ASK A QUESTION ABOUT

METEORITES

by H. H. NININGER

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H. H. NININGER

AMERICAN METEORITE LABORATORY
Denver, Colorado

by H. H. Nininger

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Meteors and Meteorites

What is a meteorite?

A *meteorite* is a natural particle of solid matter too small to be regarded as a minor planet, traveling in space, passing through the atmosphere, or having landed on the earth and still retaining its identity.

What is a meteor?

A *meteor* consists of the light phenomena occasioned by the rapid passage of a meteorite through the atmosphere. (See Fig. 2)

Why do meteorites fall?

The use of the term "fall" in relation to the arrival of a meteorite upon the earth is somewhat deceptive. In space there is no "up" or "down." Each body in the solar system, whether large or small, travels its own particular orbit operating under the influence of the larger body of which it is a satellite. The earth travels in its orbit around the sun at a speed of about 18.5 miles per second. Meteorites, traveling around the sun in somewhat more elliptical orbits, move at speeds averaging about 26.2 miles per second in the neighborhood of the earth. If a meteorite's orbit brings it too close to the earth, the earth's gravitational pull diverts it from its course and it *collides* with the earth. However, the term "fall" is both descriptive and convenient. It is therefore common for both the scientist and the layman to say that a meteorite "falls" to the earth and to refer to the total amount of material which comes down from one fireball as a "meteorite fall."

What is meant by a meteor shower?

We speak of a *meteor shower* when many meteors or "shooting stars" are observed and appear to originate in a definite location in the sky. That is, all of their trails, if projected backward, would appear to meet in a common point which is called their radiant. We speak of the Leonids, whose radiant is in the constellation Leo, or the Perseids, which seem to originate in the constellation Perseus.

How does a meteor shower differ from a meteorite shower?

A *meteorite shower* refers to the sudden showering of stones or irons over a limited area, usually a few miles in diameter. Such showering usually results from the breaking up of a single meteorite at the end of its luminous flight, but it may also result from the arrival of a number of meteorites that have been traveling together in space. (See Fig. 3)

Does the word meteorite refer to an entire fall or to individual stones or irons of a fall?

Both. The word has a dual usage. When a great meteor appears in the atmosphere one cannot be sure whether it is being produced by a single body, by several, or by many traveling in a group. In any case, there may be none, one, or many deposited on the soil. Even though a single mass may undergo disruption in the stratosphere and give rise to hundreds of fragments, these are generally completely fused over at once and land as individuals completely encased in a thin fusion crust. No one can be sure from the examination of a specimen whether it has entered the atmosphere as a separate unit or has resulted from fragmentation. Hence it may properly be referred to as *a meteorite*. Also, we speak of an entire fall, whether one or many masses, as *a meteorite*. (See Fig. 3)

Fig. 1. Artist's conception of public reaction to a daylight meteor in 1883.

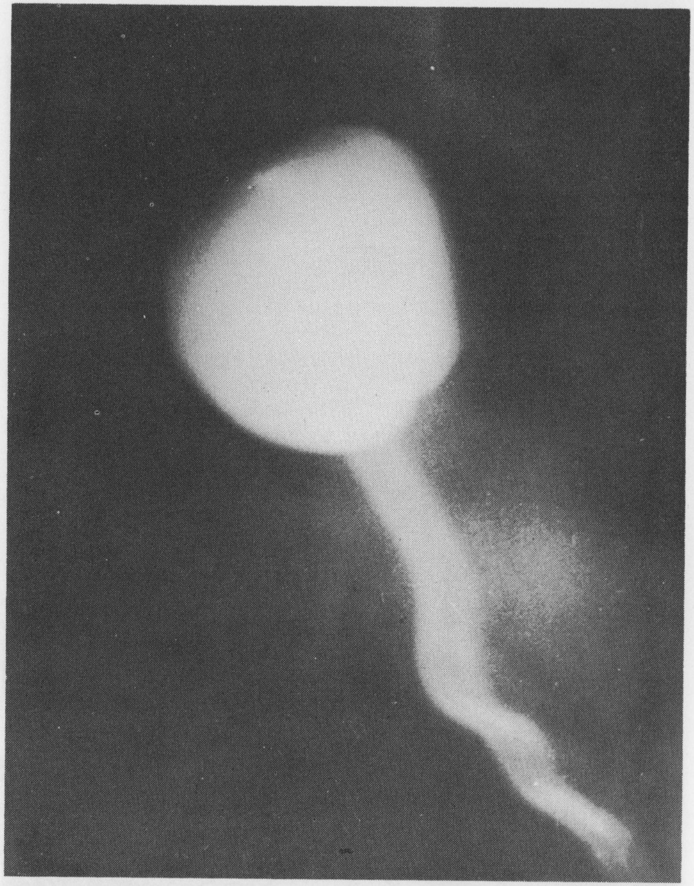

Fig. 2. Great fireball of March 24, 1933, photographed by Charles M. Brown of Mt. Dora, New Mexico, as it was in the act of exploding. Approximate altitude, 26 miles; diameter, about six miles. A survey by H. H. Nininger resulted in recovery of 7.9 pounds of meteorite fragments.

