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ABSTRACT

Discussed are meteors from an historical and astronomical viewpoint; then presented is the chemical makeup of iron meteorites, stony meteorites, and stony-iron meteorites. Age determination, moon craters, and tektites are also treated. The interested observer learns how to identify meteorites and to describe how they fall. (Author/RE)

METEORITES

Carleton B. Moore

This pamphlet describes meteors first from an historical and astronomical viewpoint. It goes on to discuss the chemical makeup of iron meteorites, stony meteorites, and stony-iron meteorites. Age determination, moon craters, and tektites are also treated. The interested observer learns how to identify meteorites and to describe how they fall.

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Meteorites

Carleton B. Moore

Series Editor: Robert E. Boyer

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Meteorites

INTRODUCTION

On the same day natives in Cuba were entertaining Christopher Columbus by diving for pearls in Tanamo Bay, a European town played host to an even more exotic visitor. On that day, November 16, 1492, a meteorite fell into the German village of Ensisheim. The townsfolk were so awed by this 127-kilogram stone that fell out of the sky that they chained it to the wall of their church. Near it they placed the following inscription: MANY KNOW MUCH ABOUT THIS STONE, EVERYONE KNOWS SOMETHING, BUT NO ONE KNOWS QUITE ENOUGH. The stone, minus odd fragments chipped off during five centuries, is still in Ensisheim today. It is the oldest preserved specimen of over 2000 known meteorites (Figure 1).

Of course the Ensisheim incident was not the first of its kind. The ancient Greeks recorded that "a stone the size of a chariot" fell on Thrace in 476 B.C. The early Egyptians, the Chinese, the Romans, and others reported similar events, and in many parts of the world strange stones and unusual chunks of metal had been found on the ground. Since 1492 several hundred meteorites have been collected from observed falls, and an even larger number of unknown age have been found and brought to museums. Large craters, scars of gigantic prehistoric meteoritic impacts, have been found throughout the world.

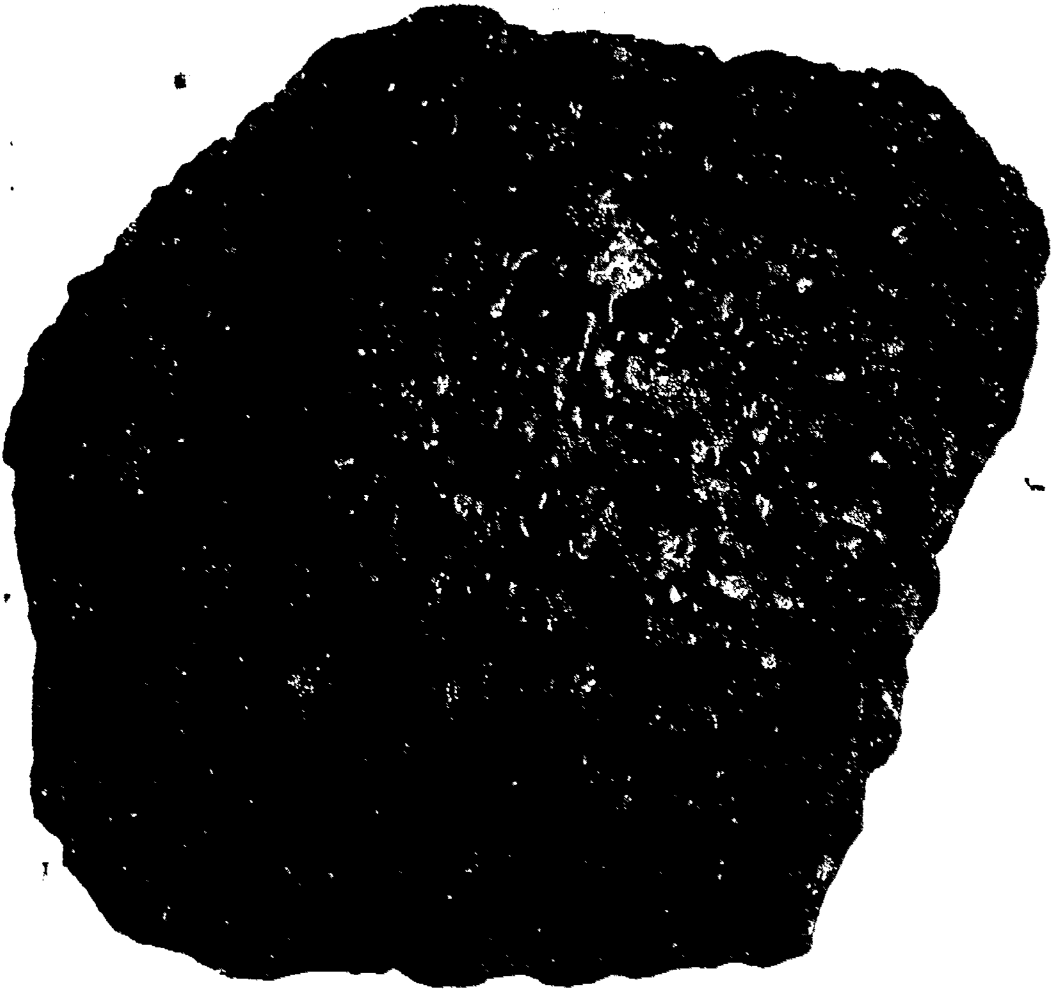


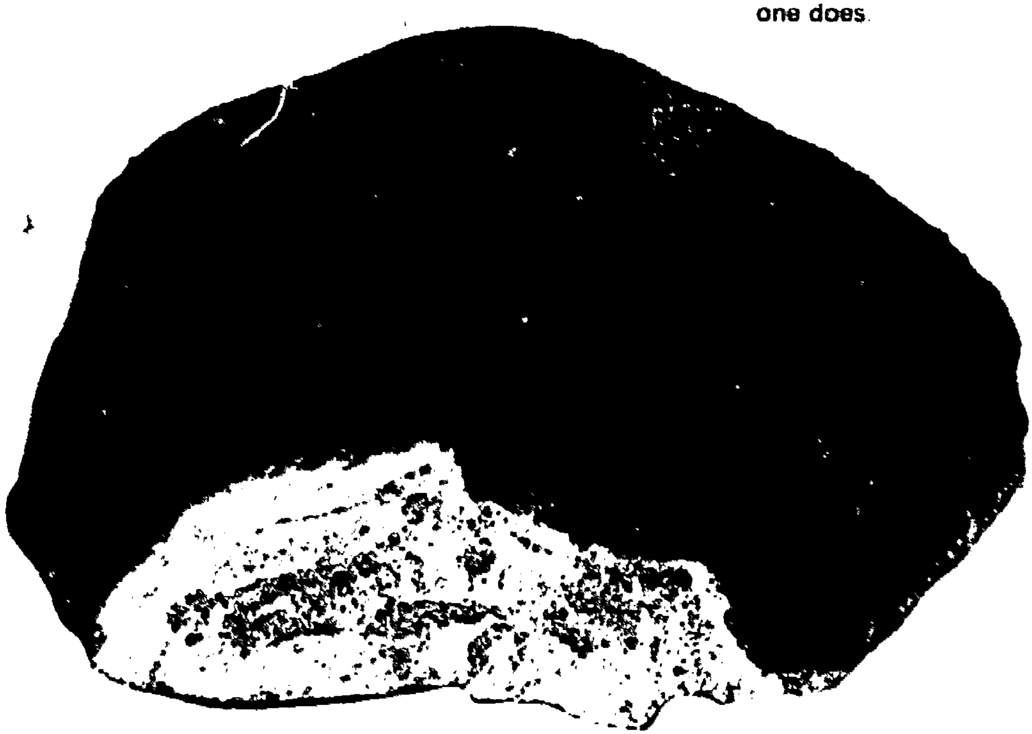
Figure 1 The Rosebud Texas meteorite Unlike many stony meteorites, it fell as a single stone As it passed through the atmosphere, its surface was melted and removed by friction Perhaps the Ensisheim meteorite looked like this before fragments were chipped off it

Meteorites were first collected as objects to be looked at by curious people, but with the development of modern science they became more valuable as a means of learning more about our solar system. Except for the pieces of the moon brought back by astronauts, meteorites are the only extraterrestrial objects available for scientific study. Too, most if not all of them probably did not come from the moon, but rather from the belt of asteroids between Mars and Jupiter. Perhaps even more important than the fact that meteorites are a "poor man's space probe" is that they are also "time probes."

Careful study has shown that they are older by a billion years or so than the oldest rock known from the surface of the earth. They appear to have remained unchanged since the solar system was born from gas and dust about five billion years ago.

Meteorites are not all the same. Some are very heavy and made of iron and nickel; others look like some of the rocks found on the surface of the earth. Most of the meteorites observed to fall are combinations of these two types. Since very few earth rocks contain metallic iron, the presence of metallic iron and nickel is good evidence that a stone is a meteorite. A few rare types of stony meteorites do not contain metal and are difficult to recognize unless they have actually been seen falling or have the shiny black melted crust produced by passing through the earth's atmosphere (Figure 2). Other rare and particularly valuable meteorites look like sooty black fragments of asphalt or tar. It is always possible that tomorrow a new unknown type may fall in your back yard.

Figure 2 A broken piece of the small Dokachi stony meteorite. The smooth black outer surface was melted by friction with the atmosphere. Most meteorites show metal on a cut surface, as this one does.



The different meteorites contain the possible answers to many scientific problems. While today, as in Ensisheim in 1492, no one knows quite enough, scientists are attempting to shed light on these still unanswered questions about our solar system, including how it formed and perhaps the origin of life itself. Today the study of meteorites concerns scientists from many fields—geology, chemistry, physics, astronomy, even biology. All have a stake in probing the questions posed by these mysterious visitors from space.

Figure 3 Meteorites may fall singly or in showers, they may be flecks of dust or huge bodies that cause explosion craters

WHEN A METEORITE FALLS

Harrison Brown of the California Institute of Technology recently calculated that about 560 meteorites large enough to be collected fall on the earth each year (Figure 3). If you scan a globe, you may easily see that most meteorites will fall into oceans and seas; in fact only about ten will be expected to fall on the continental United States. Experience has shown that scientists are lucky if they can recover one of these ten. Several may be observed to fall and never be found. Some meteorites may arrive unseen and be noticed only if they penetrate the roof of a house or land in a freshly raked garden.

A particle traveling through space plunges into the atmosphere and immediately meets the resistance of the upper air. If it is small, it may be melted away, its luminous trail fading out far above the earth. For a larger body weighing up to a metric ton, however, this is not the case. Its surface is heated by friction up to great temperatures and melted off by the resistance of the air, leaving a brilliant trail of light and smoke. As air pressure builds up ahead of it, the meteorite slows down until its original cosmic velocity has disappeared. Its fiery trail ceases and its surface begins to freeze into a glassy-smooth crust as it falls free like a bomb dropped from an airplane.

