chondri and separates them sharply from any formation seen in terrestrial rocks. The enstatite chondri have less glass than those of chrysolite. Monosomatic chondri of enstatite have never been observed, the large crystal individuals showing, as a rule, no tendency to a spherical form. Besides enstatite chondri having an eccentric arrangement of fibers, there occur those which are confusedly fibrous, and these may pass into those which

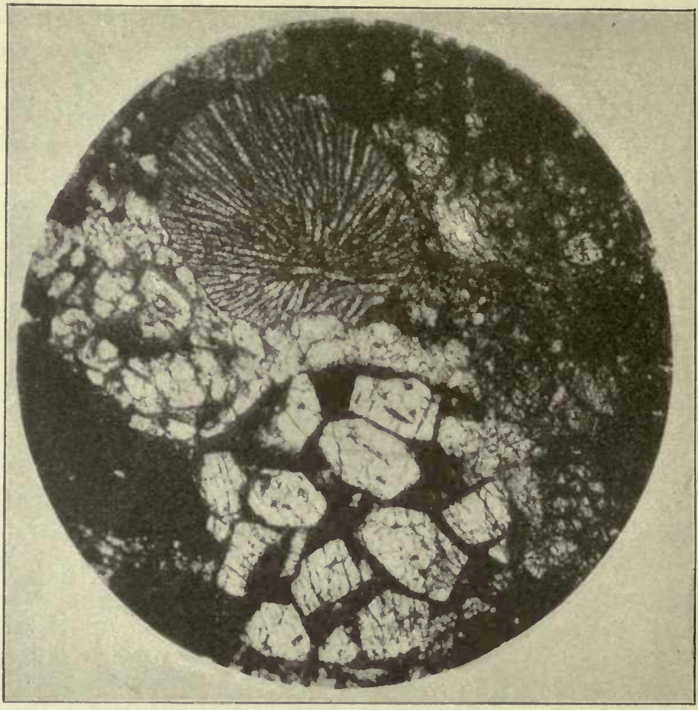

FIG. 44.— Microscopic section of the Homestead meteorite, showing an eccentric radiating enstatite chondrus and a porphyritic and a granular chrysolite chondrus. ×65. After Tschermak.

have a netted appearance from crossing fibers. Such chondri, cut at right angles to the fibers, show the fibers to have a concentric arrangement. The chondri already mentioned, which are granular in part and in part fibrous, are usually made up of the two minerals chrysolite and enstatite. These minerals may be present in about equal quantity or either may be in excess. Usually the enstatite together with glass appears to occupy the intervening spaces between the chrysolite grains, indicating that it is of later formation. Augite chondri are not common but occasionally occur. They often show a structure which indicates repeated twinning. The mineral may appear also in the form of grains, usually of a green color. These grains can be distinguished from chrysolite by their behavior in polarized light. Chondri containing plagioclase in any large quantity are rare but have been observed by Tschermak in the stone of Dhurmsala. The plagioclase alternates in bands with chrysolite and is in excess. Chondri also occur which are composed almost exclusively of glass, the only indication of the presence of other minerals being in the presence of forked microlites which may be referred to enstatite. Occasionally these microlites are of a pronounced star-like form. Chondri, or at least rounded spheres of nickel-iron, occur in some meteorites, but are not common. All gradations occur from chondri which contain grains of nickel-iron to complete spheres of nickel-iron. In the stone of Renazzo such spheres have a covering of brown glass. Some of the spheres or rounded fragments also contain pyrrhotite, but pyrrhotite of itself has never been seen to form chondri. A more or less complete rim of metal is characteristic of many chondri. The metal may occur in the form of rounded grains or as a continuous periphery. It has been suggested by Daubrée that such a rim shows that the chondrus has been subject to the reducing action of hydrogen. Besides the chondri colored black by inclusions of iron and pyrrhotite, previously described, black chondri which consist chiefly of maskelynite or granular plagioclase, occur in the stones of Alfianello, Chateau Renard, and others. These chondri are transparent and colorless about their rim, but in the interior are totally black from inclusions of angular or rounded grains, some of which are shown by their brown color to be pyrrhotite. A gathering of grains at the center distinguishes these chondri from those previously described in which the rim was black. Besides complete chondri, fragments representing various portions of a complete chondrus occur. These may, on account of their shape, be very misleading, as they may be taken for porphyritic individuals or for portions of a foreign stone if their previous chondritic origin is not recognized. Tschermak states that fragments of chondri are most numerous in the stones whose chondri have well-marked contours. So far as the association of

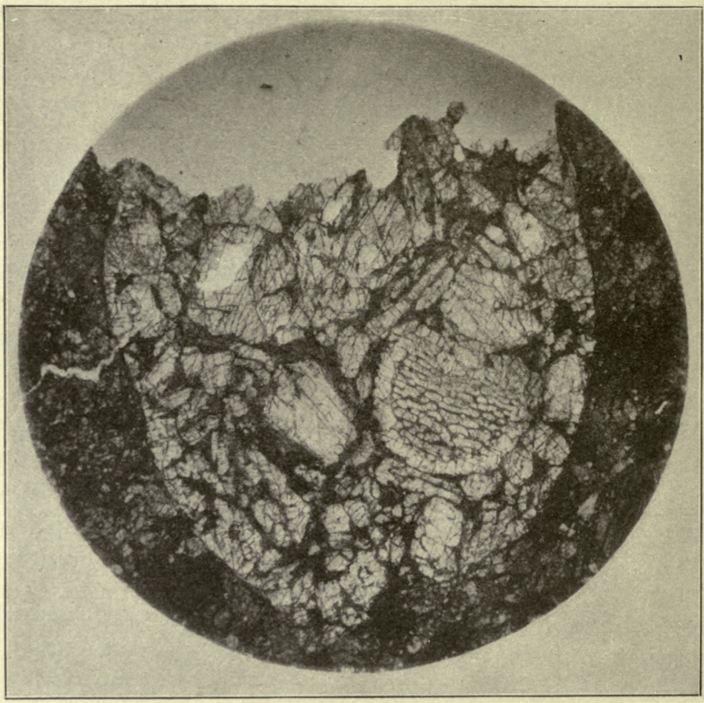

FIG. 45.— Microscopic section of the Dhurmsala meteorite, showing a large, somewhat porphyritic chrysolite chondrus enclosing a smaller one. ×8. After Tschermak.

chondri is concerned it is to be noted that chondri of more than one of the kinds above described usually occur promiscuously scattered through the same stone. There is no gathering of them into groups according to the minerals they contain. Occasionally one chondrus encloses another (Fig. 45), and still more rarely two may be joined together.

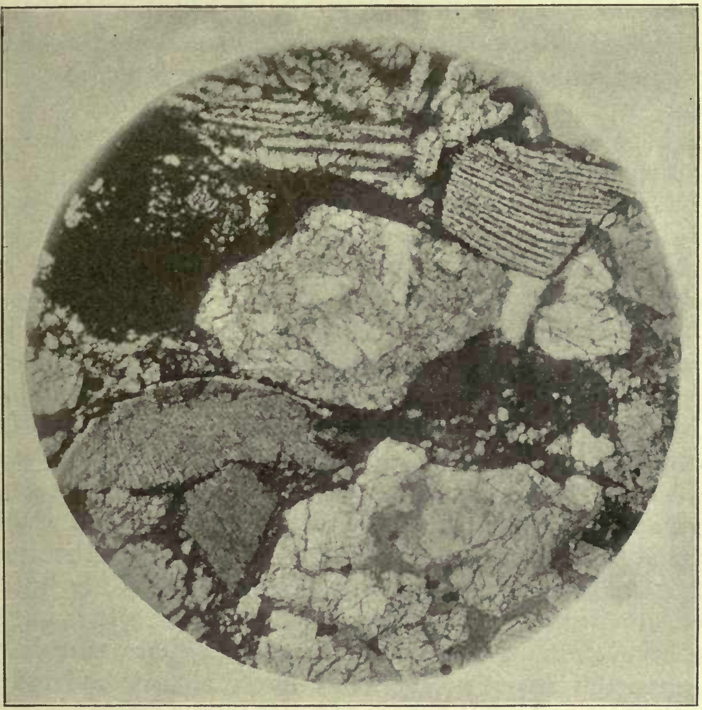

FIG. 46.— Microscopic section of the Mezö Madaras meteorite, showing fragments of chondri. Fragments of enstatite, chrysolite, and nickel-iron chondri can be recognized. X70. After Tschermak.

Broken fragments of chondri commonly occur in the stone with complete chondri. Two fragments of the same chondrus are, however, rarely if ever found in juxtaposition. Hence there must have been considerable separation of the fragments before consolidation of the stone took place, (Fig. 46).

The conditions which have brought about the formation of chondri are not well understood, though the question has been much discussed and various hypotheses have been suggested. The views of earlier observers were to the effect that the chondri represented fragments of pre-existing rock which, by oscillation and consequent attrition had obtained a spherical form. Sorby regarded chondri as produced by cooling and aggregation of minute drops of melted stony matter. Tschermak considers their origin similar to that of the spherules met with in volcanic tuffs which owe their form to prolonged explosive activity in a volcanic throat, breaking up the older rocks and rounding the particles by constant attrition.

Different views are, however, held by Brezina, Wadsworth, and others, these believing that the chondri have been produced by rapid and arrested crystallization in a molten mass.

Objections to theories of the first class are to be found (1) in the fact that the chondri usually have rough-knobbed surfaces instead of smooth ones, such as attrition might be expected to produce; (2) in the regularly eccentric form of most enstatite chondri, which attrition would be likely to destroy; and (3) in the fact that fragments of a pre-existing rock ought to show the constitution of the rock as a whole instead of a specialized structure. Objections to theories of the second class are to be found chiefly in the clearly fragmental nature of most chondritic meteorites. It is in their variation from the surrounding ground mass and in the eccentric arrangement of their fibers that chondri differ chiefly from the spherulites of terrestrial rocks.

Stone meteorites without chondri, the achondrites, usually differ considerably in structure from the chondrites although various gradations are to be seen. Porphyritic, ophitic and granular structures occur and the resemblance to terrestrial rocks is much closer than in the chondrites. There are differences, however, in the fact that the granular meteorites are only of fine grain and the ophitic and porphyritic ones vary in size of grain.

Chassigny shows the most typical uniformly granular structure, consisting as it does of isometric grains resting near one another. Occasionally angular gaps are filled by weak, doubly refracting, transparent, maskelynite-like substances. Ibbenbühren and Manegaum, both consisting of enstatite, are similar, although in Ibbenbühren the grain, according to Tschermak, is not quite uniform since small grains lie between the larger ones. Angra dos Reis is distinguished by a fine-granular structure and is so loose that pieces can be rubbed between the fingers. Lodran also shows, with the exception of the fine iron network, a structure of isometric grains which are numerously bounded by crystal faces composed of nickel-iron. Nowo Urei possesses a peculiar structure. Between grains of olivine and augite there lies a fine-grained aggregate consisting of nickel-iron, a graphitic substance, and diamond. It seems to be in the form of a dark network with its meshes filled by silicates since a great number of dark particles are bordered by silicate grains. Some varieties of magnetite-olivinite from Taberg in Sweden show similar structure, the magnetite appearing in the same form as the nickel-iron and carbonaceous substances in Nowo Urei.

All eukrites and shergottites show an ophitic structure. This is wont to be better developed the coarser the grain and can usually be recognized macroscopically in representatives of these groups. Anorthite appears in lath-shaped individuals and augite fills the spaces. In Jonzac the ophitic structure is beautifully and uniformly developed and the grain coarse. The plagioclases are 5 mm. in length and sometimes 12 mm. In Stannern and Juvinas the grain is variable in size not only in different stones but in one and the same. This change is so strong in Stannern that Tschermak considered the meteorites as consisting of three kinds of stones, and distinguished coarse-granular, radiated, and compact portions. Shergotty shows on the other hand very uniform size of grains. According to Tschermak there occur in the howardites portions with ophitic structure which he regarded as fragments of eukrites. In an essentially uniform granular structure it is common to find single individuals more or less sharply distinguished by their size, also partly well-formed crystals and partly fragmental individuals. As a rule they are the same minerals as those forming the chief mass of the stone, but exceptionally consist of other constituents. Thus in Bustee appear diopside and enstatite; in Shalka bronzite; in Manegaum chrysolite; in Bishopville enstatite and accessory plagioclase; in the howardites anorthite, pyroxene, and chrysolite. The orthorhombic pyroxenes at times reach the size of a centimeter. Bustee shows an almost porphyritic structure, since the large crystals are very prominent in a fine-grained ground mass. In Shalka the larger individuals are grouped here and there so that the coarser crystalline portions can be seen.

The mesosiderites also consist essentially of a uniformly granular aggregate of iron, olivine, enstatite, and to some extent plagioclase in which the olivine often appears porphyritic and at times in crystals which, according to Reichenbach, in Hainholz reach a size of 4½ centimeters, and according to Kunz in Mincy 10 centimeters. In the grahamites, which are nearly related to the mesosiderites and are distinguished only by the greater quantity of plagioclase, the structure is variable. According as the plagioclase or the augite reaches the stronger development, the structure appears either ophitic or granular and porphyritic, the olivines reaching, according to Brezina, a size of 1½ centimeters, but since in the mesosiderites and grahamites the nickel-iron appears often in the form of chondri, and according to Tschermak glass is sometimes present, no typical crystalline granular structure can be said to be present. Also in ophitic structure crystals of augite or anorthite appear often porphyritic. In many achondrites, mesosiderites and grahamites portions occur which have the appearance of concretionary formations and have a more or less sharp boundary. As a rule only the quantity of the constituent seems to be different from that of the main mass, but at times a different structure may be seen. Thus in Juvinas portions occur without ophitic structure 3 centimeters in size, dark and rich in augite and metallic particles. Perhaps here also belong the already mentioned granular, hard, fine-grained and easily separable portions of Manbhoom which are 2 centimeters in size and resemble the howardites. Reichenbach observed in Hainholz a compactness of structure toward the peripheral portion of the meteorite. As a rule crystalline granular meteorites possess a compact structure but the howardites are an exception and form the passage from the achondrites to the chondrites.

Large cavities in which the constituents show crystals are especially well developed in Juvinas. Such druses furnished Rose measurable crystals. Estherville also shows occasionally a drusy structure. Both Reichenbach and Newton observed that the single constituents of the stone meteorites, silicates or nickel-iron, often show a regular arrangement when light is reflected from a fractured surface or from polished faces. To see this arrangement requires, of course, careful examination, but with some care parallel systems of lines crossing at right angles may be observed. The lines seldom run straight, usually crooked. They are abundantly interrupted and often return on themselves. Recognition of the lines is the most difficult in the meteorites rich in chondri and of coarse structure; also if the structure is fine and uniform. Bluff, Crab Orchard, Hessle, Pultusk, Renazzo, Siena, Tomhannock Creek, Weston, Vaca Muerta, and Wold Cottage, furnish good examples of these lines. Newton thought that these line systems indicated that the same forces that produced octahedral figures in the iron meteorites had controlled the arrangement of the iron particles in the stone meteorites, and compared the structure with that of graphic granite.

As a rule the different stones of one and the same fall show in all essential points the same structure. Exceptions however occur. Of the numerous stones which fell at Homestead and which show the habit of a normal gray chondrite, one differed. This was a compact, dark or grayish green, poor-in-chondri stone. Among 1200 stones of Pultusk investigated by Rath one was free from chondri and poor in metallic constituents. Rath compared its habit with that of Chassigny and stated that it possessed hardly any similarity with a chondrite. Brezina distinguished it on the ground of its mineralogical composition as amphoterite-like. According to Denza, of the stones which were simultaneous in fall at Motta dei Conti and Villeneuve those falling at the former locality were richer in metallic constituents, more transparent and of finer grain. According to Tschermak, of the stones which fell at Stannern, some of the smaller were compact and homogeneous, or were plainly crystalline and of breccia-like character.

CHAPTER XI

COMPOSITION OF METEORITES

ELEMENTS

The following elements have been found in meteorites in amounts sufficient for quantitative determination:

Aluminum
Argon
Calcium
Carbon
Chlorine
Chromium
Cobalt
Copper
Helium
Hydrogen
Iridium
Iron
Magnesium
Manganese
Nickel
Nitrogen
Oxygen
Palladium
Phosphorus
Platinum
Potassium
Radium
Ruthenium
Silicon
Sodium
Sulphur
Tin
Titanium
Vanadium

These occur as follows:

Aluminum occurs combined with silica in the stony meteorites, chiefly in feldspars, and perhaps also as a constituent of some pyroxenes and chromites. It is much less abundant than in terrestrial crustal rocks.

Argon has been found as an included gas.

Calcium occurs in stony meteorites as an ingredient of anorthite and pyroxene, also in the sulphide oldhamite.

Carbon occurs (1) amorphous, (2) as graphite, (3) as diamond, (4) forming carbides of iron, nickel and cobalt and silicon, (5) as a constituent of carbon monoxide, dioxide, and marsh gas, (6) as a constituent of other hydrocarbons, and (7) probably as carbonates.

Chlorine is known to occur only in combination with iron to form lawrencite, but other modes of its occurrence are not unlikely.

Chromium occurs in combination with iron and sulphur to form daubréelite, with iron and oxygen to form chromite, and probably also in the metallic state alloyed with iron and nickel.

Cobalt occurs alloyed with iron and nickel in nickel-iron and takes part with these metals in the composition of carbides, phosphides, oxides, and probably sulphides.

Copper occurs in the form of an alloy in nickel-iron, from which it is apparently never absent.

Helium has been found as an included gas.

Hydrogen occurs as a gas either pure or combined with carbon. It also takes part in the composition of hydrocarbons and perhaps ammoniacal salts. If the water sometimes found in meteorites is of pre-terrestrial origin, this also represents a hydrogen compound.

Iridium occurs alloyed with nickel-iron. It is found only in traces.

Iron, the most important constituent of meteorites, is chiefly alloyed with nickel, cobalt, and copper. It also combines with sulphur, phosphorus, carbon, chlorine and oxygen to form sulphides, phosphides, carbides, chlorides, and oxides. In combination with sulphur and chromium it forms daubréelite and with chromium and oxygen, chromite. It is also an important ingredient of chrysolite and the pyroxenes.

Magnesium is next to iron the most important metallic constituent of meteorites. It occurs always in the combined form, chiefly as a constituent of chrysolite and the pyroxenes.

Manganese occurs in small quantity in the stone meteorites and in traces in the iron meteorites. In the iron meteorites it probably occurs alloyed with the nickel-iron as a metal. In the stone meteorites as MnO it is found both in those portions soluble and those insoluble in HCl, or, in other words, both in chrysolite and the pyroxenes. Its quantity rarely exceeds 1 per cent.

Nickel is like iron a constant and characteristic ingredient of meteorites. As a metal it forms with iron, cobalt, and copper the alloy called nickel-iron which constitutes the larger part of the iron meteorites and is also abundant in stone meteorites. Nickel takes part with iron in the formation of phosphides, carbides, and oxides and less prominently of sulphides and chlorides. From the silicates of meteorites it seems to be lacking for the most part, thus presenting a contrast to terrestrial silicates (chrysolite and the pyroxenes) which frequently contain an appreciable quantity.

Nitrogen forms a small percentage, usually less than one per cent, of the gases found in meteorites. Its occurrence as an ammoniacal compound in some of the carbonaceous meteorites is also probable.

Oxygen occurs chiefly as a constituent of the siliceous minerals of meteorites. It also takes part in the formation of the oxides such as chromite and magnetite found in minor quantities in iron meteorites. It is not found among the gases of meteorites.

Palladium has appeared as traces in one or two iron meteorites.

Phosphorus occurs chiefly in the form of schreibersite, a phosphide of iron, nickel, and cobalt. It is never lacking from the iron meteorites and is usually found in small quantity in the stone meteorites. Evidence has also been obtained of its occurrence in a free state in one stone meteorite.

Platinum occurs alloyed with nickel-iron. It is found only as traces or a few hundredths of a per cent.

Potassium occurs as an ingredient of the feldspars and may also take part in the constitution of some of the pyroxenes.

Radium has been found in a single stone meteorite, that of Dhurmsala* in the quantity of 1.12×10^{-12} per gramme. Two iron meteorites tested at the same time showed none.

Ruthenium occurs alloyed with nickel-iron. It is found only in traces.

Silicon forms with oxygen and the metals the silicates of which the stony meteorites are chiefly made up. With carbon it forms the rare carbide moissanite, and may be wholly present in this form in the iron meteorites or in part as a metal forming an alloy.

Sodium occurs like potassium as an ingredient of the

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*Strutt, Proc. Roy. Soc., 1906, A, 77, 480.

feldspars and perhaps also of some of the pyroxenes. It is more abundant than potassium.

Sulphur occurs combined with iron, nickel, cobalt, and calcium. It also enters into the composition of a class of hydrocarbons found in meteorites. It is more abundant in the stone than in the iron meteorites but is quite generally present in both.

Tin has been reported only in minute quantity and usually in the irons. It is probably alloyed with the nickel-iron.

Titanium has often been reported to the extent of a fraction of one per cent in the stone meteorites, usually in the insoluble portion and therefore believed probably to occur in the pyroxenes. Of the Angra dos Reis meteorite, which is composed almost wholly of pyroxene, TiO_2 constitutes 2.39 per cent.

Vanadium occurs as traces in the stone meteorites, probably, according to Apjohn, who found it in the Limerick meteorite, as an oxide associated with chromite, this being characteristic of its occurrence in terrestrial rocks.

Several other elements have been reported as occurring in meteorites, but the occurrence needs confirmation. Among these are arsenic, antimony, and zinc. Gold was described by Liversidge as occurring in minute yellow grains insoluble in nitric acid in the irons of Boogaldi and Narraburra.* Several elements have been observed in the spectroscopic examination of meteorites which have not been recognized by chemical analysis. Among these are barium and strontium, lead and bismuth.†

It will be seen from an examination of the list of elements most abundant in meteorites that they are of low atomic weight. Oxygen, silicon, aluminum, magnesium, calcium, sulphur, nickel, and iron are the most abundant elements and all have an atomic weight below 60. Platinum and iridium, the two heaviest elements, occur in but minute quantity.

MINERALS

The following minerals grouped according to Dana's system have been satisfactorily identified in meteorites:

*Jour. Roy. Soc. New South Wales, 1903, 37, 241.

†Lockyer. The Meteoritic Hypothesis, 1890, 59.

Elements	Diamond	C	Isometric
	Graphite	C	Hexagonal
	Nickel-iron	Fe, Ni, Co, Cu	Isometric
	Kamacite	$Fe_{14}\ Ni$	Isometric
	Taenite	$Fe_n\ Ni_n$	
	Plessite	$Fe_n\ Ni_n$	
Sulphides Phosphides and Carbides	Oldhamite	Ca S	Isometric
	Osbornite	Oxysulphide of Ca and Ti	
	Pyrrhotite	Fe S	Hexagonal
	Daubréelite	$Fe\ S.\ Cr_2\ S_3$	
	Schreibersite	$(Fe, Ni, Co)_3\ P$	Tetragonal
	Cohenite	$Fe_3\ C$	Isometric
	Moissanite	Si C	Hexagonal
Chlorides	Lawrencite	$Fe\ Cl_2$	
Oxides	Quartz	$Si\ O_2$	Hexagonal
	Tridymite	$Si\ O_2$	Hexagonal or Orthorhombic
	Magnetite	$Fe_3\ O_4$	Isometric
	Chromite	$(Fe, Mg)\ Cr_2\ O_4$	Isometric
Carbonates	Breunnerite	$(Mg, Fe)\ CO_3$	Rhombohedral
Silicates	Plagioclase	$m\ Na\ Al\ Si_3\ O_8$ $n\ Ca\ Al_2\ Si_3\ O_8$	Triclinic
	Maskelynite		
	Enstatite	$Mg\ Si\ O_3$	Orthorhombic
	Hypersthene	$(Fe, Mg)\ Si\ O_3$	Orthorhombic
	Clinoenstatite	$Mg\ Si\ O_3$	Monoclinic
	Clinohypersthene	$(Fe, Mg)\ Si\ O_3$	Monoclinic
	Diopside	$Mg\ Ca\ (Si\ O_3)_2$	Monoclinic
	Hedenbergite	$(Mg, Fe)\ Ca\ (Si\ O_3)_2$	Monoclinic
	Augite	$m(Mg, Fe)\ Ca(Si\ O_3)_2$ $n(Mg, Fe)\ (Al, Fe)_2\ Si\ O_6$	Monoclinic

Silicates	Weinbergerite	$Na\ Al\ Si\ O_4$ $3\ Fe\ Si\ O_3$	Orthorhombic
	Forsterite	$Mg_2\ Si\ O_4$	Orthorhombic
	Chrysolite	$(Mg,\ Fe)_2\ Si\ O_4$	Orthorhombic
Phosphates	Apatite	$(Ca[F,\ Cl])$ $Ca_4(PO_4)_3$	Hexagonal

Of the above minerals nickel-iron, chrysolite, and the pyroxenes are by far the most abundant. Schreibersite, daubréelite, oldhamite, moissanite, maskelynite, and weinbergerite are minerals which have not as yet been recognized terrestrially; the others are similar to terrestrial minerals. A fuller account of the above minerals follows.

DIAMOND

The first discovery of diamond in meteorites was made by two Russian mineralogists, Jerofejeff and Satschinoff,* who in 1888 found in the Russian meteorite of Nowo-Urei about 1 per cent of small, grayish grains whose hardness, specific gravity, chemical composition, and appearance under the microscope all corresponded with those of diamond. The remainder of the meteorite was composed of chrysolite, augite, carbonaceous matter, and nickel-iron. Some of the properties of the grains considered as diamond which led to their determination were their insolubility in hydrochloric, sulphuric, and hydrofluoric acids and in aqua regia; their being unaffected by fusion with soda or acid potassium sulphate, and their combustibility in a stream of oxygen. The specific gravity of the grains was between 2.89 and 3.3; hardness greater than that of corundum. By analysis 0.0124 gram of these grains gave: Carbon, 95.40; hydrogen, 3.23; ash, 3.23; total, 101.86. If the estimate that 1 per cent of the meteorite was diamond was correct, the total amount of diamond in the meteorite was 17.62 grams or 85.43 carats. The grains were of microscopic size and no definite crystal forms could be observed. Kunz and Lewis† verified the observations of Jerofejeff and

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*Verh. d. russ. min. Gesell. 1888, 2, 24, 272–292. Also Comptes Rendus 1888, 106, 1679–1681.

†Science, 1888, 11, 118–119.

Satschinoff to the extent of finding a substance in the Nowo-Urei meteorite which abraded sapphire. The next important discovery of diamond in meteorites was made by Foote and Koenig* in one of the Canyon Diablo irons. In cutting one of these irons for study a cavity was opened which contained small black grains that "cut through polished corundum as easily as a knife through gypsum." These grains were all small and black except one which was white and about ½ mm. ($^1/_{50}$ of an inch) in size. This unfortunately was lost in manipulation. The grains were regarded as diamonds because of their hardness and their indifference to chemical reagents. Later Kunz and Huntington† by dissolving portions of several Canyon Diablo meteorites obtained white grains having the appearance of beach sand which were unaffected by hydrofluoric or other acids. With these they succeeded in polishing a diamond by the methods usually employed by diamond cutters. Soon after, Huntington‡ found a vein in one of the Canyon Diablo irons which contained pyrrhotite, silica, and amorphous carbon and from this he was able to isolate some transparent, colorless diamond crystals showing the forms of octahedrons and hexoctahedrons. About ½ carat of colorless, yellow, blue, and black diamonds were thus obtained by Huntington.

Mallard,§ who also investigated the Canyon Diablo diamonds, found in a hollow of one of the irons a soft, black, carbonaceous substance in which were round, black grains from ½ to 1 mm. in size, which had sufficient hardness to scratch the cleavage surface of a colorless diamond. Friedel|| obtained from one of the irons brownish-gray grains 0.5 to 0.8 mm. in size, resembling carbonado. These had a specific gravity of 3.3 and 0.0156 grams and yielded on analysis:

$$\begin{array}{r} C = 99.36 \\ Fe_2O_3 = \underline{1.28} \\ 100.64 \end{array}$$

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*Am. Jour. Sci., 1891, 3, 42, 415–417.
†Am. Jour. Sci., 1893, 3, 470–473.
‡Proc. Am. Acad. Sci., 1894, 29, 204–211.
§Comptes Rendus, 1892, 114, 812–814.
||Bull. Soc. Franc. Min., 1892, 15, 258–263.