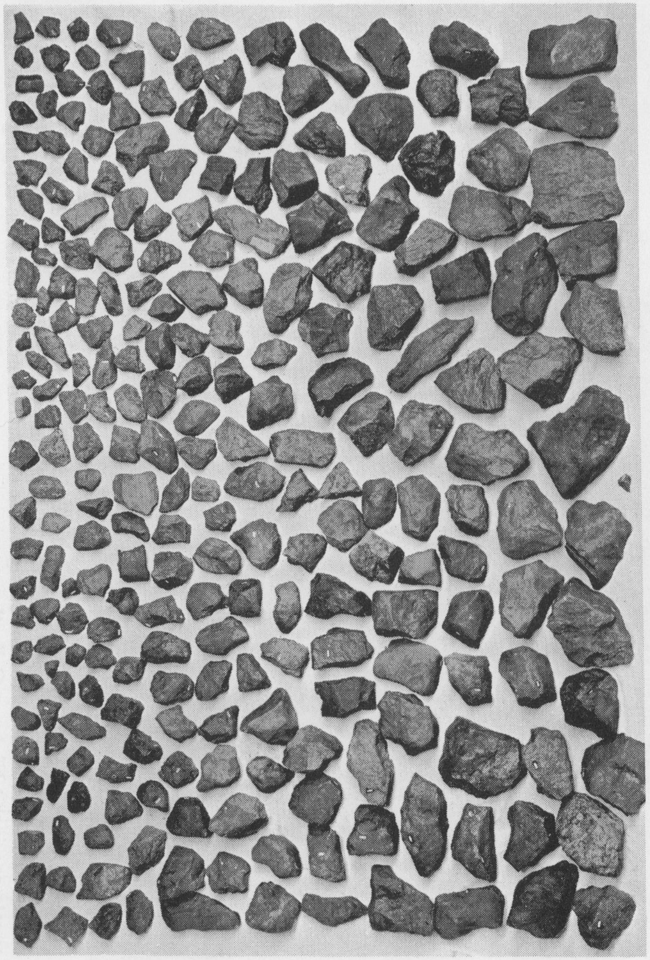

Fig. 3. Some of the more than 1,500 pounds of meteorite specimens collected from the Plainview, Texas, shower, one of the largest meteorite showers on record. **Nininger Collection.**

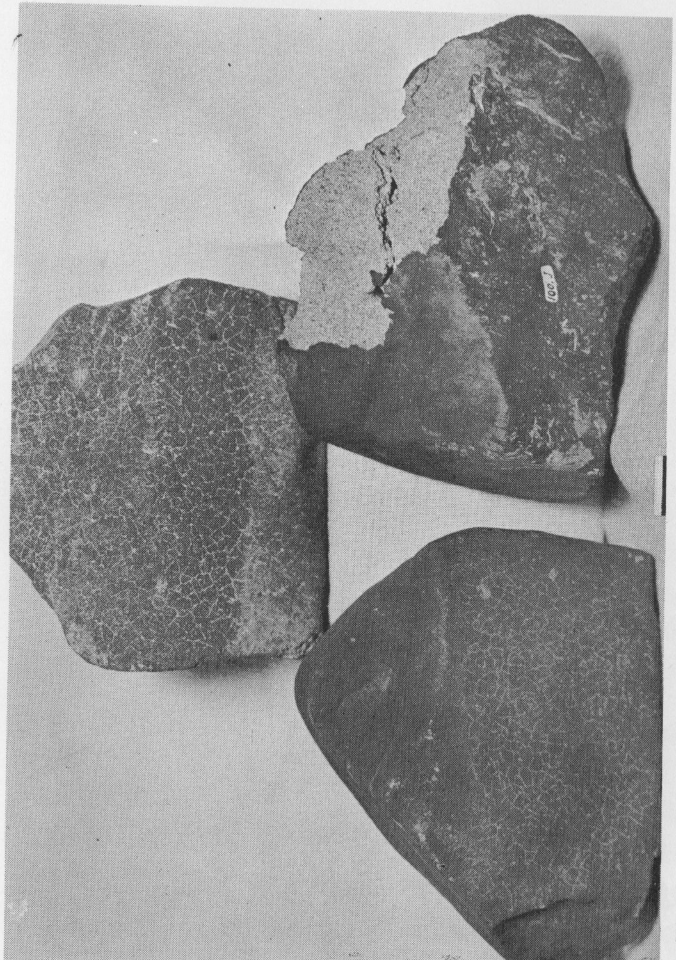

Fig. 4. A group of stony meteorites which fell near Richardton, North Dakota, on June 30, 1918. The stony interior is gray with the black fusion crust showing many minute contraction cracks. The specimen on the lower right has uncharred straw fibers still clinging to it. (Bar equals one inch.) **Nininger Collection.**

Are meteorites stars?