Huge meteorites with a mass of ten metric tons or more are too large to be strongly affected by the friction of the air. In such cases, the meteorite remains a fireball that hits the surface of the earth with most of its original speed (Figure 3). This type of impact produces a *hypervelocity* or *explosion crater*, a crater formed when the large object meets the earth and releases so much energy that it causes terrific devastation. On impact, most of the meteorite and the ground it hits are instantly compressed, heated, and turned partly to vapor. The vapor expands with a terrific explosion, blowing a large part of the meteorite out of the earth, vaporizing it, and gouging out an enormous crater. The remaining pieces of the shattered meteorite are spread over the surrounding area, accompanied by a blast of air hot enough to burn up nearby plants and animals. Shock waves shoot out from the crater, breaking up the rock beneath it. Such a frightening event once occurred in northern Arizona some 20,000 years ago. Today the event is preserved as the Barringer Meteorite Crater near Winslow.

A more typical meteorite fall took place in western Oklahoma on November 25, 1943. The first indication of this event came when newspapers and the radio reported that the ground shook near Leedey, Oklahoma, when a large fireball appearing to fall from the sky traced a colorful path across the state. Almost immediately Oscar Monnig and H. H. Nininger, two dedicated meteorite hunters, started toward the apparent area of impact. When they arrived in Leedey, they were lucky enough to find a farmer who had heard something land with a thud in a nearby field. A careful search of the field turned up a black-crusted meteorite weighing several kilograms. Even though the field was freshly plowed and was soft, the stone did not bury itself; instead it made a small dent in the ground and bounced out beside it. The searchers knew that stony meteorites like the one they found often break into many fragments high in the atmosphere. By showing local farmers and students what the meteorite looked like they were able to find 21 other pieces. These pieces weighed from 60 grams to 20 kilograms and were spread over an area about 18 kilometers long and 5 kilometers wide (Figure 4). The largest piece was found at the far end of this elliptical area. Many additional pieces probably remained undetected, especially very small ones.

The meteorite found by Monnig and Nininger was named the Leedey meteorite after the place where it was found. Meteorites are named after the nearest post office or a large geographic feature such as a mountain or lake.

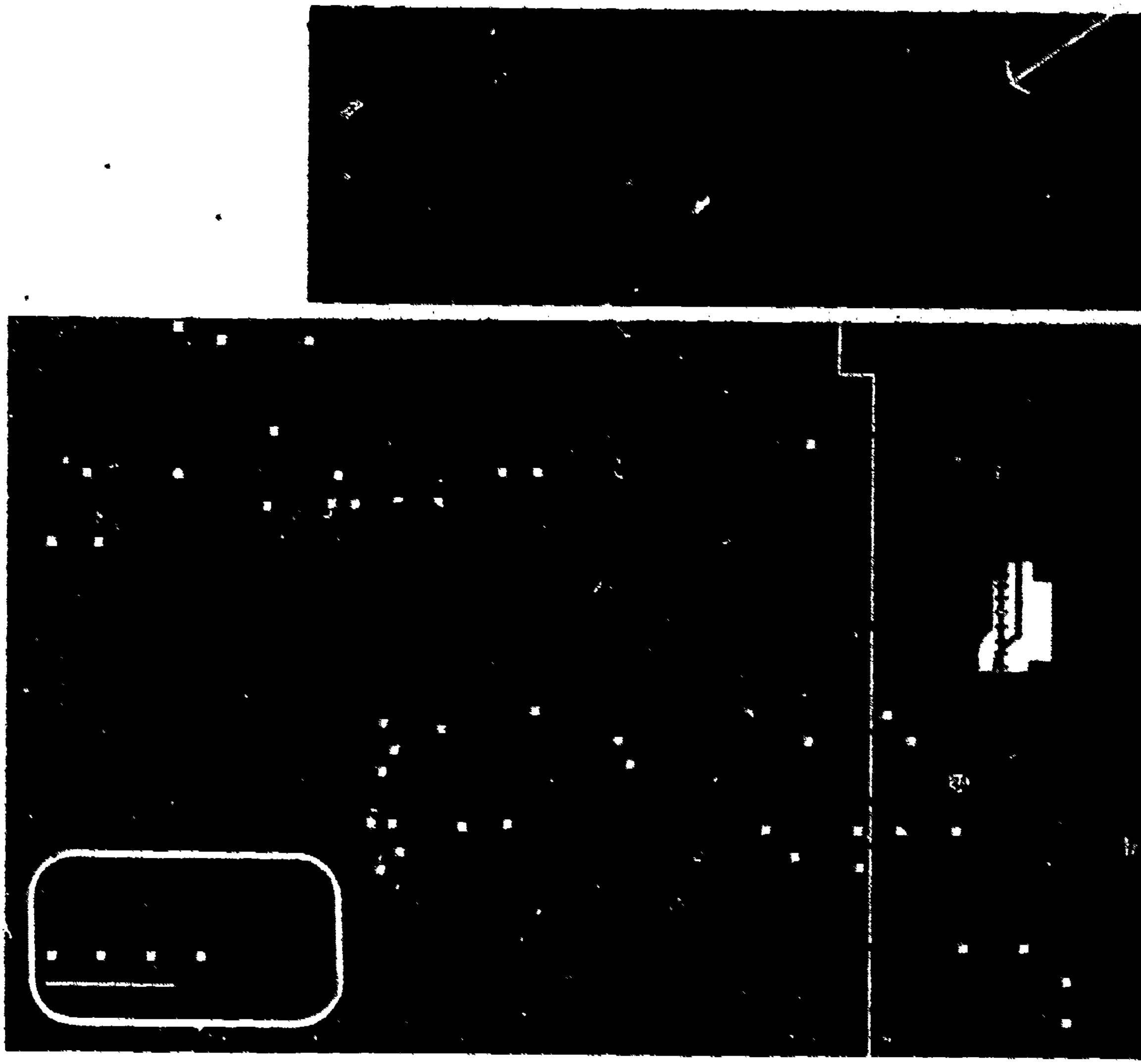


Figure 4. The Leedey meteorite broke up in the air. Its fragments were scattered for 18 kilometers.

In addition to finding the pieces of the Leedey meteorite, Monnig and Nininger attempted to find out as much as possible about the fall, including the direction of arrival. By talking to a dozen chance observers, mostly local farmers, they learned that a brilliant blue-white light, visible at first for over 200 kilometers, moved from the southeast to the northwest for several seconds. Near the end of this display came a loud explosion, and the glowing body was broken into a multitude of fragments, which turned from white to red as they fell toward the ground. Although the glowing fragments were scattered by the explosion, they continued in about

Figure 5 Drawing of a meteorite falling in France in the early 1800's

the same direction as the original body. A very large bright fragment seemed to continue farther than its companions. The actual fireball effect occurred for less than one minute, but a trail of dark dust remained behind until blown away by the wind.

The fall of a meteorite is certainly startling to those who see it (Figure 5). Such terrifying events are bound to become surrounded with a great deal of superstition and misconceptions. One such misconception is that a meteorite will be an intensely hot, dangerous object on the ground for quite some time after it falls. There is actually no record of a fallen meteorite setting anything on fire. A new-fallen iron meteorite may be just a little too hot to handle with comfort, a stone meteorite only warm. In fact, in 1917 a stone meteorite dug up in Wisconsin only minutes after it fell was so cold that frost formed on it in the hot July air.

This can occur because a meteorite traveling through outer space has a temperature many degrees below zero. In the few seconds it passes through the atmosphere, its surface is heated up thousands of degrees, melts, and is forced away as the meteorite falls. The surface is removed so fast that the great heat does not have time to penetrate very far into the meteorite. This principle is the basis for the heat shields on the re-entry capsules of spacecraft.

SHOOTING STARS AND METEOR SHOWERS

The first thoughts of a chance observer or finder of a meteorite are often not connected with its composition and features, but rather, "Where did it come from?" and "Why did it fall to earth?" Perhaps you will never see a large fireball, but away from the lights of the city, on almost any clear moonless night you can see "shooting stars." These momentary streaks of light are not really stars falling from the firmament; they are *meteors*, streaks of light caused by small specks of matter striking the atmosphere at high speed and "burning up" long before nearing the earth itself.

The word *meteor*, then, refers to the streak of light caused when the piece of matter heats up to incandescence in its passage through the atmosphere. The piece of matter itself is sometimes called a *meteoroid*. But if the meteoroid is large enough to survive the trip through the atmosphere and hit the earth, it is called a *meteorite*. A large, especially bright meteor is called a fireball or *bolide*.

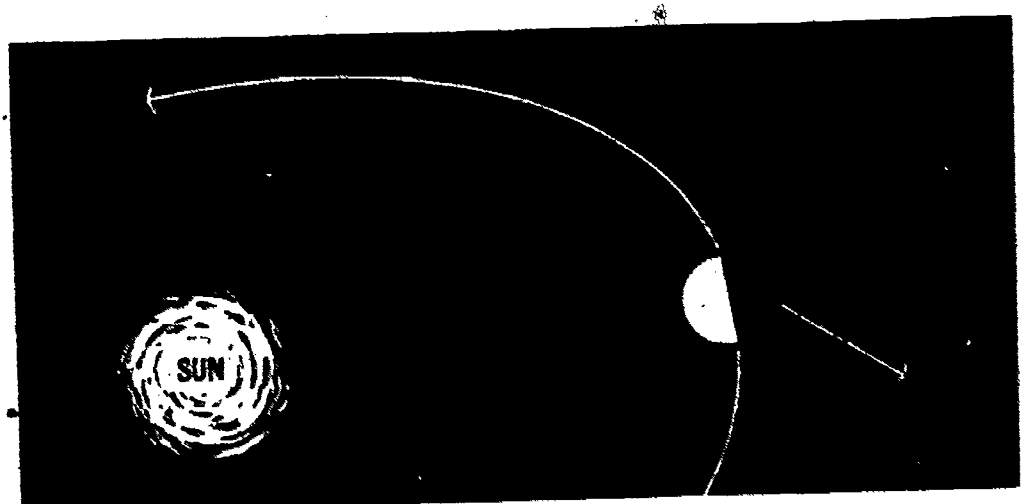
In 1798, two meteor-watching German students named Brandes and Benzenberg realized that, although they were standing several kilometers apart, each saw the same meteors—but in different parts of the sky. They realized then that meteors could not be either local lightning flashes or events taking place at great distances from the earth—as far

Figure 6. By comparing the angles at which they see a meteorite, observers A and B can figure out how far away it really is

away as the moon or the planets. Can you see from Figure 6 why they knew this?