Later, small, transparent, and colorless diamond grains were found by Friedel in Canyon Diablo. Moissan* obtained by solution of a fragment of Canyon Diablo weighing 4 grams, three forms of carbon, (1) dust-like, carbonaceous particles, (2) rounded, compact fragments, and (3) crumpled, thin particles of brownish color. After treatment of this mixture with boiling sulphuric and hydrofluoric acids and potassium chlorate, two yellowish, bort-like fragments were obtained which had the hardness of diamond. Later,† Moissan dissolved a mass of the Canyon Diablo iron weighing 53 kgs. (116 pounds) in hydrochloric acid and obtained about 800 grams of carbonaceous residue. In this he found diamond, both as very small, black, rounded grains, and as transparent, drop-shaped or rounded octahedral forms. Derby‡ and Cohen§ both examined specimens of Canyon Diablo for diamonds without success. Both used for the tests complete individuals weighing about 200 grams each which they dissolved in dilute HCl. The residues obtained were completely soluble in stronger acids. These tests show that diamond is not uniformly distributed through the Canyon Diablo meteorites. Where it occurs it is found to be most abundant near nodules. In Carcote, a crystalline chondrite, Sandberger|| found dull black grains, hardness 9, not affected by acids, which he regarded as weathered carbonado. Weinschenk¶ found in the residue of Magura which was insoluble in acids, colorless grains and splinters partly isotropic and partly doubly refracting which scratched ruby and gave CO_2 on burning. The presence of diamond in this meteorite was thus indicated. No other meteorites have been reported to contain diamonds. Moissan° examined Kendall Co., Dehesa, and Toluca for diamond without success. The Ovifak iron likewise yielded negative results to the investigations of Moissan and Cohen. By seeking

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*Comptes Rendus, 1893, 116, 218–224 and 288–290.

†Comptes Rendus, 1904, 139, 773–780.

‡Am. Jour. Sci., 1895, 3, 49, 108.

§Meteoreisenstudien, xi, A. N. H. Wien, 1900, 15, 374.

||Neues Jahrb 1889, 2, 180.

¶Ann. Wien Mus., 1889, 4, 99–100.

°Comptes Rendus, 1895, 131, 483–486.

to reproduce experimentally the conditions under which diamonds seemed to have been formed in the Canyon Diablo meteorites, Moissan* was able to produce artificial diamonds. Moissan's method consisted in strongly compressing pure sugar charcoal in a cylinder of soft iron and closing this by a plug of the same metal. This he placed in a crucible containing about 200 grams of molten iron, melted it by means of an electric furnace, withdrew the crucible at once from the furnace and cooled it as rapidly as possible. The object of the sudden cooling was to form a crust on the mass so as to exert a pressure on the interior as the latter cooled, since iron, like water, expands as it solidifies. Water may be employed as a cooling medium but owing to the formation of a badly conducting layer of steam, immersion in molten lead for cooling purposes was found to be preferable. After cooling, the iron was dissolved in hydrochloric acid and a residue consisting of graphite, a maroon-colored variety of carbon, carbonado, and diamond was obtained. This residue was treated with aqua regia, hot sulphuric acid, hydrofluoric acid, potassium chlorate, and fuming nitric acid and the residues then left were treated with liquids of different densities to separate them. From a separation with bromoform, small fragments having the form, hardness, luster, and chemical composition of diamond were obtained. Pure, limpid diamonds in some cases were found which reached a diameter of 0.5 mm.

Analogous to this discovery it may be noted that microscopic diamonds were found in several hard steels by Rossel.† It may also be noted that the stone meteorites which contain diamonds have a composition similar to that of the peridotites in which the South African diamonds are found. Carbon in graphitic cubic form was noted by Haidinger and Partsch in the Magura meteorite‡ and regarded by them as a pseudomorph after pyrite, especially as planes believed to be those of the pentagonal dodecahedron were observed. Rose§ later suggested an origin of the cubes from diamond

*Comptes Rendus, 1893, 116, 218–224, and 1894, 118, 320–326.

†Comptes Rendus, 1897, 123, 113.

‡Pogg. Ann., 1846, 67, 437–439.

§Abh. Berlin Akad., 1863, 40 and 1872, 532–533.

and showed by experiment that diamond heated out of contact with air becomes opaque and of graphitic appearance. The cubes from Magura were described more fully later by Brezina,* who stated that they reached a size of 2.5 mm. The planes were somewhat arched and the solid angles rounded. Planes of the dodecahedron and tetrakishexahedron, the latter having the symbols 310 and 320, were found modifying the crystals. The carbon of which they were composed was partly earthy and grayish-black in color and partly foliated and of shining metallic luster. The scales of the latter variety showed an arrangement parallel to the three axes of a cube.

Similar cubes, though smaller, were isolated in large numbers by Fletcher† from the Youndegin meteorite and called by him cliftonite in honor of R. B. Clifton, professor of physics at Oxford. These were grayish-black, opaque crystals averaging ¼ mm. in thickness, having a predominant cubic form which was modified occasionally by the dodecahedron and a tetrakishexahedron. Rounded and depressed planes were also observed. Some individuals were found to be hollow, others to have a shelly structure. No cleavage was discernible. Hardness was 2.5; specific gravity 2.12; streak black. The chemical characters agreed completely with those of graphite. Fletcher regarded the crystals as a distinct form of carbon deserving the rank of a new species, but the weight of opinion at the present time tends to consider them as pseudomorphs after diamond, for which the name cliftonite can be conveniently retained. Rose's experiments, which as previously remarked showed that diamond can be completely converted to a graphitic form like that of cliftonite by continued heating out of contact with air, makes this origin seem more probable. Rose found that the high temperature of the electric furnace was necessary for the change, the temperature at which cast iron melts having no effect. Cliftonite was also observed by Fletcher in the iron of Cosby Creek. Huntington‡ found cliftonite in Smithville in the forms of

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*A. N. H. Wien, 1889, 4, 102–106.

†Min. Mag., 1887, 7, 124–130.

‡Proc. Am. Acad. Sci., 1894, 29, 255.

cubo-octahedrons, unmodified cubes, and cubes truncated by the dodecahedron and a very obtuse tetrakishexahedron. He also found a skeleton octahedron of graphite 3/8 of an inch in diameter in a nodule of graphite from Cosby Creek. Cohen and Weinschenk* found cliftonite in Toluca in the form of elongated groups composed mostly of cubes but occasionally containing octahedrons. The largest crystals reached a size of only 0.1 mm. They oxidized somewhat more slowly to graphitic oxide by treatment with potassium chlorate and nitric acid than graphite from the same meteorite. With the exception of Toluca, cliftonite seems to be confined to the coarse octahedral irons.

GRAPHITE

This substance occurs in grains of sufficient size for ready examination only in the meteoric irons. In these it is usually in the form of nodules but sometimes occurs in plates or grains. The nodules often reach considerable size. One nodule taken from the Cosby Creek iron is as large as a small pear and weighs 92 grams. Even larger ones were found in the Magura iron. Toluca, Cranbourne, Chulafinnee and Mazapil are other irons which contain considerable graphite. Graphite has been estimated to form 1.17 per cent of the mass of Magura and 0.8 per cent of the Cosby Creek iron. The mineral is usually associated with iron sulphide. With this it may be intimately intergrown or the one may enclose the other. Its texture is compact rather than foliated. Smith found that the meteoritic graphite oxidized much more rapidly than terrestrial graphite on treatment with nitric acid and chlorate of potash. This feature distinguishes it from the amorphous carbon separated from cast iron. The meteoritic graphite is also very pure. Although occurring in nodules of the size described, which must have segregated from the surrounding mass, the ash amounted, in an analysis made by Smith, to only 1 per cent. By ether was extracted a small quantity of a substance made up of sulphur and a hydro-carbon, which constituted the only other impurity. Emphasizing

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*Meteoreisenstudien, A. N. H. Wien, 1891, 6, 140–141.

the differences between meteoritic and terrestrial graphite Smith was inclined to believe that the graphite of meteorites must have been formed by the action of bi-sulphide of carbon upon incandescent iron rather than that it was analogous in its origin to terrestrial graphite. Ansdell and Dewar, however, concluded from elaborate comparisons of meteoritic and terrestrial graphite that they were similar in origin, and were formed by the action of water, gases, and other agents on metal carbides.

AMORPHOUS CARBON

Meteorites of the group known as carbonaceous meteorites, as well as some others, are permeated by a dull-black, pulverulent coloring matter which is usually left as a residue on treatment of the meteorite with acid. This residue sometimes amounts to from 2 to 4.5 per cent of the mass.

A residue similar in character though smaller in amount is likewise found after dissolving many of the iron meteorites. These residues on being heated in air, glow, usually become lighter in color and give off carbon dioxide. They must therefore be considered practically pure carbon.

Berzelius and Wöhler believed this carbon to have originated, so far as the carbonaceous meteorites are concerned, from the decomposition of the hydrocarbons of the latter. In this respect they regarded it analogous to terrestrial humus, though of very different origin. Smith considered it similar in origin to the graphite of iron meteorites and Weinschenk believes it similar to one of the forms of carbon produced in the making of cast iron. No indications that it had an organic origin have ever been discovered.

NICKEL-IRON

Nickel-iron is the substance of which the metallic portion of meteorites is chiefly composed. The iron meteorites consist of it almost wholly and from the stone meteorites it is perhaps never altogether absent, although Roda, Chassigny, Shalka, and Angra dos Reis have been described as without it. In the carbonaceous meteorites it is not present as such but their oxidation products indicate that it occurred in them. From this almost universal presence of nickel-iron in meteorites, Bombicci has argued that the magnetism of meteorites is the property by virtue of which they are drawn to the earth, the latter acting as a magnet to attract them.

In composition the nickel-iron of meteorites is not a substance of fixed proportions but an alloy of iron and nickel in which the percentage of nickel lies between 6 and 20 per cent, and for the most part below 11 per cent. In the stone meteorites the percentage of nickel is sometimes higher. Thus in the nickel-iron of Honolulu, Mordvinovka, Nerft, and Middlesbrough percentages of nickel of 37.73, 21.16, 20.94, and 23.01 per cent, respectively, have been reported.

Accompanying the nickel of nickel-iron, cobalt and copper seem to be universally present. The percentages of cobalt vary as a rule between 0.5 and 2.5 per cent (in Uricoechea 2.56 per cent). Those of copper range from traces to a few tenths of one per cent. The percentages of cobalt or copper seem to hold no definite relation to the amount of nickel, although irons rich in nickel are usually correspondingly rich in cobalt.

The color of nickel-iron varies from iron-gray or steel-gray in alloys poor in nickel, to tin-white and silver-white in those rich in nickel. Under the microscope in reflected light, nickel-iron exhibits a bluish reflection.

Nickel-iron is more or less easily soluble in the common cold, dilute acids, also in solutions of copper sulphate, copper chloride, copper ammonium chloride, mercurous chloride, bromine water, and iodine with potassium iodide. By cold, dilute hydrochloric acid (1 HCl:20 aq.) the nickel-poor alloys are completely and the nickel-rich partly dissolved.

The specific gravity of nickel-iron varies chiefly between 7.6 and 7.9, although determinations as low as 6.5 and as high as 8.1 have been reported. Normally it should be higher the greater the percentage of nickel since while the specific gravity of pure iron is 7.88 that of pure nickel is 8.8.

In cohesive properties nickel-iron varies considerably, being now hard, now soft, now tensile, now brittle, now malleable, and now non-malleable. Of 52 iron meteorites accounts of which were collected by Cohen, 48 were reported to be malleable and 4 not malleable. The malleability of much nickel-iron is attested by the fact that it has been manufactured both by barbarous and civilized peoples into utensils and ornaments such as knives, spearheads, horseshoes, nails, and rings. In boring and cutting iron meteorites very different qualities are exhibited by different individuals, some yielding easily to tools and others only with difficulty. These differences may be due to variations in the quality of the nickel-iron itself or more often probably to the presence of harder minerals, such as cohenite and diamond. The iron of Canyon Diablo shows great resistance to tools, due undoubtedly to included diamond.

All nickel-iron seems to take a good polish. It is also magnetic and many iron meteorites show polarity acquired probably by induction from the earth. The location of the magnetic poles has been determined near the ends of individuals of Staunton, Welland, Tonganoxie, Bingera, and Imilac.

The nickel-iron of meteorites is as a rule quite compact. Fletcher describes cavities bounded by planes (negative crystals) in the meteorite of Greenbrier County, and in Lick Creek portions possessed a porous character. Of the iron meteorites nickel-iron forms the entire substance without regular boundaries except as octahedral or cubic cleavage may appear. In the iron-stone meteorites it may appear either as a network the meshes of which are filled with silicates (pallasites), or as apparently rounded grains united by threads, or as branching threads filling spaces between the silicates (mesosiderites). In the chondritic meteorites nickel-iron takes the form of isolated grains or variously shaped, often toothed flakes filling the spaces between the silicates. Regular forms more or less resembling crystals are occasionally observed. Siemaschko described crystals from Tabory weighing 0.2 grams showing the combination 100, 111, 110, and *hk*0. Incomplete cubes with vicinal faces of a tetrakishexahedron have been described from Barbotan by Partsch and Pfahler. Goalpara furnished cubelike crystals according to Tschermak, and Tomatlan octahedrons according to Shepard. Wöhler described six and four-sided forms from Parnallee which he interpreted as fragments of a dodecahedron. Brezina noted crystals of nickel-iron in the druses of Estherville.

Besides crystals nickel-iron occurs in rounded forms resembling chondri. Such forms observed in Hainholz reached a diameter of 22 mm. (1 inch) and in Mincy 6 cm. (2½ inches). Of other chondri nickel-iron often constitutes a large part. In these it takes the form of flakes, foliæ, grains, and cuboidal forms having at times a concentric arrangement. Such chondri have been noted in Renazzo. Meso-Madarasz, Borkut, Dhurmsala, Gopalpur, and Tieschitz. In many of the siliceous chondri of stone meteorites nickel-iron often forms a periphery either as separate grains or as a thin, coherent, irregular cover. In Parnallee a cylinder of nickel-iron was observed of the dimensions 1 x ¾ mm. In several of the stone meteorites films and scales of nickel-iron occur, appearing in section as fine metallic veins.

Although the nickel-iron of meteorites appears in a polished piece to be a homogeneous substance of uniform composition, investigation shows that it is in reality a complex substance, made up of alloys containing different quantities of nickel. The existence and character of these alloys is easily made evident by subjecting a polished surface of the nickel-iron to the action of heat, acids, or other etching agent. Figures of a more or less banded character then appear on the surface of the iron showing its complex structure. The discovery of this means of investigating the character of nickel-iron was made, as has previously been mentioned, by Alois von Widmanstätten of Vienna in 1808. The production of these figures by heating can be accomplished by placing a thin section of the meteorite upon an asbestos plate and placing it over a Bunsen burner. According to the degree of oxidation the different alloys then appear in different colors, as for instance blue, purple, and yellow. Although this was the method first employed by Widmanstätten it is rarely used at the present time since the employment of liquid etching agents is simpler and gives more delicate results. Of these agents the most convenient and satisfactory is usually nitric acid. For preliminary testing the acid diluted to about one-tenth its normal strength may be applied to a small, flat, freshly filed surface of the nickel-iron. In four or five minutes the character of the figures will usually be roughly outlined.

For etching of a plate for careful study of the figures more pains should be taken. Meteorites differ in the degree and speed with which they are attacked, some etching easily and quickly with weak acid, others only after longer treatment with stronger acid. The surface of the meteorite to be investigated should be flat and smooth and the larger the surface the greater will be the opportunity afforded to study the details of its structure. Foote Mineral Company of Philadelphia, who have had excellent success in etching meteorites, have given the writer the following details of their method of etching:

1. Wash the specimen with benzine.

2. Lacquer the unpolished back and edges with a lacquer known as "steel gloss," diluting it about one-half with benzine. When this side is dry, carefully remove with benzine any lacquer which may have run over the edges onto the polished surface. An electric fan greatly hastens the drying of the lacquer.

3. Lacquer any nodules. They should be completely covered, as they are readily attacked by the acid, and will stain the etched surface.

4. Place the iron so that the polished surface is horizontal. Wash with a 5 to 15 per cent solution of C. P. nitric acid for from 15 seconds to 4 or 5 minutes, until the etching is brilliant. If etched much longer, the iron will darken. When the surface begins to get rough, the maximum brilliancy has been reached. The acid should be kept as thick and as even as possible by rubbing the plate with a large brush. As the acid becomes discolored, it should be brushed off and fresh acid added.

5. To clean and facilitate rapid drying, quickly put the section into clean warm water (120° to 130° F.) for several minutes, rubbing with a brush.

6. Dry in a few seconds with blotting-paper.

7. Thickly lacquer the etched surface at once. To avoid oxidizing, the operations from 4 to 7 should be accomplished as quickly as is practicable, by having all materials at hand.

Where possible the writer has found the etching to be more delicately performed if the plate to be etched is dipped into the acid with the side to be etched down instead of up and instead of pouring the acid on the plate. Such dipping facilitates removal by gravity of the products of etching. Nevertheless, in many instances the size and shape of the plate prevent such immersion and the acid must be poured on. Other etching agents besides nitric acid which may be employed are dilute hydrochloric acid, the addition to which of a small volume of choride of antimony is said to lessen subsequent rusting, a solution of sulphate of copper, the deposited copper being removed by ammonia, solutions of chloride of mercury, chloride of gold, chloride of platinum, fused alkalies or bromine water. The figures obtained with some of these agents are said to differ from those obtained in other ways.

Upon the great majority of iron meteorites the figures which appear upon etching show the nickel-iron to be made up of three different alloys differing in form, color, luster, and degree of solubility. One of these alloys appears as bands of iron-gray color and dull luster, which on heating are more thickly covered with oxide or on etching are more depressed than the other alloys. The bands cross each other in manifold fashion, and while rather uniform in width in any single meteorite in different meteorites show variations in width from ½ to 2 mm. and in length from a few millimeters up to 10 cm. (2½ inches). This alloy was called by Reichenbach Balkeneisen or Kamazit from *κάμαξ*, a pole or shaft, and is known in English as kamacite. Bordering the bands of kamacite appear others which are narrower, silver-white in color and more brilliant in luster. Their substance is less attacked by acids or oxidizing agents and hence they stand out in relief. To this alloy the name Bandeisen or Taenit from *ταινία*, a ribbon, was given by

Reichenbach. These two alloys run parallel to and adjoining each other and together form what is known as a lamella. The crossing of these lamellae in network fashion leaves angular spaces or meshes which are often filled by a third alloy generally of darker color and duller luster than the kamacite. This third alloy is known as plessite from Reichenbach's name Plessit or Fülleisen. Its degree of oxidation and solubility is intermediate between that of kamacite and taenite. The three alloys together are known as the trias or triad.

Meteorites containing or made up of nickel-iron which exhibit these three alloys are known as octahedral meteorites or octahedrites since the arrangement of the lamellae in such meteorites proves to be parallel to the planes of an octahedron. Two other classes of iron meteorites as already noted display no such compound structure. These are the hexahedrites or cubic meteorites and ataxites or meteorites without structure. The hexahedrites are made up of but a single one of the above alloys, kamacite, while the ataxites have a diverse composition.

KAMACITE

Balkeneisen

Kamacite is the predominant constituent of nickel-iron. Of the cubic iron meteorites and some of the ataxites it forms practically the entire mass and in the octahedral meteorites it is more abundant than any other constituent. In color it is iron-gray as contrasted to the tin-white of taenite and the usually darker gray of plessite. It is soluble in dilute acids of the stronger class such as HCl 1:20 and very slowly even in acetic acid. Its specific gravity ranges from 7.78 to 7.87 and its hardness is between 4 and 5.

According to structure, three different kinds of kamacite are recognized: hatched, spotted, and granular. The hatched kamacite (Brezina's schraffirten Kamazit, Reichenbach's Feilhiebe) is characterized by being covered by networks of fine lines tending to cross at right angles. These are like the Neumann lines of the cubic meteorites on a smaller scale. The spotted kamacite (Brezina's fleckig

Kamazit) shows varying dark and light spots from unequal reflections of light. The appearance is caused by groups of lines or pits. The spots are of irregular outline and rarely exceed 1 mm. in diameter. The granular kamacite (Brezina's körnige or abgekörnt Kamazit) consists of grains separated by rather deep channels. This separation usually appears only after strong etching. The grains may be coarse (1 to 2 mm. diameter) or fine (0.1 to 1 mm. diameter.)

All these kinds of kamacite may be found in different meteorites. The cubic meteorites are composed almost wholly of hatched kamacite and some of the ataxites almost wholly of granular kamacite. The other kinds of kamacite are seen in the bands of different octahedral meteorites.

Several kinds of kamacite are also distinguished according to their position or form. These kinds are known as swathing kamacite, swollen kamacite, grouped kamacite, and unequally grouped kamacite. Swathing kamacite (Brezina's Wickelkamazite, Reichenbach's Fülleisen or Wulsteisen) is seen enclosing accessory constituents in meteoric irons. It usually forms a band two or three millimeters broad around accessory minerals, following their outlines within and not conforming to the general structure of the meteorite without. Swollen kamacite (Brezina's wulstiger Kamazit) is a characteristic form assumed by the kamacite bands of many of the octahedral meteorites. Such bands are short, swollen in the middle, and often have rounded ends bounded by taenite. Grouped kamacite (Brezina's gescharter Kamazit) consists of bands lying close together, parallel and generally elongated. It characterizes many octahedral meteorites. Unequally grouped kamacite (Brezina's ungleich gescharter Kamazit) consists of grouped bands of different lengths, of which the middle ones are usually the longer. Such bands may be seen in many octahedral meteorites.

In addition to these forms of kamacite, certain jagged and angular fragments found remaining behind after the solution in dilute HCl of the kamacite of many octahedral meteorites prove on analysis to have a composition near that of kamacite. Their lower solubility is believed to be generally due to included schreibersite or cohenite.

All the above-named forms of kamacite have a chemical composition closely approximating that represented by the formula $Fe_{14}Ni$ of which the percentages are Fe 93.11 per cent, $Ni+Co=6.89$ per cent $=100$.

Analyses of kamacite of the various kinds mentioned are given below, the kamacite of octahedral irons being given first, as it was in these that kamacite was first distinguished.

ANALYSES OF KAMACITE

I. Kamacite of octahedral meteorites.

	Fe	Ni	Co	Cu	C	Total	Fe : Ni+Co
1.......	93.01	6.22	0.77	tr.	....	100	13.98 : 1
2.......	93.09	6.69	0.25	....	0.02	100.05	14.09 : 1

REFERENCES

1. Bendego. Isolated by Derby, analyzed by Florence and Dafert: Ann. Mus. Rio de Janeiro, 1896, ix, 140 and 183. Calculated to 100 after deducting insoluble residue.
2. Welland. Davison: Am. Jour. Sci., 1891 (3), xlii, 64. Plates 1 to 2 mm. thick, of the color of cast-iron, with wrinkled surface and covered with a thin layer of magnetite; brittle; conchoidal fracture.

II. Swathing kamacite.

Fe	Ni	Co	Total	Fe : Ni+Co
92.62	6.55	0.83	100	13.19 : 1

RFFERENCE

Glorieta. Cohen and Weinschenk: A. N. H. Wien, 1891, vi, 158.

III. Jagged, residual kamacite.

	Fe	Ni	Co	Cu	C	Total	Fe : Ni+Co
1...........	92.62	6.81	0.57	....	....	100	13.19 : 1
2...........	93.01	6.25	0.74	....	....	100	13.98 : 1
3...........	93.27	6.04	0.64	....	0.05	100	14.67 : 1
4...........	93.89	5.30	0.61	....	0.20	100	16.69 : 1
5...........	94.05	5.26	0.57	....	0.12	100	16.95 : 1
6...........	94.09	5.51	....	0.05	0.34	100	17.77 : 1

REFERENCES

1. Canyon Diablo. Florence: Am. Jour. Sci., 1895 (3), xlix, 104. Calculated to 100 after deducting 0.31 per cent taenite and 0.35 per cent schreibersite.
2. Magura. Sjöström: A. N. H. Wien, 1898, xiii, 484. Calculated to 100 after deducting 0.58 per cent schreibersite.
3. Magura. Manteuffel: A. N. H. Wien, 1892, vii, 156.
4. Staunton. Manteuffel: A. N. H. Wien, 1892, vii, 157.
5. Toluca. Manteuffel: A. N. H. Wien, 1892, vii, 157.
6. Canyon Diablo. Florence: Am. Jour. Sci., 1895 (3), xlix, 104. Calculated to 100 after deducting 0.31 per cent taenite and 0.35 per cent schreibersite.

IV. Angular, residual kamacite.

Fe	Ni	Co	Total	Fe : Ni+C.
92.94	6.18	0.88	100	13 . 83 : 1

REFERENCE

Magura. Cohen and Weinschenk: A. N. H. Wien, 1891, vi, 152.

TAENITE

Bandeisen, Meteorin, Edmondsonite.

Taenite is the ingredient of octahedral nickel-irons which occurs in thin plates. These are usually of a nickel-white color though they become by oxidation golden to isabel-yellow. They border the kamacite bands and containing more nickel are less attacked by etching agents. They, therefore, stand in relief. The thickness of the taenite plates may vary from 0.03 to 0.25 mm. Taenite is less liable to decomposition than kamacite, and hence often remains in the form of bright, more or less elastic plates after the decomposition of the mass of a meteorite. These plates often have a crumpled, wavy appearance. They resemble schreibersite, for which they have sometimes been mistaken, in being strongly magnetic but fuse with more difficulty B.B. Taenite is attacked slowly by cold, dilute acids and considerably but not entirely dissolved. Concentrated nitric and hydrochloric acids and copper-ammonium chloride dissolve it completely. Analyses of taenite show percentages of nickel varying from about 13 to 48 per cent, cobalt being also usually reported in quantity up to 2 per cent. These analyses indicate that taenite has not a uniform composition. S. W. J. Smith* has observed that taenite isolated mechanically usually contains less nickel than that isolated chemically through the prolonged action of dilute acid, and states that this indicates that taenite contains considerable kamacite which is dissolved out by the acid. The analyses given below do not bear out this statement however since the percentage of nickel seems to be entirely independent of the manner in which the material for analysis was obtained.

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*Phil. Trans. London, 1908, Ser. A., vol. 208, p. 21.

Furthermore the structure of the taenite bands indicates a complex composition. Tschermak found the taenite lamellae of Ilimaë to consist of a fine network of different bodies which he regarded as chiefly nickel-iron mixed with pure iron. Taenite occurs only in the octahedral irons and more abundantly in the fine octahedrites than in the coarse. Thus Cohen* estimated the percentage of taenite in the coarse octahedrite of Wichita as 2.64 per cent, while in the medium octahedrites Toluca and Misteca he regarded it as 6.79 per cent and 6.75 per cent, respectively, and in the fine octahedrites Chupaderos and Glorieta Mountain 10.24 per cent and 11.35 per cent.

The composition of taenite as shown by various analyses is as follows:

ANALYSES OF TAENITE

	Fe	Ni		Co	Cu	C	Total	Fe : Ni+Co +Cu
1	86.44	13.02		0.54	....	....	100.00	6.9 : 1
2	85.00	14.00		....	....	....	99.00	6.4 : 1
3	85.00	15.00		....	....	....	100.00	6.0 : 1
4	83.28	.....	16.68	....	0.04	....	100.00	5.2 : 1
5	80.30	.....	19.60	....	....	....	99.90	4.1 : 1
6	74.78	24.32		0.33	....	0.50	99.93	3.2 : 1
7	73.10	23.63		2.10	....	1.17	100.00	3.0 : 1
8	73.0	27.00		....	....	....	100.00	2.8 : 1
9	72.12	27.73		0.02	....	0.12	100.00	2.7 : 1
10	71.29	26.73		1.68	....	0.30	100.00	2.6 : 1
11	70.14	29.74		....	....	....	99.88	2.5 : 1
12	69.30	29.73		0.60	....	0.37	100.00	2.4 : 1
13	68.13	30.85		0.69	0.33	....	100.00	2.2 : 1
14	65.54	32.87		1.59	....	....	100.00	2.0 : 1
15	65.39	33.20		1.41	....	....	100.00	2.0 : 1
16	65.26	34.34		0.40	....	....	100.00	2.0 : 1
17	63.55	34.65		1.01	0.30	0.49	100.00	1.9 : 1
18	63.04	35.53		1.43	....	tr.	100.00	1.8 : 1
19	61.89	36.95		0.36	....	0.80	100.00	1.7 : 1
20	61.87	.....	38.13	....	tr.	....	100.00	1.7 : 1
21	57.18	34.00		....	....	0.55	91.73	1.7 : 1
22	50.73	47.80		0.63	0.37	0.47	100.00	1.1 : 1

REFERENCES

1. Cosby Creek. Reichenbach, Jr.: Pogg. Ann., 1861, xciv, 258. Plates 8 cm. long and 2½ cm. broad, mechanically isolated by Reichenbach, Sr. Mean of three analyses.

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*Meteoreisenstudien, ii, A. N. H. Wien, 1892, vii, 160, 161.

2. Charcas. Meunier: Ann. Chim. et Phys., 1869 (4), xvii, 31. Particles mechanically isolated by their color.

3. Caille. Meunier: Ann. Chim. et Phys., 1869 (4), xvii, 32. Net-like web, isolated by means of dilute nitric acid.

4. Casas Grandes. Tassin: Proc. U. S. Nat. Mus., 1902, xxv, 73.

5. Kenton Co. Nichols: Pub. Field Col. Mus., 1902, Geol. Ser., i, 315. Thin, tin-white, elastic magnetic plates, 4 mm. square, with finely ribbed surface.

6. Welland. Davison: Am. Jour. Sci., 1891 (3), xlii, 66. Mechanically isolated plates $\frac{1}{15}$–$\frac{1}{30}$ mm. thick, silver-white to bronze-yellow, flexible and elastic.

7. Staunton. Cohen and Weinschenk: Ann. Wien Naturhist. Mus., 1891, vi, 146. Gray, relatively thick and brittle plates. Isolated by dilute HCl. Calculated to 100 after deducting schreibersite.

8. Cosby Creek. Smith: Comptes Rendu, 1881, xcii, 843. Little thin plates of white metallic color left after dissolving the iron in acid.