No. Stars are great gaseous bodies far beyond the limits of our solar system. The sun is a star much nearer than any of the others, so it appears larger. Meteorites are solid substance and most of them at least apparently have had their origin within our solar system.

Do meteorites come from the moon?

No. It can be well demonstrated that the moon cannot be the source of meteorites. They come at too great speed to have originated in, or on, the moon. They have too great density and they travel in orbits which are inconsistent with lunar origin.

Do meteorites come from other planets?

No, apparently not. The gravitation of each planet, together with its enveloping atmosphere, should it have an atmosphere, is sufficient to insure against the escape of such material as a meteorite.

Might meteorites have been ejected from our own volcanoes?

No. There are several good reasons why we are sure meteorites are not of volcanic origin. 1) They are strikingly different from all volcanic rocks. 2) They arrive with too great a velocity. No volcanic explosion seems to be of sufficient force to project rock fragments through the atmospheric blanket to distances such as would allow them to return at the high velocities which characterize meteoritic flight.

Are comets meteorites?

It has generally been assumed that comets are swarms of meteorites which are held within bounds by their mutual attraction. Such swarms may be dispersed by their near approach to various planets or other larger bodies, after which some or all of the meteorites may continue to move in the same orbit but in a sparse stream rather than a dense swarm. Several such streams of small meteorites are encountered by the earth from time to time and result in our skies being more or less lighted by numbers of "shooting stars."

Recently a somewhat different theory has been developed which pictures the nucleus of a cometary swarm as meteorites actually bound together by ices. Each time this frozen mass approaches the sun parts of it are set free from the mass and though they may continue to travel with it they tend to become scattered along the orbit in which the mass had been moving.

What, then, is the origin of meteorites?

There is no positive answer as yet. The most acceptable theory at present is that meteorites have had their origin in the disruption of a planet, or possibly two planets, which at one time existed in our solar system. Such a disruption, it is believed, would account for both the asteroidal bodies (which range from 450 miles in diameter downward) and the smaller bodies which we call meteorites. A number of mechanisms which could accomplish the disruption of a planet have been suggested. The most prominent—particularly since the bulk of the asteroids are concentrated in the area between Mars and Jupiter—are the intense gravitational pull of Jupiter as the disruptive force of a single planet, or the collision of two smaller planets which had been sharing the same area of the solar system with their orbits intersecting one another more or less at right angles. The core of a planetary body would,

if the planet were of structure similar to that of the earth, yield the metallic meteorites, while the outer portion would provide the predominantly stony meteorites.

A recently derived theory suggests that collisions between asteroids and between fragments of such collisions are the source of the meteorites which come to earth. This theory assumes that asteroids were formed directly from clouds of cosmic dust and did not result from the disruption of a larger body.

Does the speed of a meteorite increase as it nears the earth?

In space, the meteorite's speed increases as it approaches the earth, but once it enters the atmosphere it loses speed rapidly. The air acts to check its flight much more abruptly than brakes act to slow an automobile when applied to full capacity.

Do meteorites fall in a molten condition?

Meteorites have never been known to fall in a molten condition. The heat of friction is limited to their surfaces.

Do meteorites start fires?

Meteorites do not start fires even when they fall into some easily combustible material such as dry grass or straw. Meteorites do not reach the ground in blazing condition.* The light phenomenon which we see as a meteorite plunges through

*The one exception to this rule is the extremely rare crater-forming meteorite which is so huge that it resists the braking effect of atmospheric friction and explodes upon reaching the earth. See chapter on "Meteorite Craters."

the atmosphere on its way to earth ceases at heights of from 5 to 40 miles above the earth's surface depending upon the height at which the meteorite passes below the speed at which friction causes its surface to become incandescent. Since the heat of the arriving meteorite is the direct result of friction, and since it is only surface heat not affecting the interior of the moving body, meteorites are seldom very warm upon reaching the ground—some have been recovered directly after fall which had frost on their exterior surfaces when picked up. Many meteorites have been known to fall into houses, barns, garages, and haystacks without starting fires. (See Fig. 4)

Meteorites, then, have been known to strike buildings?

Yes, in at least 30 instances. As recently as September 9, 1961, a stony meteorite was reported to have struck a house in Texas.

Do meteorites arrive on the earth more frequently at one season than another?

Meteorites seem to arrive just as frequently at one time of the year as another, although most finds are made in the summer when the days are longer and when people are out of doors more of the time.

Do meteorites fall more abundantly on some parts of the earth's surface than on others?

There seems to be no evidence that meteorites fall more frequently on one part of the earth than on another. Records of falls depend mostly on whether persons are present to see them strike the ground and whether they appreciate the importance of reporting them.

Do meteorites fall more frequently at night than in daylight?

Falls occur either day or night impartially, so far as can be ascertained.

Of the meteorites which have been recovered, have the majority fallen at night or in daylight?

The majority of meteorites recovered have fallen during daylight hours. Night arrivals are less likely to be found because it is impossible for people to see them strike the ground at night.