On November 13, 1833, a great shower of meteors was seen in the Americas; it seemed to spread out from a point in the sky near the constellation Leo. Some observers realized that the particles must have been moving together through space before they hit the earth's atmosphere; otherwise they would have been more spread out. If the particles come into the atmosphere in parallel paths, they look as if they spread out from one point in the sky. This is called the *radiant* of a meteor shower and is illustrated in Figure 7. The radiant

Figure 7 Because the meteoroids that make up a meteor shower move toward the earth in parallel paths, they appear to spread out from one point, the radiant.



point in the sky is the direction from which a cloud of meteoroids approaches observers.

Meteor showers occur with great regularity several times a year. Some involve hundreds or thousands of brilliant meteors in the course of an hour or so. Table 1 shows the approximate dates each year when it is possible to observe some of these fireworks. Meteor showers are usually named for their radiant points; for example, the Orionid shower's radiant is in the constellation Orion.

Table 1. Some Annual Meteor Showers

Shower	Date of Maximum Visibility
Quadrantid	January 3
Lyrid	April 21
Eta Aquarid	May 4
Delta Aquarid	July 29
Perseid	August 12
Orionid	October 22
Taurid, North	November 1
South	November 16
Leonid	November 17
Geminid	December 12

Do meteors come from within the solar system or outside it? To find out, scientists had to know both the direction from which they entered the atmosphere and their velocity. The faster a particle hit the atmosphere, the brighter it would glow. In addition, the *bigger* the particle, the brighter it would glow and the longer it would last. The picture was further complicated by, the earth's motion (Figure 8). Meteors seen in the morning would be hitting the earth's atmosphere at their own velocity plus the velocity of the earth in its orbit around the sun. Meteors seen in the evening would be hitting the atmosphere at a smaller velocity—the velocity of the meteor *minus* the velocity of the earth in its orbit. The earth's motion also causes more meteors to be seen in the morning than in the evening, for the same reason that more bugs hit a car's windshield than its rear window.

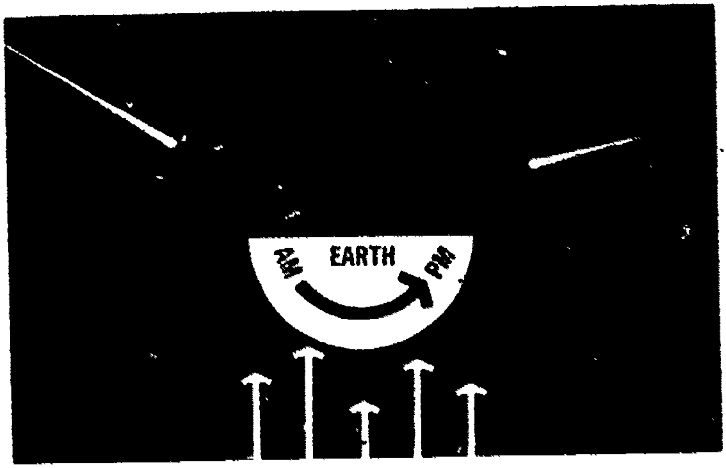


Figure 8 Meteoroids moving in the same direction as the earth have to catch up with it and come down relatively slowly. Those moving in the opposite direction have head-on collisions and come down relatively fast

Not until the development of modern photographic techniques were astronomers able to determine precise velocities for meteors. Before photography, the position, intensity, and duration of meteors all had to be estimated.

A time-exposure photograph taken through a large telescope will show streaks due to meteors that have passed. If you take a camera far from street lights on a clear, dark, moonless night and leave it pointing upward with the shutter open for an hour or so, you will get the same results. In fact, one of the largest photographic studies of meteors was undertaken by astronomers of the Harvard Observatory in just this way. By counting the streaks, the Harvard meteor patrol could estimate the total number of meteoroids coming into the earth's atmosphere every hour. More recently, it has been discovered that radar will detect meteors both day and night. Allowing for the fact that the camera and the radar can see only a small portion of the sky, it is estimated that over twenty million meteoroids strike the earth's atmosphere every 24 hours. Very few of them are large enough to reach the earth's surface as meteorites. Very small fragments are often called *micrometeorites* and have been collected from Antarctic ice and deep-sea cores. It has been estimated that over one thousand tons of meteorites, micrometeorites, and cosmic dust arrive on the earth each day. While this amount may appear large, at this rate of collection during the entire four to five billion-year history of the earth it would have formed a layer of dust only about 30 centimeters deep. On the active earth this material is constantly being transformed by erosion and mountain building.

Radar measurements and earlier photographic investigations allow accurate tracks of the meteoroids through the atmosphere to be calculated. On the basis of these observations, Fred Whipple at the Harvard Observatory calculated that most meteors, including shower meteors, have orbits similar to those of comets. In fact, he was able to calculate that many of the meteor showers have the same orbits as known comets. This led him to explain shower meteors as the "dust trails" of comets.

As the comet speeds along its elongated elliptical orbit, small particles may break off the solid head and eventually be spread out thinly along its path. Thus each year when the earth, in its orbit around the sun, runs into the comet's orbit, the fine particles will strike our atmosphere and be seen as meteor showers (Figure 7). Other meteors may be the lost remains of very old comet trails or stray particles pulled from their regular paths by the gravitational attraction of the planets.

About 10 to 15 percent of the meteors studied do not seem to fit the comet pattern. A very small number appear to be going so fast that they cannot be traveling in elliptical orbits like the comets; these may be intruders from other parts of the universe. The rest appear to have orbits similar to those of asteroids and may, in fact, be asteroid fragments. The *asteroids* are small planetlike bodies which revolve around the sun in orbits between those of Mars and Jupiter. Most show quite circular orbits, but some move in quite close to the sun. These bodies range in size from about 770 kilometers in diameter for Ceres, the largest known asteroid, to below the limits of detection of our largest telescopes. There are probably many thousands of tiny particles in the asteroid region of the solar system. Many asteroids large enough to be studied show quite circular shapes, while others are quite angular, perhaps from collisions with other asteroids. Such collisions are known to occur often enough to explain the odd-shaped bodies. Collisions and the pull of gravity of the planets, especially the large planet Jupiter, may move asteroids into orbits crossing that of the earth. Since material arrives on the earth from the region of the asteroids and the far-reaching comets, meteorites may be fragments of either asteroids or comets or both.

Since most meteorite falls are not observed by astronomers able to calculate orbits, orbit identification based on chance observations is quite questionable. But imagine the excitement when in 1959 the fall of a fireball was photographed entirely by chance by two astronomical observatories about 50 kilometers apart near Pribram, Czechoslovakia. From the photographs astronomers were able to tell not only the speed and orbit of the meteoroid, but also how much material had been burned off in its flight through the atmosphere. The position of the meteorite was easily located. It was a stony meteorite similar to the one found near Leedey, Oklahoma. The orbit calculated for the Pribram meteorite indicated that it came from the asteroid belt, supporting the earlier ideas that this region of our solar system is a source of meteorites. Until a recovered object is actually shown to have a cometlike orbit, comets cannot be proved to be sources of meteorites. No meteorite has ever been recovered during a display of shower meteors.

In January, 1970, observers were able to determine the orbit of another meteorite as they did the Pribram stone. This was made possible through the Prairie Network, a grid of cameras about 300 kilometers apart over the middle of the United States set up by scientists from the Smithsonian Astrophysical Observatory (Figure 9). Each station has five cameras, one pointing in each direction of the compass and one straight up. The approaching

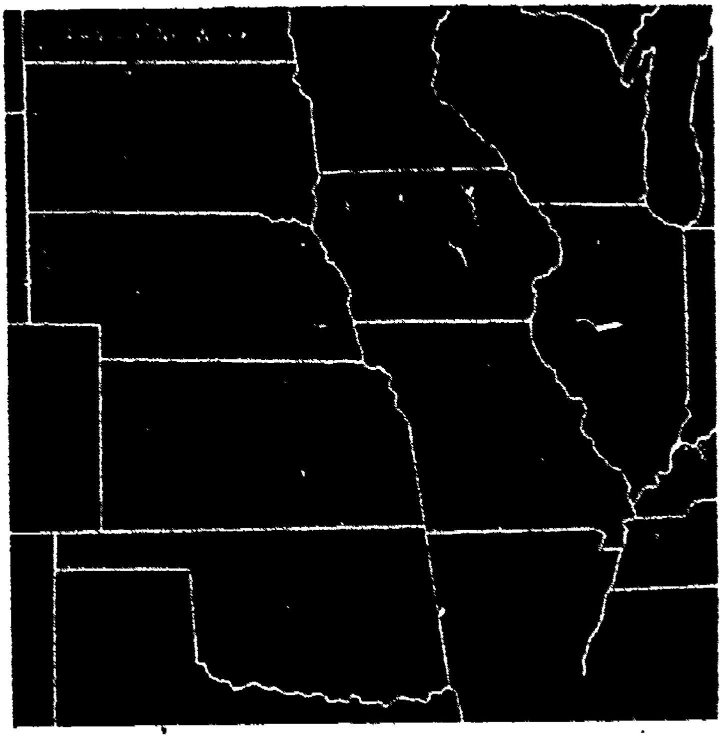


Figure 9 The Prairie Network is a grid of cameras set up to track meteorites

fireball triggered a photoelectric cell on the cameras and took its own picture several times in a timed sequence. Photographs from two stations enabled the scientists operating the Prairie Network to estimate the impact point of the meteorite. The largest piece of the meteorite and an additional fragment were recovered near Lost City, Oklahoma. The calculated orbit for this meteorite is shown in Figure 10.