9. Canyon Diablo. Tassin: Smithsonian Misc. Coll., 1907, i, 212. Calculated to 100 after deducting 0.26 per cent schreibersite.

10. Magura. Weinschenk: Ann. Wien Naturhist. Mus., 1889, iv, 97. Thin, tough, silver-white lamellae soluble with difficulty in acids. Isolated by dilute HCl. Calculated to 100 after deduction of schreibersite.

11. Cranbourne. Flight: Phil. Trans. London, 1882, No. 171, 888. White, flexible, magnetic, triangular or rhombic mechanically isolated plates.

12. Misteca. Cohen: Ann. Wien Naturhist. Mus., 1892, vii, 152. Dull and brittle plates. Isolated by HCl. Calculated to 100 after deducting schreibersite.

13. Canyon Diablo. Florence: Am. Jour. Sci., 1895 (3), xlix, 105. Thin tin-white, flexible plates. Calculated to 100 after deduction of 3.60 per cent schreibersite.

14. Wichita Co. Cohen and Weinschenk: Ann. Wien Naturhist. Mus., 1891, vi, 155. Isolated by dilute HCl. Calculated to 100 after deduction of schreibersite.

15. Chupaderos. Manteuffel: Ann. Wien Naturhist. Mus., 1892, vii, 150. Brittle, tin-white plates. Isolated by HCl. Calculated to 100 after deducting schreibersite.

16. Toluca. Cohen and Weinschenk: Ann. Wien Naturhist. Mus., 1891, vi, 137. Tin-white, flexible plates. Isolated by HCl. Calculated to 100 after deducting schreibersite.

17. Canyon Diablo. Fahrenhorst: Ann. Wien Naturhist. Mus., 1900, xv, 376. Thin, flexible plates partly appearing made up of many lamellae, light-yellow or grayish. Schreibersite, 2.34 per cent deducted.

18. Glorieta Mountain. Cohen and Weinschenk: Ann. Wien Naturhist. Mus., 1891, vi, 137. Tin-white, flexible, grouped plates. Isolated by HCl. Calculated to 100 after deducting schreibersite.

19. Bischtübe. Cohen: Ann. Wien Naturhist. Mus., 1897, xii, 54. Large, flexible plates with included schreibersite. Isolated by HCl.

20. Penkarring Rock. Fletcher: Min. Mag., 1899, xii, 174. Thin, flexible plates. Analysis calculated to 100 after deducting 4.18 per cent schreibersite.

21. Medwedewa. Berzelius: Pogg. Ann., 1833, xxxiii, 133. Analysis of skeleton material left behind after dissolving in HCl.

22. Beaconsfield. Sjöström: Monatsberichte Berlin Akad., 1897, 1041. Tinto silver-white, lustrous plates. Iron determined by difference.

The analyses, as will be observed, show variations of composition from Fe_7Ni to $FeNi$. While this variation is a wide one it is evident that it is between certain limits, and that it would be incorrect to ascribe too indefinite a composition to taenite.

PLESSITE

Fülleisen

The term plessite or fülleisen was applied by Reichenbach to the nickel-iron alloy filling the spaces or fields between the lamellae of octahedral meteorites, and the term is still used in this sense. This alloy is usually of darker color and duller luster than kamacite, and as a rule is surrounded by a border of taenite. The amount of plessite occurring in this way varies in different irons. When the fields are more abundant than the lamellae, plessite is correspondingly more abundant, but in some irons there is an almost complete absence of fields and therefore of plessite. In some of the finely laminated octahedrites, as Butler, there are no distinguishable fields but plessite forms the principal mass of the meteorite with octahedral lamellae scattered through it either singly or in bundles. In several pallasites also plessite strongly predominates. While plessite thus appears to have a certain individuality, a little examination of it with a lens or even the naked eye, especially as it occurs in the fields of octahedral meteorites, shows that it is not a homogeneous substance. Often the fields show a structure which simply repeats that of the rest of the meteorite on a smaller scale. The plessite is in these cases made up of kamacite and taenite perhaps less perfectly separated than in the larger lamellae. Davison* carefully separated by hand-picking the two constituents of this character making up the fields of the Welland meteorite and found that they corresponded both physically and in chemical composition to the kamacite and taenite of the same meteorite. The kamacitic portion of the plessite was made up of minute rods $1/6$ to $1/3$ mm. in diameter and the taenitic portion of bands $1/130$ to $1/220$ mm. thick. It is evident from all these considerations that much plessite represents simply less individualized portions of the meteorites in which it occurs and its composition would therefore correspond in general to that of the meteorite itself. Its composition may therefore be safely considered as intermediate between that of kamacite

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*Am. Jour. Sci., 1891, 3, 42, 65.

and taenite, or between $Fe_{14}Ni$ and FeNi. From analogies with the behavior of other alloys it has been suggested by Fletcher* that the behavior of these nickel-iron alloys may be illustrated by that of a fused mixture of silver and copper. When the percentage by weight of silver is 72, and that of copper 28, says Fletcher, solidification begins, not at a temperature between 960° and 1083°, the solidifying temperatures of silver and copper, respectively, but at a temperature below both, namely 770°. The solid which first separates has the same percentage composition as the original mixture; the part still fused has thus itself the same percentage composition as before, and continues to solidify at the same temperature, and in the same way, until the solidification is complete. Such a mixture, having a definite composition and a definite temperature of solidification, was for a time regarded as a definite chemical compound with a complex chemical formula, but on microscopic examination the resultant solid was found to be heterogeneous; minute particles of the silver and copper were seen to lie side by side, the particles being granular or lamellar in form according to the circumstances of the cooling. If the percentage of silver is different from 72, whether it be higher or lower, the solidification begins at a higher temperature than 770°; whence the mixture containing 72 per cent of silver has been conveniently termed *eutectic* (i.e., very fusible).

When the silver is in excess of 72 per cent, the excess of silver gradually collects together and solidifies at various parts of the cooling fused mass; the still fused portion thus gradually becomes poorer in that metal, and the temperature, instead of remaining constant, gradually falls during the separation of the solid. At length the percentage of silver in the fused portion falls to 72 per cent and the temperature to 770°; the solid which now begins to form is no longer pure silver, but a material containing 72 per cent of that metal; and it continues to have the same percentage composition as the surrounding liquid, and the temperature of solid and liquid to be 770°, until the solidification is com-

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*Fletcher, Introduction to the Study of Meteorites. British Museum, Nat. Hist., London, 1909, p. 40.

plete. The final solid thus consists of blebs of silver scattered through a fine groundmass of eutectic mixture of silver and copper. Similarly, if the copper is in excess of 28 per cent, the final solid consists of blebs of copper scattered through a fine groundmass of eutectic mixture of silver and copper. Hence Fletcher suggests that plessite is a eutectic of nickel-iron, and that the kamacite and taenite first separated from it. Prof. Rinne* is of the opinion, however, that separation took place after solidification. Hence he proposes the term eutropic instead of eutectic as it avoids the conception of fusion.

It is evident that further study of these points is desirable. Experimental investigation should show whether iron-nickel alloys have a eutectic and if so the composition of that eutectic. According to the different development of taenite in plessite the appearance of plessite may vary from a dull, dark-gray to a lighter-colored, glittering alloy. In some meteorites also, especially the pallasites, plessite may have a spotted appearance like spotted kamacite.

OLDHAMITE

This is a simple calcium sulphide which has been found in a few meteorites. It is light brown in color and transparent when pure. Hardness 4, specific gravity 2.58. It is soluble in water, isotropic, and has equal cleavage in three directions, hence is doubtless isometric. It was first discovered by Maskelyne in the Bustee meteorite, occurring in rounded grains coated with gypsum through alteration. He gave it the name oldhamite in honor of R. D. Oldham, Director of the India Geol. Survey. The mineral was found occurring in chestnut-brown spherules scattered at one end of the meteorite. These spherules, as nearly as can be determined from Flight's figure† range from 6 mm. in diameter down. The composition of the spherules was determined by Maskelyne, in two analyses, I and II, to be the following:

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*Neues Jahrb. für Min., 1905, Bd. I, 122.

†A Chapter in the History of Meteorites, 1887, 118.

		I	II
Oldhamite	Calcium monosulphide	89.369	90.244
	Magnesium monosulphide	3.246	3.264
Gypsum		3.951	4.189
Calcium carbonate		3.434	.....
Trolite		.....	2.303
		100.	100.

Oldhamite was observed in the Hvittis meteorite by Borgström* as present in the form of transparent grains 3 mm. in diameter and of a brownish yellow color. The mineral was isotropic and easily dissolved, with evolution of H_2S, by acetic acid. Little honey-yellow grains seen in Bishopville were regarded by Maskelyne as oldhamite and Brezina saw similar ones in Aubres. As the water extract of Morristown contained calcium sulphide, Merrill† concluded that oldhamite was present in that meteorite. Tassin concluded‡ from an analysis of the non-magnetic portion of Allegan that oldhamite occurred in that meteorite also, but could obtain no visible evidence of its presence. Merrill also observed the mineral in Indarch. Oldhamite is notable in being a meteoritic mineral which has not yet been discovered terrestrially. Vogt observed it in furnace slags.§

OSBORNITE

In the brown spherules of oldhamite found in the Bustee meteorite, Maskelyne observed minute octahedrons having a golden color and luster.|| They were not affected by acids nor by fusion with potassium carbonate. Ignited in dry chlorine they glowed, lost their metallic luster and left a deliquescent residue. Only .002 of a grain could be obtained for analysis, hence only qualitative determinations could be made. These showed the presence of calcium, sulphur, and an element which was regarded as either titanium or zirconium. On account of the resistance to acids which the mineral exhibited, Maskelyne thought it should probably

*Die Meteoriten von Hvittis and Marjalahti, Helsingfors, 1903, 35.

†Am. Jour. Sci., 1896, 4, 152–153.

‡Proc. U. S. Nat. Mus., 1908, 34, 433–434.

§Arch. Math. Nat., 1890, 14, 72.

||Phil. Trans., 1870, 109, 198–202.

be regarded as an oxysulphide of calcium and titanium or zirconium rather than a simple sulphide. He named the mineral osbornite in honor of Mr. Osborne, who had brought the Bustee meteorite to England and collected information regarding the fall. The mineral has never been reported from any other meteorite.

PYRRHOTITE

Troilite

Iron sulphide was early recognized as a constituent of meteorites, Count Bournon having noted it in several meteorites in 1802. He regarded it, however, as pyrite. The easy decomposability by acids of the meteoritic iron sulphide as compared with pyrite was soon noted, however, and the sulphide was then assumed to be pyrrhotite, especially since Rose in 1825 found crystals in Juvinas which gave forms identical with those of pyrrhotite. Several later investigators found the composition of the iron sulphide of iron meteorites to be FeS, thus differing from that of pyrrhotite which was regarded as $Fe_{11}S_{12}$. Accordingly Haidinger in 1863* proposed the name troilite for the simple iron sulphide of meteorites, a name given in honor of the Jesuit priest, Dominico Troili, who had described in 1766 the Albareto meteorite and mentioned the occurrence of iron sulphide in it. Inasmuch as Rose's measurements indicated that the iron sulphide of one of the stone meteorites was pyrrhotite while analysis gave the composition of the iron sulphide of iron meteorites as FeS, it was for some time thought that the iron sulphide of stone meteorites should be regarded as pyrrhotite and that of iron meteorites as troilite. This view was adopted by Cohen† in his earlier work but modified later. Meunier‡ was of the opinion that all meteoritic iron sulphide was pyrrhotite, and adopted for pyrrhotite the formula $Fe_{11}\ S_{12}$. Hintze§ considers troilite a

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*Sitzb. Wien Akad., xlvii, II, 287–289.

†Meteoritenkunde, 1894, Heft I, 190.

‡Meteorites, Paris, 1884, 62.

§Handbuch der Mineralogie, 630.

synonym for pyrrhotite but gives pyrrhotite the formula FeS.

Analyses show no essential difference between the iron sulphide of iron and stone meteorites and according to Busz* the measurements upon which Rose based his determination of the crystal form of the Juvinas troilite were approximate only and showed great variations.

The latest work upon the subject has been that of Allen and associates,† who, although they do not seem to have worked upon meteoritic iron sulphide directly, concluded from an elaborate general study of the sulphides of iron that troilite should not be considered to differ mineralogically from pyrrhotite, it being simply the end point of a series of solid solutions. The larger percentage of iron in the pyrrhotite of meteoritic irons as compared with that in terrestrial pyrrhotite they regard as due to the excess of iron present at the time of formation of the sulphide. It is thought probable by them that the pyrrhotite of stone meteorites does not contain this excess of iron. It may be desirable, therefore, to use the general name pyrrhotite for the iron sulphide of meteorites in general, and that plan is here adopted. It may be remarked that troilite differs from terrestrial pyrrhotite in being easily decomposed by acids, in leaving no residue of sulphur after such decomposition, in being as a rule non-magnetic, and in having a higher specific gravity than terrestrial pyrrhotite.

The color of meteoritic pyrrhotite varies from bronze-yellow to tomback brown, the darker color tending to be acquired on exposure. Hardness 4, specific gravity 4.68–4.82. Streak grayish black. Luster metallic. Fuses easily B.B. to a black, magnetic globule. Easily decomposed by hydrochloric acid with evolution of hydrogen sulphide. Crystal form as determined by Rose in Juvinas (Fig. 47) and Brezina in Bolson de Mapimi, hexagonal. The following forms are reported:

o (0001), r $(10\bar{1}0)$, t $(11\bar{2}0)$, s $(10\bar{1}1)$, P $(20\bar{2}1)$, v $(11\bar{2}1)$

Brezina reports cleavage ∥ to the base and the pyramidal

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* Neues Jahrbuch, 1895, i, 125–6.

†Am. Jour. Sci., 1912, 4, 33, 213.

planes *P* $(20\bar{2}1)$ striated ‖ to the base. Linck at first concluded from the cleavage of troilite that its form was isometric, but later* regarded the form as like that of pyrrhotite. Such crystals as have been found have been of small size and with imperfect, rounded faces. They occur in druses of the stone meteorites. Besides Juvinas they have been reported from Richmond, Farmington, and Estherville. Most of the pyrrhotite in stone meteorites occurs in the form of small, scattered grains without angular or regular outline. These grains rarely reach a diameter of more than a few millimeters although Rose reported one in Grüneberg 13 mm. in diameter. Vein-like masses 5 cm. long have also been described. In the chondritic meteorites pyrrhotite is especially common in scattered grains. It is frequently intergrown with nickel-iron in all proportions but it also occurs singly. The darker color and dull luster of pyrrhotite easily distinguish it from nickel-iron and further distinction may be obtained by allowing a meteorite section to stand a few minutes in a solution of copper sulphate. Copper will then be deposited upon the nickel-iron but not upon the pyrrhotite, since pyrrhotite does not reduce copper from a solution of copper sulphate. So far as has been observed, the distribution of the pyrrhotite in the chondritic meteorites bears no especial relation to the structure of the chondri.

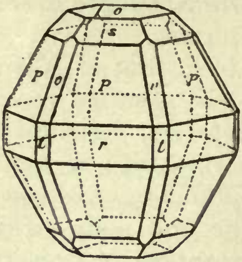

FIG. 47.—Pyrrhotite crystal from the Juvinas meteorite. After Rose.

In the iron meteorites pyrrhotite is common and abundant. It especially characterizes the medium octahedrites, and occurs in them in much larger masses than in the stone meteorites. A nodule of pyrrhotite isolated by Smith from Cosby Creek weighed 200 grams, and one obtained from Magura was 13 centimeters long. Nodules of a spheroidal form are a common mode of occurrence. Other common forms are cylindrical, lens-shaped, oval, and indented. In certain sections a ring-like form may be presented. A re-

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*Cohen, Meteoritenkunde, Heft I, 1894, 191, and Heft II, 1903, 248.

markable mode of occurrence is that forming the so-called Reichenbach lamellae (Fig. 48). These are small plates of pyrrhotite distributed through the nickel-iron of some meteorites and oriented according to the planes of a cube. These lamellae though occasionally larger, range as a rule from 0.1–0.2 mm. in thickness and from 1–3 cm. in length. Staunton, Trenton, Victoria West, Cleveland, Merceditas, and especially Jewell Hill are meteorites which exhibit these lamellae. The lamellae were first observed by Reichenbach in Lenarto and Caille. Tschermak noted their orientation parallel to the three planes of a cube in the Ilimaë and other meteorites,* and Brezina proposed the

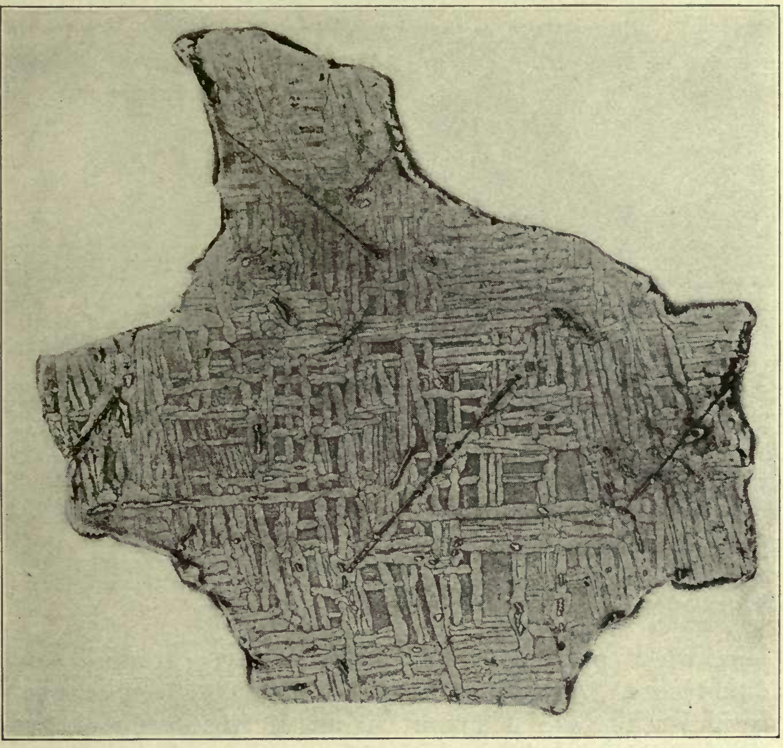

FIG. 48.— Reichenbach lamellae as seen in the Ilimaë meteorite.

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* Denkschrift Wien Akad., 1871, 31, 192–4.

term Reichenbach lamellae* by which they are now generally known. The formation of Reichenbach lamellae in a meteorite must occur prior to that of the nickel-iron. Schreibersite sometimes borders the lamellae. Associated with large nodules of pyrrhotite other minerals are frequently found, often with a more or less zonal arrangement. Graphite and schreibersite thus frequently join with pyrrhotite and occasionally chromite and daubréelite. A common zonal arrangement, seen especially in Wichita and Canyon Diablo, is an interior of pyrrhotite surrounded by a layer of graphite and that by one of schreibersite or cohenite.

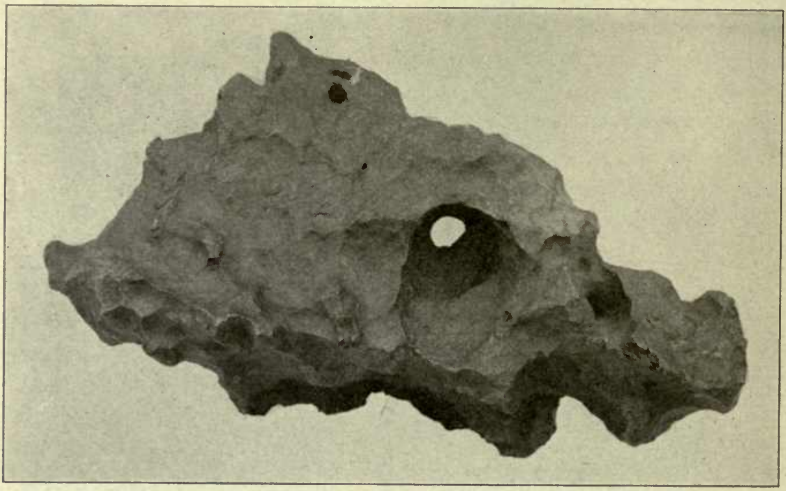

FIG. 49.— An iron meteorite of the Canyon Diablo fall which is perforated probably by the fusing out of a nodule of pyrrhotite. The weight of this individual is 219 lbs.

Pyrrhotite, like impurities in artificial iron, tends to be most abundant toward the periphery of a meteoric individual. Owing to this fact and its easy fusibility it may play an important part in the shaping of the pittings which characterize the surface of meteorites. More striking still are the results it produces when an entire nodule fuses out

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*Denkschrift Wien Akad., 1880, 43, 13–16.

and leaves a hole which may pass entirely through an iron meteorite. (Fig. 49.)

Most of the analyses of meteoritic pyrrhotite show a close approximation to the formula FeS the percentages of which are: Fe 63.60, S 36.40. In the 26 analyses here given only three depart far from this formula and these standing alone can hardly be regarded conclusive. As a rule the quantity of nickel, cobalt, or copper present is very small. Meteoritic pyrrhotite in this respect therefore differs to a marked degree from schreibersite, since in the latter nickel and cobalt are essential constituents.

ANALYSES OF PYRRHOTITE

	Fe	Ni	Co	Cu	SiO_2	S	Total	Fe+Ni+Co +Cu : S
1	65.28	....	....	....	....	34.72	100	1 : 0.929
2	64.19	0.13	....	....	....	35.68	100	1 : 0.969
3	63.93	....	....	....	....	36.07	100	1 : 0.985
4	63.84	tr.	....	....	....	36.16	100	1 : 0.989
5	63.82	....	....	....	....	37.36	101.18	1 : 1.023
6	63.80	....	....	....	....	36.28	100.08	1 : 0.993
7	63.61	....	....	0.08	....	36.33	100.12	1 : 0.997
8	63.53	0.42	....	....	....	36.05	100	1 : 0.986
9	63.48	....	....	....	....	36.21	99.69	1 : 0.996
10	63.47	....	....	....	....	35.89	100	1 : 0.988
11	63.41	....	....	....	....	36.29	99.70	1 : 1
12	63.40	0.20	....	....	....	36.21	99.81	1 : 0.993
13	63.35	....	....	....	....	35.91	99.26	1 : 0.990
14	63.34	....	....	....	....	36.66	100	1 : 1.011
15	63.28	0.45	tr.	....	....	35.59	99.59	1 : 0.976
16	63.00	1.02	....	....	0.67	35.27	99.96	1 : 0.954
17	62.65	1.96		....	....	35.39	100	1 : 0.958
18	62.38	0.32	....	tr.	0.56	35.67	99.01	1 : 0.994
19	62.32	1.58	....	....	....	36.10	100	1 : 0.988
20	62.21	0.16	0.56	....	....	35.05	98.49	1 : 0.977
21	62.01	0.89		....	....	38.28	101.18	1 : 1.064
22	61.80	1.56		....	....	36.64	100	1 : 1.012
23	61.11	....	....	....	....	39.56	100.67	1 : 1.113
24	59.01	0.14	....	tr.	....	40.03	99.18	1 : 1.118
25	58.94	0.42	....	....	....	39.99	99.35	1 : 1.118
26	58.07	4.34	1.52	....	....	36.07	100	1 : 0.990

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1. Bendego. Dafert: Ann. Mus. Nac. Rio de Janeiro, 1896, ix, 129. After separation of 5.26 per cent of insoluble residue, consisting chiefly of daubréelite and schreibersite. Traces of nickel, cobalt and silica were found. The material analyzed consisted of non-magnetic particles which dissolved without evolution of sulphur in moderately concentrated HCl.

2. Tennasilm. Schilling: Archiv. für die Naturk. Liv., Esth. u. Kurlands, 1882 (1), ix, 109. Calculated to 100 after deducting 0.357 per cent residue. The lens showed an admixture of nickel-iron.

3. Rowton. Flight: Phil. Tr. London, 1882, No. 171, 896. Iron determined by difference.

4. Sokobanja. Losanitsch: Ber. der deutsche Chem. Gesell. Berlin, 1878, xi, 97. Copper not present. Sulphur determined by difference.

5. Nenntmannsdorf. Geinitz: Neues Jahrbuch, 1876, 609–610.

6. Cosby Creek. Smith: C. R., 1875, lxxxi, 978.

7. Cranbourne. Flight: Phil. Tr. London, 1882, No. 171, 891. Mean of 4 analyses after deduction of 0.215 per cent and 0.297 per cent insoluble residue, 0.13 per cent chlorine and 0.207 per cent sulphur.

8. Bear Creek. Smith: Am. Jour. Sci., 1867 (2), xliii, 66. Calculated to 100 after deducting 1.81 per cent of residue.

9. Cosby Creek. Smith: C. R., 1875, lxxxi, 978.

10. Seeläsgen. Rammelsberg: Monatsber. Berlin Akad., 1864, 368. Sulphur determined by difference, 0.64 per cent manganese.

11. Jelica. Losanitsch: Berichte der deutsche Chem. Gesell. Berlin, 1892, xxv, 880. No nickel or cobalt.

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13. Seeläsgen. Rammelsberg: Monatsber. Berlin Akad., 1864, 368.

14. Sierra de Chaco. Domeyko: C. R., 1864, lviii, 555.

15. Bjurböle. Borgström: Bull. Com. Geol. de Finlande, 1902, Nr. 12, 25. Mean of several closely agreeing analyses.

16. Steinbach. Winkler: Nova acte Halle Akademie, 1878, xl, No. 8, 357.

17. Cosby Creek. Rammelsberg: Pogg. Ann., 1864, cxxi, 367. Calculated to 100 after deducting 0.74 per cent residue. Sulphur determined by difference.

18. Tazewell. Smith: Am. Jour. Sci., 1855 (2), xix, 156.

19. Seeläsgen. Rammelsberg: Zeit. der deutsch. geol. Gesell. Berlin, 1870, xxii, 894. Sulphur determined by difference. Calculated to 100 after deducting 0.18 per cent P.

20. Cosby Creek. Smith: Am. Jour. Sci., 1876 (3), xi, 433. Dissolved by HNO_3 from a nodule of graphite; 0.30 per cent MgO.

21. Nocoleche. Cooksey: Records of Australian Museum, Sydney, 1897, iii, 53. The material analyzed was treated with mercuric chloride for some time to remove 34.6 per cent intermingled nickel-iron.

22. Cosby Creek. Rammelsberg: Pogg. Ann., 1864, cxxi, 367. Calculated to 100 after deducting 0.60 per cent residue. Sulphur determined by difference.

23. Danville. Smith: Am. Jour. Sci., 1870 (2), xlix, 91.

24. Toluca. Meunier: Ann. Chim. et Phys., 1869 (4), xvii, 42.

25. Jelica. Meunier: Ann. geol. de la Pen. Balkanique, 1893, iv, 5–10.

26. Beaconsfield. Sjöström: Sitzb. Berlin Akad., 1897, 1044. Material, separated with great care, consisted of non-magnetic grains ½–2 mm. in diameter. Graphite 0.33 per cent, traces P and Cl.

DAUBRÉELITE

This mineral, originally discovered by Smith in one of the Coahuila irons* is an iron-chromium sulphide peculiar to meteorites. Its composition is FeS, Cr_2S_3. It is found in nearly all the cubic iron meteorites and has also been identified in the irons of Toluca, Nelson County, Cranbourne, Canyon Diablo and others. It has never been found in stone meteorites. It usually accompanies pyrrhotite, either bordering nodules or crossing them in veins. Sometimes, how-

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*Am. Jour. Sci., 1876, 3, 12, 109; 1878, 3, 16, 270.

ever, it occurs as thin plates or grains. It is black in color, has a black streak, is of metallic luster, brittle and not magnetic. It is infusible before the blowpipe and becomes magnetic in the reducing flame. It is not attacked by hot or cold hydrochloric acid, but is completely dissolved by nitric acid without the separation of free sulphur. This solubility distinguishes it from chromite. Its system of crystallization is not known though it exhibits rectangular and triangular partings which indicate one of the systems of high symmetry. Sp. gr. = 5.01. Meunier obtained the mineral artificially by treating an alloy of iron and chromium at a red heat with hydrogen sulphide.

Smith obtained as the mean of three analyses:

S 42.69, Cr 35.91, Fe 20.10 = 98.70

The theoretical composition is:

S 44.3, Cr 36.3, Fe 19.4 = 100

The chromium content of iron meteorites soluble in nitric acid or aqua regia has usually been ascribed to daubréelite but as Cohen points out* this is only allowable when sufficient sulphur is present to form this mineral.

SCHREIBERSITE

Phosphornickeleisen, Rhabdite, Dyslytite, Lamprite, Glanzeisen, Partschite

The name schreibersite was first applied to a nickel-iron phosphide occurring in the form of large crystals or grains. To occurrences of the same substance in needle or plate-like forms the name rhabdite was long applied as it was at first thought to be a different mineral from schreibersite. The composition and physical properties of rhabdite were, however, shown by Cohen to be the same as those of schreibersite and rhabdite is now regarded as a variety of schreibersite. The term nickel-iron phosphide is sometimes used as a general one to include both schreibersite and rhabdite, but in these pages the term schreibersite is used as a general name for the species.