If this is true, why do we often hear people tell of seeing meteorites strike near by and nearly always at night?

A bright light of short duration is very deceptive as to its distance from the observer. Experience has proven that a brilliant meteor at a distance of 100 to 200 miles nearly always appears to be very near, often less than a mile from all of those who see it, even though the observers are scattered throughout several states.

About how far away is the flight of a large meteorite visible in daylight?

The meteoric displays of daylight falls have frequently been witnessed from as far away as 200 to 300 miles.

What is the average size of the small meteorites which produce our "shooting stars"?

There is a difference of opinion on this question. Some believe that they are very minute, of the order of sand grains in size. Others believe they are larger, perhaps the size of marbles.

On what are these estimates of very small size based?

They are based mainly on the amount of light generated by these bodies as they are being disintegrated; in other words, the measurement of the light which we call a meteor. Some students (the writer included) believe that the disintegration of meteorites cannot be accurately measured by the amount of light produced, that perhaps much of the mass may not be transformed into light but may be dissipated in ways not detectable from the ground.

Since there appears to be a continuous gradation in size from meteors so small as to be visible only through telescopes to those which deliver our museum specimens on the soil, it seems useless with our present methods to try to estimate the size of a particular "shooting star" or to establish an average.

How large must a meteorite be when it enters the atmosphere from space in order that it may deposit specimens on the soil?

We estimate that anything smaller than from 10 to 20 pounds, about the size of a large cantaloupe, would not survive the destructive forces of atmospheric friction.

Can one estimate the size of a meteorite by the appearance of the meteor it produces?

One can learn very little about the size of a meteorite by observing the meteor which it produces. The composition of a meteorite, its speed relative to the earth (if approaching for a head-on collision with the earth its relative speed is much greater than when overtaking the earth from the rear), the degree of light or darkness (moonlight, daylight, or starlight)

in which one observes it, the clarity or haziness of the atmosphere, and the nearness of the observer, all make a great difference in the appearance of the meteor. Also, experiments have proved that one cannot accurately judge the size of a luminous body when seen from a distance.

When a meteor vanishes from sight while high in the air, does it mean that the meteorite has been consumed?

Not necessarily, although for the small "shooting star" this would likely be the case. But nearly all meteorites that land on the earth vanish from sight while still miles above the soil. This is because air resistance has reduced their speed to such extent that they are no longer heated to incandescence by friction. Without the light phenomenon they are not visible at the heights at which this occurs, usually 5 to 15 miles.

What is the significance of the apparent bursting of a meteorite which is commonly witnessed at the end of its burning flight?

This phenomenon almost certainly involves the more or less complete disintegration of the meteorite due to the impaction of atmosphere in front of the moving mass to such a degree that the meteorite is crushed against it. It is also believed by some that the impacted and highly heated air undergoes a sort of explosive action at this point, adding to the meteorite's destruction.

What is the nature of the "smoke trail" or "cloud" which is often seen in the wake of daylight falls?

The behavior of these clouds and the accompanying "showers of gravel" that have been noted by those under them point definitely to the conclusion that the cloud is composed, in part at least, of meteoritic dust. The study of the structure and surface features of meteorites from such falls points to the same conclusion. (See Figs. 5, 23)

How can one know whether a meteorite has reached the soil when he sees a large meteor?

One can never be certain that a ponderable portion of a meteorite will survive its violent passage through the atmosphere and the destructive bursting which ends its luminous flight unless one actually sees a black object passing through the air following the passage of a meteor or sees the dirt kicked up as the object arrives at the ground. But if a meteor is seen in bright daylight, or if at night it produces a light somewhat larger than the apparent size of Venus or Jupiter, one may be fairly certain that the meteor has been caused by a meteorite of sufficient size to deposit ponderable material upon the earth. If the meteor vanishes while still "high in the air" and is followed in a few moments by a loud, thunderous noise coming from the direction in which the meteor was seen, it is certain that the terminal point of the meteor has been close and that whatever material remains will come to earth within a radius of possibly 50 miles. On the other hand, if a large meteor appears to reach the ground, the meteorite which produced it was so far away that it passed over the horizon while still high in the air—that is, from 5 to 15 miles high. In such case portions of it may have reached the ground at a distance of 200 miles or more from the observer.

Are the thunderous noises which accompany the arrival of meteorites due to their impact on the soil?