CRATERS

Over the years since the Ensisheim fall, many people have witnessed the fall of meteorites like the Leedey meteorite that have broken up in the air and spread stones over a wide area. Sometimes stony-iron meteorites have been seen that landed in one piece. The largest single stone meteorite yet found in one piece fell in a cornfield in Kansas. Its one-ton mass punched a neat hole in the ground

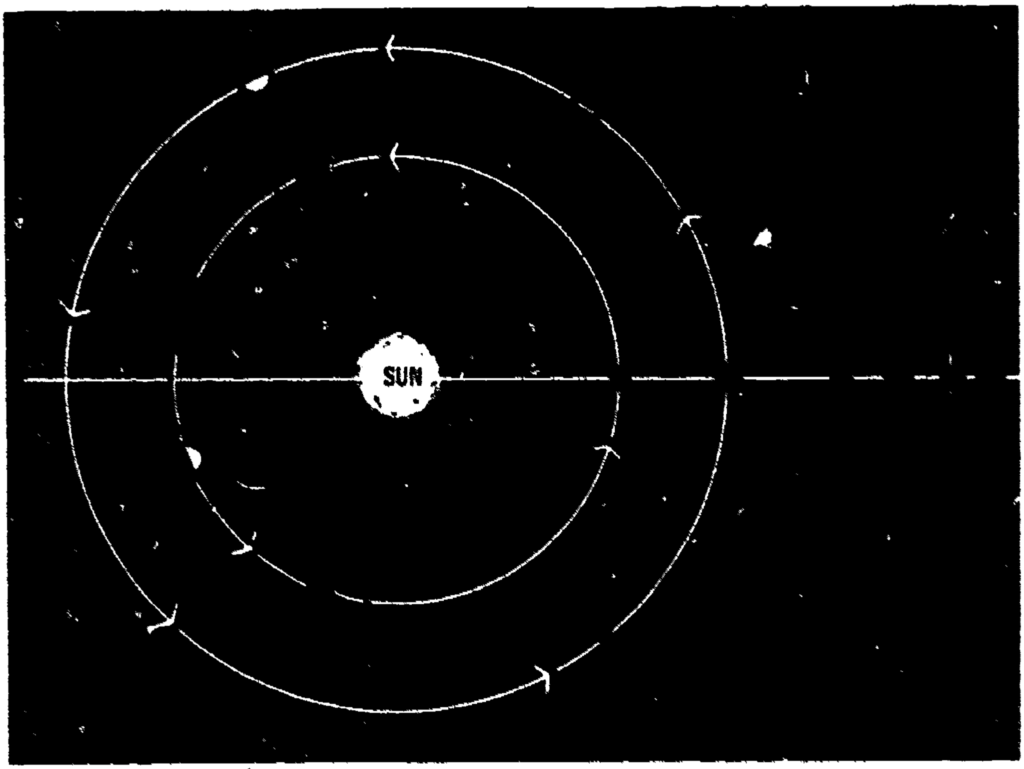


Figure 10. The photographs of the fall of the Lost City meteorite taken by the Prairie Network enabled the Smithsonian Astrophysical Observatory to calculate that the meteorite came from the asteroid belt.

about three meters deep and one meter in diameter. The largest iron meteorite fell near the Sikhote-Alin Mountains in eastern Siberia in February, 1947. This gigantic meteorite broke up in the air (Figure 11) and showered the swampland with more than 300 fragments, the largest one weighing about 1700 kilograms. A total of 13 tons of material was recovered from craters produced on impact. This iron meteorite broke up because it contained zones of a brittle material called *schreibersite*, a compound of iron, nickel, and phosphorus. If the meteoroid had held together, a small explosion crater might have been formed and most of the meteorite been lost forever.

Siberia had also experienced an even larger event in 1908. A gigantic fireball produced an explosion near the Tunguska River that broke windows over 100 kilometers away. The blast of air from the explosion was even recorded on barographs (devices that record air pressure) as far away as London.

England. For several nights afterward, people in Europe and Asia enjoyed especially beautiful sunsets caused by the lingering dust and smoke from the explosion.

In 1921 a Russian scientist, L. A. Kulik, organized an expedition to go to the remote region and search for the meteorite. The scientists were able to find its position deep in the forest by locating burned and devastated trees (Figure 12). These trees were uprooted or broken off in an area about 50 kilometers in diameter. They had fallen outward from the probable point of explosion. Near the center the trunks of some trees still stood, burned, dead, and stripped of their branches. The effects of the blast were visible 200 kilometers from the center, and it has been estimated that the mass that fell must have weighed hundreds, if not thousands, of tons.

Figure 11 Russian stamp showing a drawing of the fall of the great Sikhote-Alin iron meteorite Note the great trail of dust and smoke following the fireball

Figure 12 Schematic representation of the area devastated by the Tunguska meteorite in Siberia in 1908 Black lines enclose areas with different degrees of devastation, with greatest damage in the center Arrows representing trees indicate their line of fall

The scientists found at least ten craters that measured from 10 to 50 meters across. In one of these, they found pulverized rock and quartz that had been fused and contained small grains of nickel-iron.

These relatively small craters are among the smallest explosion craters ever found, and they are so out of proportion with the reported size of the blast that scientists had a difficult time explaining them. Recent work has shown that a gigantic object probably exploded in mid-air. If it was the core of a comet made up mostly of frozen gases, it would have been completely vaporized by such an explosion, with only a little dust settling to the ground.

THE ANATOMY OF METEORITES

Although the studies by astronomers have revealed a great deal about meteorites, they have also raised a number of questions, the answers to which must come from chemists, mineralogists, and physicists.

Meteorites are classified into three basic groups: the irons, the stones, and the stony-irons. Many people when they hear the name "meteorite" think immediately of the large masses of iron displayed at museums and planetariums throughout the country. In fact, it is true that many museums house more iron meteorites than the two other types. Iron meteorites are often large and, since they are difficult to damage, they are put out for visitors to inspect. But Table 2 tells a different story. When the meteorites seen to fall and then recovered are compared with those found on the ground, you can see that by far the most common meteorites to fall are the stones; irons are the next most common, and stony-irons are relatively rare. On the other hand, you would be much more likely to recognize an iron, or even a stony-iron, than you would a stony meteorite if you were hunting for them.

Table 2. Types of Recovered Meteorites

	Falls	Finds	Total
Irons	42	503	545
Stony-irons	12	55	67
Stones	628	304	932
Total	682	862	1544

Nearly anyone who found a piece of metal like the irons or even the stony-irons would recognize it as a meteorite or at least as a rather peculiar object. On the other hand, it takes some knowledge of geology to differentiate between a stony meteorite and a normal rock. Furthermore, the irons take a long time to rust away, perhaps because of their high nickel content, while the stony meteorites are much less resistant to the effects of weathering. So it is not really surprising that most of the "finds" are irons.

As you can also see in Table 2, only a few hundred meteorites have been seen falling and then located. In fact, it is very rare to see a meteorite fall. Fortunately, it is even rarer that anyone gets hit. Only one person is on record as being hit by a meteorite, and she was not seriously hurt.

Iron Meteorites

Iron meteorites (Figure 13) consist of nickel and iron in amounts that vary from meteorite to meteorite, as well as small and varying amounts of other elements such as cobalt, phosphorus, sulfur, carbon, and chromium. There is proportionately much more nickel in an iron meteorite than is found in terrestrial rocks or most man-made steels. The nickel content may be anywhere from 5 percent to 60 percent of the total material.

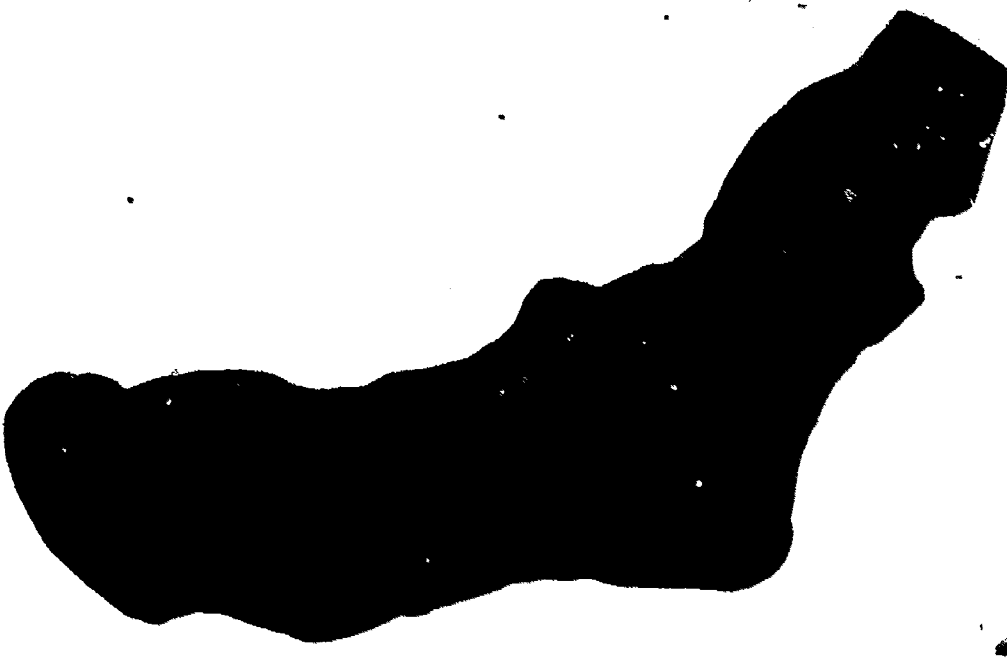


Figure 13. The Bald Eagle, Pennsylvania, iron meteorite. The holes or "thumbprints" may have formed where inclusions of the soft mineral troilite (Figure 15) were removed by atmospheric friction.

When an iron meteorite is studied, it is often cut, polished, and etched with acid. When most iron meteorites are etched, a curious and beautiful pattern called the Widmanstatten figure emerges. The *Widmanstatten figure* (Figure 14) is a network of bands crossing one another in a regular pattern. The bands are formed by two minerals or alloys making up the meteorite. One of these minerals, called *kamacite*, contains about 6 percent nickel. It makes up the wide bands seen in Figure 14A.

These kamacite bands are separated from each other by thinner bands of *taenite* that have over 12 percent nickel in them. Metallurgists studying meteorites have shown that the iron meteorites were originally molten. As the molten metal cooled, it solidified into large metallic crystals. Over millions of years the solid crystals cooled very slowly and the iron and nickel atoms slowly moved through the crystals to develop the Widmanstatten pattern. The plates of this pattern grew parallel to the faces of an eight-sided figure called an octahedron, and iron meteorites with the Widmanstatten pattern are called *octahedrites* (Figure 14B).

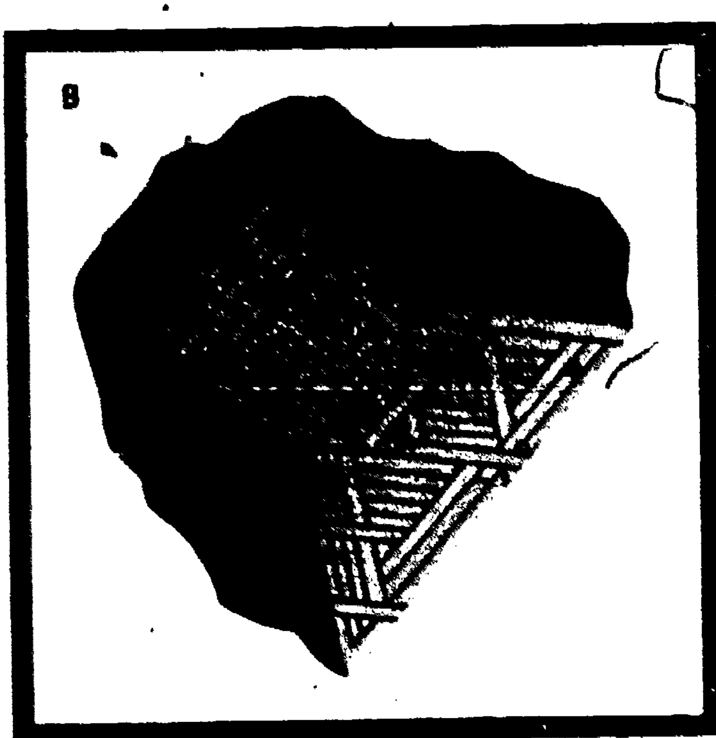


Figure 14. (A) Close-up of the Widmanstatten figure on a cut iron meteorite. Bands of low-nickel kamacite are bordered by high-nickel taenite. (B) Diagram of an octahedrite, showing the Widmanstatten figure.