The color of schreibersite on fresh fracture is tin-white;

*Meteoritenkunde, Heft II, 256.

it tarnishes, however, readily to bronze-yellow. When fresh its lighter color distinguishes it readily from pyrrhotite, kamacite and plessite but not so readily from taenite and cohenite. In fact it has often probably been confounded with taenite but though resembling that alloy in color it can readily be distinguished from it by its lack of elasticity. Schreibersite is extremely brittle. Its hardness is about 6.5. Determinations of its specific gravity vary from 6.3 to 7.3, but the majority of determinations give a value near 7. Schreibersite is strongly magnetic and may be made to acquire and hold polarity. It occurs in the form of crystals, grains, foliae, and especially as needles, to which latter form the name rhabdite (*ῥάβδος*, a rod) is applied.

The habit of the crystals varies from compressed-prismatic to vertical-tabular. The crystals sometimes reach a length of 5½ inches (14 cm.) as in Carlton. Owing to the rounding of planes and angles crystallographic determinations have not thus far been possible. Often a hollowing of the ends of the crystals such as is characteristic of pyromorphite occurs and in one such hollow on a crystal from Toluca, taenite was found. Cleavage in three perpendicular directions is usually observable, that perpendicular to the length of the crystal being the best defined. The tetragonal system of crystallization is thus indicated. By allowing a crystal of schreibersite to fall on paper, separation into cuboidal forms often takes place. Disintegration also often occurs by mere standing, thus suggesting that a condition of tension like that shown by Prince Rupert drops, exists. In the form of grains or flakes schreibersite may be discerned in an etched section or its presence may only become known upon dissolving the nickel-iron. In Ilimaë isolated grains were observed by Tschermak to be collected in the neighborhood of Reichenbach lamellae. Often schreibersite is intergrown with pyrrhotite and graphite. Graphite nodules may serve as a nucleus for the growth of schreibersite crystals or they may be surrounded by an envelope of the latter mineral. The needle-like or lath-shaped forms of schreibersite known as rhabdite usually have angular terminations. They are usually very thin in proportion to their length. In thickness Cohen obtained measurements varying from .001 to .05 mm. while in length some were 5 mm. long. In the latter direction, however, the measurement might well be incomplete since the needles break easily. The width of the 5 mm. crystal was 1.5 mm. Angular measurements made by Deecke and Scheerer showed values close to 90°. Thus the tetragonal form is further indicated. Vertical striations often characterize the needles.

In the irons of Santa Rosa, Seeläsgen, Braunau, and Misteca the arrangement of rhabdite was found to be parallel to cubic faces. In Indian Valley, Kunz and Weinschenk noted an arrangement parallel to the Neumann lines. In Hex River the rhabdite is arranged in parallel zones, but the needles are differently oriented in each. Zones poor in rhabdite or free from it lie between those rich in rhabdite. There is also a difference in the size of the needles in the different zones, and the smaller needles appear more numerous and more crowded than the larger. A similar arrangement was observed by Brezina in the iron of Holland's Store. In Braunau, according to Tschermak, there are gradations from true rhabdite needles to schreibersite-like foliae, the latter being bounded by three planes perpendicular to each other and arranged partly parallel to the faces of the main individual and partly parallel to the twinning lamellae. This is explained by Tschermak as a simultaneous crystallization of nickel-iron and schreibersite, the slow-forming twinning lamellae giving the schreibersite more opportunity to extend in the direction of breadth. Somewhat similar foliae were isolated by Cohen from Hex River. The largest of these was 2.6 mm. long, 1.6 mm. broad, but most were much smaller. Still there was complete separation in form and dimensions between needles and plates. The plates were usually bounded by six planes at right angles to each other, the four subordinate ones being probably cleavage planes. On some of the edges of the planes angles of about 150° could be noted. The surface of the planes was either smooth or corrugated, the corrugations running sometimes in two directions.

Brezina[*] noted an arrangement of schreibersite lamellae parallel to the planes of the dodecahedron. These he found in Tazewell, Ballinoo, and Narraburra. The plates have the same relation to schreibersite that those of pyrrhotite (Reichenbach lamellae) have to that mineral except that the pyrrhotite lamellae are arranged parallel to the cube, while those of schreibersite are parallel to the dodecahedron.

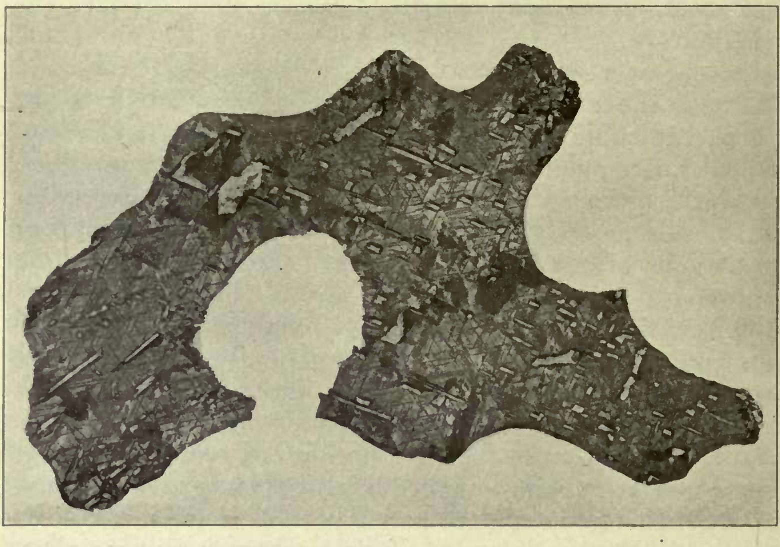

Fig. 50.— Brezina's lamellae (dodecahedral schreibersite lamellae) as seen in the Narraburra meteorite.

Cohen has given the name of Brezina's lamellae to schreibersite plates arranged in this way. The accompanying figure (Fig. 50) shows the Brezina lamellae in Narraburra as observed by Liversidge.[†]

Numerous analyses of schreibersite and rhabdite have been made all indicating a formula $(Fe, Ni, Co)_3P$. The ratio of Fe : Ni+Co varies, but considered as 3 : 1 which seems to be about the average, the percentages become Fe 62.6, Ni+Co 21.9, P 15.5. In view of the large, constant percentage of nickel, Borgström has urged[‡] that the formula

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[*] Sitzb. Wien. Akad., 1904, 113, 1–7.

[†] Jour. Roy. Soc. N. S. W., 1903, xxxvii, Pl. xvii.

[‡] Die Met. v. Hvittis u. Marj., Helsingfors, 1903, 67.

of schreibersite should be regarded as $Fe_2Ni\ P$, in which case the percentages would be Fe 55.5, Ni 29.1, P 15.4. The percentage of Ni+Co is much less variable apparently in rhabdite than in schreibersite. A complete list of analyses follows. In cold, dilute acids and in copper ammonium chloride schreibersite is insoluble, the latter property furnishing a means of distinguishing it from cohenite and taenite. Unlike these minerals also it does not reduce copper from copper sulphate solution. By warm, concentrated HCl or aqua regia schreibersite is easily dissolved and thin plates are attacked by cold, dilute HCl.

For isolation of schreibersite Meunier recommends boiling a powder of the mineral with a concentrated solution of copper sulphate, separation of precipitated copper with fuming nitric acid, treatment of the residue with a magnet to separate it from graphite, and solution of any pyrrhotite present by treatment with dilute nitric acid. Before the blowpipe schreibersite fuses easily to a magnetic globule. After boiling with nitric acid, ammonium molybdate gives a yellow precipitate of ammonio-phospho-molybdate. Heating of the fine powder with magnesium wire in a closed tube and treatment of the assay with water gives hydrogen phosphide, H_3P, recognizable by its garlic-like odor.

Schreibersite is almost universally present in the iron meteorites, in fact is perhaps never lacking from them. The distribution of schreibersite in an individual meteorite is usually quite irregular. Thus from three different pieces of Glorieta Mountain Cohen obtained values varying from 2.85 to 8.11 per cent of schreibersite according to what part the sample was taken from, and similar determinations of Toluca by different authorities show percentages varying from 0.34 to 4.93 per cent. It is quite impracticable, therefore, to determine accurately the amount of schreibersite in a meteorite by calculation from the amount of phosphorus obtained in a single analysis.

As between schreibersite and rhabdite the octahedrites usually contain more schreibersite, the hexahedrites and ataxites more rhabdite. Yet both may occur in about equal quantity as in Seeläsgen, while in Magura and Sarepta certain parts contain an excess of schreibersite and others of rhabdite. The iron-stone meteorites usually contain schreibersite, as do probably also the stone meteorites. At least it is customary to assign to this mineral percentages of phosphorus shown by analyses. Yet this amount is sometimes so large, e.g., 0.76–0.91 per cent in the nickel-irons of Nerft, Honolulu, Zsadany and Bachmut and 2.03 per cent in the nickel-iron of Carcote that it is suggested by Cohen* that it is questionable whether this is properly referable to schreibersite. In a later note in view of the discovery of free phosphorus in Saline by Farrington, Cohen suggests that the phosphorus may be present in the free state.

As was early pointed out by Smith, schreibersite is a mineral peculiar to meteorites and one of the most significant in interpreting their origin. Terrestrially phosphides do not occur, since free oxygen changes them to phosphates. The existence of schreibersite in meteorites is therefore, proof of absence of free oxygen where they were formed. Törnebohm has reported schreibersite to be present in the terrestrial iron of Ovifak, his determinations being based on the presence of magnetic particles with metallic luster which did not precipitate copper from a copper sulphate solution and were only slightly attacked by hydrochloric acid. Such a determination is, however, too incomplete to be reliable. In the Santa Catarina iron Daubrée found a prismatic crystal terminating in eight planes which he regarded as schreibersite. Also a substance isolated by Derby from this iron by means of dilute hydrochloric acid gave percentages on analysis by Cohen closely approximating the composition of schreibersite. A number of iron or nickel phosphides resembling schreibersite have been obtained artificially. Thus Sidot by allowing vapor of phosphorus to pass over piano wire in a porcelain tube at a red heat and later heating the product, obtained in the interior of the metallic mass hard, steel-colored, four-sided prisms, reaching a centimeter in size and having the composition Fe_4P (P 12.1 per cent). By fusion of calcium

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*Meteoritenkunde, Heft I, 136.

phosphide, powdered charcoal, and nickel oxide, Garnier obtained a compound having the formula Ni_5P. It was in the form of long, prismatic, light yellow crystals determined by Jannetaz to be tetragonal. Their hardness was 5.5; sp. gr. 7.283.

By slight heating of finely divided iron in vapor of phosphorus Hvoslef obtained a compound having the formula Fe_2P from which by strong heating under a cover of borax, a regulus of dark iron-gray color, brittle, magnetic, and attacked neither by hydrochloric or nitric acids resulted. It contained 16 per cent P, corresponding to the formula Fe_3P. G. = 6.28.

Rhabdite-like, steel-gray, brittle, magnetic, tetragonal prisms were found by Mallard accompanying augite and anorthite among the products of a furnace at Commentry. After subtracting Fe and As the composition of the substance corresponded to the formula Fe_7P_2.

ANALYSES OF SCHREIBERSITE

	P	Fe	Ni	Co	Cu	Total	Substance taken	Fe+Ni+Co:P
1	16.10	72.62	10.72	0.56	....	100	0.5375	2.869 : 1
2	16.04	69.55	14.41		....	100	......	2.877 : 1
3a	15.74	69.54	13.81	1.31	....	100.40	0.4499	2.955 : 1
3b	15.80	70.07	14.57	0.43	0.03	100.90	0.8030	2.959 : 1
4	15.70	61.78	21.93	0.38	0.21	100	0.6886	2.937 : 1
5	15.70	54.12	29.71	0.47	....	100	0.5045	2.925 : 1
6	15.68	50.52	33.90	0.62	0.22	100.94	0.6761	2.955 : 1
7	15.49	63.36	19.63	1.23	....	99.71	0.4086	2.978 : 1
8	15.47	65.75	18.35	0.43	....	100.00	0.5644	2.996 : 1
9	15.45	54.43	29.36	0.67	0.34	100.25	0.3260	2.990 : 1
10	15.45	71.70	12.58	0.32	....	100.05	0.6490	3.014 : 1
11	15.37	58.54	26.08	0.05	tr.	100.04	......	3.009 : 1
12	15.38	63.97	19.15	1.68	....	100.18	0.4115	3.020 : 1
13	15.31	57.46	25.78	1.32	....	99.87	0.1328	3.015 : 1
14	15.01	57.11	28.35	tr.	....	100.47	......	3.106 : 1
15	15.00	64.69	20.11		....	99.80	......	3.099 : 1
16	14.93	55.15	29.15	0.21	....	99.44	0.5152	3.086 : 1
17	14.88	66.92	18.16	0.62	....	100.58	0.4023	3.158 : 1
18	14.86	56.53	28.02	0.28	....	99.69	......	3.113 : 1
19	14.76	69.45	15.79		....	100.00	0.619	3.172 : 1
20	14.58	66.72	17.54		0.13	98.97	......	3.171 : 1
21	14.25	55.13	30.62		....	100.00	......	3.277 : 1
22	14.17	68.11	17.72		....	100.00	0.028	3.324 : 1
23	13.80	63.04	23.07	0.03	....	99.94	......	3.419 : 1
24	13.51	56.12	29.18		....	98.81	......	3.443 : 1

REFERENCES

1. Zacatecas. Scherer: Meteoritenkunde, Heft I, 131. Calculated to 100, after deduction of 4.60 per cent chromite and 0.88 per cent daubreelite.

2. Cranbourne. Flight: Ph. Tr., 1882, 892; mean of two analyses. Nickel determined by difference. "Large, brass-yellow prisms, with distinctly basal cleavage, slowly soluble in muriatic or nitric acid."

3a. S. Juliao de Moreira. Cohen: N. J., 1889, i, 220; mean of two analyses; brittle, steel-gray, crystalline fragments, shading to bronze-yellow.

3b. S. Juliao de Moreira. Fahrenhorst: Meteoreisenstudien, xi, A. N. H. Wien, 1900, xv, 389. The determination of Cu was made on 19.183 grams.

4. Kendall County. Scherer: Meteoritenkunde, Heft II, 233.

5. Mount Joy. Fahrenhorst: Meteoreisenstudien, xi, A. N. H. Wien, 1900, xv, 388. Slight mixture of rhabdite. Calculated to 100 after deduction of 0.42 per cent chromite and silicate.

6. Magura. Fahrenhorst: Meteoreisenstudien, xi, A. N. H. Wien, 1900, xv, 377.

7. Glorieta Mountain. Cohen and Weinschenk, A. N. H. Wien., 1891, 157; large and very brittle crystals.

8. Bischtübe. Cohen: Meteoritenkunde, Heft I, 131. Calculated to 100, after deduction of 0.07 per cent residue.

9. Cosby Creek. Fahrenhorst: Meteoreisenstudien, xi, A. N. H. Wien, 1900, xv, 372.

10. De Sotoville. Cohen: Meteoritenkunde, Heft II, 233.

11. Canyon Diablo. Tassin: Smithsonian Misc. Coll., 1908, 50, 212. Flattened and angular nodules and rounded grains. G-7.20.

12. Toluca. Cohen and Weinschenk: A. N. H. Wien, 1891, vi, 138; very brittle crystals, up to 5 mm. in length, tin-white and very lustrous; cobalt probably estimated too high on the basis of the nickel; no copper.

13. Hraschina. Cohen and Weinschenk: A. N. H. Wien, 1891, vi, 149. Fragments.

14. Toluca. Meunier: A. Ch. P. (Paris), 1869 (4), xvii, 45, 57; microscopic scales, slowly soluble in warm muriatic acid; trace of magnesia.

15. Casas Grandes. Tassin: Proc. U. S. Nat. Mus., 1902, xxv, 73.

16. Marjalahti. Borgström: Die Meteoriten von Hvittis und Marjalahti, 1903, 66.

17. Beaconsfield. Sjöström: Monatsberichte Berlin Akad., 1897, 1040. Large crystals.

18. Tazewell. Smith: Am. Jour. Sci., 1885 (2), xix, 157; yellow, irregular spangles.

19. Bohumilitz. Berzelius: Pogg. Ann., xxvii, 131; gilt scales; calculated to 100, after deduction of 2.04 Si. and 1.42 C.

20. Canyon Diablo. Florence: Am. Jour. Sci , 1895 (3), 49, 107. From a vein enclosed by cohenite Tin found qualitatively.

21. Cambria. Silliman and Hunt: Am. Jour. Sci, 1846 (2), ii, 375; blackish-gray folia, mixed with bright flakes; calculated to 100 after deduction of 10 per cent Si. The analysis gave a sum of only 90 per cent.

22. Elbogen. Berzelius: Pogg. Ann., 1834, xxxiii, 137.

23. Canyon Diablo. Tassin: Smithsonian Misc. Coll., 1908, 50, 211. Broad, thin, dark steel-gray, flexible, magnetic lamellae. G=7.09.

24. Cranbourne. Flight: Ph. Tr., 1882, 892; very brittle, coarse powder, readily soluble in concentrated muriatic acid.

ANALYSES OF RHABDITE

	P	Fe	Ni	Co	Cu	Total	Amount taken	Fe+Ni+Co : P
1	16.35	48.85	33.15	1.65	....	100.00	......	2.780 : 1
2	15.49	51.10	32.99	0.42	....	100.00	0.2563	2.967 : 1
3	15.46	56.71	27.36	0.47	....	100.00	0.2772	2.984 : 1
4	15.32	55.30	28.78	0.60	....	100.00	0.3276	3.015 : 1
5	15.09	52.42	33.51		0.25	101.27	0.476	3.106 : 1
6	15.05	41.54	42.61	0.80	....	100.00	0.0986	3.053 : 1
7	15.03	52.54	31.71	0.72	....	100.00	0.5985	3.076 : 1
8	14.86	46.22	37.98	0.96	....	100.00	0.2255	3.107 : 1
9	12.95	49.33	38.24		....	100.52	......	3.672 : 1

REFERENCES

1. Santa Rosa. Coahuila: Wichelhaus, Pogg. Ann., 1863, cxviii, 633; glistening needles insoluble in nitric acid.

2. Lime Creek. Cohen: A. N. H. Wien, 1894, ix, 115. Calculated to 100, after deduction of 1.54 per cent chromite and 2.62 per cent daubréelite; the analysis gave only 95.57 per cent.

3. Hex River Mountains. Cohen: A. N. H. Wien, 1894, ix, 110. Calculated to 100 after deduction of 0.53 per cent chromite and 0.68 per cent daubréelite.

4. Sancha Estate, Coahuila. Cohen: A. N. H. Wien, 1894, ix, 106. Calculated to 100, after deduction of 0.43 per cent chromite and 0.28 per cent carbon.

5. Bendego. Florence: Ann. Mus. Nac., Rio de Janeiro, 1896, ix, 182. Mixed with schreibersite. Trace of tin. Material not treated with salt of copper.

6. Beaconsfield. Sjöström: Monatsber. Berlin Akad., 1897, 1041. Iron determined by difference. Cobalt determination incomplete.

7. Bolson de Mapimi. Cohen: A. N. H. Wien, 1894, ix, 103. Calculated to 100, after deduction of 0.96 per cent residue and 2.15 per cent daubréelite.

8. Seeläsgen. Cohen: Meteoreisenstudien, V, A. N. H. Wien, 1897, xii, 52.

9. Cranbourne. Flight: Ph. Tr., 1882, 891. Apparently quadratic, very brittle prisms, impervious to muriatic acid. Identified by Flight with rhabdite.

COHENITE

Lamprite in part

Cohenite is a carbide of iron, nickel and cobalt, having the formula $(Fe, Ni, Co)_3C$. It is found chiefly in the iron meteorites of the group of coarse octahedrites, having been identified in Beaconsfield, Bendego, Canyon Diablo, Magura, and Wichita County. It appears as silver-white, strongly magnetic and brittle crystals oxidizing to bronze yellow or tomback brown. Streak gray-black. Hardness 5.5–6. Sp. gr. 7.20–7.65, (Hussak 6.18). Cohenite is insoluble in dilute HCl but is slowly dissolved by concentrated acid, and gives off in the latter process a petroleum-like odor. It is also soluble in copper ammonium chloride.

It was first distinguished as a separate mineral by Weinschenk in 1889, having been previously mistaken for schreibersite. It differs from schreibersite in being infusible and in giving no precipitate with ammonium molybdate. Crystals of cohenite are usually of elongated form and are often arranged parallel to the octahedral bands of their host. Definite forms have been described only by Hussak* who found them constituting crystalline aggregates in the Bendego meteorite. By dissolving the iron in weak acid these aggregates became separated and on the crystals so obtained Hussak identified the following isometric forms: *a*(100), *o*(111), *d*(110), *p*(221) and probably (311), (322) and (944). The habit of the crystals was tabular. In Magura they reach a length of 8 mm. Carbides of composition similar or nearly similar to cohenite are found in artificial iron and in the native iron of Greenland.

ANALYSES OF COHENITE

	Fe	Ni	Co	C	Total	Fe+Ni+Co : C
1	94.34	0.13		5.53	100	3.67 : 1
2	91.69	2.21		6.10	100	3.30 : 1
3	91.45	2.47	0.10	5.98	100	3.35 : 1
4	91.31	1.77	0.25	6.67	100	3.00 : 1
5	91.06	2.20	....	6.73	100	2.97 : 1
6	90.94	2.22	0.30	6.54	100	3.06 : 1
7	90.80	2.37	0.16	6.67	100	3.00 : 1
8	89.81	3.08	0.69	6.42	100	3.11 : 1

REFERENCES

1–2. Canyon Diablo. Florence: Am. Jour. Sci., 1895 (3), xlix, 105–106. 1. Isolated crystals after deducting 3.64 per cent schreibersite. 2. Plates intergrown with schreibersite.

3. Canyon Diablo. Tassin: Smithsonian Misc. Coll., 1907, 50, 212. Thin plates and rounded grains. Calculated to 100 after deducting .18 per cent schreibersite.

4. Canyon Diablo. Fahrenhorst: A. N. H. Wien, 1901, xvi, 375. Calculated to 100 after deducting 4.68 per cent of schreibersite.

5. Bendego. Dafert: Meteoritenkunde, Heft I, 117. Calculated to 100 after deducting 5.68 per cent schreibersite.

6. Beaconsfield. Sjöström: Monatsber. Berlin Akad., 1897, 1043. Calculated to 100 after deducting 26.12 per cent schreibersite.

7. Wichita. Sjöström: Zeitschrift für anorgan. Chemie, Hamburg and Leipzig, 1896, xiii, 57. Calculated to 100 after deducting 9.35 per cent schreibersite.

8. Magura. Weinschenk: A. N. H. Wien, 1889, iv, 95. Mean of three analyses calculated to 100 after deducting .65 per cent schreibersite. Traces of Cu and Sn found.

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*Arch. Mus. Nac. Rio de Janerio, 1896, 9, 161–5.

Moissanite

A silicide of carbon having the formula SiC was first found by Moissan* in the residue left after dissolving a 53 kg. piece of Canyon Diablo in hydrochloric acid, and treating this residue with hydrofluoric acid and boiling sulphuric acid. The mineral occurred in the form of small hexagonal crystals of a generally green color but varying from pale green to emerald green. Specific gravity 3.2. The mineral was unattacked by acids but gave potassium silicate on fusion with caustic potash and CO_2 on fusion with lead chromate. Kunz† suggested the name moissanite for the mineral in honor of its discoverer. In physical and chemical properties the mineral agrees with the previously known and artificially produced carborundum. Forty-four crystal forms have been identified on carborundum but none on moissanite. Moissan simply stated that the edges of the crystals observed by him were well-formed and the sides perpendicular.

Lawrencite

This name is applied to ferrous chloride, $FeCl_2$, found sometimes in solid form but usually deliquescent in green drops on meteorites. The solid form has been reported only in the meteorites of Laurens, Smith Mountain, and Tazewell. These are all fine octahedrites with high percentages of nickel. Little description of the appearance of the substance was given by the finders. It was simply stated that it occurred in crevices and became soft on exposure. The name lawrencite was given to the mineral by Daubrée in honor of J. Lawrence Smith.‡ More frequent than the solid form of the mineral is the occurrence in the manner first described by Jackson in the meteorite of Limestone Creek.§ Jackson states that having washed the iron several times in distilled water he filed one side of it bright and left it exposed to the air. In a few days numerous drops of a

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*Comptes Rendus, 1904, 139, 778, and 1905, 140, 405–406.

†Am. Jour. Sci., 1905, 19, 396–397.

‡C. R., 1877, 84, 69.

§Am. Jour. Sci., 1838, i, 34, 333.

grass-green liquid collected on the surface of the iron and these soon became externally coated with a thin, brown film. The drops had a slightly alkaline, astringent taste but gave no alkaline reaction with turmeric paper. Qualitative tests showed the presence of iron, nickel, and chlorine. Quantitative analysis (reduced to percentages by Cohen*) gave:

Fe	Ni	Cl
51.02	18.14	30.84 = 100

Fe+Ni : Cl = 1.4 : 1

Analysis of scraped material was also made by Jackson and another by Hayes but these analyses appear to have been much contaminated by foreign material. All show higher percentages of iron than normal ferrous chloride and thus indicate that impure material was used. The percentages for pure ferrous chloride are:

Fe	Cl
44.1	55.9

On exposure to the air, lawrencite rapidly turns brown and becomes earthy, showing a change to ferric chloride (molysite), and ferric hydroxide (limonite). The reaction is:

$$6\ Fe\,Cl_2 + 3O + 3\ H_2O = Fe_2\,O_6H_6 + 4Fe\,Cl_3$$

The ferric chloride is, however, reduced by contact with iron to form ferrous chloride again:

$$4\ Fe\,Cl_3 + 2Fe = 6\ Fe\,Cl_2$$

so that the process is continuous. In addition there may occur a formation of free acid through hydrolysis of ferric chloride:

$$4\ Fe\,Cl_3 + 6\ H_2O = Fe_2\,O_6H_6 + 6\ HCl + 2\ Fe\,Cl_3$$

In connection with these chemical changes there is an increase of volume which causes splitting and disintegration of the meteorite.

All lawrencite of meteorites shows qualitatively and quantitatively nickel present with the iron. This probably gives the green color to the mineral as compared with

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*Meteoritenkunde, 1894, Heft I, 231.

ferrous chloride which is colorless. The latter has been reported at Vesuvius. Meteoritic lawrencite is, then, a mixture of iron and nickel chlorides. It was early suggested that the lawrencite of meteorites was not a primary constituent, and might have been formed by the absorption of chlorine by the meteoric mass from the earth's atmosphere or the soil. This was the view of Shepard* and Mallet.† But as lawrencite varies in quantity in meteorites and exudes from pieces freshly cut from the interior of meteorites, there can be little doubt that it is an original constituent. It is known to be present, as has been mentioned, in clefts and hollows and it is also regarded by Cohen as distributed "in the intermolecular spaces."‡ Its distribution is indicated in a general way in a meteorite by areas inclined to rust. The borders of accessory constituents are, as is well known, especially liable to such a change. Cohen thinks it probable that the lawrencite of a meteorite gradually works outward by diffusion. He bases this view upon the fact that in the unaltered interior of Forsyth he found 0.17 per cent of chlorine but in the rust crust 4.99 per cent. Nevertheless it is highly probable also that the lawrencite is more or less irregularly distributed. In Deep Springs the non-rusted portion showed 0.016 per cent chlorine, and the easily rusting portion 0.99 per cent, while Venable found 0.39 per cent in a mass analysis. In Deep Springs, as in the Cape iron and Lick Creek, the easily rusting portions are divided by rather sharp boundaries from those which do not rust. Probably through a process of diffusion to the surface and thus of escape, the lawrencite of a meteorite often seems to disappear after a time. This exhaustion is shown by a cessation of the tendency to rust. Cohen describes such a cessation in a section of the Cape iron after a period of 15 years, and in one of Sao Juliao after a much shorter time.

The presence of chlorine, indicating lawrencite, is often reported in iron meteorites in appreciable percentages by

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*Am. Jour. Sci., 1842, 1, 43, 359–362.

†Am. Jour. Sci., 1871, 3, 2, 14.

‡Meteoritenkunde, 1903, Heft II, 266.

analysts, the largest per cent found being 1.48 per cent, reported by Jackson in Limestone Creek. According to experiments made by Cohen,* the extraction of chlorine for analysis can best be made by digesting a few grams of the meteorite in dilute sulphuric acid. Dilute nitric acid or boiling water is less effectual for this purpose. It is to the presence of lawrencite in meteorites that their frequently observed "sweating" is doubtless to be ascribed. Over the surface of such meteorites the continuous formation of liquid drops may be observed and relatively rapid decomposition of the mass takes place, at least until a protective crust is formed. Conspicuous examples of such meteorites are Cranbourne and Toluca. Other meteorites, such as St. Genevieve, some individuals of Canyon Diablo, etc., show no tendency to sweating or rusting although in a fall consisting of numerous individuals, such as Toluca and Canyon Diablo, there is marked difference in the rusting tendency of different individuals. Lawrencite seems to be almost wholly associated with nickel-iron and to be confined, therefore, largely to the iron meteorites. "Sweating" of some iron-stone and stone meteorites indicating the probable presence of lawrencite in them has, however, been observed. Such meteorites include Crab Orchard, Hainholz, Morristown, and Sierra de Chaco among the iron-stones and Charwallas, Marion, and Nagaya among the stones.