The thunderous rumbling and roaring that people hear

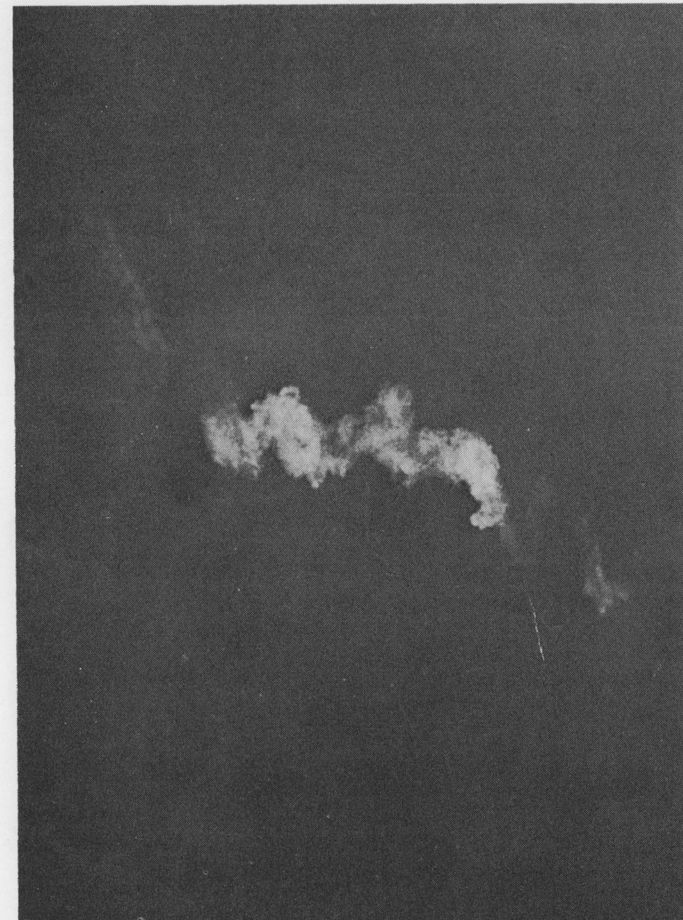

Fig. 5. Meteoritic dust cloud photographed by Al Asnis from Pampa, Texas, May 20, 1944. None of the meteorite was recovered.

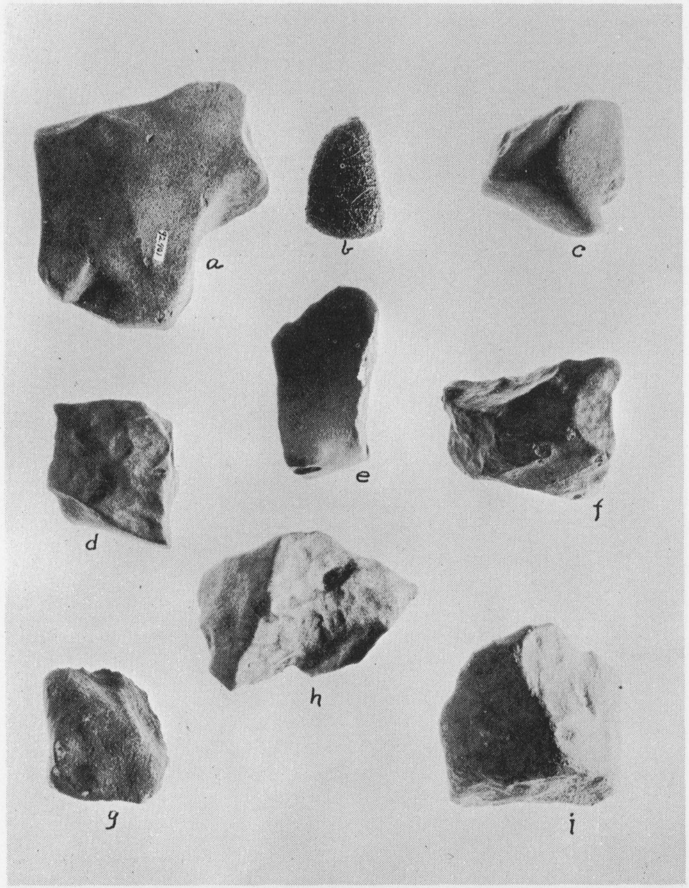

Fig. 6. A group of stony meteorites showing variations in shape and surface markings. a. Plainview, Texas; b. Pasamonte, New Mexico; c. Plainview, Texas; d. Forest City, Iowa; e. Archie, Missouri; f. Harrisonville, Missouri; g. Richardton, North Dakota; h. Beardsley, Kansas; i. Plainview, Texas. **Nininger Collection.**

Fig. 7. Cape York, Greenland. This specimen, called "Ahnighito" (the tent) by the Eskimos and measuring 11½x7½x6 feet as its greatest dimensions, was found on a small island about six miles off shore from where two smaller irons of the fall (3 tons and ½ ton respectively) were found. **Photo courtesy American Museum of Natural History, New York.**

Fig. 8. Paragould, Arkansas. An 800-pound stony meteorite, largest piece of the fall of March 17, 1930. Located through the interviewing by H. H. Nininger of witnesses of the fall.

within an area of several hundred square miles when a meteorite comes to earth are due to disturbances in the atmosphere through which it has passed. The meteorite rends the atmosphere much the same as does a bolt of lightning, and thunder results from the rearranging of the disturbed atmosphere.

Also the sonic booms or blasts produced by jet planes when breaking the sound barrier are doubtless simulated by meteorites as they are decelerated to a speed below that of sound.