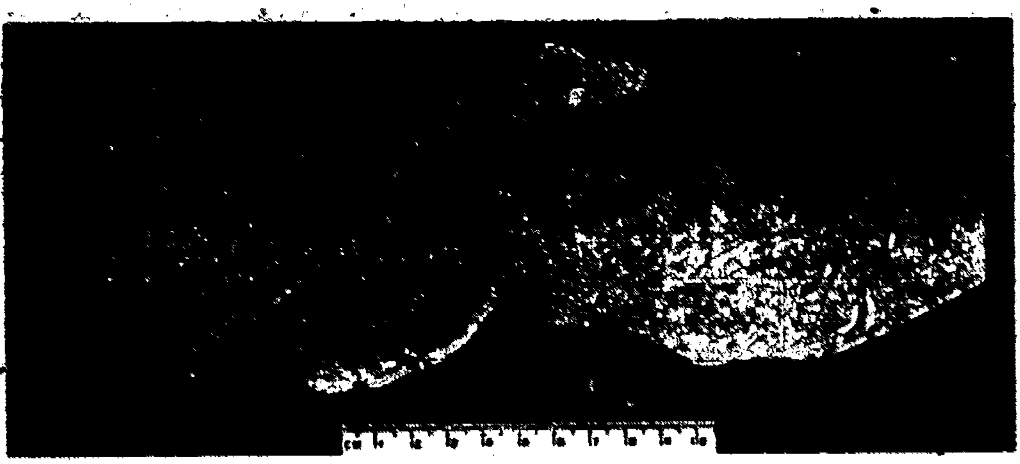


Figure 15. Polished slice of the Bella Roca iron meteorite. To show the Widmanstatten figure, the surface has been etched with dilute nitric acid, which attacks the low-nickel kamacite plates more rapidly than the taenite. The large dull areas are troilite (FeS), which is not soluble in molten nickel-iron.

If an iron meteorite contains less than 6 percent nickel, only kamacite will form. Meteorites made up of this single mineral phase are called *hexahedrites*. If the meteorite contains more than 12 percent nickel, only taenite is formed. Such meteorites are called *ataxites*.

Some iron meteorites contain still other minerals. It is common to see a brown mineral called *troilite* (Figure 15). This mineral is made up of iron and sulfur. It differs from the common mineral iron pyrite, or "fool's gold," by having only one sulfur atom for each iron atom instead of two. While meteorites have no chemical elements in them that are not found on the earth, many iron meteorites contain two unique minerals. These are *schreibersite*, a compound of iron, nickel, and phosphorus, and *cohenite*, made up of iron, nickel, and carbon.

One of the most interesting minerals found in iron meteorites is diamond. The Canyon Diablo meteorite found near the Barringer Meteorite Crater, Arizona, for example, contains many diamonds. Since diamonds require very high pressures deep in the earth to make them, scientists thought for many years that iron meteorites containing diamonds must have come from the core of a broken-up planet. It has recently been demonstrated that diamonds may also be made from carbon by rapid, intense shock waves. Sufficiently strong shock waves may occur in large meteoroids on impact with the earth or with each other in space. This alternative method for producing diamonds in meteorites is important, for it does not require that the meteoroids be formed by the breakup of a planet. There is some evidence that the meteoroids, and therefore the asteroids, have always been smaller bodies.

Stony Meteorites

Stony meteorites are composed of minerals similar to those found on the earth, the silicates, which because of their abundance are often called "the rock-forming minerals." All silicate minerals contain the chemical elements silicon (Si) and oxygen (O). These are combined with other abundant elements—magnesium (Mg), iron (Fe), aluminum (Al), calcium (Ca), and sodium (Na)—to form different mineral phases. Although all the other chemical elements are found in stony meteorites, they

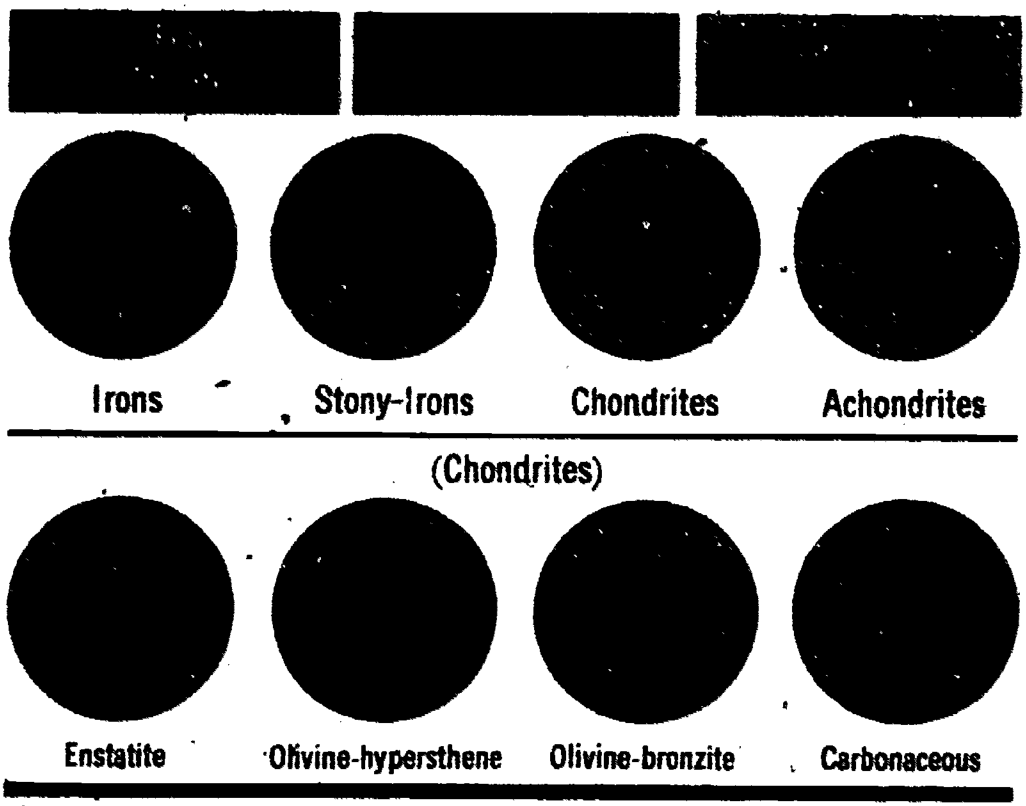


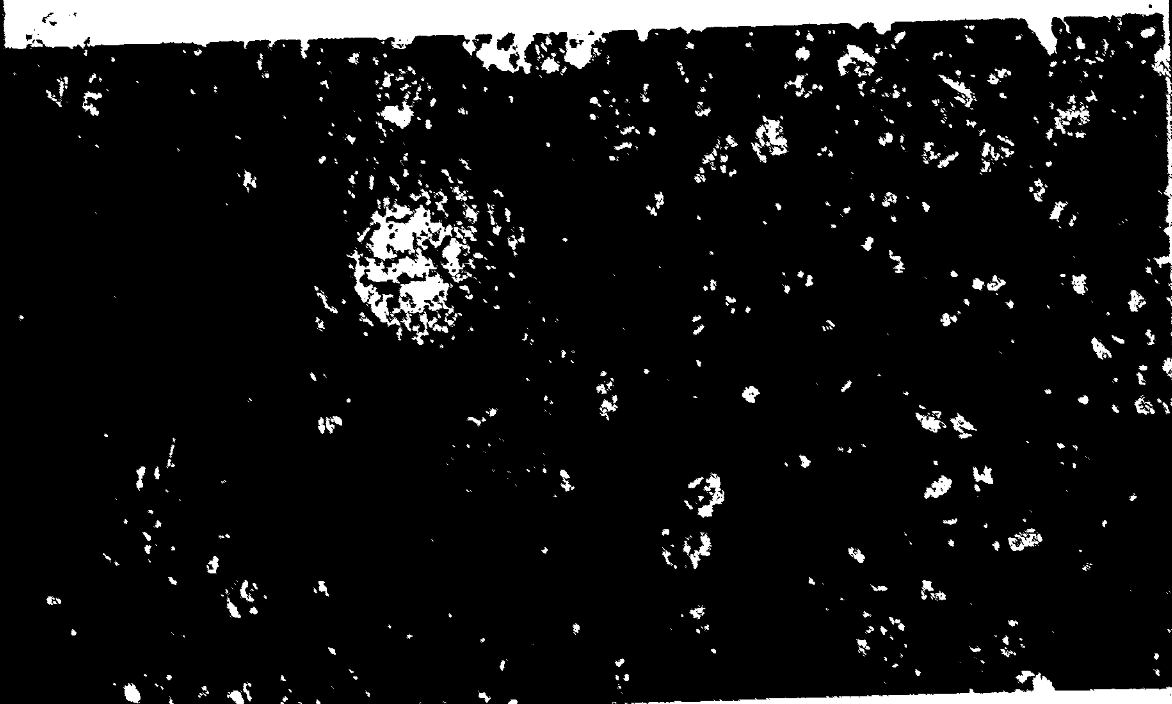
Figure 16. Mineral makeup of the different types of meteorites.