Other salts besides lawrencite soluble in water have been found in some meteorites, chiefly carbonaceous ones, the porous texture of which suggests absorption or formation of these salts from the earth's atmosphere rather than their existence as primary constituents. The soluble salts so found include chlorides and sulphates of sodium, potassium, ammonium, magnesium, and calcium. They are usually found in the water extract of the meteorite but occasionally are obtained as sublimates from heating the meteorite in powdered form.

WATER

Water is as a rule conspicuous by its absence from meteorites, yet in some occurs in appreciable quantities. As

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*Meteoritenkunde, 1903, Heft II, 266.

the meteorites in which it is chiefly found are of a porous nature, some authorities are inclined to regard its origin in meteorites as always terrestrial. It is perhaps never a primary constituent and yet some meteorites which have been picked up immediately after their fall show a rusting of the interior which would seem pre-terrestrial. In the carbonaceous meteorites Alais, Cold Bokkeveld, Nagaya, and Orgueil, water has been found in quantities of from 6 to 11 per cent. From these it is obtained by heating to a temperature above 100° C. In other stony meteorites such as Bishopville, L'Aigle, and Pultusk, water has been obtained in quantities of from 0.1 to 1.43 per cent by heating the stone to redness. Part of such water doubtless exists in combination, as for example, with iron forming iron hydroxide and it has been suggested that part may be formed from hydrocarbons by heating. No mineral in meteorites except limonite (if that be an original constituent) possesses water. Pisani observed that the powder of the Orgueil meteorite which lost 9.15 per cent water by drying, took up 7 per cent again in a few hours.

QUARTZ

On the whole, quartz is conspicuous by its absence from meteorites. It has, however, been identified in several irons, though almost wholly in their superficial portions. This has caused some authorities to doubt whether quartz is ever an original constituent, but there are reasons for believing that it is so.

The first satisfactory observation of quartz in meteorites was by Rose* of grains which he observed in the crust of one of the Toluca irons. These were further studied in 1895 by Laspeyres† who found in the earthy, loamy crust of a Toluca individual weighing 10 kilos numerous brilliant quartz crystals reaching a size of 2 mm. The crystals showed the forms $\infty R\ (10\bar{1}0)$, $R\ (10\bar{1}1)$ and $-R\ (01\bar{1}1)$. They also had the usual characters of siliceous meteoritic minerals in being fissured and brittle and in showing rounded

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*Monatsber. Berlin Akad., 1861, 406–407.

†Zeitschrift für Kryst., 1894, xxiv, 485–488.

edges and solid angles. The specific gravity was 2.65. Index of refraction about that of Canada balsam. High interference colors. Silica skeleton with salt of phosphorus. Soluble in hydrofluoric acid. Unaltered by strong heating in the oxidizing flame. Other occurrences of quartz have been noted in the insoluble residues of meteoric irons. Thus Joy found in the insoluble residue of Cosby Creek some white, opaque, and some transparent grains which would scratch glass but not quartz and which he, therefore, regarded as quartz. Similar residues were found by Cohen and Weinschenk in all the irons they investigated. These included Beaconsfield, Bischtübe, Glorieta Mountain, Hex River Mountains, Ivanpah, Kokstad, Lime Creek, Locust, Magura, Misteca, Rasgata, Schwetz, and Toluca. The grains found were colorless and transparent and averaged less than 0.1 mm. in diameter. From the pyrrhotite of Caille and Charcas apparent quartz grains were isolated by Daubrée and from the schreibersite of Sao Juliao by Cohen. In none of these occurrences has the quartz been found in place, hence its existence as a fundamental constituent of meteorites is not altogether certain, but indications point strongly to a pre-terrestrial origin for the grains found.

TRIDYMITE

Asmanite

Tridymite has been identified in the iron-stone meteorite of Steinbach and its probable presence has been reported in Vaca Muerta and Crab Orchard, which are also iron-stone meteorites, and in the stone meteorite Fisher. In Steinbach the tridymite occurs as colorless, rounded grains or plates which reach 3 mm. in their largest dimension. They are generally stained with iron superficially and like other meteoritic minerals are much rounded. The grains also are brittle and have a resinous luster. The hardness is given as 5.5 by Maskelyne, 6.5 by Rath. Specific gravity 2.24–2.27. Maskelyne regarded the mineral as orthorhombic and considered it, therefore, a new species to which he gave the name asmanite from *ásman*, the Sanskrit word for thunderbolt.* Assuming an orthorhombic form for the mineral Maskelyne distinguished twelve forms, the equivalents of which in the now generally accepted hexagonal system have not as yet been determined.

The existence of tridymite in a meteorite shows, according to the researches of Wright and Larsen,† that it has been heated to a temperature above 800° C, since tridymite forms between 800° and 1625° C.

MAGNETITE

Several stone or iron-stone meteorites have been found to contain black, magnetic grains which dissolved in hydrochloric acid without effervescence to form a yellow solution. In the meteorites of Shergotty and Doña Inez these are sufficiently abundant to form an essential constituent, in Shergotty constituting 4.57 per cent. Similar grains occur as inclusions in maskelynite, pyroxene, and chrysolite in the above and other meteorites. They are regarded as magnetite.

No well-marked crystals of meteoritic magnetite have as yet been described.

In several iron meteorites magnetite has been reported as a constituent but few analyses have been made. Tassin‡ observed a chromiferous magnetite occurring as rounded grains of blue-black color and dull luster in Canyon Diablo, associated with "troilite and silicon compounds in areas rich in carbon." Analysis gave:

Fe_2O_3	65.25
FeO	30.05
Cr_2O_3	5.20
	100.50

Meunier analyzed magnetite from the crust of Toluca obtaining the material by first treating the crust with

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*Phil. Trans., 1871, 161, 361.

†Am. Jour. Sci., 1909, 4, 27, 423.

‡Proc. U. S. Nat. Mus., 1908, 34, 687.

chloride of mercury, then with very dilute HCl and then with magnets. His analysis gave:

Fe_2O_3	68.93
FeO	28.12
NiO	2.00
CoO	tr.
	99.05

That the crust formed upon the surface of iron meteorites in passing through the air has the composition of magnetite was also shown by Farrington* from an analysis of such a crust upon the Quinn Canyon meteorite by Nichols. The analysis calculated to 100 after deduction of extraneous compounds gave:

Fe_2O_3	72.38
FeO	27.62
	100.

CHROMITE

Chromite is a common constituent of meteorites, being not infrequent in the irons and almost universally present in the stones. It occurs in the stones usually in the form of grains, often of microscopic dimensions, though sometimes as large as a pea. In thin sections it can usually be readily recognized by its translucent ruby to purple color and isotropic characters. In the irons it usually occurs in nodules, sometimes of considerable size, as in the case of one of the Coahuila irons, where one of oval form found by Smith measured 5 x 7 inches (12 x 17 mm.) in diameter. This was a black, granular mass, feebly translucent and of dark reddish-purple color. In other irons, as in Carthage, Schwetz, and Bendego, chromite occurs closely associated with pyrrhotite and cohenite. It is usually in octahedral crystals averaging about one millimeter in diameter. From Bendego highly modified crystals were obtained by Hussak,† and the following forms determined: 111, 110, 100, 553, 774, 221,

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*Pubs. Field Museum, 1910, Geol. Ser., iii, 176.

†Ann. Mus. Nac. Rio de Jan., 1896, 9, 165–171.

552, 331, 441, 211, 311, 210, 310, 510. Only a few of these forms occur in terrestrial chromites. The octahedron predominated, but the crystals were often tabular from the large development of two of the planes. In Ensisheim Shepard identified the forms 111 and 110; in Lodran Lang observed 111, 110, and 311; and in Greenbrier County Fletcher reported 111, 110, and 221. Borgström* found well-defined crystals about 2 mm. in diameter at the boundary between the chrysolite and nickel-iron of the Marjalahti meteorite. The dominant forms were 111 and 110. Combined with these were 331, 311, and 551 of which the latter had not previously been noted on the mineral. The physical and chemical properties of meteoritic chromite do not differ essentially from those of terrestrial chromite except that meteoritic chromite is sometimes probably decomposed by acids. This is assumed from the content of Cr_2O_3 often found in the soluble portion of meteorites. The color of meteoritic chromite is in general black, with sub-metallic luster; streak brown; non-magnetic or only weakly so; sometimes very brittle.

Analyses of meteoritic chromites show the presence of considerable alumina and magnesia.

ANALYSES OF METEORITIC CHROMITE

	Cr_2O_3	Al_2O_3	Fe_2O_3	FeO	MgO		Total
1	65.63	3.78	....	25.84	4.27	NiO 0.73	100.25
2	65.49	....	....	33.00	0.40	SiO_2 0.50	99.39
3	65.01	9.95	....	18.97	5.06		98.99
4	64.91	9.85	....	17.97	4.96	SiO_2 1.38	99.07
5	63.40	5.30	....	26.30	5.00		100.
6	62.71	....	....	33.83	....		96.54
7	62.00	....	41.00	....	....		103.
8	61.39	1.96	....	30.46	6.70		100.51
9	59.85	....	....	27.93	12.22		100.
10	56.82	11.36	....	26.14	5.68		100.
11	56.70	12.38	....	27.60	4.00		100.68
12	52.13	10.25	....	37.68	....		100.06
13	39.40	28.50	....	31.50	0.60		100.
14	24.60	....	54.50	....	20.90		100.

REFERENCES

1. Marjalahti. Borgström: Geol. Foren. i. Stockholm Förh., 1908, 30, 331. Crystals, 2 mm. in diameter.

2. Admire. Tassin: Proc. U. S. Nat. Mus., 1908, 34, 686. Non-magnetic, jet-black grains of brilliant luster.

*Geol. Foren. i. Stockholm, Förh., 1908, 30, 331.

3. Mount Vernon. Tassin: Proc. U. S. Nat. Mus., 1908, 34, 685. Brilliant black crystals.
4. Mount Vernon. Tassin: Proc. U. S. Nat. Mus., 1908, 34, 686. Minute, rounded, brownish-black grains.
5. Canyon Diablo. Tassin: Proc. U. S. Nat. Mus., 1908, 34, 688. Small, black, octahedral crystals and rounded grains.
6. Coahuila. Smith: Am. Jour. Sci., 1881, 3, 21, 462. Large nodule.
7. Bjurböle. Ramsay and Borgström: Bull. Comm. Geol. de Finlande, 1902, 12, 13. Black powder.
8. Marjalahti. Tassin: Proc. U. S. Nat. Mus., 1908, 34, 687. Brilliant, blue-black crystals.
9. Klein-Wenden. Rammelsberg: Ber. Berlin Akad., 1844, 245.
10. Shalka. Foullon: A. N. H. Wien, 1888, 3, 199.
11. Allegan. Tassin: Proc. U. S. Nat. Mus., 1908, 34, 688. Blackish-brown grains.
12. L'Aigle. Schwager: Sitzber. München Akad., 1878, 8, 39-40.
13. Sewrukof. Eberhard: Arch. f. d. Nat. Lib. Ehst. Kurl., 1882, 9, 137.
14. Lodran. Rammelsberg: Abh. Berlin Akad., 1870, 93. Cohen states that this analysis is of doubtful accuracy Meteoritenkunde, 1, 246.

BREUNNERITE

Determination of carbonates in meteorites has thus far been confined to the observation of small, transparent crystals which were isolated from the meteorite of Orgueil. These had characters which indicated that they were breunnerite, iron-magnesium carbonate (Mg, Fe) CO_3. The crystals were of rhombohedral form, with angles of 105°–107° and exhibited cleavage in three directions. They showed weak, pearly luster. They dissolved slowly in cold HCl and showed qualitatively iron, magnesia and carbonic acid.* The crystals were of small size (½–¾ mm.) and few in number. As Orgueil is a very porous meteorite it has been suggested that this carbonate may have been formed by the action of the terrestrial atmosphere, but as some crystals were found in the interior of the meteorite it is possible that they were of primary origin.

FELDSPAR

Minerals of the feldspar group are common constituents of the stone meteorites, though less abundant than chrysolite and enstatite. They are chiefly prominent in the groups of eukrites and howardites, and among the silicates of the grahamites. Small percentages of alkalies found in the chondrites are usually regarded as indicating the presence of

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*Pisani: Compt. Rendus, 1864, 59, 135.

feldspars in them though the feldspars are difficult to detect by optical means. The most common and best defined feldspar occurring in meteorites is anorthite. As seen with the naked eye, especially in the eukrites, it is usually nearly opaque, dull, and of a snow-white color. In some meteorites, however, it becomes more or less transparent and has a marked vitreous luster. It occurs in the form of crystals, grains, and splinters and these are usually of appreciable size. One crystal in Jonzac measured 1 cm. in length. The crystals are usually more or less lath-shaped. The meteorites in which the feldspars are abundant usually exhibit the ophitic structure which is frequently observed in diabase. As in terrestrial rocks, this structure is due to the fact that the feldspars crystallized before the pyroxenes. Terminated crystals of anorthite have been found in druses of Juvinas and have been measured and described by Rose, Lang and Tschermak. Their forms are shown in the accompanying figure (Fig. 51) of which the first shows a twin, the second a tabular habit, and the third a Carlsbad twin. The forms observed were:

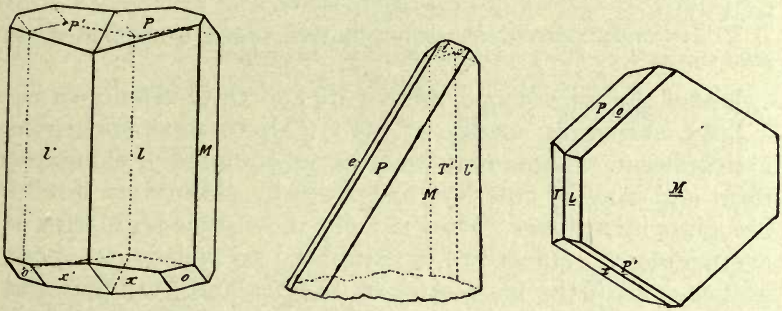

FIG. 51.— Forms of anorthite from the Juvinas meteorite. After Rose, Lang and Tschermak.

M 010
P 001
e $0\bar{2}1$

T′ $\bar{1}\bar{1}0$
l′ $\bar{1}10$
x $10\bar{1}$

o′ $\bar{1}11$
p′ $\bar{1}\bar{1}1$

Meteoritic anorthite is soluble in hot HCl. It has been isolated and analyzed only in the eukrites and grahamites. The following analyses have been made:

ANALYSES OF ANORTHITE

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	Total
1	44.38	33.73	3.29	18.07	0.36	1.03	0.33	101.19
2	46.19	31.26	2.93	16.98	1.12	1.14	0.50	100.12
3	42.91	36.76	....	17.56	....	2.77	....	100.00
4	42.87	36.59	....	17.50	....	2.04	1.00	100.00
5	42.02	37.77	....	16.41	0.96	....	....	97.16

REFERENCES

1. Juvinas. Rammelsberg: Pogg. Ann., 1848, 73, 588. Isolated crystals.
2. Stannern. Rammelsberg: Pogg. Ann., 1851, 83, 592. Isolated crystals.
3. Petersburg. Calculated by Rammelsberg from the alumina and alkali of Smith's mass analysis. Abh. Berlin Akad., 1870, 129.
4. Frankfort. Calculated by Rammelsberg from the alumina and alkali of Brush's analysis. Abh. Berlin Akad., 1870, 131.
5. Morristown. Merrill: Am. Jour. Sci., 1896, 4, 2, 151. Analysis of 0.19 gram separated by heavy solution. Na_2O not determined.

Under the microscope, meteoritic anorthite usually shows a large extinction angle, 30°–38°. Microscopic inclusions are common. These may be either of rounded or elongated form and may be colorless to brownish. Many are doubtless glass inclusions. They usually show some regularity of arrangement. Anorthite is estimated to constitute about 35 per cent of the meteorites of Juvinas and Stannern and from 20 to 30 per cent of those of Petersburg and Frankfort. In the residue from the solution in nitric acid of Bischtübe, a meteoric iron, Kislakowski* found about 8 per cent of siliceous grains which he regarded as anorthite. Chondri made up wholly of anorthite have been observed in several meteorites.

Feldspars other than anorthite have rarely been isolated from metorites and their presence can usually be more readily inferred than proven. Where seen, their appearance under the microscope is to be distinguished from that of anorthite by their narrower and more abundant twinning lamellae and smaller extinction angle. They are not attacked by hot, concentrated HCl, and hence are found on analysis in the portion insoluble in acids. Like anorthite they occur as laths, grains, and splinters. As laths they are especially well seen in some of the grahamites, having been observed in Vaca Muerta and Crab Orchard. Where feldspar is not very abundant as a constituent it commonly

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* Bull. Soc. Imp. de Moscou, 1890, No. 2, 190–197.

occurs in grains, often of small size and not even showing twinning lamellae. In such cases the grains exhibit undulatory extinction. Plagioclase grains were isolated by Prendel from Zabrodje and Grossliebenthal which showed in Zabrodje extinction angles of 12° and 2°, indicating feldspar of the composition Ab_6An_1 and in Grossliebenthal angles of 8° and 1° indicating feldspar of the composition, Ab_4An_1.

In the residue after dissolving the Toluca iron in HCl, Laspeyres found plagioclase grains showing twinning lamellae. Plagioclase other than anorthite has not been isolated from meteorites for chemical analysis but the following compositions have been calculated from mass analyses:

ANALYSES OF METEORITIC PLAGIOCLASES

	SiO_2	Al_2O_3	CaO	Na_2O	K_2O	Total
1....................	64.97	22.06	3.01	9.96	....	100
2....................	63.50	22.20	4.00	9.20	1.10	100
3....................	61.85	24.09	5.25	8.81	....	100
4....................	53.17	29.51	11.55	4.33	1.44	100

REFERENCES

1. Hessle. Lindstrom: Bihang Svenska Vet. Akad. Stockholm, 1869, 8, 723.
2. Hvittis. Borgström: Die Met. von Hvittis u. Marjalahti. Helsingfors., 1903, 32. Calculated to 100 after deducting intermixed chrysolite.
3. Gopalpur. Tschermak: Sitz. Wien Akad., 1872, 65, 1, 143–144.
4. Tennasilm. Schilling: Archiv. fur Naturkunde Liv. Ehst. u. Kurlands, 1882, 1, 9, 113.

The first three feldspars are oligoclase, having the respective compositions, Ab_6An, Ab_4An, and Ab_3An. No. 4 is labradorite, Ab_2An_3. The feldspars of a large number of meteorites were studied optically by H. Michel.* He found the feldspar of the eukrites and howardites to be largely anorthite while that of the chondrites was chiefly oligoclase. Considering the chondrites alone, the white chondrites were found to have abundant feldspar while the black chondrites were free from it. Other chondrites had varying amounts according as they approached either one of these classes. In the chondrite of Waconda containing light and dark portions the amount of feldspar differed in each as if they were separate meteorites. In many chondrites in which the presence of a feldspar was indicated by chemical analysis, glass took the place of the expected feldspar. It was apparent,

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*Tsch. Min. u. Pet. Mitt., 1912, 31, 563–658.

therefore, that the glass had the composition of feldspar of which it may have been, according to this author, an alteration product, although a primary origin is entirely possible.

MASKELYNITE

A mineral of hitherto unknown characters was found by Tschermak* making up 22½ per cent of the meteorite of Shergotty. It was colorless, isotropic, transparent, of vitreous luster, and conchoidal fracture. Hardness 6; specific gravity 2.65. Before the blowpipe it fused in thin splinters to a clear, colorless bead. The fine powder was slightly decomposed by hydrochloric acid. The mineral occurred in feldsparlike laths bounded by straight lines. Lines parallel to their lengths gave these laths an appearance like plagioclase, but the cleavage of plagioclase was lacking. Analysis of the mineral after deduction of 4.7 per cent iron oxide which was ascribed to included magnetite, gave, when calculated to 100, the composition:

SiO_2	Al_2O_3	CaO	Na_2O	K_2O
56.3	25.7	11.6	5.1	1.3 = 100

This corresponds to a plagioclase composed of 51.75 per cent albite and 48.25 per cent anorthite, if K_2O be omitted and the analysis be calculated to 100.

To this mineral Tschermak gave the name maskelynite in honor of N. Story-Maskelyne. Tschermak regarded it a fused feldspar At the same time by Foullon and later by several observers a similar mineral was found forming an accessory constituent in many of the chondrites. It was described by Cohen,† in Madrid, as being in the form of small, elongated or rounded particles lying among the essential minerals and taking part in the constitution of the chondri. The grains had a diameter of 0.1 mm. or more, were irregularly bounded, had weak double refraction and occasional indulatory extinction. The index of refraction was about that of Canada balsam.

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*Sitz Wien Akad., 1872, 65, 127–131.

†Mitth. nat. Verein Neu-Vorp. u. R., 1896, 28, 103–105.

Winchell* found in Fisher in the midst of an isotropic substance, portions which were doubly and more highly refracting and which showed lamellae resembling those of plagioclase. The axial angle was 15°. Both the isotropic and doubly refracting portions gave the same qualitative composition. Winchell regarded the isotropic substance as glass from which the anisotropic mineral had crystallized. This anisotropic mineral he regarded as maskelynite. While Tschermak regarded maskelynite as a fused feldspar, Groth and Brezina consider it a distinct mineral allied to leucite. Its exact nature is yet to be determined.

ORTHORHOMBIC PYROXENES

Enstatite, Bronzite and Hypersthene

Chladnite, Piddingtonite, Victorite, Shepardite

Orthorhombic pyroxenes rank third in quantity among the constituents of meteorites, being exceeded only by nickel-iron and chrysolite. Together with chrysolite they form almost the entire substance of the great group of chondritic stone meteorites and are also an important ingredient in the howardites, rodites, amphoterites, mesosiderites, and grahamites. Enstatite constitutes one meteorite, Bishopville, almost alone, and hypersthene is practically the sole constituent of Manegaum, Ibbenbühren, and Shalka. These pyroxenes are colorless to snow-white in enstatite and present various shades of gray, green, and brown in bronzite and hypersthene. Inclusions may also darken the color. Often a color like that of chrysolite is exhibited and partly for this reason the recognition of orthorhombic pyroxene was not made until late in the study of meteorites. Other distinguishing characters of the orthorhombic pyroxenes as seen in meteorites are a frequent fibrous structure, prismatic cleavage, pinacoidal parting, straight extinction, low interference colors, prismatic habit, and little or no solubility in acids. The first to detect the occurrence of orthorhombic pyroxene in meteorites was Lang† who determined the

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* Amer. Geol., 1897, 20, 316–317.

†Sitz. Wien Akad., 1869, 59, 2, 848–856.

pyroxene in Steinbach previously regarded as monoclinic to be orthorhombic.

By his investigations and those of others the following crystal forms have been determined on the orthorhombic pyroxenes of meteorites:

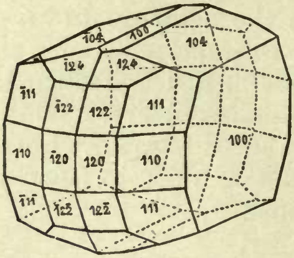

Fig. 52.—Enstatite from the Steinbach meteorite. After Lang.

a..100
b..010
c..001
m..110
a..230
ζ..350
n..120
ρ..250

η..140
β..320
z..210
δ..520
λ..310
k..012
q..023
t..011

g..021
v..031
d..201
f..502
o..111
x..221
u..232
p..121

r..252
c..212
y..432
i..211
s..623
ξ..412
π..323
ψ..421

Axes $\breve{a} : \bar{b} : c' = 0.9702 : 1 : 0.5709$.

Fig. 52 shows the habit of the pyroxene observed by Lang although the figure is more or less ideal. Weisbach* observed the form shown in Fig. 53 in Rittersgrün which is of the same fall as Steinbach. The stone meteorites of Bustee, Lodran, Manegaum, Mässing, Mocs, Misshof, and the iron of Bendego are other meteorites from which simple forms of orthorhombic pyroxene have been isolated and measured. The recognition of orthorhombic pyroxene in Breitenbach by Lang led to the appreciation of its wide distribution and our present knowledge that it is one of the most abundant of meteoritic minerals. Optical characters and chemical analyses afford the chief means for recognizing its presence as its occurrence is usually in the form of small individuals. Yet, as has been remarked, some mete-

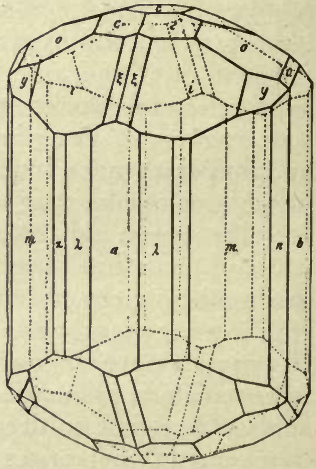

Fig. 53. Enstatite from the Steinbach (Rittersgrün) meteorite. After Weisbach.

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*Neues Jahrbuch, 1882, 2, 253.

orite falls consist alone of this mineral. Previous to the recognition of the orthorhombic pyroxene the substance of the meteorites composed of it almost wholly had frequently been regarded as new minerals and had received the names chladnite and shepardite in Bishopville, piddingtonite in Shalka, and victorite in Copiapo. In the chondritic meteorites orthorhombic pyroxene enters largely into the formation of the chondri. The structure of the chondrus is usually polysomatic and the habit of the individuals is largely prismatic to fibrous. An eccentric rayed arrangement is also highly characteristic. The fibres may be so fine as to appear compact and rarely may be irregularly arranged. Intergrowths with chrysolite forming chondri are common, and occasionally association with monoclinic pyroxenes may be observed. At times the orthorhombic pyroxene forms a network cementing larger crystals.

The following analyses have been made of orthorhombic pyroxenes mechanically isolated from meteorites:

ANALYSES OF ORTHORHOMBIC PYROXENES OF METEORITES

	SiO_2	MgO	CaO	FeO	Fe_2O_3	Al_2O_3	K_2O	Na_2O	Total
1	55.76	41.85	3.89	....	....	....	....	....	101.50
2a.	57.60	40.64	....	....	1.44	....	0.39	0.91	100.98
2b.	57.58	39.33	2.06	....	0.48	....	0.57	0.67	100.69
2c.	58.44	38.94	1.68	....	1.18	....	0.33	0.36	100.93
3a.	59.97	39.33	....	....	0.40	....	....	0.74	100.44
3b.	57.52	34.80	0.66	MnO 0.20	1.25	2.72	0.70	1.14	98.99
4	59.05	37.10	0.98	FeO 0.90	....	1.09	0.47	0.68	100.27
5	55.35	32.85	0.58	12.13	....	0.60	....	....	101.51
6	57.49	25.78	2.12	10.59	MnO 0.49	2.08	....	1.45	100.00
7	56.05	30.85	....	13.44	....	....	....	....	100.34
8a.	53.07	28.55	0.90	16.53	....	0.47	....	0.22	100.00
8b.	55.55	27.73	0.09	16.53	....	....	....	0.92	100.82
8c.	52.78	24.18	0.50	22.43	....	....	....	....	99.89
9a.	54.47	26.12	1.39	17.15	MnO 0.28	1.06	....	....	100.47
9b.	54.51	26.43	1.04	17.53	MnO 0.29	1.26	....	....	101.06
10a.	54.22	23.57	1.51	20.70	....	....	....	....	100.00
10b.	55.70	22.80	1.32	20.54	....	....	....	....	100.36
11	51.61	16.05	3.68	24.54	....	7.36	....	....	103.24

G=3.20—3.43

REFERENCES

1. Copiapo. Meunier: Cosmos, Paris, 1869, 5, 583–585.

2. Bustee. Maskelyne: Phil. Trans. Roy. Soc. London, 1870, 160, 206. The iron oxide obtained was in part ascribed to intermixed nickel-iron, the lime to intergrown augite. (a) Dark-gray tabular crystals. (b) Translucent gray crystals. (c) Transparent crystals.

3. Bishopville. (a) Smith, Am. Jour. Sci., 1864, 2, 226. Mean of two analyses. (b) Rammelsberg, Berlin Akad., 1861, 898. Probably a little plagioclase was intermingled.

4. Hvittis. Borgström: Helsingfors, 1903, 30.

5. Lodran. Tschermak: Sitzb. Wien Akad., 1870, 61, 2, 471. Some chrysolite and perhaps anorthite were mixed with the substance analyzed.

6. Rittersgrün. Winkler: Nova acta Akad. Halle, 1878, 40, No. 8, 365. Mean of two analyses. Calculated to 100 after deducting 0.98 per cent chromite.

7. Breitenbach (same as Rittersgrün). Maskelyne: Phil. Trans. Roy. Soc. London, 1870, 160, 361. Mean of two analyses.

8. Shalka. (a) Foullon: A. N. H. Wien, 1888, 3, 198. Calculated to 100 after deducting 0.39 per cent troilite and 1.74 per cent chromite. (b) Rammelsberg, Berlin Akad., 1870, 319, 0.33 per cent chromite deducted. (c) Maskelyne: Phil. Trans. Roy. Soc. London, 1870, 367. Mean of two analyses.

9. Ibbenbühren. Rath: Berlin Akad., 1872, 34. (a) Light-gray to white grains of the ground mass. (b) Light yellowish-green larger grains.

10. Manegaum. Maskelyne: Phil. Trans. Roy. Soc. London, 1870, 212–213. (a) Ground mass. Calculated to 100 after deducting 1.03 per cent chromite. (b) Pale yellowish-green grains.