The impact of a meteorite of a few pounds or even one of several hundred pounds is not a very noisy occurrence. It is merely a "thud" of lesser or greater magnitude, depending on the size of the object and the nature of the soil. Stones of 10 to 50 pounds would be heard to strike the ground from distances of a few hundred yards.

What is the best procedure for one to follow when he sees a brilliant fireball, either day or night, which he thinks may have deposited meteorites on the earth?

1) The first and most important thing to do is to note carefully the exact direction from you in which the meteor disappeared. Select a landmark as far from you as possible which is directly in line with the vanishing point of the fireball.

2) Mark the exact spot where you were standing when the observation was made.

3) Note the exact time of the occurrence and then listen for and note the time detonations, if any, are heard.

4) Draw two lines on a paper, one representing the horizon and the other the course of the meteor, indicating the angle of descent or slant of its line of flight as it appeared from your position.

5) Note how many degrees above the horizon the light

vanished. Remember, it is 90° from the horizon to a point directly overhead. Another way to record this is to look at the face of a clock. Imagine yourself at the center point of the dial. Let the number 9 represent the horizon. Then 10 will be 30° high, 11 will be 60°, and 12 will be 90°. A rough approximation of elevation can be determined by extending the arm full length with the hand held at right angles to it. The width of the palm plus the extended thumb will provide a measurement of approximately 15°.

For one not trained in astronomy or surveying of any kind, an even better and simpler way is to quickly get himself into a position such that he can line up the vanishing point of the fireball with some point such as a tree, building, or telephone pole, being careful, of course, to note exactly where he stood when observing it.

6) Obviously, in the rare event that a camera is at hand a photograph should be made of any trace of dust cloud that remains in the meteor's wake. Such a photograph will be much more useful if some nearby objects are included in the view. However, since such clouds move rapidly (although they often appear to be stationary) one should note the exact time the photograph is made, then by careful subsequent observation, using terrestrial objects for reference, determine the rate and direction of movement.

7) Notify a meteoritics laboratory as soon as possible so that a trained meteoriticist can make on-the-spot instrument measurements and begin an intensive survey to recover meteorite specimens from the fall.

Why is the study of meteorites important?

Scientists consider meteorites to be "natural space probes," for in their travels through the solar system they have been subjected to nearly every element of the space environment. When they come to earth, the story of their travels and the

conditions under which their travels took place can be learned from careful studies of the meteorites and the space-induced isotopes which they contain. From these studies man can learn much which will be of immeasurable value when the first prolonged space flight is undertaken.

Meteorites also hold many of the major secrets of the solar system and of the universe. Through a study of them we learn much about the origin and construction of the solar system. From them we can also learn much about the construction of our own earth.

The science of meteoritics is yet in its infancy; there is much to be accomplished.

When a meteorite falls, to whom does it belong?

The laws covering the ownership of meteorites have largely grown out of lawsuits between the finders of meteorites and the owners of the land on which the finds were made. In such cases, the courts have decided that the meteorite belongs to the land on which it falls or to the land upon which it is found.

How are meteorites named?

Meteorites are named after the locality in which they fall or are found; that is, they receive the name of the nearest post office or other geographic subdivision which is of sufficient importance to be listed in an atlas or gazetteer.

The Nature of Meteorites

What are meteorites made of?

Meteorites are made of the same elements of which the earth is composed. In the meteorites thus far recovered and studied, such minerals as iron, nickel, cobalt, phosphorus, and magnesium are somewhat more common than they are in the earth's crustal rocks in general, but not to an extent which makes meteorites stand out as greatly different in composition from the rocks which are of earth origin.

Aren't all meteorites mainly metal?

No. The majority of meteorites consist mainly of stony matter although most do contain metal in varying amounts. It is presently believed that something over 90 per cent of all meteorites which fall are composed mainly of stony matter. Those which could be classified as nickel-iron will account for not over 3 per cent of the total increment. (See chapter on "Classification of Meteorites.")

But aren't all meteorites attracted by a magnet?

No. Only those meteorites which contain enough metal are attracted to a magnet. All nickel-iron meteorites are attracted and stony meteorites are attracted in proportion to the amount of metal they contain. Those which contain no metal are not attracted at all. The stones from Johnstown, Colorado; Sioux County, Nebraska; Bishopville, North Carolina; Pena Blanca Springs, Texas; Lafayette, Indiana; Nahkla, Egypt; Washougal, Washington; Santa Cruz, Mexico; Shalka, India; and a number of others are so poor in magnetic constituents that they are not noticeably affected by even a powerful magnet.

All meteorites do not contain nickel-iron then?

The majority of meteorites do contain some nickel-iron but some contain none at all.

Do some meteorites contain nickel and no iron?

In so far as is known, nickel and iron in meteorites are always alloyed. That is, if metallic iron is lacking, so is the nickel, and if nickel is missing, so is metallic iron.

Are meteorites round?