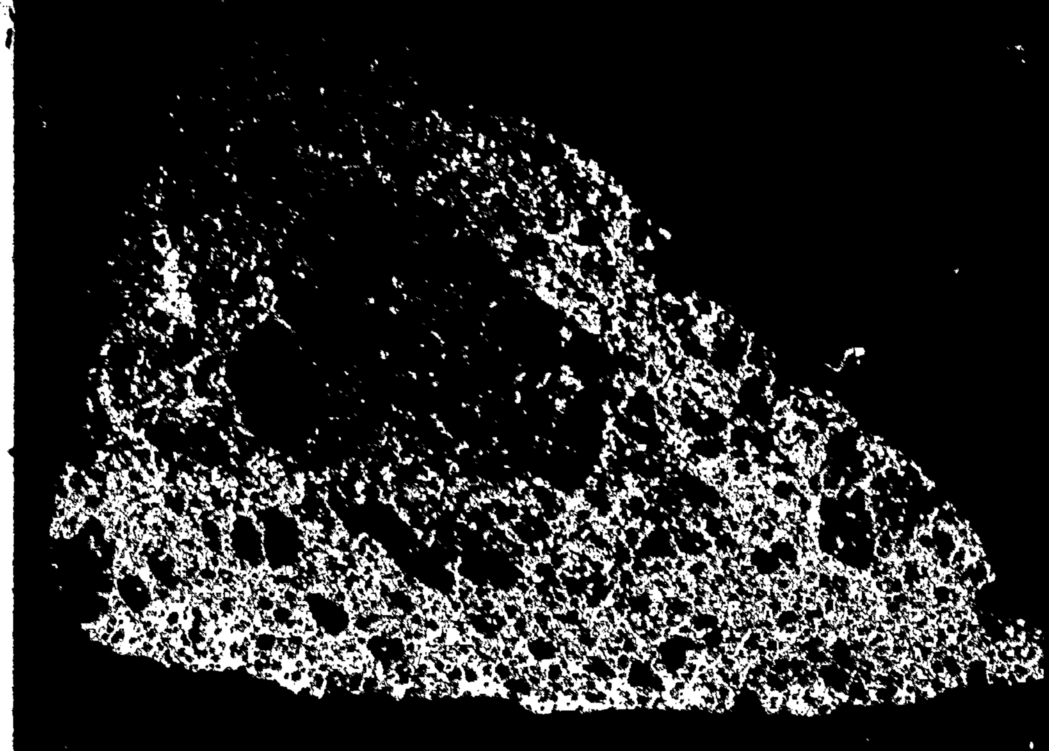
are much less abundant than those mentioned here. The most common minerals found in the stony meteorites are olivine [$(Mg,Fe)_2SiO_4$], pyroxene [$(Mg,Fe)SiO_3$], and plagioclase feldspar [$(Ca,Na)(Al,Si)_2Si_2O_8$]. Various other minerals are also found in stony meteorites, including nickel-iron and troilite (Figure 16).

The stony meteorites are not only the most abundant type, but they also have the greatest variety in composition, color, and structure. They are divided into two groups on the basis of their structure, the chondrites and the achondrites. The *chondrites* are made up of small spherical lumps of silicate minerals or glass called *chondrules* (Figure 17) held together by a fine-grained cement or matrix. In some of them nickel-iron is quite abundant; in others it is absent. All contain iron sulfide. An important feature of all chondrites is that although their mineral makeup, color, and number of chondrules may vary, all are similar in their total chemical composition.

The *achondrites* (Figure 18) do not have chondrules in them; their textures are, instead, similar

Figure 17. Microscopic view of a very thin slice of a chondrite. Note the round chondrules in a fine-grained matrix. The black areas contain nickel-iron and troilite.





to those of common volcanic rocks, especially basalts. Achondrites appear to have formed when molten rock cooled to form crystals. Often they show the effects of a violent event that shattered and crushed their minerals.

Figure 18. Cut and polished piece of the Johnstown, Colorado, achondrite. This meteorite contains no chondrules but is made of fractured crystals of a silicate mineral. There are almost no metal fragments.

The chondrites have been the most interesting as well as the most perplexing to scientists. They are the most abundant type of meteorite. They have been shown by radioactive dating to be the oldest rocks in our solar system and seem to have changed little if at all since their formation 4.5 billion years ago. But the origin of the chondrules is still an unsettled problem. Some scientists prefer a theory of origin involving the formation of molten droplets from a silicate net. Others favor a direct formation from a cool dust cloud. A clear understanding of the origin of meteorites and the earth and other planets depends on a satisfactory theory for the origin of chondrules.

It is possible to develop a model by which all the other types of meteorites—irons, achondrites, and stony-irons—can be derived from a melted chondrite.

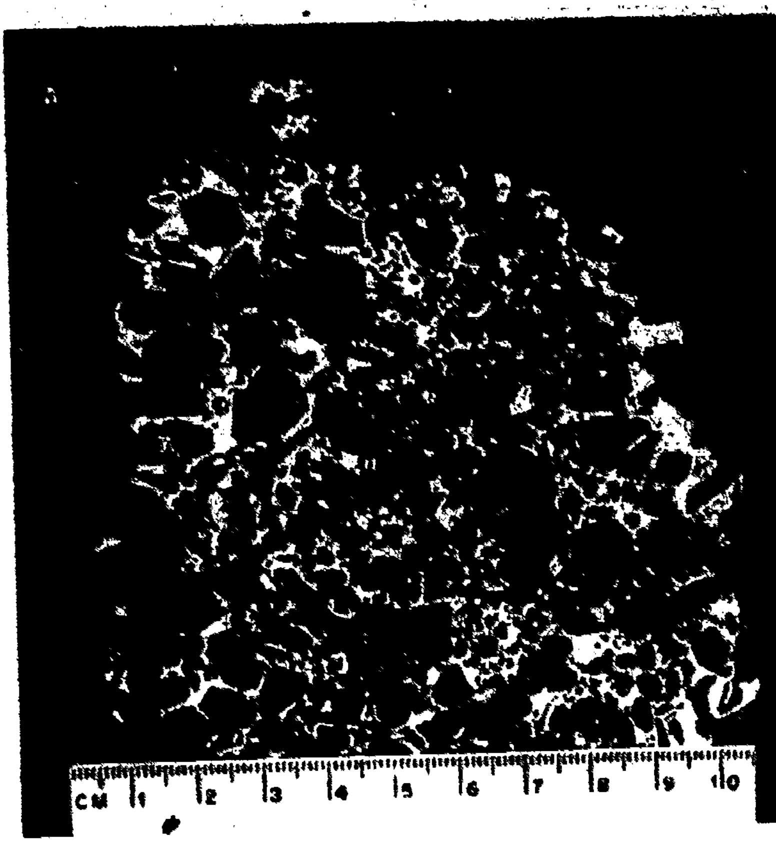


Figure 19. Stony-iron meteorites, cut and polished. (A) Pallasite, consisting of fragments of the mineral olivine in bright nickel-iron. (B) Mesosiderite, in which flecks of nickel-iron are imbedded in stone.

Stony-Irons

The stony-irons, like the stony meteorites, come in two varieties. Both are about half nickel-iron and half silicate material. The *pallasites* are meteorites made up of a network of nickel-iron in which olivine crystals are distributed (Figure 19A). Many of their properties seem to relate them closely to the iron meteorites. The *mesosiderites* appear to be mixtures, or breccias, made up of iron-nickel fragments imbedded in stony material (Figure 19B). There is some evidence that they have been formed by mixing pallasites with achondrites, a very curious combination indeed.

Carbonaceous Chondrites

In 1806, near the French town of Alais, the first representative of a very unusual type of meteorite was observed to fall. It was a sooty-black, soft stone that appeared to have a high concentration of some form of carbon. Since 1806 fewer than 25 of these rare meteorites have been recovered. They are the *carbonaceous chondrites* (Figure 20). Their

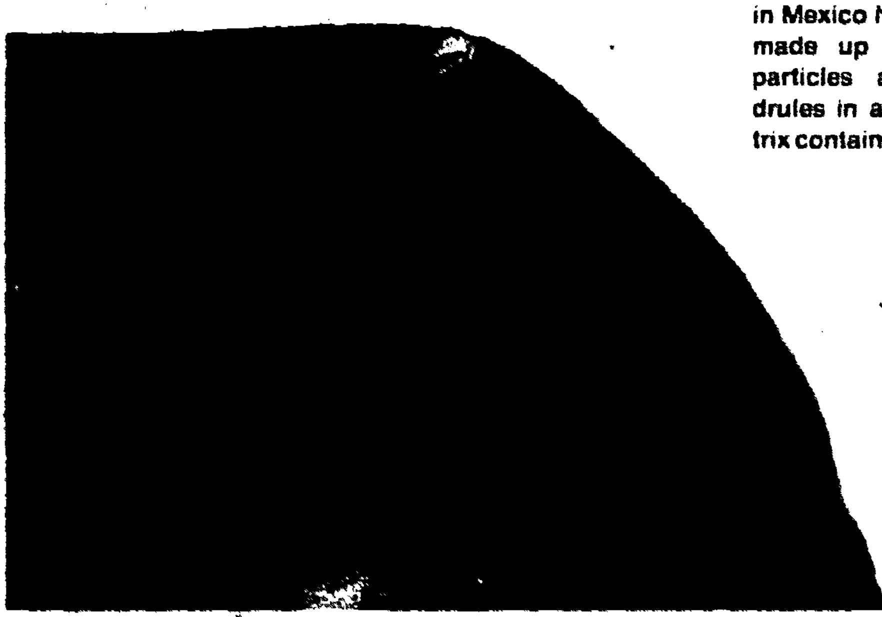


Figure 20. Slice of the Pueblito de Allende carbonaceous chondrite, which fell in Mexico in 1969. It is made up of silicate particles and chondrules in a black matrix containing carbon.

chemical composition is similar to that of the common chondrites except that they contain carbon compounds and water-bearing silicate minerals. Some of them have noticeable chondrules in their structure, but others appear to be just homogeneous black claylike objects. As early as 1839, the Swedish chemist J. J. Berzelius investigated the carbonaceous chondrite Alais and discovered that the carbon compounds in it resembled the organic compounds found in decaying living matter. This immediately raised the question of whether these meteorites came from a parent body upon which living material existed. Berzelius decided they did not. The name "organic matter" does not need to imply that it must come from living organisms. Scientists have shown in the laboratory that it is possible to produce organic compounds from inorganic chemicals. In fact, a famous experiment performed by S. L. Miller and Harold Urey produced organic molecules similar to some found in living things by passing an electrical spark through a mixture of the vapors of hydrogen, ammonia, methane, and water. The mixture had been chosen to represent the possible atmosphere of the primitive earth. Such reactions may have produced the organic compounds in the carbonaceous chondrites.

Starting about 1960, scientists have been intensely studying the organic material in the carbonaceous chondrites. There seems little question that the carbon compounds exist, and that they show some amazing similarities to the organic molecules making up living systems. But the question still remains: How did they get there? If they are the remains of life, perhaps carbonaceous chondrites contain some fossil remains. Although some biologists have found what they think are microscopic fossils, their existence is not generally accepted.

The study of these interesting rare meteorites is still going on. Perhaps the answers to these questions must wait for further study of the surfaces of the moon and Mars or until samples of more carbonaceous chondrites are obtained. Carbonaceous chondrites may quite possibly fall more commonly than thought, but their softness, lack of resistance to weathering, and inconspicuous appearance would make them less apt to be collected.