11. Sierra di Deesa. Meunier: Cosmos, 1869, 584.

A marked feature of the composition shown by these analyses is the lack of an intermediate content of iron. The transition is sudden from a composition in which MgO is practically the only base to one in which a considerable percentage of FeO appears. In other words enstatite and hypersthene occur without intervening bronzite. Hence though the orthorhombic pyroxene of meteorites is usually spoken of as bronzite, that mineral, if the limits used by Dana (up to 12-15 per cent FeO) are adopted, seems to be rarely present. The pyroxene of Breitenbach which Lang called bronzite possesses the characters of hypersthene in being optically negative and in having the bisectrix ⊥ to *a*. Its dispersion, however, was $\rho < \nu$ or that of bronzite. The axial angle was 98°.

Cohen* suggests that a rough approximation of the amount of iron in the pyroxene of most meteorites can be obtained by heating the powder. If the substance is rich in iron, a brownish or brownish-yellow color is obtained on heating, whereas, if iron is absent or nearly so, only a pale

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*Meteoritenkunde, Heft II, 280.

brown or no change will be observed. For such a test any chrysolite in the powder should first be removed by a heavy solution. Enstatite, bronzite, and hypersthene accompanying one another were observed by Prendel* in Grossliebenthal. He found enstatite and bronzite characterizing the chondri, and hypersthene the ground mass. The bronzite contained glass inclusions while the characteristic form of the hypersthene was that of needles arranged parallel to their vertical axes.

The portion of the chondrites and mesosiderites insoluble in acid usually is made up chiefly of orthorhombic pyroxenes. Hence analyses of this portion practically give the composition of these pyroxenes. The following analyses selected by Cohen† illustrate compositions obtained by this method.

ANALYSES OF INSOLUBLE SILICATES FROM METEORITES

	SiO_2	MgO	CaO	FeO	Al_2O_3	K_2O	Na_2O		Sum
1	57.80	39.22	....	0.91	2.07	....	....		100
2	56.74	24.05	3.41	8.04	5.63	0.25	1.88		100
3	55.79	24.99	3.40	8.79	4.90	0.12	2.01		100
4	57.37	23.54	3.41	8.03	5.07	0.23	1.38	MnO 0.63	99.66
5	56.20	24.19	3.37	9.27	4.38	0.92	2.22	P_2O_5 0.07	100.55
6	58.42	28.04	3.04	10.99	1.12	....	....		101.61
7	57.81	24.97	5.31	10.99	0.23	....	0.84		100.15
8	57.60	23.97	5.70	11.24	0.43	....	1.24		100.18
9	52.90	24.82	....	10.00	5.96	0.48	2.98	MnO 0.31	97.45
10	54.42	29.11	2.46	14.03	....	....	....		100.02
11	56.71	25.99	1.77	13.21	2.32	....	....		100
12	53.74	22.23	5.54	13.17	5.32	....	....		100
13	55.98	26.08	....	14.89	3.05	....	....		100
14	51.10	27.70	....	17.20	2.83	....	....		98.83
15	52.56	20.28	5.02	16.18	4.15	....	1.81		100
16	53.82	23.41	1.77	18.65	2.35	....	....		100
17	54.02	23.45	tr.	18.10	2.30	tr.	1.58	MnO 0.36	99.81
18	54.12	24.50	....	21.05	0.03	....	0.09		99.79
19	56.66	20.84	....	23.55	....	....	....		101.05
20	50.52	8.09	9.27	27.94	4.18	tr.	tr.		100.

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1. Molina. Meunier: Ann. Chem. Phys., 1869, 4, 17, 12.
2. Cape Girardeau. Dana and Penfield: Am. Jour. Sci., 1886, 3, 32, 230. 1.67 per cent chromite deducted.
3. Salt Lake City. Dana and Penfield: Am. Jour. Sci., 3, 32, 228. 1.71 per cent chromite deducted.

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*Mem. Soc. Nat. Russie, Odessa, 1893, 18.

†Meteoritenkunde Heft I, 283.

4. Ställdalen. Lindström: Öfversigt Kongl. Vetenskaps Akad. Stockholm, 1877, No. 4, 37.

5. Pultusk. Rammelsberg: Monatsber. Berlin Akad., 1871, 451. Mean of two analyses.

6. Mighei. Meunier: Comptes Rendus, 1889, 109, 977.

7. Rochester. Smith: Am. Jour. Sci., 1877, 14, 221. 0.15 per cent chromite deducted.

8. Cynthiana. Smith: Am. Jour. Sci., 1877, 14, 226. 0.56 per cent chromite deducted.

9. Aussun. Harris: Inaug. Diss. Göttingen., 1859, 49.

10. San Emigdio. Whitfield: Bull. U. S. G. S., 1891, No. 78, 97. 1.32 per cent chromite deducted.

11. Zsadany. Cohen: Verhandl. Nathist. med. Ver. Heidelberg, 1878, 161.

12. Richmond. Rammelsberg: Monatsber. Berlin Akad., 1871, 456.

13. Hainholz. Rammelsberg: Monatsber. Berlin Akad., 1871, 323.

14. Roda. Pisani: Comptes Rendus., 1874, 1508.

15. Gnadenfrei. Lasaulx: Monatsber. Berlin Akad., 1879, 769.

16. Llano del Inca. Eakins: Bull. U. S. G. S., 1891, No. 78, 97. 1.32 per cent chromite deducted.

17. Waconda. Smith: Am. Jour. Sci., 1877, 3, 13, 212.

18. Estherville. Smith: Am. Jour. Sci., 1880, 3, 19, 462.

19. Sokobanja. Losanitsch: Ber. deutsch. chem. Gesell. Berlin, 1878, 11, 98. 0.11 per cent chromite deducted.

20. Tadjera. Meunier: Ann. Chim. Phys., 1869, 4, 17, 16. 0.18 per cent chromite deducted.

Clinoenstatite and Clinohypersthene

The name clinoenstatite was proposed by Wahl* to designate a monoclinic magnesian pyroxene occurring in stony meteorites. The presence of such a pyroxene seems first to have been noted by Fouqué and Lévy† but Allen, Wright, and Clement‡ were the first to give it extended study. In Bishopville the latter authors found the mineral forming parallel intergrowths with ordinary enstatite, it being marked chiefly by its oblique extinction $c : \mathrm{c} = 21° 8'$. Similar intergrowths were produced artificially by these authors by rapidly cooling a molten mass of pure magnesium silicate. The slower the cooling the greater the quantity of clinoenstatite obtained. They, therefore, concluded that the presence of these intergrowths in meteorites indicated rapid cooling. In their first paper these authors stated that the enstatite of the meteorite was all changed to the monoclinic form on heating to 1450°. In a later paper, however,§ they stated that at about 1365° clinoenstatite is trans-

*Tsch. Min. u. Petr. Mitth., 1907, 26, 121.

†Bull. Soc. Min., 1881, 279.

‡Am. Jour. Sci., 1906, 4, 22, 385–438.

§Am. Jour. Sci., 1909, 4, 27, 45.

formed into an orthorhombic form quite distinct from enstatite and unknown in nature. In clinoenstatite the plane of the optic axes is normal to the plane of symmetry and not in the plane of symmetry as in ordinary enstatite. The specific gravity of the artificial clinoenstatite was 3.192. In addition to clinoenstatite there occur in meteorites according to Wahl clinobronzite and clinohypersthene. They differ from clinoenstatite just as their corresponding orthorhombic homologues do. Such pyroxenes, according to Wahl, especially characterize the chondrites, and much of what has previously been regarded as other monoclinic pyroxenes, such as diopside and augite, may belong to the monoclinic forms of the enstatite-hypersthene group.

MONOCLINIC PYROXENES

Monoclinic pyroxenes have been described from a number of meteorites and form an essential constituent of the eukrites, howardites, bustites, ureilites, shergottite and angrite, and are an accessory constituent in the grahamites, mesosiderites, and some chondrites. Except for diopside in the meteorites of Bustee and El Nakhla the monoclinic pyroxenes have usually been referred to augite, but their chemical composition makes it unlikely that this mineral is as common as has been reported, since chemically the composition of these pyroxenes is nearer that of hedenbergite. The monoclinic pyroxenes usually occur as grains and splinters without well-defined outlines. These grains are generally brown or in transmitted light brownish-gray and show little or no pleochroism. Prismatic cleavage is present and occasionally a pinacoidal cleavage corresponding to that of diallage. Some writers regard diallage as frequently present on account of this cleavage but according to Cohen it is in no case so well-marked as to make the similarity to terrestrial diallage certain. Simple twins or twinning lamellae on the plane of the orthopinacoid were noted by Lane and Patton in the augite of Llano del Inca. Parting parallel to the base is also common. In the chondritic meteorites the monoclinic pyroxene is generally of a greenish color, shows repeated twinning and appears partly in grains and partly in laths. It occurs partly alone and partly accompanied by chrysolite, orthorhombic pyroxene, or glass. Where monoclinic pyroxenes occur in crystals they often contain inclusions of brownish glass and black grains. These are sometimes arranged parallel to the base so as to give a black-lined effect. In Nowo-Urei black grains are arranged peripherally in the pyroxene.

Diopside

Diopside was found by Maskelyne in Bustee in the form of splinters and crystal grains, chiefly accompanying concretions of oldhamite. The color of the grains was gray to light violet. The forms 001, 100, and 110 were determined and the presence of the negative unit pyramid was indicated. The prismatic angle lay between 85° 8′ and 86° 20′. The angle of extinction was 52½°, the axial plane perpendicular to the edge 001 ∧ 100. In the zone 001 : 011 pleochroism was observed, the color on the clinopinacoid being reddish violet to slate color. Prismatic cleavage and parting parallel to 100 were observed as well as a microscopic parting resembling that of diallage. Black, needle-like inclusions parallel to 100 and inclusions of enstatite parallel to the base were present. The mean of two analyses gave the following:

SiO_2	Fe_2O_3	CaO	MgO	Na_2O	Li_2O
55.49	0.54	19.98	23.33	0.55	tr. =99.89

This gives a ratio of CaO : MgO = 1 : 1.635. The mineral is thus more magnesian than terrestrial diopside. Maskelyne was inclined to ascribe this content of magnesia to the included enstatite, but Cohen thinks its amount insufficient. Of the meteorite of El Nakhla, according to Berwerth,* diopside forms an important part, in fact, about three-fourths. It occurs in this meteorite in the form of transparent, grayish green grains and prisms up to 1 mm. in length. Only prismatic and pinacoidal planes were observed. Twinning on 100 was frequent. The optical character was positive and the plane of the optic axes was in the symmetry plane.

Some minute plates of a straw-yellow color, which Rose

*Tsch. min. u. pet. Mitth., 1912, Bd. 31

observed in Juvinas and which Rammelsberg referred to titanite, were regarded by Tschermak as diopside. Owing to a fine lamellar structure he regarded them as paramorphs after augite. Tschermak also referred to diopside some grayish green crystals in Mocs which differed from the accompanying orthorhombic pyroxene in color and optical characters.

Tschermak described and figured from druses of Juvinas a crystal of augite having a diopside-like habit which Cohen suggested* was probably diopside. This crystal showed the following forms: *a*(100), *b*(010), *c*(001), *m*(110), *f*(310), *x*(510), *u*(111) and *o*(221). It is shown in Fig. 54. The extinction angle on the clinopinacoid was 52° 10′. A structure of numerous thin lamellae parallel to the base probably indicated twinning. Inclusions of black or brown rounded inclusions generally arranged parallel to the base were observed passing to a dust-like fineness. The brown, transparent inclusions were determined to be glass. Emergence of an optic axis was noted on orthopinacoidal sections as in the Ala diopside.

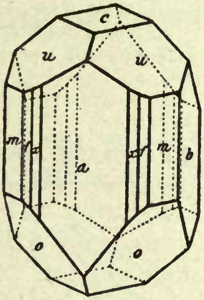

FIG. 54.— Diopside? from the Juvinas meteorite. After Tschermak.

HEDENBERGITE

It has already been remarked that the chemical composition of several meteoritic pyroxenes reported to be augite more nearly resembled hedenbergite since alumina was almost entirely lacking. A mechanically isolated pyroxene from Shergotty also gave Tschermak a similar result. The analyses follow:

ANALYSES OF HEDENBERGITE

	SiO_2	Al_2O_3	FeO	MnO	CaO	MgO	K_2O	Na_2O	Total
1a.	52.50	0.24	31.06	....	5.73	10.06	0.41		100.
1b.	52.88	....	30.70	....	6.32	10.10	....	....	100.
2a.	49.31	2.63	28.24	1.25	8.18	9.94	0.10	0.35	100.
2b.	50.40	....	31.64	....	7.62	10.34	....	....	100.
3	52.94	....	29.76	....	5.44	11.86	....	....	100.
4	50.25	....	31.62	....	6.96	11.17	....	....	100.
5	56.05	2.55	7.21	0.38	2.33	31.48	....	....	100.
6	52.34	0.25	23.19	tr.	10.49	14.29	....	tr.	100.56

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*Meteoritenkunde, Heft I, 293.

REFERENCES

1. Juvinas. Rammelsberg: (a) Siliceous portion undecomposed by acid. Calculated to 100 after deducting 2.13 per cent chromite and 0.16 per cent TiO_2. Pogg. Ann., 1848, 73, 589. (b) Calculated from the composition of the siliceous portion after deducting calculated anorthite. Abh. Berlin Akad., 1870, 129.

2. Stannern. Rammelsberg: (a) Siliceous portion not decomposed by acid. Calculated to 100 after deducting 0.83 per cent chromite. Pogg. Ann., 1851, 83, 592. (b) Calculated like 1b. Same reference.

3. Petersburg: Calculated by Rammelsberg from Smith's mass analysis. Abh. Berlin Akad., 1870, 129.

4. Luotolaks: Calculated by Rammelsberg from Arppe's analysis. Abh. Berlin Akad., 1870, 135.

5. Nowo-Urei: Calculated by Jerofejeff and Latschinoff from analysis of the undecomposed siliceous portion. Verhandl. russ. Min. Gesell., St. Petersburg, 1888, 24, 17, 23.

6. Shergotty: Tschermak. Sitzb. Wien Akad., 1872, 65, 126, and Tsch. Mitth., 1872, 88.

From the above it seems likely that this variety of pyroxene is a common constituent of meteorites and that much that has hitherto been called augite should be referred to it.

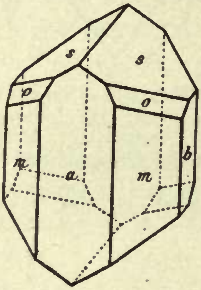

FIG. 55.—Augite from the Juvinas meteorite. After Rose.

AUGITE

Augite has been determined both by optical and chemical means in only one meteorite, Angra dos Reis. Of this meteorite, according to Ludwig and Tschermak* augite constitutes about 93 per cent. It takes the form of grains of a dark brown color showing red by transmitted light. It shows well-marked pleochroism, *a* being pale yellowish-green, *b* carmine-red, and *c* carmine-like red. The maximum extinction angle is 37°. Cleavage straight or undulating. There are inclusions of glass, rounded grains of chrysolite and angular ones of troilite. The glass is of a brown color. The augite is considerably attacked by warm hydrochloric acid. Analysis showed the following composition:

SiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	MgO	K_2O	Na_2O	TiO_2	Total
45.28	9.40	0.33	7.48	24.83	9.63	0.20	0.28	2.57	=100

TiO_2 is regarded as replacing SiO_2.

From druses in Juvinas Rose obtained crystals showing typical augite forms, a drawing of which is shown in Fig. 55.

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*Tsch. Min. u. Pet. Mitth., 1909, 28, 114.

The forms observed were *a*(100), *b*(010), *m*(110), *s*($\bar{1}11$) and *o*($\bar{2}21$).*

WEINBERGERITE

A black mineral occurring in spherical aggregates of radiating fibers was found by Berwerth† in the iron meteorite of Kodaikanal. From analyses he obtained the formula $NaAlSiO_4+3\ FeSiO_3$. The optical properties indicated orthorhombic crystallization. Berwerth gave the mineral the name weinbergerite. Its occurrence has not been noted in any other meteorite.

FORSTERITE

This mineral occurs in rounded grains in the iron of Tucson. The grains average from .05 to .20 mm. in diameter, though varying from .01 to 1 mm. The grains are rounded to oval in shape and in some cases give suggestions of crystal boundaries. They are white as isolated but colorless in thin section. They contain few inclusions or cracks. Their determination as forsterite rests on the following analysis by Fahrenhorst.‡

SiO_2	FeO	CaO	MgO	
43.29	0.52	1.13	54.92	=99.86

$SiO_2 : FeO+CaO+MgO = 1 : 1.95.\quad G=3.2$

A nearly pure magnesium silicate is thus indicated. The grains were separated for the analysis by dissolving the iron in copper ammonium chloride.

CHRYSOLITE

This mineral is, next to nickel-iron, the most abundant constituent of meteorites. It is an essential ingredient of the pallasites, mesosiderites, grahamites, and amphoterites, and of one meteorite, Chassigny, it is practically the only constituent. In all the chondritic meteorites chrysolite plays a large rôle and is probably the most abundant constituent since an average of 66 analyses compiled by Rammels-

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*Pogg. Ann., 1825, 4, 174–180.

†Tsch. Min. Mitth., 1906, 25, 181.

‡Meteoritenkunde, Heft II, 275.

berg showed the proportion of soluble to insoluble silicates or essentially of chrysolite to bronzite to be 9 : 8.* The presence of chrysolite in meteorites was early recognized. Pallas in 1776 described the Pallas iron as containing "rounded and elongated drops of a very brittle but hard, amber-yellow, transparent glass." Count Bournon in 1802 showed that this was similar to terrestrial chrysolite and Howard in the same year gave an analysis which was doubtless incorrect in the percentage of silica shown (55.7 per cent) but otherwise indicated the mineral to be chrysolite.

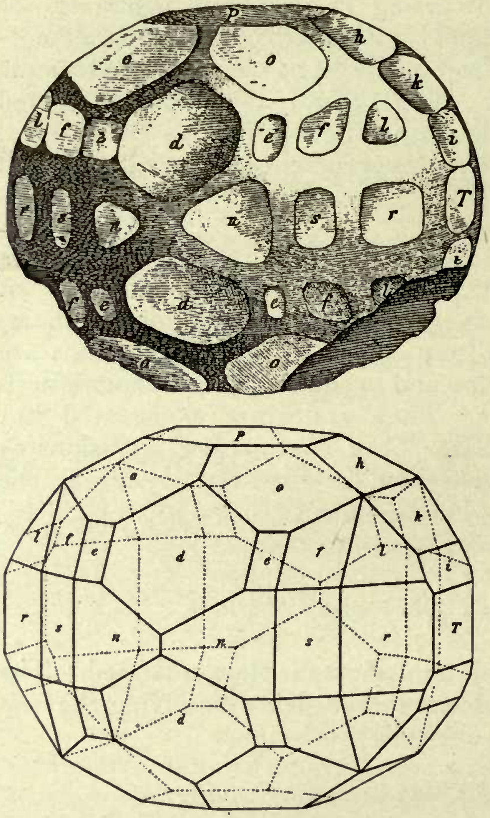

Fig. 56.— Forms of chrysolite from the Pallas meteorite. Upper figure, natural form of crystal. Lower figure, as ideal crystal would appear. After Kokscharow.

The chrysolite of meteorites occurs in the form of crystals, grains, and fragments. As crystals it has been described fully only from the Pallas and Lodran meteorites. In these it occurs in rounded forms with facets separated by rounded surfaces as shown in Fig. 56. The lower figure shows the crystal form which would be produced if the planes were continued. Rose in 1825 determined 11 forms and Kokscharow in 1870 added 8 to these.

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*Chem. Natur. der Met., 1879, ii, 47–51.

The following 19 forms have thus far been identified. The letters are those of Kokscharow.

p. . . .001
T . . .010
n. . . .110
s 120
r 130
w . .012
h. . .011
k. . .021
i. . .041
β. . .106
v. . .102
γ . . hol
d. . .101
q. . .116
o. . .112
e. . .111
f. . .121
l. . .131
a. . .hkl

Fig. 57 shows simple forms observed by Rose.

The rounded appearance of the chrysolite crystals so characteristic of its occurrence in the pallasites seems to be peculiar to meteorites as it has never been observed terrestrially. It suggests partial fusion. In certain of the iron-stone meteorites, notably Eagle Station, the chrysolite is in angular instead of rounded forms. In this meteorite the grains reach a dimension of 35 mm. while in the meteorite of Mincy, Kunz* reported a crystal measuring 10 by 8 centimeters (4 by 3 inches).

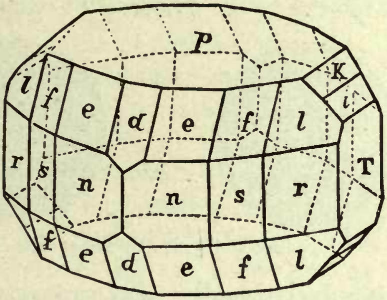

Fig. 57.— Common forms of meteoritic chrysolite. After Rose.

In color the chrysolite of meteorites varies from yellowish-green to yellowish-white and from transparent to opaque. It also frequently appears dark reddish-brown and opaque owing to staining by iron oxide. In the chondritic meteorites chrysolite may constitute most of the chondri and also occur as an important constituent of the ground mass. In the chondri of which it forms the principal part it is usually more or less intergrown with glass, while in other chondri it may be accompanied by pyroxenes, nickel-iron, etc. In chondri made up of chrysolite and glass alternate arrangements of the two substances are common and a more or less regular pattern is usual. Thus the lamellae may run in a single direction, in two directions or four directions (Fig. 58), or the pattern may be fan-shaped, mesenteric, or net-

*Am. Jour. Sci., 1887, 3, 34, 467.

like. In all these cases there may be simultaneous extinction of the chrysolite lamellae in polarized light, or circular extinction, or different extinction in different directions. Tschermak applied the term monosomatic to those chondri which he regarded as consisting of one individual and polysomatic to those consisting of several individuals, but it is difficult in many if not most cases to determine whether one or many individuals are present. Often the nucleus or central portion of a chondrus will be of one generation and the rim of another. At least a well-marked gap often separates the two. Instead of occurring in lamellar form in the chondri chrysolite may appear as porphyritic crystals. These often have well-defined crystal outlines among which the forms of the prism and brachypinacoid predominate. Again the chrysolite chondri may be made up of grains of different size. It is not uncommon to observe a ring of nickel-iron and pyrrhotite bordering the chrysolitic chondri. In Chassigny, made up almost wholly of chrysolite, the mineral is in the form of greenish-yellow grains, small and considerably fissured. It also contains inclusions of brownish glass to some extent. The chrysolite of Angra dos Reis contains negative crystals reaching a size of .02 mm. on which the forms 010, 110, 021, and 101 were recognized by Tschermak. He also noted rounded inclusions of brownish glass and canals filled with a yellowish-brown amorphous substance. In Zavid, Berwerth observed crystals made up of rounded grains oriented alike optically. These crystals were fresh in the interior but toward the exterior showed low interference colors which seemed to indicate a molecular change. These forms were regarded by Berwerth* as

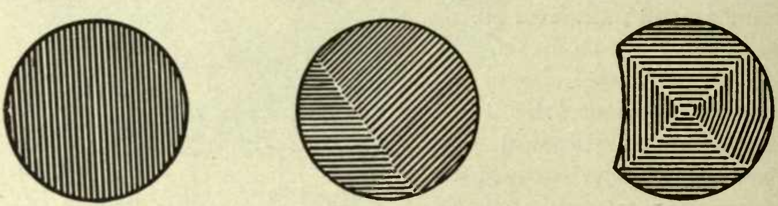

Fig. 58.— Typical arrangements of chrysolite lamellae in chondri.

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*Wiss. Mitth. Bosni. u. Herzegov., 1901, 8, 412–413.

having constituted one individual which was later separated. In contrast to this Tschermak* found that large porphyritic chrysolites in Goalpara were made up of numerous small grains of different orientation showing that the individuals had been formed by aggregation. The chrysolite of the mesosiderites and grahamites is usually in the form of individuals of large size. These individuals have crystal boundaries but are rarely, if ever, suitable for measurement. Opaque inclusions consisting probably chiefly of pyrrhotite and dark glass are common. Often the exterior of the individuals is of a two-fold nature. The outer zone is fine grained and turbid, the inner impregnated with black grains. The interior often contains fine, needle-like inclusions of gray or brown color, arranged parallel to two directions and showing a fine grating structure.

It is in the pallasites that chrysolite shows its most complete development. Here it occurs in rounded or angular forms on which crystal planes can often be observed. The individuals are usually of moderate size, at least not as large as in the mesosiderites and grahamites. The chrysolite of the pallasites seems to have formed before the nickel-iron, for when the facetted or rounded individuals of chrysolite are removed from the nickel-iron, the latter cavities conform to the shape of the chrysolite. A prominent feature of the pallasite chrysolites is the abundance of fissures which traverse them. These are irregular in their course and dimensions and are not cleavage planes. Characteristic of the fissures is the deposit of an opaque, reddish-brown coating of iron oxide along their walls. Abundant inclusions also characterize the chrysolite of some pallasites. Some of these inclusions are rod-like and hair-like forms usually lying parallel and sometimes in three directions. Other inclusions are in the form of opaque, dark grains often with a dendritic arrangement. At rare intervals gas cavities and hollow canals may be observed. The distribution of the chrysolite in the nickeliron is usually fairly uniform and regular but it may be irregular. Some individuals of the Brenham fall show abundant chrysolite,

*Sitzb. Wien Akad., 1870, 62, 2, 856.

others none at all. The color of the chrysolite of the pallasites varies also. In some, as Brenham, it is transparent, yellowish-green and of resinous luster; in others it is dark, opaque, and dull.

Cohen* remarks as especially characteristic of meteoritic chrysolite the following: "Abundance of fissuring, tendency to incomplete growths, richness in inclusions, and lack of microlites, fluid inclusions, and alteration products."

ANALYSES OF METEORITIC CHRYSOLITE

	SiO_2	MgO	FeO	MnO	Al_2O_3	Total
1	42.02	47.25	12.08	tr.	0.46	101.81
2	40.96	46.43	12.61	....	....	100.
3	40.87	46.93	12.11	....	....	99.91
4	40.86	47.35	11.72	0.43	....	100.36
5	40.83	47.74	11.53	0.29	....	100.39
6	40.79	47.05	12.10	....	0.02	99.96
7	40.70	48.02	10.79	0.14	tr.	99.65
8	40.26	47.26	11.86	....	....	99.38
9	40.24	47.41	11.80	0.29	0.06	99.80
10	40.02	45.60	14.06	0.10	....	99.78
11	39.94	47.02	12.93	0.11	....	100.
12	39.80	43.68	16.34	tr.	0.37	100.19
13	39.61	48.29	11.88	0.19	0.21	100.18
14	39.14	47.63	13.18	....	....	99.95
15	38.48	48.42	11.19	0.31	0.18	98.58
16	38.25	49.68	11.75	0.10	....	99.78
17	37.90	41.65	19.66	0.42	....	99.63
18	37.58	43.32	18.85		....	99.75
19	37.34	33.60	27.88	0.48	$\left\{\begin{matrix}K_2O\\0.70\end{matrix}\right\}$	100.
20	36.92	43.16	15.49	1.68	....	97.25
21	35.33	33.35	31.32	....	....	100.

Specific gravities of the above vary from 3.35–3.42. Ratios of SiO_2 : MgO + (Fe, Mn)O = 1 : 1.928—2.209 and of MgO : (Fe, Mn)O = 7.9—1.9 : 1

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A marked feature of the composition of meteoritic chrysolite is the almost complete absence of nickel oxide, whereas in terrestrial chrysolite it is an almost constant constituent. The difference is doubtless due, as Daubrée has suggested, to incomplete oxidation. Iron is more easily oxidized than nickel and nickel would, therefore, not be attacked by oxygen until complete oxidation of the iron had taken place. As the presence of nickel-iron in meteorites shows that such complete oxidation almost never takes place, the presence of nickel in such products of oxidation as chrysolite is hardly to be expected.

APATITE

Apatite was described by Berwerth* as occurring in the meteorite of Kodaikanal. Short-prismatic, skeletal, and granular forms were noted, the skeletal forms being horseshoe and knob-shaped. Cross sections showed prismatic cleavage. The mineral was colorless and transparent. For

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*Tsch. Min. u. Pet. Mitth., 1906, 25, 188.

the most part it was intergrown with pyroxene and weinbergerite, from which it was distinguished by its optical characters. The intergrowths also gave a reaction for phosphoric acid. Small, colorless grains which were optically negative and uniaxial, and showed a double refraction weaker than that of nepheline, were found by Ludwig and Tschermak* in Angra dos Reis and referred by them to apatite. A content of 0.13 per cent P_2O_5 shown by analysis seemed further to indicate this mineral.

A colorless constituent with irregular outlines found in many chondritic meteorites by Tschermak and referred by him doubtfully to monticellite is, according to later investigations by Merrill,† probably the phosphate of lime, francolite. The mineral as seen in meteorites is weakly birefracting with interference colors not exceeding gray-white of the first order. It is biaxial and probably positive, in which latter respect it differs from francolite. It is easily and completely soluble in nitric acid.