No. They may be any other shape. If there are any round ones they are yet to be discovered. (See Figs. 4, 6)

Is there any special shape that characterizes meteorites?

About the only general description that applies to meteorites is that they are mostly irregular in shape. Stony meteorites are, however, notably lacking in sharp edges, corners, or flat surfaces, such as are common in stratified rocks. (See Fig. 6)

How large are meteorites?

When they reach the earth meteorites may be of any size, from the size of fine gravel to several tons in weight.

Is there any size more common than any other?

Comparatively few meteorites have been found of more than 100 pounds in weight and smaller sizes are more numerous than larger. Probably more than half of all that have been collected have been less than an ounce in weight.

Isn't it true that large meteorites bury themselves and are for this reason less likely to be discovered?

Yes. The larger a meteorite is the deeper it will penetrate the earth, other things being equal. Stony meteorites larger than 25 pounds usually penetrate below plow depth (unless striking on rock or frozen ground) and are therefore unlikely to be found unless seen to strike the ground. Metallic meteorites penetrate more deeply than do stones of the same size. The larger meteorites which have been found were generally in situations where the ground level had been lowered by erosion.

Are metallic meteorites larger than stony meteorites?

If we were to judge by the finds so far made we would conclude that the largest meteorites to reach the earth are metallic. This may be due to the fact that stony meteorites are less resistant to the destructive force of atmospheric friction. Observations made on meteorite falls indicate that some stony meteorites of immense size undergo almost complete disintegration in the stratosphere, producing enormous dust clouds, yet a diligent search may yield little or nothing by way of meteorite specimens.

Which are the largest known meteorites?

The largest meteorites so far discovered are as follows:

Name	*Class*	*Size*
Hoba West, Africa	nickel-iron	120,000 lb. (Est.)
Ahnighito, Greenland	nickel-iron	68,000 lb.
Bacubirito, Mexico	nickel-iron	54,000 lb. (Est.)
Mbosi, Africa	nickel-iron	52,000 lb. (Est.)
Chupaderos, Mexico	nickel-iron	46,000 lb.
Willamette, Oregon	nickel-iron	31,000 lb.

Note that all of the above list are of the metallic class.

The largest stony meteorites collected are as follows:

Name	*Size*
Norton, Kansas	2,000 lb. (Approximate)
Long Island, Kansas	1,244 lb. (Approximate)
Paragould, Arkansas	800 lb. (Approximate)
Hugoton, Kansas	770 lb. (Approximate)
Morland, Kansas	660 lb. (Approximate)
Knyahinya, Czechoslovakia	640 lb. (Approximate)

All of these stones showed some evidence of breakage on impact or subsequently through weathering, hence the "approximate" weights. For example, Hugoton, Kansas, recovered from a cornfield, was crumbling badly at plow depth and, subsequent to its removal, about 125 pounds of fragments, evidently broken from it, were recovered in the process of cultivation within a radius of a few yards, thus bringing the total to nearly 900 pounds. (See Figs. 7, 8)

What are the smallest meteorites that have been collected?

The smallest stony meteorites so far collected weighed less than 1/50 gram, or about 1/1400 ounce. Metallic specimens of about the same dimensions have been found. However, this does not take into account the little droplets or *metallic spheroids* discovered in connection with meteorite craters. (See chapter on "Meteorite Craters.") These are meteoritic in origin but have resulted from the complete re-working of the original meteorite. Some of these are so small that a million of them would weigh scarcely more than an ounce.

Are meteorites heavier than terrestrial rocks?

Not all meteorites are heavier than terrestrial rocks in proportion to their size. Some have a specific gravity no greater than that of certain terrestrial rocks. In most cases, however, they are quite heavy due to their varying content of nickel-iron.

Are nickel-iron meteorites heavier than artificial nickel-steel in proportion to their size?

No. Nickel-iron meteorites have about the same weight as an equal volume of artificial nickel-steel. To many they seem to possess greater density, but this is probably because we ordinarily see artificial steel in the form of plates and bars and not in the irregularly shaped masses which characterize meteorites. Statements that nickel-iron meteorites are heavier than lead or gold have appeared in certain publications but these are entirely false.

Can meteorites be broken with a hammer?

Many stony meteorites are readily broken by a hammer. Indeed, some are so frail that they must be handled with extreme care to avoid crumbling. Metallic meteorites, however, are very nearly unbreakable but they can be badly mutilated by hammering. Such mutilation should be avoided.

Why is it important not to break up meteorites when found?

When a specimen comes into the hands of a scientist he prefers to have it as complete as possible. Often the surface features of a meteorite are of as great scientific importance as the interior. Meteorites should therefore not be broken by the finder except where necessary to obtain a sample for testing from a specimen too large to handle entire. In any case, the removal of such samples should be done with great care.