AGES OF METEORITES

In order to write an accurate history of meteorites, it is necessary to know not only what happened, but also when. Physicists and geochemists have been able to learn more about the "whens" in the history of meteorites by studying the isotopes in them. *Isotopes* are atoms of the same element with a different number of neutrons; if these isotopes decay or break down by giving off energy or particles, they are called *radioactive isotopes.*

Scientists have found radioactive isotopes of such elements as potassium, uranium, rubidium, thorium, and carbon in meteorites. Atoms of these isotopes, such as potassium-40 (K^{40}) and uranium-238 (U^{238}), decay into atoms of other elements. By

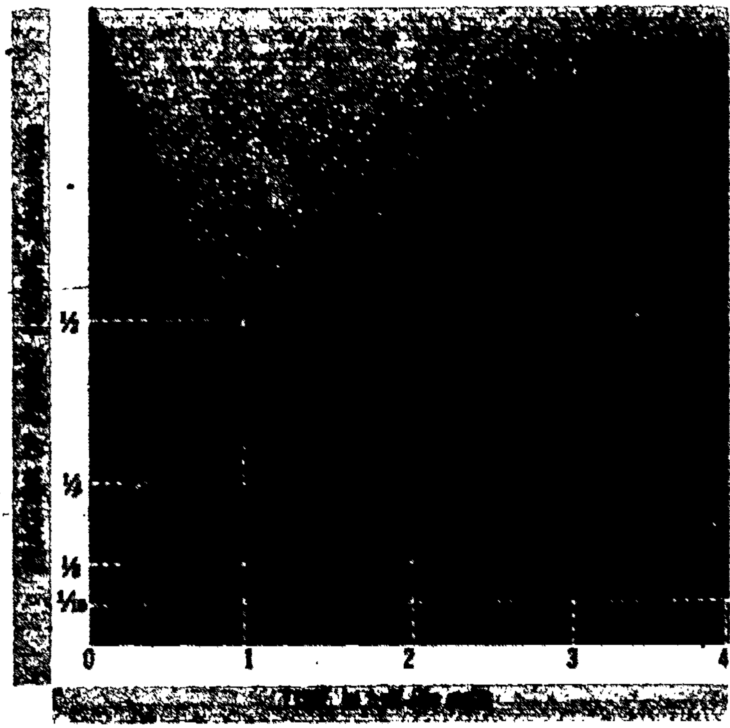


Figure 21. Decay of a radioactive isotope into its daughter isotope. Half-life is the amount of time it takes for half of the existing parent atoms to decay.

measuring the relative amounts of these isotopes and their decay products (Figure 21), the age of the meteorites can be determined. Using these "atomic clocks," scientists have determined that meteorites formed about 4.5 billion years ago. If collisions, heating, or other catastrophic events took place during the history of a meteoroid, these atomic clocks may read incorrectly. Careful studies of the isotopes in meteorites may indicate when such events took place.

Isotopic changes in atoms may also take place if they are bombarded by high-energy particles. Such particles exist in outer space in the form of *cosmic rays*, and physicists can detect these isotopic changes in meteorites with instruments called mass spectrometers. Meteorites that have been

Figure 22. Craters on ...moon. Note the ... of sizes.

traveling in space for long periods of time and continuously bombarded by this high-energy radiation are thus cosmic ray meters. By carefully studying the isotopic changes, physicists may tell how long a meteoroid has existed as a small body, in other words, the time at which it broke off from a larger body. The cosmic ray exposure ages show some interesting variations. Meteorites of the same type seem to have broken up at about the same time and probably came from the same parent body. The iron meteorites broke off in two events, one 600 million years ago and one 900 million years ago. The chondrites seem to be much younger. They were formed by a number of separate breakups about 25,000 and 3 million, 4 million, 10 million, and 25 million years ago. This may mean that the meteoroids arriving on the earth were formed in a few major collisions rather than by a string of smaller ones.

THE MOON, CRATERS, AND TEKTITES

A major feature of the bleak lunar surface is the large number of craters (Figure 22), caused by a constant bombardment of meteoroids not hindered by an atmosphere. Close-up photographs from lunar probes have revealed small craters and pits within larger craters, which are in turn within even larger craters. One of the largest is Clavius with a diameter of 233 kilometers. Its rim is about 1500 meters above the surrounding surface and 4500 meters above the crater floor. The prominent crater Copernicus is about 80 kilometers in diameter. The Mariner IV probe has found similar evidence of meteorite impact on Mars.

To prepare to study lunar craters, astrogeologists first looked in great detail at the few recognized craters on the earth. The best-preserved is the Barringer Meteorite Crater in Arizona (Figure 23).

Figure 23. Aerial view of the Barringer Meteorite Crater near Winslow Arizona. The crater, formed by a large iron meteorite about 20,000 years ago, is about 1.6 kilometers in diameter and 200 meters deep.

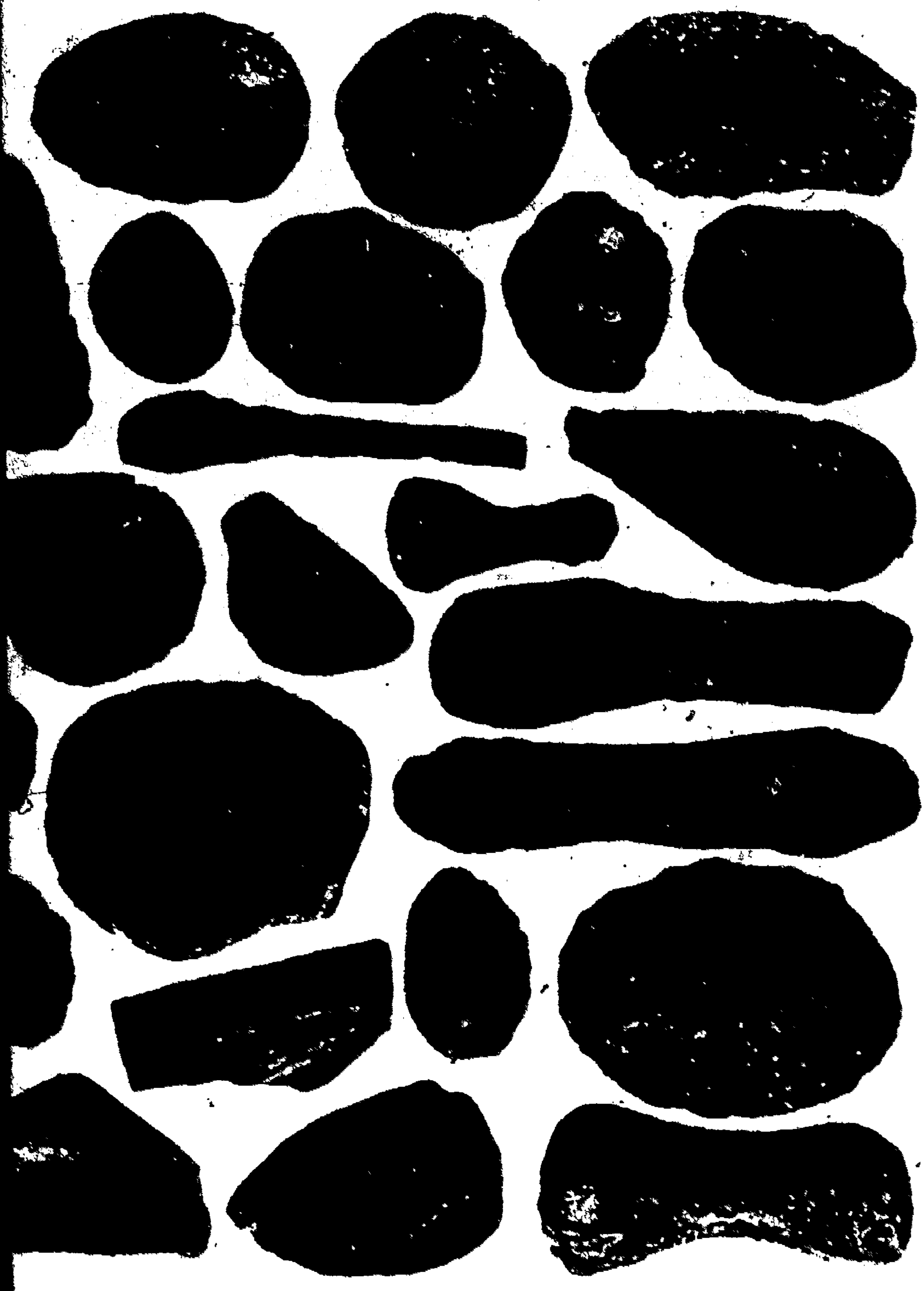
In the early 1900's, a mining engineer from Philadelphia named D. M. Barringer became convinced that the crater had been formed by the impact of a colossal meteorite. However, although he drilled several holes hundreds of meters down into the limestone and sandstone beneath the crater, he was unable to find the meteorite. The origin of the crater continued to be disputed for many years.

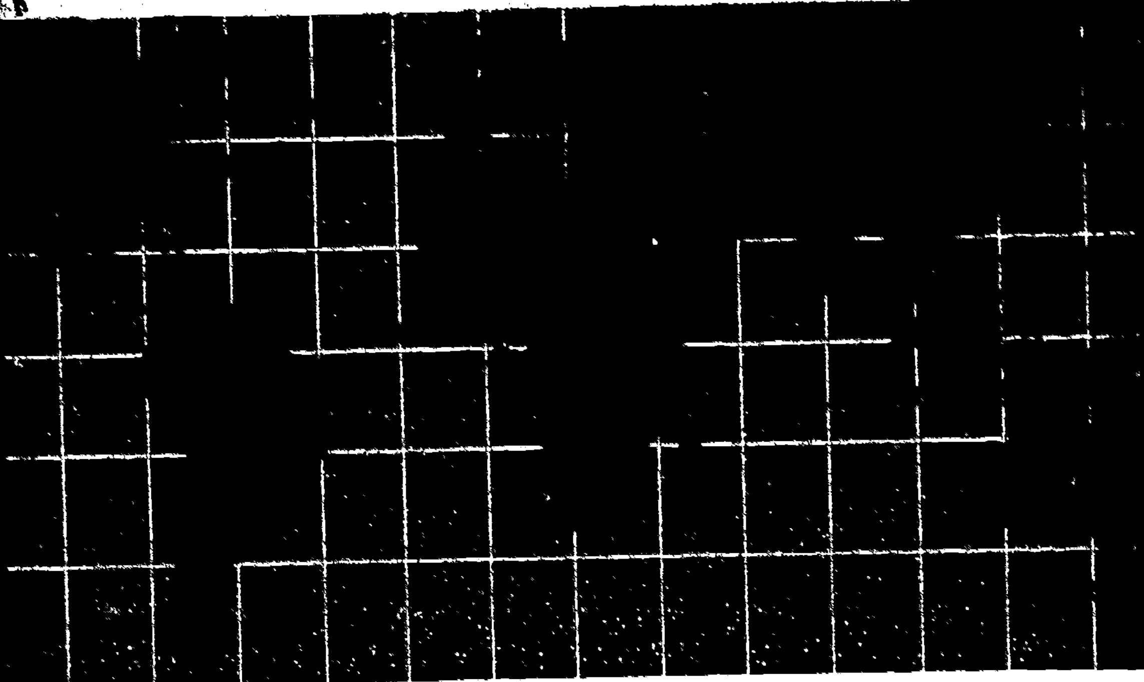
Then, in 1960, in the crushed sandstone at the bottom of the crater, E. T. C. Chao of the United States Geological Survey found a mineral that has never been found on earth outside the laboratory—a form of silicon dioxide (SiO_2) which can form only under tremendously high pressures. This mineral has been produced in the laboratory by subjecting common quartz to extremely high pressure. Found in nature only at meteorite craters, this mineral *coesite* is now considered a reliable indication that a crater was produced by a meteorite.