HYDROCARBONS

The hydrocarbons found in meteorites may be divided, following Cohen,‡ into three classes: (*a*) compounds of carbon and hydrogen; (*b*) compounds of carbon, hydrogen, and sulphur; and (*c*) compounds of carbon, hydrogen, and oxygen. Hydrocarbons especially characterize the carbonaceous meteorites but have been obtained from some other meteorites, such as Collescipoli and Goalpara. The hydrocarbons of the first class are obtained by treating carbonaceous meteorites with alcohol or ether. These hydrocarbons are resinous or wax-like bodies which completely volatilize on the application of heat. When heated in a closed tube the resinous substances first fuse, and then are decomposed forming amorphous carbon and an oil having a bituminous or fatty odor. Such substances were considered by Wöhler similar to ozocerite and by Shepard they were regarded as meteoritic petroleum. Friedheim states that a substance

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*Tsch. Min. u. Pet. Mitth, 1909, 28, 112.

†Proc. Nat. Acad. Sci., 1915, 1, 302.

‡Meteoritenkunde, Heft. I, p. 159.

extracted by him from the meteorite of Nagaya by means of ether had a bituminous odor, volatilized at 200° and resembled a product of distillation of brown coal. A similar substance extracted by Roscoe from the meteorite of Alais was found to have a composition corresponding nearly to the formula CH_{2n}.

Hydrocarbons of the second class were obtained by Smith by treating the graphite of iron meteorites and some carbonaceous meteorites with ether. The compounds obtained were fusible and volatile. He regarded them as having the general composition $C_4H_{12}S_5$. He obtained similar products by treating cast iron with ether or petroleum as did also Berthelot by the action of ether on sulphur or iron sulphide in the presence of oxygen.

Hydrocarbons of the third class have been obtained from the meteorites of Orgueil and Hessle. The Orgueil extract resembled peat, humus, or lignite in its composition and properties. That from Hessle had approximately the composition $nC_8H_9O_2$.

The above mentioned facts make it clear that a number of meteorites contain products of an easily destructible, volatile, and combustible character which resemble terrestrial bitumens, petroleum, or oxygenated hydrocarbons. The quantity of these products is relatively small, being less than 1 per cent in the majority of meteorites in which they occur. Yet that they occur at all is significant. While some have urged that these products might have arisen from the union of their elements in the terrestrial atmosphere there seems little reason for doubting their pre-terrestrial origin. There is no evidence that life had anything to do with their origin. We must conclude that they were formed in an inorganic way by a union of their elements.

The occurrence of hydrocarbons in meteorites shows (1) that such meteorites could not have been subjected to any high degree of heat, at least subsequent to the formation of these compounds, and (2) that the heating of meteorites during their fall to the earth must have been in many cases only superficial.

The trails of light, sometimes enduring several minutes, which have been observed following in the wake of some meteors may perhaps indicate the presence of carbonaceous matter in those bodies. The fall of Hessle was accompanied by luminous effects and the precipitation of a brownish-black powder which contained 71 per cent carbonaceous matter. Some carbonaceous meteorites have fallen, however, without exhibiting any marked luminous phenomena.

GLASS

This is an abundant constituent of the stone meteorites, few if any being entirely without it. It is variously distributed, occurring now as vein matter, now scattered through the substance of chondri, now enclosed in the substance of a single mineral, and now enclosing various minerals.

In Parnallee, Mezo-Madaras, Chassigny, Farmington, and a few other meteorites glass was so abundant as to have been described as forming a network in which other minerals are imbedded. Its occurrence in this manner is rare, however, it playing usually a merely accessory part. It chiefly abounds as inclusions and intergrowths in chrysolite, taking in this association a great variety of forms. Other minerals too, frequently have inclusions of glass. It may occur in fragments of considerable size or the particles may be of a dustlike minuteness. The prevailing color of the glass of meteorites is brown. Much is, however, colorless and some occurs so dark as to be opaque. Grayish and greenish tones occur but are rare.

In chondri glass is notably abundant. By all these occurrences a rapid crystallization or cooling of the meteorite substance is indicated. Like the glass of terrestrial lavas it seems to be the result of cooling so rapidly as to prevent differentiation and orderly crystallization.

INCLUDED GASES

That meteorites might contain an appreciable quantity of free gases in addition to their solid constituents was probably early surmised but the first investigation of the matter seems to have been made by Graham.* In 1867 this investigator heated a strip of Lenarto to red heat in a vacuum for 35 minutes. From 5.78 cc. of the meteorite he thus obtained 5.38 cc. of gas or 0.93 volumes. The nature of this gas he did not investigate but on further heating the iron for 100 minutes he obtained 1.65 volumes of gas which had the composition: H_2, 85.68; CO, 4.46; CO_2 none; N_2, 9.86. As he thus obtained gas to about three times the volume of the specimen, and this gas was largely hydrogen, Graham concluded that the meteorite must have come from a dense atmosphere of hydrogen gas. In 1872 Mallet† subjected a piece of Staunton weighing 124+ grams, to a treatment like that given by Graham to Lenarto and obtained after a total heating of 14½ hours, 3.17 volumes of gas having the composition: H_2, 35.83; CO, 38.33; CO_2, 9.75; N_2, 16.09.

Mallet's results differed from those of Graham in finding less H_2 and more CO and CO_2. Subsequent to the work of Graham and Mallet elaborate investigations of the gases of meteorites were made by A. W. Wright‡ which form the foundation of most of our knowledge of these substances. Wright investigated the gases given off from six stone and five iron meteorites and obtained the following results, the numbers in the third line in each case giving the percentage of each gas in the total amount obtained. They are not the simple averages of the numbers above them but the means reduced according to the volumes in each case:

ANALYSES OF GASES OF STONE METEORITES

Name	Temperature	Volumes	H_2	CO_2	CO	N_2	CH_4
New Concord	500°	2.06	12.37	82.28	2.16	0.93	2.26
	Red heat	0.93	69.43	16.79	8.71	3.41	1.66
	Total	2.99	31.89	59.88	4.40	1.78	2.05

*Proc. Roy. Soc., 1867, 15, 502.

†Proc. Roy. Soc., 1872, 20, 365–370.

‡Am. Jour. Sci., 1875, 3, 9, 294–302 and 459–460; 1876, 3, 11, 253–262; 12, 165–176.

ANALYSES OF GASES OF STONE METEORITES—Continued

Name	Temperature	Volumes	H_2	CO_2	CO	N_2	CH_4
Homestead	500°	1.04	34.82	58.04	4.01	3.13	0.0
	Red heat	1.46	74.49	19.16	0.21	6.14	0.0
	Total	2.50	57.88	35.44	1.80	4.88	0.0
Pultusk	350°	0.99	13.36	81.01	1.99	1.91	1.73
	Red heat	0.76	49.99	33.97	7.35	2.69	6.00
	Total	1.75	29.50	60.29	4.35	2.25	3.61
Parnallee	350°	1.56	8.72	87.53	1.13	1.40	1.22
	Red heat	1.17	20.03	72.43	2.53	1.79	3.22
	Total	2.73	13.59	81.02	1.74	1.57	2.08
Weston	350°	2.69	8.59	86.29	1.84	2.09	1.19
	Red heat	0.80	28.16	62.18	3.43	3.13	3.10
	Total	3.49	13.06	80.78	2.20	2.33	1.63
Cold Bokkeveld	300°	7.45	Tr.	87.34	5.08	1.65	5.93
	500°	17.78	0.54?	95.53	1.32	0.47	2.14
	Total	25.23	0.38?	93.11	2.42	0.84	3.25

ANALYSES OF GASES OF IRON METEORITES

Name	Temperature	Volumes	H_2	CO_2	CO	N_2
Tazewell	500°	1.87	41.51	18.34	38.45	1.70
	Red heat	1.30	44.76	7.76	45.75	1.73
	Total	3.17	42.66	14.40	41.23	1.71
Shingle Springs	500°	0.65	60.92	19.98	13.52	5.58
	Red heat	0.32	84.40	1.10	10.39	4.11
	Total	0.97	68.81	13.64	12.47	5.08
Magura	500°	8.89	40.62	18.20	38.72	2.46
	Red heat	38.24	12.84	11.25	74.59	1.32
	Total	47.13	18.19	12.56	67.71	1.54
Red River	500°	1.10	81.81	9.76	8.43	.....
	Red heat	0.19	49.24	2.18	48.58	.....
	Total	1.29	76.79	8.59	14.62	.....
Charlotte	Total	2.20	71.40	13.30	15.30	.....

The most noticeable feature of these analyses is the contrast which is shown between the stone and iron meteorites in the kind of gases evolved. In the stone meteorites CO_2 is more abundant, in the iron meteorites H and CO.

Several other experiments made by Wright served to answer special inquiries, such as whether the different ingredients of a stone meteorite varied as to the kinds of gas evolved, what the effects of different temperatures were, and what the effects of time.

The test of the different portions of a stone meteorite gave the following:

	Volumes	H_2	$CO+CO_2$	N_2
Entire stone	1.87	50.93	48.07	1.00
Magnetic portion, 0.51	1.48	59.38	38.72	1.90
Non-magnetic portion, 0.97		30.96	66.96	2.08

The results show that the distribution of gases among the different ingredients of a stone meteorite is about that between stone and iron meteorites.

The effects of different temperatures on a specimen of Homestead were as follows:

Gas	100°	250°	Below red heat	Low red heat	Full red heat
CO_2	95.46	93.32	42.27	35.82	5.56
CO	.00	1.82	5.11	0.49	0.00
H_2	4.54	5.86	48.06	58.51	87.53
N_2	0.00	0.00	4.56	5.18	6.91
Total	100.	100.	100.	100.	100.

Here it will be seen that a striking decrease in CO_2 and increase in H occurs with rising temperature.

In order to determine the effect of time, if any, Wright analyzed the gases from a Homestead specimen three months after its fall and a year later. The gases given off were similar in both cases except that a slight loss of CO_2 occurred.

Following Wright several determinations of meteoritic gases have been made of which the following are the most important. Flight* determined the gases from two iron meteorites, Rowton and Cranbourne, as follows:

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*Phil. Trans., 1882, No. 171, 893–6.

Name	Vol.	H_2	CO_2	CO	N_2	CH_4
Cranbourne	3.59	45.79	0.12	31.88	17.66	4.55
Rowton	6.38	77.78	5.15	7.34	9.72	....

These results correspond with those of previous investigators.

Several stone meteorites were tested for gases by Dewar and Ansdell* in 1886. Their results, which follow, harmonize with those of Wright.

Name	Vol.	H_2	CO_2	CO	N_2	CH_4
Pultusk	3.54	18.14	66.12	5.40	2.69	7.65
Mocs	1.94	22.94	64.50	3.90	3.67	4.41
Dhurmsala	2.51	28.48	63.15	1.31	1.31	3.90

The values for Pultusk were obtained from a completely encrusted stone in order to minimize the effect of possible absorption of gases from the atmosphere. For the other meteorites coarse powder was used. The results do not indicate that atmospheric absorption influences the gases evolved. In the same investigation Dewar and Ansdell analyzed the gases from Orgueil, a carbonaceous meteorite, with unusual results, since 57.87 volumes were given off of which SO_2 constituted 83 per cent. The investigators regarded the SO_2 as arising from the decomposition of sulphate of iron. Omitting this, 9.8 volumes remained which had the following composition: CO_2, 76.05; CO, 11.67; CH_4, 8.93; N_2, 3.33. This result is remarkable for the absence of hydrogen, as it was evolved by all other meteorites, but it may have been given off and combined with some other ingredient.

In an effort to discover what portion of a meteorite, if any, might be the parent of the gases evolved, the same investigators analyzed a number of graphites, including that of meteorites (termed celestial graphite by them) for their gaseous contents. Considerable quantities of gases were obtained from these graphites, but Dewar concluded that "the large quantities of gas occluded in celestial meteorites cannot be explained by any special absorptive power of this variety of carbon."

Subsequent to the work of Dewar and Ansdell little was done by any investigator in the study of meteorite gases

*Proc. Roy. Inst., 11, 541–552.

until in 1908 R. T. Chamberlin* reviewed the whole subject and determined the gases from two stone and one iron meteorite. His determinations from meteorites which had not previously been tested were as follows:

Name	Vol.	H_2	CO_2	CO	N_2	CH_4
Allegan	0.49	16.73	41.74	38.61	0.00	2.92
Estacado	0.84	36.25	28.47	29.31	1.69	3.39
Toluca —						
(*a*)	24.42	17.84	43.29	35.48	1.93	1.44
(*b*)	10.09	18.49	22.32	53.99	3.19	1.91
(*c*)	1.85	14.54	6.40	71.05	5.53	2.35

The three determinations of Toluca were made in an effort to obtain material free from rust. For (*a*) borings and filings which proved to be slightly rusted were used, for (*b*) borings which were found to contain a little rust, and for (*c*) borings free from rust. Chamberlin regarded the results of these three determinations as showing that the presence of a little rust had a great effect on the gases produced. He suggested that the great volume of gas obtained by Wright from Magura (47.13 vols.) was probably due to the presence of rust.

Chamberlin's results differ somewhat from those of previous investigators in showing less contrast in the gases evolved by stone as compared with iron meteorites and in showing more CO. Still the differences from previous results are not great, and on the whole support earlier conclusions as to the nature of the gases evolved from stone and iron meteorites respectively.

To recapitulate, and omitting the results of Magura and Orgueil and two of Toluca as being affected by variables, the gases obtained from stone and iron meteorites are as follows, the arrangement being in accordance with the percentage of hydrogen:

SUMMARY OF ANALYSES OF GASES FROM STONE METEORITES

Name	Vols.	H	CO_2	CO	N	CH_4	Analyst
Homestead	2.50	57.88	35.44	1.80	4.88	0.00	Wright
Estacado	0.84	36.25	28.47	29.31	1.69	3.39	Chamberlin
New Concord	2.99	31.89	59.88	4.40	1.78	2.05	Wright
Pultusk	1.75	29.50	60.29	4.35	2.25	3.61	Wright
Dhurmsala	2.51	28.48	63.15	1.31	1.31	3.90	Dewar and Ansdell
Mocs	1.94	22.94	64.50	3.90	3.67	4.41	Dewar and Ansdell

*Pubs. Carnegie Inst. of Washington, 1908, No. 106.

SUMMARY OF ANALYSES OF GASES FROM STONE METEORITES—Continued

Name	Vols.	H	CO_2	CO	N	CH_4	Analyst
Pultusk............	3.54	18.14	66.12	5.40	2.69	7.65	Dewar and Ansdell
Allegan............	0.49	16.73	41.74	38.61	0.00	2.92	Chamberlin
Parnallee..........	2.63	13.59	81.02	1.74	1.57	2.08	Wright
Weston............	3.49	13.06	80.78	2.20	2.33	1.64	Wright
Cold Bokkeveld....	25.23	0.38?	93.11	2.42	0.84	3.25	Wright

SUMMARY OF ANALYSES OF GASES FROM IRON METEORITES

Lenarto...........	2.85	85.68	.....	4.46	9.86	....	Graham
Rowton...........	6.38	77.78	5.15	7.34	9.72	....	Flight
Red River.........	1.29	76.79	8.59	14.62	....	....	Wright
Charlotte..........	2.20	71.40	13.30	15.30	....	....	Wright
Shingle Springs.....	0.97	68.81	13.64	12.47	5.08	....	Wright
Cranbourne........	3.59	45.79	0.12	31.88	17.66	4.55	Flight
Tazewell..........	3.17	42.66	14.40	41.23	1.71	....	Wright
Staunton..........	3.17	35.83	9.75	38.33	16.09	....	Mallet
Toluca	1.85	14.54	6.40	71.05	5.63	2.35	Chamberlin

As to the manner in which gases are held by meteorites it would be simplest to suppose that the gases occupy cavities in the minerals of the meteorites, but microscopic examination shows very few such cavities. On account of the lack of such cavities, Travers* thought that the gases obtained from meteorites must be of wholly secondary origin, being formed in the process of heating the meteorites for analysis, since it is known that the action of FeO on water can produce hydrogen and that of FeO on CO_2, carbon monoxide. Since, however, water is lacking in meteorites and CO_2 is a gas, the supposition is not satisfactory. There is no doubt, however, that chemical interaction under the influence of heat may produce gases and modify those already in the meteorite. Thus CO_2 is rapidly reduced to CO in contact with heated iron.

Occlusion in the manner in which platinum, for example, holds hydrogen, seems to be the most reasonable way of explaining the gaseous content of meteorites. To be sure, the nature of occlusion is itself mysterious, it not being known whether it represents a sort of solution or whether the metals form compounds with the gases which are later dissociated. Occlusion is known to be in part also dependent on porosity.

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*Proc. Roy. Soc., 1896, 60, 156–160.

CHAPTER XII

CLASSIFICATION OF METEORITES

There have been many efforts to form a classification of meteorites which should be at the same time practical, convenient, and accurate. The continual increase in the number and kinds of meteorites since their preservation and study was first seriously attempted has, however, steadily complicated the problem and at times it has been a question whether the effort to produce a classification could keep pace with the increase in the number of meteorites.

The simple distinction of iron from stone meteorites was made at an early time, having been suggested by Klaproth in 1807, and this fundamental distinction has been observed by all later classifiers, though with variations. Maskelyne in 1863 divided meteorites into the three fundamental classes of stones, iron-stones, and irons, and suggested for them the since much-used terms of aërolites, aërosiderolites, and aërosiderites. The last term is usually shortened to siderites. Daubrée, in 1867, basing his classification on the presence or absence of iron, divided meteorites into siderites and asiderites, although the latter group is very small. The siderites Daubrée subdivided into those consisting wholly of iron and those consisting of iron and silicates. The first he called holosiderites, the second he subdivided into syssiderites and sporadosiderites. The sporadosiderites he subdivided again into three groups according to decreasing quantities of iron.

Of further efforts to subdivide meteorites into groups subordinate to the great groups of iron and stones two systems have found chief adoption in later years, and of these one is gradually receiving the wider acceptance. The first of these systems was an elaboration by Meunier of Daubrée's system, and consisted of adopting certain falls as types for groups. Of these groups there were in Meunier's latest classification 62. The second system is an outgrowth of the suggestions of various German authorities of whom Gustave Rose was perhaps the first. In 1862 he suggested a classification for the stones based on their mineralogical composition and proposed names for the different groups which have been widely adopted. The first division of the stones was based on the presence or absence of chondri. Those without chondri, the achondrites, as they were called, were subdivided into meteorites composed of single minerals and those consisting of two or more minerals. The group consisting of augite and anorthite was designated as eukrites from two Greek words meaning well-defined. Other groups were designated by names of early investigators such as Chladni and Howard. The meteorites containing chondri, known as chondrites, were divided into groups based on color or structure. This classification, elaborated later by Tschermak and Brezina, has come into general use and furnishes perhaps the most convenient method which is at present available of grouping meteorites according to physical characters.

The classification in its latest form as given by Brezina* is here shown:

ROSE-TSCHERMAK-BREZINA SYSTEM OF METEORITE CLASSIFICATION

I. STONES. Silicates prevalent.

A. ACHONDRITES

Stones poor in iron. In the main without round chondri.

1. Chladnite. (Chl). Chiefly bronzite.
2. Chladnite, Veined. (Chla). Bronzite with black or metallic veins.
3. Angrite. (A). Chiefly augite.
4. Chassignite. (Cha). Chiefly olivine.
5. Bustite. (Bu). Bronzite with augite.
6. Amphoterite. (Am). Bronzite with olivine.
7. Rodite. (Ro). Bronzite with olivine, breccia-like.
8. Eukrite. (Eu). Augite with anorthite.

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*Proc. Am. Phil. Soc., 1904, 53, 211–247.

9. Shergottite. (She). Augite with maskelynite.
10. Howardite. (Ho). Bronzite, olivine, augite, and anorthite.
11. Howardite, Breccia-like. (Hob). Bronzite, olivine, augite, and anorthite.

B. CHONDRITES

Bronzite, olivine, and nickel-iron. Round, rounded, or polyhedric chondri

12. Howarditic Chondrite. (Cho). Polyhedric segregations preponderating, round chondri scarce. Crust bright in parts.
13. Howarditic Chondrite, Veined. (Choa). Polyhedric segregations predominating, round chondri scarce. Metallic or black veins.
14. White Chondrite. (Cw). White, rather friable mass with few, chiefly white, chondri.
15. White Chondrite, Veined. (Cwa). White, rather friable mass with few, chiefly white chondri. Black or metallic veins.
16. White Chondrite, Breccia-like. (Cwb). White, rather friable mass with few, chiefly white chondri, breccia-like.
17. Intermediate Chondrite. (Ci). Firm, polishable mass with white and gray chondri breaking with matrix.
18. Intermediate Chondrite, Veined. (Cia). Firm, polishable mass, with white and gray chondri breaking with matrix. Black or metallic veins.
19. Intermediate Chondrite, Breccia-like. (Cib). Firm polishable mass with white and gray chondri breaking with matrix, breccia-like.
20. Gray Chondrite. (Cg). Firm, gray mass, chondri of various kinds breaking with matrix.
21. Gray Chondrite, Veined. (Cha). Firm, gray mass. Chondri of various kinds breaking with matrix, veined.
22. Gray Chondrite, Breccia-like. (Cgb). Firm, gray mass. Chondri of various kinds breaking with matrix, breccia-like.

23. Orvinite. (Co). Black, infiltrated mass: fluidal structure; surface uneven; crust incomplete.
24. Tadjerite. (Ct). Black, semi-glassy, crust-like mass with similar surface.
25. Black Chondrite. (Cs). Dark or black mass. Chondri of various kinds breaking with matrix.
26. Black Chondrite, Veined. (Csa). Dark or black mass. Chondri of various kinds breaking with matrix; veined.
27. Ureilite. (U). Black mass, chondritic or granular, iron in veins or incoherent.
28. Carbonaceous Chondrite. (K). Dull black, friable chondrite with free carbon and of low specific gravity. Nickel-iron nearly or wholly wanting.
29. Carbonaceous Chondrite, Spherulitic. (Kc). Dull gray or black, friable mass with free carbon; chondri not breaking with matrix. Nickel-iron.
30. Carbonaceous Chondrite, Spherulitic, Veined. (Kca). Dull black, firm mass with free carbon; chondri not breaking with matrix. Nickel-iron. Metallic veins.
31. Spherulitic Chondrite. (Cc). Friable mass with firm chondri of radiate structure, not breaking with matrix.
32. Spherulitic Chondrite, Veined. (Cca). Friable mass with firm chondri of radiate structure, not breaking with matrix; black or metallic veins.
33. Spherulitic Chondrite, Breccia-like. (Ccb). Friable, breccia-like mass with firm chondri of radiate structure, not breaking with matrix.
34. Ornansite. (Cco). Friable mass of chondri.
35. Ngawite. (Ccn). Friable, breccia-like mass of chondri.
36. Spherulitic Chondrite, Crystalline. (Cck). Slightly friable, crystalline mass with firm chondri of radiate structure, some breaking with matrix.
37. Spherulitic Chondrite, Crystalline, Veined. (Ccka). Slightly friable, crystalline, veined mass with firm chondri of radiate structure, some breaking with matrix.

38. Spherulitic Chondrite, Crystalline, Breccia-like. (Cckb). Slightly friable, crystalline, breccia-like mass with firm chondri of radiate structure, breaking with matrix.
39. Crystalline Chondrite. (Ck). Hard, crystalline mass with firm chondri of radiate structure, breaking with matrix.
40. Crystalline Chondrite, Veined. (Cka). Hard, crystalline, veined mass with firm chondri of radiate structure, breaking with matrix.
41. Crystalline Chondrite, Breccia-like. (Ckb). Hard, crystalline, breccia-like mass with firm chondri of radiate structure, breaking with matrix.

C. ENSTATITE-ANORTHITE-CHONDRITES

Enstatite, anorthite and nickel-iron with round chondri

42. Crystalline Enstatite-Anorthite-Chondrite. (Cek). Hard crystalline mass with firm chondri of radiate structure, breaking with matrix.

D. SIDEROLITES

Transition from stones to irons. Nickel-iron in the mass cohering; on sections separated

43. Mesosiderite. (M). Crystalline olivine and bronzite with nickel-iron.
44. Grahamite. (Mg). Crystalline olivine, bronzite and plagioclase with nickel-iron.
45. Lodhranite. (Lo). Granular, crystalline olivine and bronzite with nickel-iron.

II. IRONS. Metallic constituents prevalent or forming entire mass

E. LITHOSIDERITES

Transition from stones to irons. Nickel-iron cohering in mass and in sections.

46. Siderophyre. (Si). Grains of bronzite with accessory asmanite in trias.
47. Pallasite, Krasnojarsk group. (Pk). Rounded crystals of olivine in trias.

48. Pallasite, Rokicky group. (Pr). Polyhedric crystals of olivine, partly broken, and fragments separated by nickel-iron.
49. Pallasite, Imilac group. (Pi). Olivine crystals fissured and compressed.
50. Pallasite, Bitburg group. (Pb). Olivine crystals in fine, brecciated trias.

F. OCTAHEDRITES

51. Kamacite, taenite, and plessite (trias), in lamellae and concamerations of the four octahedral faces.
52. Finest Octahedrite. (Off). Lamellae up to 0.2 mm. thickness.
53. Fine Octahedrite, Victoria group. Ofv. Lamellae of troilite and schreibersite in fine trias.
54. Fine Octahedrite. (Of). Thickness of lamellae 0.2–0.4 mm.
55. Fine Octahedrite, Fused. (Ofe). Figures disordered by fusion; points instead of troilite lamellae.
56. Medium Octahedrite. (Om). Thickness of lamellae 0.5–1 mm.
57. Medium Octahedrite, Fused. (Ome). Figures disordered by fusion. Points instead of taenite lamellae.
58. Coarse Octahedrite. (Og). Thickness of lamellae 1.5–2.0 mm.
59. Coarse Octahedrite, Fused. (Oge). Figures disordered by fusion. Points instead of taenite lamellae.
60. Coarsest Octahedrite. (Ogg). Thickness of lamellae 2.5 mm. and more.
61. Breccia-like Octahedrite, Netschajevo group. (Obn). Medium octahedrite brecciated with nodules of silicate.
62. Breccia-like Octahedrite, Kodaikanal group. (Obk). Fine octahedrite, brecciated with nodules of silicate.
63. Breccia-like Octahedrite, Copiapo group. (Obc). Coarsest Octahedrite brecciated with nodules of silicate.
64. Breccia-like Octahedrite, Zacatecas group, (Obz). Octahedral nodules breccia-like, with spherules of troilite.

65. Breccia-like Octahedrite, N'goureyma group. (Obzg). Fused and drawn-out iron of the Zacatecas group.

G. HEXAHEDRITES

Structure and cleavage hexahedral

66. Normal Hexahedrite. (H). Neumann lines, not granular.
67. Grained Hexahedrite. (Ha). Structure and cleavage running through the whole mass. The mass consists of grains with differently oriented spangling.
68. Brecciated Hexahedrite. (Hb). Mass containing differently oriented hexahedral grains.

H. ATAXITES

Structure interrupted

69. Cape group. (Dc.) Rich in nickel; sharp (hexahedral?) etching bands in dull mass.
70. Shingle Springs group. (Dsh). Rich in nickel; indistinct parallel blebs.
71. Babbs Mill group. (Db). Rich in nickel; lustreless, homogeneous mass.
72. Linnville group. (Dl). Rich in nickel; meandering veined or latticed.
73. Nedagolla group. (Dn). Poor in nickel, grained, no ridges.
74. Siratik group. (Ds). Poor in nickel; shows ridges, incisions or enveloped rhabdites.
75. Primitiva group. (Dp). Poor in nickel; silky streaks and luster.
76. Muchachos group. (Dm). Poor in nickel, grained, porphyritic with forsterite.

While as a means of distinguishing meteorites by their more obvious physical characters this classification is perhaps as convenient as any yet devised, it is chiefly unsatisfactory in its subdivision of the great group of chondrites, since the classes are distinguished only by color, a character which can be of little fundamental importance, although it is true that meteorites consisting largely of enstatite or hypersthene are likely to be of somewhat lighter color than those largely composed of chrysolite.

In an effort to establish a quantitative classification the characters of which should more sharply and surely divide meteorites, the writer has applied to meteorites the principles of the American quantitative classification of rocks. As the details of this classification are somewhat too elaborate for the limits of this work the reader is referred to the original publication in which the classification is described in full.*

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*Pubs. Field Museum, 1911, Geol. Ser., 3, 195–228.

CHAPTER XIII

ORIGIN OF METEORITES

The origin of meteorites has always been a subject of great interest, perhaps that of greatest interest connected with them. Yet it is a subject in regard to which little satisfactory information can be given. Two lines of inquiry seem open, the first to endeavor to decipher the origin of meteorites from details of their structure and composition, and the second to follow them back along their celestial paths as far as possible into the regions of space from whence they came. So far as the structure and composition of meteorites are concerned there can be no doubt that meteorites are of igneous origin. All terrestrial analogies indicate that in cosmic furnaces of some sort, fires glowed which gave meteorites the structures which they present to us. As between iron and stone meteorites, some differences of conditions existed which gave them somewhat different structures, since the iron meteorites show well-formed crystallization as if they had been maintained in a uniform condition of temperature, and that sufficient to keep them liquid or viscous for a long time, while the stone meteorites exhibit glass, chondritic structures, and other evidences of a hasty crystallization which indicate rapid cooling. Yet the substance of the two kinds of meteorites tends to grade from one to the other; the nickel-iron and pyrrhotite of the stone meteorites is the same as that of the iron meteorites, and the silicates of the stone meteorites suffer gradual diminution as they pass to the iron meteorites. Such facts suggest that the iron and stone meteorites may have been associated in some cosmic mass, the materials of which were assorted according to their specific gravity. In such a mass the metal would be at the center while the lighter silicates would be at the surface. In the cooling of such a mass the exterior or siliceous portion would congeal more quickly than the interior metallic nucleus. The latter would thus possess conditions favoring more nearly complete crystallization. So far as the substance of meteorites is concerned, it may be noted that their principal ingredients, nickel-iron, chrysolite, and bronzite are substances which have all about the same freezing point — between 1400° and 1500° C. What significance this fact may have in indicating the origin of meteorites the writer is unable to say, but it seems probable that it has some meaning.