The meteorite that caused the Barringer Meteorite Crater probably weighed about two million tons and measured 25 to 60 meters across—far too large to be slowed by atmospheric friction. It must have struck the earth at a speed of about 50,000 kilometers an hour, causing an explosion equal to the force of a giant hydrogen bomb. Only fragments of this huge body were not vaporized; they were scattered about on the plain or squeezed into the rock deep beneath the crater. The compression caused by this terrific impact is thought to have been sufficient to produce the diamonds in the surviving fragments.

In recent decades interest in giant craters has grown rapidly, and greater efforts to locate them have, not unexpectedly, turned up a considerable number. Aerial photography, used especially in Canada, has proved to be a highly useful tool. In all, more than 40 giant craters can now definitely be attributed to the fall of meteorites. A large suspected crater is the Vredefort Crater in South Africa, with a diameter of 40 kilometers—more than 33 times that of the Barringer Crater in Arizona. More huge explosion craters will probably be identified in the future. Many that must have existed long ago, however, have been obliterated by erosion and weathering. Were it not for the steady destruction by weathering of the signs of old meteorite falls, the surface of the earth might very well look more like the pockmarked moon, where there is neither water nor weather as we think of it.

Some scientists have long believed that when large meteoroids collide with the moon, fragments are thrown off into space and some may be pulled to the earth. Perhaps these moon samples are already in our meteorite collections. This idea is being tested by the scientists analyzing the material brought back from the lunar surface by the Apollo astronauts. Some scientists think that basaltic achondrites may be from the moon because they are similar to the first lunar surface chemical analyses sent back by the Surveyor vehicles. Others say that any material blasted from the surface would be melted into glass, unlike the achondrites, which are crystalline. This hypothesis is supported by the large amount of glass found on the moon's surface.





Also, sprinkled around the earth's surface are interesting small glassy objects called *tektites* (Figure 24).

Tektites often have unusual shapes like dumbbells, teardrops, and little buttons. Although they look much like pieces of obsidian, a rock formed in volcanoes and lava flows, they are chemically different. They can be found in places such as Australia and Texas, far from any volcanic activity (Figure 25).

Tektites have never been seen to fall. On the basis of their distribution and the small nickel-iron spheres they contain, many researchers think they are material splashed from large meteorite craters on earth. The slaglike material around the Barringer Meteorite Crater does not at all resemble tektites, but it is thought that tektites are the splashes from much larger impacts than the ones that produced it.

Figure 25. World-wide distribution of tektites. Groups of tektites from certain areas have been given distinctive names. Open circles designate craters formed by meteorites that may have produced nearby tektites

Figure 24 (Left) Tektites oddly-shaped pieces of glass perhaps formed in explosion craters

A problem of this theory is that some tektites appear to have been melted twice, first when they were formed and again as they were shaped in passing through the earth's atmosphere. If they were formed from large impacts of meteoroids with the earth, tektites would have had to be thrown high above the atmosphere—perhaps into orbit—and then re-enter. No known crater on earth is large enough to have been formed from such an event.

A third possibility is that, since tektites are different from any material on the surface of the earth, they may have come from the interior of some large natural satellite, planet, or other body that has since broken up into smaller fragments.

What tektites are and where they come from is one of the many mysteries involved in the study of meteorites. Do they come from the moon, from some unknown crater on the earth perhaps covered by water or ice, or from somewhere else? The study of the rocks returned from the moon does not seem to support any of these ideas. Maybe the results of further missions to the moon and the other planets will help solve the mystery.

SUMMARY

Understanding the origin and history of the meteorites is essential to understanding the origin of our solar system. In fact, it is likely that finding a satisfactory explanation for the chondrites will unravel much of the mystery of the early history of the sun and planets. During the past decade, great strides in meteorite investigation have taken place. They resulted both from the stimulus of our interest in space and the development of new scientific techniques for meteorite investigation. In spite of this concentrated effort, however, there is still disagreement with respect to many of the critical aspects of meteorites. Investigators are continuing to probe meteorites in order to gain more knowledge of their structure and composition, in order to form a base of primary knowledge with which to build, strengthen, change, or eliminate some of our alternative theories on the origin and history of meteorites.

Some of the knowledge concerning meteorites is fairly generally accepted. Most meteorites appear to come from the asteroid belt and have undergone episodes of violent shock sometime during their flight through space. Isotopic data indicate that the meteorites arriving on the earth may have been produced by a relatively small number of collisions. It is difficult to derive a model for the origin of all the different types from a single parent body.

The chondrites provide the major roadblock to the acceptability of most meteoritic models. Were they formed before or after the accumulation of the primary bodies? How large were these bodies? To what temperature have they been heated? To what extent has change or metamorphism taken place? Were the chondrules formed by volcanic processes, by localized melting, perhaps by a shock phenomenon, or are they the remnants of the first material to condense from the gaseous mass of the protosolar system? Perhaps they are pieces knocked from the surface of the moon by other meteorite impacts.

In order to answer such questions, the apparent chemical groupings of the meteorites, the relatively constant chemical compositions of the chondrites in spite of their different states of oxidation, and the existence of high-temperature silicates and low-temperature organic compounds found together in the rare carbonaceous chondrites must first be explained; the temperature and pressure conditions under which they formed must be further investigated; and many other facts must be uncovered.

IDENTIFYING METEORITES AND DESCRIBING FALLS

While the recovery of new meteorites is so important to science, the amateur investigator may, as so often in the past, start the chain of events moving by tracking down and recovering a new meteorite fall. To identify a suspected meteorite, you should ask the following questions:

1) Is the specimen heavy for its size?
2) Is the specimen solid?
3) Is the specimen brown or black on the outside?
4) Is the specimen irregular in shape?
5) Is the specimen different from the surrounding country rocks?
6) Does the specimen show flecks of metal on a cut or ground surface?

If the answer to all of the above questions is yes, there is a good probability that the specimen is a meteorite. It should then be taken or sent to one of the centers of meteorite research for positive identification.

Objects often called "meteorwrongs" and commonly mistaken for meteorites include pieces of furnace and smelter slag. They may contain free iron in drops or pellets, or nodules of iron compounds. Old rusted pieces of steel from tools or grinding balls are also often suspected of being meteorites. A simple test for the presence of nickel will usually show that these are man-made.

If you are fortunate enough to see a fireball, record the following information:

1) At what time of day did the fireball appear?
2) For how many seconds did the fireball last?
3) How bright was the fireball, and what shape did it have?
4) Was an explosion apparent at any time? If so, what color effects were noticed?
5) Did the fall leave a trail of luminous material or smoke? If so, how long was it observable?

6) What was its apparent path in the sky? (To evaluate this information properly, locate the observer's position and note the meteorite's path with respect to physical features or stars.)
7) Were there any sound effects? If so, what was the time difference between the light phenomena and arrival of the first sound?
8) Was the place of contact with the earth observed or found? What was the nature of the surface where the fall took place? Was a crater or depression formed? (If more than one fragment fell, this should be noted for each specimen and the exact location marked on a map or on the ground.)
9) What was the nature of the meteorite that fell? Was it or its fragments hot or cold? How much did the various fragments weigh? Were they damaged by the fall, or did they have complete fusion crusts?

Information of this type compiled by many observers will make it possible to properly record the circumstances of the fall.

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Glossary

achondrite—stony meteorite, generally with a crystalline texture similar to igneous rocks.

bolide (fireball)—large, especially bright meteor.

carbonaceous chondrite—chondrite with high carbon content. The carbon may be in the form of organic material, graphite, or carbonate minerals.

chondrite—most common type of stony meteorite. They contain small spherical bodies about one millimeter in diameter called *chondrules*. All chondrites have similar chemical compositions.

coesite—high-pressure form of quartz (SiO_2) formed in nature by hypervelocity meteorite impacts.

hypervelocity crater—meteorite impact or explosion crater formed by a high velocity meteorite impact. Commonly called an explosion crater. On earth they are always large, but on the moon they may be microscopic.

meteor—the streak of light caused by a solid particle from space heating up to incandescence in its passage through the atmosphere.

meteorite—meteoroid that hits the earth without being completely vaporized.

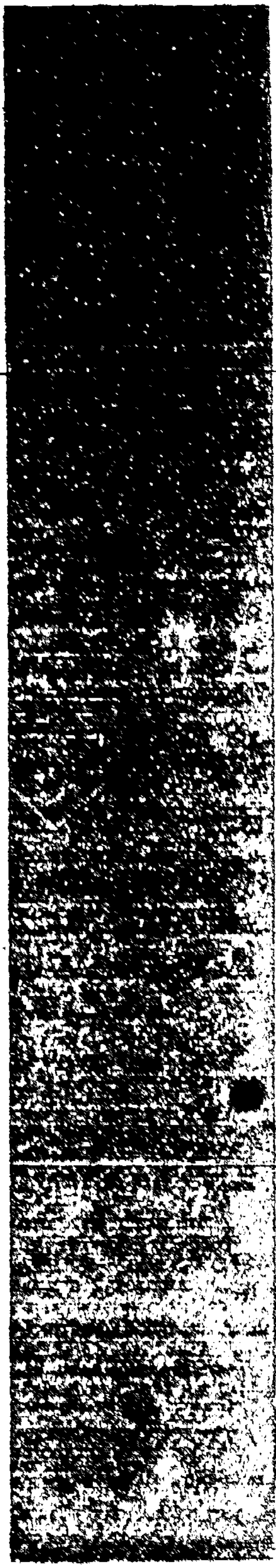
meteoroid—solid object in space, from a speck of dust to a body weighing several million tons.

micrometeorite—meteorite smaller than about a millimeter in diameter.

radioactive isotope—atom that is unstable and will decay to a more stable form, either directly or through a chain of events. Those useful for geologic dating include uranium-238, uranium-235, thorium-232, potassium-40, and rubidium-87.

tektite—object composed of silica-rich glass, apparently produced in large impact craters. Tektites are distributed over several restricted geographical areas on the earth's surface.

Widmanstatten figure—pattern developed on a polished, etched iron meteorite due to the octahedral arrangement of plates of two iron-nickel phases, kamacite and taenite.



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