The fact that the silicates of meteorites, such as chrysolite, enstatite and feldspar, constitute some terrestrial volcanic rocks, has perhaps given rise to the suggestion made at different times that meteorites may represent matter which was originally ejected by the earth's volcanoes and is falling back again. Except for the similarity of material, there seems to be no good reason for such an assumption. Even the similarity of material fails so far as the iron meteorites are concerned, for no such substance as that of the iron meteorites has ever been ejected by terrestrial volcanoes. The native iron of Greenland somewhat resembles meteoritic iron but while seemingly of eruptive origin it shows no evidence of ever having been connected with explosive volcanoes. Moreover, while analogous to meteoritic iron, the Greenland iron shows marked differences which enable it readily to be distinguished. The percentage of nickel is lower in the Greenland iron than in any meteoritic iron, unless a few unsatisfactory analyses be accepted, the percentage of carbon is higher, and no typical octahedral or other meteoritic figures are exhibited on etching.

Another meteoritic feature not found terrestrially is that of chondritic structure. While the spherulites sometimes found in volcanic rocks partially resemble chondri there are many features which are lacking and they cannot be regarded as identical. Even if materials exactly similar to those of meteorites could be found upon the earth, it would still be necessary to bear in mind, before a terrestrial origin of meteorites could be accepted, that terrestrial volcanoes have never been known to exert the great energy which would be necessary in order to throw material out beyond the range of the earth's attraction. To do this, as shown by the accompanying figure (Fig. 59) a velocity of at least five miles per second must be given to a body. To produce the velocity which meteorites have, the force must have been even greater, since meteorites come to the earth with planetary velocities and must have had such velocities initially. There is no reason to suppose that terrestrial volcanoes ever exhibited forces of such intensity as this. Moreover, if terrestrial volcanoes have ever sent out matter in this way, its quantity, in order to produce the supply of meteorites which reaches the earth, must have far exceeded any amount that terrestrial volcanoes have yet been observed to produce. Of the material ejected only a very small quantity would be likely to be drawn into the range of the earth's attraction again.

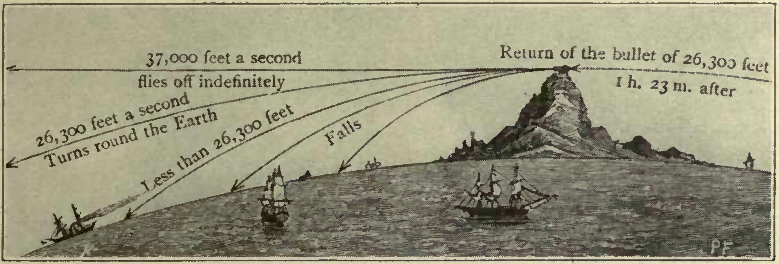

FIG. 59.— Effect of earth's gravitation on bodies of different velocities.

Since the moon's surface is apparently dotted with large volcanoes, though they appear to be at the present time extinct, it has been suggested that meteorites are material ejected by the volcanoes of the moon. This is also an assumption which is discredited by available evidence and the same objections apply to this view as to that which supposes meteorites to have come from terrestrial volcanoes. The forces and quantity of matter required to produce meteorites from the moon would be far beyond that likely to have been afforded by lunar volcanoes. Moreover, the velocity of lunar fragments reaching the earth would be only six and a half miles a second, while meteorites have much higher velocities.

A possible origin of meteorites from the sun has also been suggested. Objections to this view are found in the difficulty of conceiving how a globe in so vaporous and heated a condition as the sun would produce solid bodies. Even if the sun has a solid core from which such bodies could start they would need to pass through an atmosphere of immense heat before they could arrive in free space, and it seems hardly possible that the solid nature of small bodies could be preserved under such conditions. Moreover the paths of many meteorites are much inclined to the ecliptic, while a body ejected from the sun and reaching the earth would move in a line parallel to the ecliptic.

The class of heavenly bodies to which the origin of meteorites has been most generally ascribed within recent years is that of the comets, (Fig. 60). Largely through the work of H. A. Newton, the orbits of many of the important shooting star or meteor showers were found to be identical with those of comets, these orbits being in some cases those of comets which had disappeared. Thus the August meteors or Perseids were found to have the same orbit as Tuttle's comet and the November or Leonids the same as that of Tempel's. Biela's comet, which disappeared in 1872, has its place in the heavens represented by the Andromedes shower. Accordingly Newton believed and the view has been widely adopted, that the difference between large and small meteors is simply one of size and that a meteorite is the solid product of a large meteor. If the differences between meteorites and star showers were only those of size, this view might be accepted, but an investigation of the matter discloses other points of difference. Of these, perhaps the most important one is that meteorites do not fall at the times of the shooting star showers. A single case is known—that of the Mazapil iron, which fell November 27, 1885—of a meteorite falling at the time of a star shower, but so isolated a case could be accounted for purely as a coincidence. If meteorites and star showers have the same origin star showers would be expected to yield large numbers of meteorites. The data given under times of fall, page 39, show that the times when meteorite falls are most

Fig. 60. Daniels' Comet, August 10, 1907.

abundant are not those of star showers. Hence it seems that if comets produce meteorites, they are comets of a different nature from those which produce star showers or shooting stars (Fig. 61).

According to the meteoritic hypothesis of J. Norman Lockyer, meteorites are the primary dust of the universe out of which all cosmic bodies have been produced. "All self-luminous bodies in the celestial spaces," according to this hypothesis, "are composed either of swarms of meteorites or of masses of meteoritic vapor produced by heat. The heat is brought about by the condensation of meteor swarms due to gravity, the vapor being finally condensed into a solid globe." * According to this theory the light of the nebulae is due to constant collisions of the constituent

Fig. 61.— A shooting star trail, showing sudden increase in brightness. Yerkes Observatory. June 7, 1899.

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*The Meteoritic Hypothesis, 1890, 527.

meteorites. G. H. Darwin discussed the mechanical condition of such a swarm and concluded that it would be dynamically analogous to a gas. Chamberlin* showed that such a swarm would probably, on account of the frequent and violent collisions of its meteoritic components, pass into the gaseous condition and thus produce a body in no way differing from the familiar gaseous nebula. Inquiry was further carried on by Chamberlin to determine whether some other form of meteoritic assemblage might be postulated which might produce in its evolution such bodies as the earth or others of the solar system. He reached the conclusion that formidable difficulties in preparing such a hypothesis would be found in the high ratio of the kinetic energy of meteorites to their mutual gravitation, in the sparseness of distribution of meteoritic matter, and in the enormous period of time necessary for such an assemblage. Chamberlin concluded, however, that if a meteoritic swarm could by any means acquire a large mass the probabilities of its holding its own members and capturing additional meteorites would be very favorable. No form of the meteoritic hypothesis which has yet been propounded seems able to explain the manner in which meteorites are produced.

Another origin suggested for meteorites is that they are parts of a shattered planet or planetoid. Such an origin would, according to the author's view, be that which is indicated as most probable by the structure and composition of meteorites. Further, all evidence seems to indicate that meteorites are fragments of some pre-existing body rather than independent celestial bodies. How large the bodies may have been of which meteorites once formed a part is of course uncertain. The rings of Saturn (Fig. 62) are known to be made up of multitudes of small, solid bodies, and it may be bodies of this nature that are the source of supply of meteorites. The planetoids, some of which are known to be of irregular form, are another possible source. Two chief difficulties arise in ascribing the origin of meteorites to disintegrated bodies within the solar system, (1) the difficulty of conceiving of a disintegrating force, and

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*Geology, 1906, 2, 14.

(2) the difficulty of explaining the inclination of the orbits of some meteorites to the ecliptic.

So far as the first difficulty is concerned, it seems hardly likely that a solid, independent form is always the final stage in the evolution of matter. The fact that comets break up shows that some disruptive forces exert their influence among cosmic bodies in amount sufficient to start them in new courses. The so-called rills upon the moon's surface indicate the existence of disruptive forces of some kind in that satellite which might gradually disintegrate it. A probable source of disruption has been suggested by Chamberlin* as being found in the differential attraction produced by the passage of a small body within a certain distance of a larger, dense one. The distance within which disruption would take place for incompressible fluids of the same density is given by Roche (Roche's limit) as 2.44 times the radius of the large body. Since solid bodies possess some internal elasticity it is probable that the passage of a

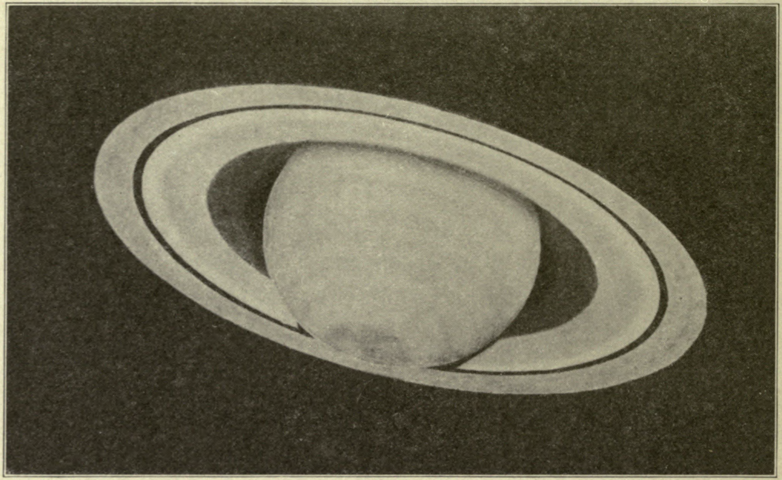

Fig. 62.— The planet Saturn and its rings. These rings are composed of multitudes of small solid bodies which may be of a meteoritic nature. From drawing by Barnard, July 7, 1898.

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*Astrophys. Jour., 1900, 14, 17–40.

larger body at a somewhat greater distance than this even would disrupt a smaller one. Here then is a possible shattering force. Another would be found in collisions of two bodies, but these would be less numerous than approaches, and taking place between bodies moving at planetary velocities would be likely to generate so much heat as to vaporize the substance of the colliding bodies. The passage of a large body near a small one would, in addition to exerting a disrupting effect, tend to change the orbit of the smaller body. Such a change has often been observed to be produced in the orbit of a comet by its passage near a planet. Hence a comet passing near a smaller body might change the orbit of the latter, drawing it out of the ecliptic and giving it a hyperbolic or even parabolic form. By this means the inclination of some meteoritic orbits may have been produced.

It was the opinion of Newton* that the orbits of the larger meteorites are allied much more closely with the group of comets of short period than with those of parabolic orbits, and this conclusion seems to point to an origin of meteorites within the solar system. W. H. Pickering † asserts that the orbits of the majority of meteorites do not even reach as far as the zone of planetoids. On the other hand, Schiaparelli felt convinced from mathematical considerations that meteorites come from the world of fixed stars. The meteorite of Pultusk he stated came from the constellation of the Great Bear and that of Knyahinya from Pisces. It is evident that more study of the orbits and velocities of meteorites is needed before a satisfactory decision as to their point of origin can be reached.

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* Am. Jour. Sci., 1888, 3, 36, 13.

† Pop. Astron., 1910, 18, 245.

CHAPTER XIV

TERRESTRIAL RELATIONS

It has already been remarked that stone meteorites resemble certain volcanic rocks of the earth. The rocks which they resemble are chiefly terrestrial peridotites, lherzolites, wehrlites, etc., which are rocks composed largely of chrysolite or of chrysolite and pyroxene. From these the chondritic meteorites essentially differ only in their content of metallic grains and in their chondritic structure. From terrestrial dolerites, the eukritic meteorites differ scarcely at all. The iron meteorites have (as already noted) a terrestrial counterpart in the masses of native iron found in Greenland, though the latter contain less nickel and more carbon than iron meteorites and do not exhibit Widmannstätten figures on etching. But many of the important rock forming minerals of the crust of the earth are either lacking or play an insignificant part in the formation of meteorites. Such are quartz, orthoclase, the acid plagioclases, the micas, amphiboles, leucite, and nepheline. Vice versa, the chief mineral constituents of meteorites do not occur in large amount in the earth's crust. Such are nickel-iron, the orthorhombic pyroxenes, and chrysolite. Looked at chemically it may be said that terrestrial rocks abound in silica (free and combined), lime, alumina, and alkalies, while meteorites abound in iron, nickel, and magnesia.

These differences will not appear so great if we remember that changes may have been wrought in the composition of the earth's crust which have not taken place in meteorites. The active agents water and oxygen which are lacking in meteorites are continually working upon the earth's crust to change its composition. Also the carbonic acid of the earth's atmosphere would act upon metasilicates as follows:

$$MOSiO_2+CO_2=SiO_2+MOCO_2$$

or upon the orthosilicates:

$$(MO)_2SiO_2+2CO_2=SiO_2+2MOCO_2$$

Here M represents any base. Such agencies working for long periods of time in connection with gravitational movements might produce considerable modification of the composition of the earth's crust as compared with its original composition. It should be remembered too that the crust of the earth to a depth of ten miles, which is the only portion with which we are accquainted, constitutes only about $^1/_{130}$ part of the earth as a whole. In comparing, therefore, the composition of the crust of the earth with that of meteorites, a few meteorites may be sufficient to represent the known crust. Taking for this purpose the composition of four well-known meteorites, those of Petersburg, Stannern, Juvinas, and Frankfort, which meteorites also nearly correspond in specific gravity with the earth's crust, the comparison with the average composition of the earth's crust is as follows:

	I Four meteorites	II Average of terrestrial rocks
SiO_2	49.85	58.24
Al_2O_3	11.14	15.80
Fe_2O_3 FeO	18.87	7.21
MgO	9.83	3.84
CaO	9.44	5.22
Na_2O	0.63	3.91
K_2O	0.14	3.16
H_2O	....	1.79
TiO_2	0.03	1.04
P_2O_5	0.07	.37
	100.00	100.58

A comparatively slight enrichment in some ingredients of the above meteoritic magma and impoverishment in others, which might be carried on progressively, would produce in time a composition like that of the earth's crust.

Further, if it were possible to compare the composition of meteorites with that of the earth as a whole it is possible that an even greater similarity would be found to exist. The average composition of meteorites as determined by the sum of all reliable analyses is as follows:*

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*Farrington Pubs. Field Museum, 1910, Geol. Ser., 3, 213.

AVERAGE COMPOSITION OF METEORITES

Fe	68.43
SiO_2	11.07
Ni	6.44
MgO	6.33
FeO	4.55
Al_2O_3	.74
CaO	.65
S	.49
CO	.44
Na_2O	.23
P	.14
Cr_2O_3	.12
Fe_2O_3	.11
NiO	.06
K_2O	.05
MnO	.04
C	.04
Cu	.01
Cr	.01
P_2O_5	.01
TiO_2	.01
SnO_2	.01
	99.98

Calculated as elements this becomes

Iron	72.06
Oxygen	10.10
Nickel	6.50
Silicon	5.20
Magnesium	3.80
Sulphur	.49
Calcium	.46
Cobalt	.44
Aluminum	.39
Sodium	.17
Phosphorus	.14
Chromium	.09
Potassium	.04
Carbon	.04
Manganese	.03
Other elements	.05
	100.00

Such a mixture would have a density very near that of the earth as a whole, which is 5.57. That the interior of the earth may be largely composed of iron is indicated by its rigidity, which is about that of steel, and also by its magnetic properties. Also it is well known that some cause must produce the high specific gravity of the earth as a whole as compared with that of its crust, since the whole earth has a specific gravity more than twice as great as that of its crust. The earth's interior must be denser than its exterior, either because the interior contains material which is inherently more dense or if of originally light material, because it has been made dense through pressure. That the material of the earth's interior must be subjected to enormous pressures there can be no doubt, though the pressure increases in a diminishing ratio toward the center. We have no means of determining what the effect of such pressures would be, but no phenomena within our observation indicate that the pressure would be able to more than double the density of materials as would be necessary if the density of the materials of the crust of the earth were changed to that of the earth as a whole. Accordingly the existence of inherently denser material in the interior seems probable. The average specific gravity of meteorites seen to fall is 3.59, or calculated by the weight of each fall, 3.65. No calculation of the specific gravity of all meteoritic matter has yet been made.

Certain physical effects exerted upon the earth as a whole by the fall of meteorites and shooting stars should be considered. It is evident that the constant addition of meteoric matter must cause a continual increase in the size of the earth although, of course, at a very slow rate. Thus, according to Young,* the meteoric matter received daily by the earth, if we accept one grain as the average weight of a shooting star, would be only about one ton, after making a reasonable addition for meteorites. If we multiply this estimate by one hundred, which will certainly be liberal, then the amount of meteoric matter received by the earth in a year would reach the very respectable figure of 36,500 tons; and yet, even at this rate, assuming the specific gravity of the average meteor as three times of that water, it would take about 1,000,000,000 years to accumulate a layer one inch thick over the earth's surface.

Again, says Young, theoretically, the encounter of the earth with meteors must shorten the year in three distinct ways:

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*Astronomy, p. 440.

First. By acting as a resisting medium, and so diminishing the size of the earth's orbit, and indirectly accelerating its motion, in the same manner as is supposed to happen with Encke's comet.

Second. By increasing the attraction between the earth and the sun through the increase of their masses.

Third. By lengthening the day — the earth's rotation being slower by the increase of its diameter, so that the year will contain a smaller number of days.

The whole effect, however, of the three causes combined, does not amount to 1–1000 of a second in a million years. The diminution of the earth's distance from the sun, assuming that one hundred tons of meteoric matter fall daily, and also assuming that the meteors are moving equally in all directions with the parabolic velocity of twenty-six miles per second, comes out about 1–20,000 of an inch per annum.

Theoretically, also, the same meteoric action should produce a shortening of the month, but an investigation by Oppolzer to see what amount of meteoric matter would account for the observed lunar acceleration indicates that it would require an amount immensely greater than that actually received by the earth.

Each meteor or meteorite brings to the earth a certain amount of heat developed in the destruction of its motion; and at one time it was thought that a very considerable percentage of the total heat received by the earth might be derived from this source. Assuming, however, as before, the fall of one hundred tons of meteoric matter daily with an average velocity of twenty miles per second relative to the earth, the whole amount of heat comes out about 1–20 calorie per annum for each square metre of the earth's surface — as much in a year as the sun imparts to the same surface in about one-tenth of a second.

One other effect of meteoric matter in space should be alluded to. It must be necessarily render space imperfectly transparent, like a thin haze. Less light reaches us from a remote star than if the meteors were absent.

It would seem probable that the constant fall of shooting stars and small meteorites might produce an amount of meteoritic dust which would be perceptible in favorable localities such as snow covered surfaces or the ocean bottom. Little of such material has, however, ever been satisfactorily detected. The meteoritic nature of some dusts collected from the Greenland snows has been indicated by a content of nickel, and some spherules obtained in deep sea dredging seem to be true meteoritic chondri but observations of such material have been few.

CHAPTER XV

METEORITE COLLECTIONS

For the acquirement of knowledge regarding meteorites, collections of these bodies are of the utmost value. The size of meteorites is fortunately such as to permit in most cases their ready transportation to locations where their various features can be minutely and carefully studied. This is true even of the great Cape York meteorite weighing nearly 40 tons, which was removed from Greenland to New York City (Fig. 63). Moreover, the structure and composition of any individual meteorite or of the individuals of any meteorite fall are so nearly constant that portions of meteorites may safely be distributed for purposes of study and thus facilities be provided in many places for the investigation of these bodies.

Previous to the eighteenth century, meteorites were rarely preserved by intention unless some superstition was connected with their fall or peculiar characters. An iron meteorite which fell probably about 1400 A. D. has ever since that time been preserved in the town hall of Elbogen, Bohemia (Fig. 64). The meteorite was known as the "Bewitched Burggrave" and according to tradition the mass represented a tyrannical burggrave (a court official) who had been turned into iron in punishment for his cruelty. A meteoric stone weighing about 300 pounds which fell at Ensisheim in Alsace, November 16, 1492, was preserved in the church of that place at that time by order of the emperor. A large part of it still hangs in the Town Hall of Ensisheim. Several stones kept in temples of the Greeks and Romans, including "Diana of the Ephesians," were probably meteorites but have not been preserved to us. The sacred stone which is still worshiped at Mecca is, however, probably a meteorite and several meteorites have been kept in Japanese temples. The preservation of meteorites

Fig. 63.— Moving the great Cape York meteorite (weight 36 tons) through the streets of New York City.

for scientific purposes was not undertaken to any extent until about the beginning of the nineteenth century, since scientific men up to that time were unwilling to believe that stones would fall from the sky. Careful investigation of several such reputed occurrences, however, notably that at L'Aigle, France, in 1803 established the truth of the phenomenon, and since then collecting of these bodies has been actively carried on.

The first collections were formed in the museums of the capitals of Europe and most of these collections have been admirably maintained. The Royal Cabinet of Vienna, which afterward became the Natural History Museum, obtained its first meteorite specimen in 1747. Up to 1805 the number of falls represented there had increased only to eight. In 1835 it had reached the number of fifty-six and in 1856 was one hundred and thirty-six. At the present time (1915) the collection contains representatives of nearly six hundred and fifty falls. For many years the collection was the largest in the world and its successive curators, Partsch, Hörnes, Brezina, and Berwerth, were zealous students of the subject. Much of our knowledge of meteorites has, therefore, been acquired through studies of the Vienna collection. The British Museum had in 1807 four meteorite specimens and in 1860, sixty-eight. It comprises at the present time representatives of about six hundred falls, many of the speci-

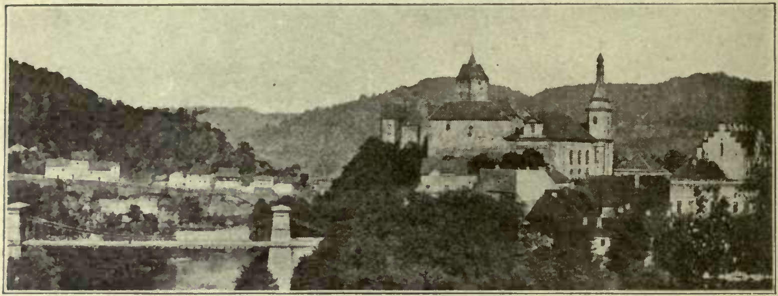

FIG. 64.— Town hall at Elbogen, Bohemia, in which an iron meteorite called the "Bewitched Burggrave" has hung (with some interruptions) since about 1400 A. D.

mens of which are of unique interest and value. As with the Vienna collection the curators of the British Museum collection have been leading investigators, as the names of Flight, Maskelyne, and Fletcher will show. The meteorite collection of the Natural History Museum of Paris possessed early in the nineteenth century a score of specimens which had increased in 1860 to sixty-four. This collection now numbers nearly six hundred falls, many of which are of great importance. The long connection of Meunier with this collection, which happily still continues, has been fruitful of rich contributions to meteoritics. The Royal Natural History Museum of Berlin early received the collection of Chladni numbering representatives of about fifty falls and under the care of Rose, Klein, and others has kept pace with other important collections in its growth. Other large and representative collections in Europe are to be found in Buda-Pesth, Greifswald, Stockholm, Göttingen, Dorpat, and Strasburg. Large private collections are also possessed there by Prof. Friedrichs in Vienna, Marquis de Mauroy in Wassy, France, and Max Neumann in Gratz.

In the United States collecting of meteorites began with the preservation at Yale College in 1807 of the meteorites which fell at Weston, Connecticut, in that year. In 1810 the large Gibbs iron weighing nearly a ton (1635 pounds) was brought from Texas after much hardship and difficulty. This was presented to the Yale collection in 1835. Other important falls have been added to the collection from time to time and it now includes representatives of nearly two hundred and fifty. Harvard University obtained specimens of about fifty meteoric falls from Prof. J. P. Cooke but gained its most valuable specimens by the purchase in 1883 of the collection of Dr. J. Lawrence Smith. The total number of falls now represented in the Harvard collection is about three hundred. A collection of about the same size is possessed by Amherst College, its acquisition having been due chiefly to the labors of Prof. C. U. Shepard. Large collections of meteorites are possessed by the Natural History Museums of Washington, New York, and Chicago, that of the last city at the Field Museum being now the largest

FIG. 65.— Meteorite collection of Field Museum of Natural History, Chicago.

in the world (Fig. 65). This collection was inaugurated in 1894 at the time of the founding of the Field museum by purchase of collections from George F. Kunz and Ward's Natural Science Establishment. In 1912 the private collection of Prof. Henry A. Ward numbering over six hundred falls was added to the collection and thus the most representative series of meteorites in the world was secured. The meteorite collection at Washington at the United States National Museum has been gathered since 1880. Over four hundred falls are now represented in this collection and among them are the unrivaled Tucson ring and the historic Casas Grandes. The American Museum of Natural History in New York City has a collection representing nearly five hundred falls including the great Cape York masses and the large Willamette iron. There are small collections of meteorites in this country numbering from fifty to one hundred and fifty falls at Adelbert College, Ohio, the Milwaukee Public Museum, the University of Minnesota, the Academy of Sciences of Philadelphia, and the Academy of Sciences at St. Louis. At the Mexican National Museum and School of Mines in the City of Mexico the great Mexican irons of Chupaderos, Morito, Zacatecas, etc., are preserved, together with many other smaller but important meteorites. At Calcutta, India, a large collection of meteorites has been for many years maintained, its growth being favored by the large number of stone meteorites which have fallen in India. In Japan, Australia, South Africa, and other parts of the world meteorite collections are gradually being gathered and thus facilities are rapidly being widely increased for the preservation and study of these bodies.

TABLE OF METEORITIC MIN

I

General Characters	Species	Composit
Non-magnetic or only slightly so before heating. B. B. fuses to magnetic globule. When roasted in the open tube or on charcoal gives the odor of SO_2 and reddens litmus paper. Decomp. by HCl and HNO_3. Easily soluble in HCl with evolution of H_2S. Sol. in HNO_3 with evolution NO_2	Pyrrhotite	FeS
Strongly magnetic before heating. Gives no odor on roasting nor reddening of litmus paper. Heated with magnesium wire in a closed tube and moistened with water gives the disagreeable odor of phosphuretted hydrogen. Soluble in HCl and Aqua regia. Insol. in copper ammonium chloride. Treated with HNO_3 or dissolved in HCl gives yellow ppt. with Am MoO_4. Decomp. with difficulty by HNO_3	Schreibersite	(Fe, Ni, Co

General Characters		Specific Characters		INFL
Magnetic before heating	Reacts for nickel	Malleable Sol. in HCl or HNO_3	Nickel-iron	Fe+Ni+C
			Kamacite	Fe_{14} Ni+C
		Usually in flexible plates which fuse on thin edges B. B. Sol. in copper ammonium chloride	Taenite	Fe_7 Ni+Co Fe Ni+
		Brittle. Fuses in R. F. emitting sparks. Decomposed with difficulty by concen. HCl. Sol. in copper ammonium chloride	Cohenite	(Fe, Ni, Co
	Fine powder slowly but completely soluble in HCl		Magnetite.	Fe_3O_4
Not magnetic before heating	Impart a green color to salt of phosphorus or borax bead (Chromium)	Reacts for sulphur when roasted in open tube. Becomes magnetic when heated in R. F. Brittle. Sol. in HNO_3 and Aqua Regia	Daubréelite	FeS, Cr_2S_3
		A little of the fine powder when mixed with an equal volume of Na_2CO_3 and intensely heated on charcoal gives a magnetic mass. Insol. in acid	Chromite	FeO, Cr_2O_3
Soft. Soils the fingers. Very refractory. Deflagrates with KNO_3. Use equal parts mineral and KNO_3.			Graphite	C

RALS WITH METALLIC LUSTRE

IBLE

Color	Streak	Cleavage and Fracture	Hardness	Spec. Grav.	Fusibility	Crystallization
Bronze-yellow to brown	Grayish-black	Uneven	4	4.68–4.82	2.5–3	Hexagonal
Tin-white, steel-gray, bronze-yellow	Grayish-black	Brittle	6.5	6.3–7.28	2.5	

BLE

Steel-gray	Steel-gray	Octahedral Cubic Hackly	4–5	7.3–7.5	Isometric
Steel-gray				7.80–7.88	Isometric
Tin-white to golden-yellow					Isometric
Tin-white, bronze-yellow			5.5–6	7.23–7.24	Isometric
Iron-black	Black	Parting octahedral. Uneven	6	5.18	Isometric
Black	Black	One direction		5.01	Massive Scaly
Iron-black to brownish black	Dark brown	Uneven	5.5	4.6	Isometric U. massive
Iron-black	Black	Basal (perfect)	1–1.5	2.20	Hexagonal Rh. Foliated

GENERAL INDEX

INDEX OF METEORITES