Fig. 9. A Plainview, Texas, specimen exhibiting good fusion crust. **Nininger Collection. Photo by U. S. National Museum Staff.**

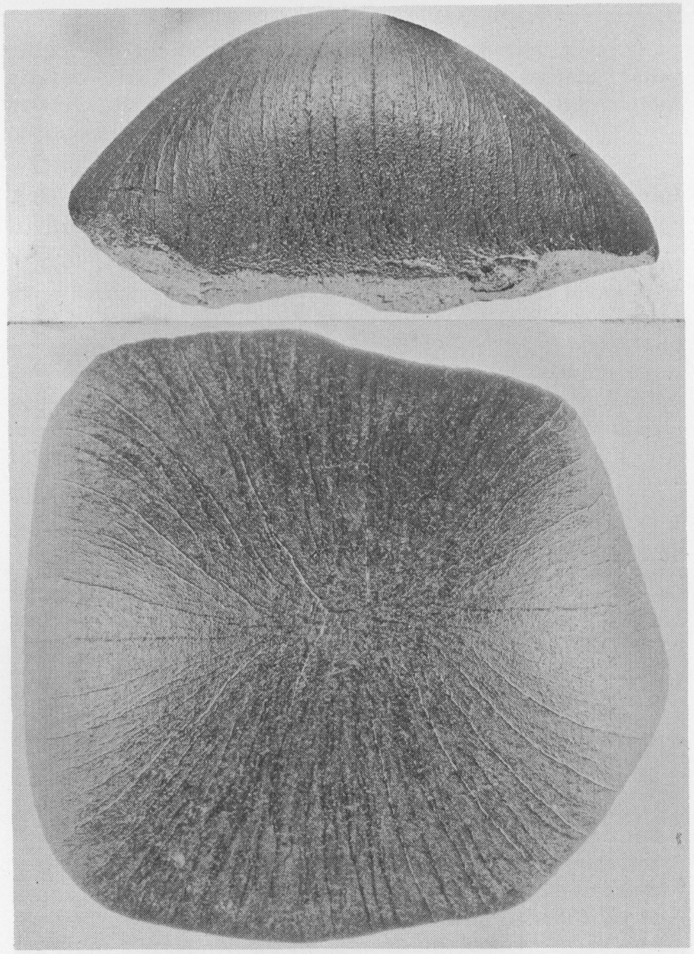

Fig. 10. Lateral or side (top) and front (bottom) views of the perfectly oriented achondritic meteorite from Lafayette, Indiana. Note thread lines radiating from center of front face. **Photo courtesy Chicago Field Museum.**

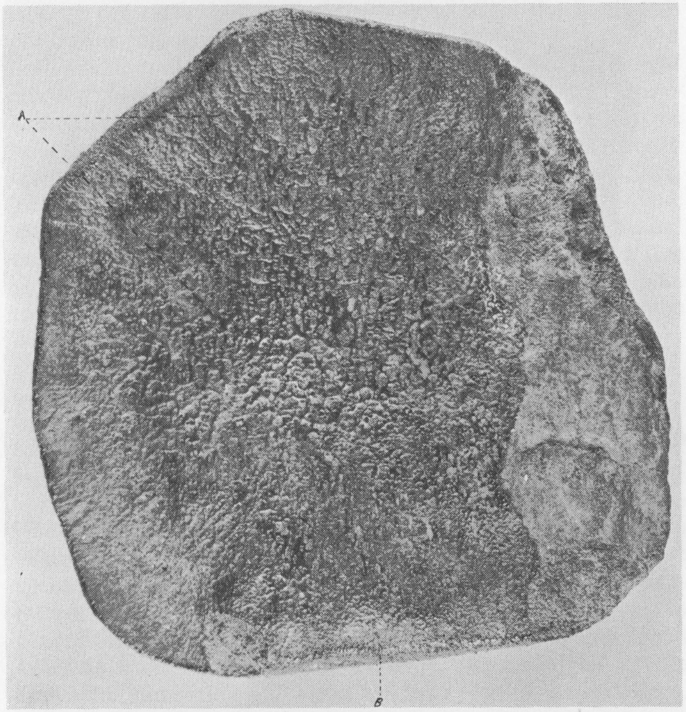

Fig. 11. Basal view of the oriented Lafayette, Indiana, meteorite. "A" indicates areas of collapsed bubbles. "B" a ridge of slag separating base from lateral surface. **Photo courtesy of Chicago Field Museum.**

Fig. 12. Oriented nickel-iron meteorite from Bruno, Saskatchewan, Canada, exhibiting both extensive pitting and fine thread lines. **Nininger Collection. Photo by U. S. National Museum Staff.**

What color are meteorites?

Most meteorites are covered with a thin, black or dark gray crust (technically termed a *fusion crust*) when they arrive on the earth, but in the majority of cases the interior is gray. (See Fig. 4) Frequently, however, they are dark colored both inside and outside. Rarely a fall occurs which is light colored throughout and which develops a brownish or straw-colored crust, or no crust at all. These meteorites tend to be poor in nickel-iron. Such were the falls at Bishopville, South Carolina; Cumberland Falls, Kentucky; Pena Blanca Springs, Texas; and Norton, Kansas. Doubtless many more of these than we learn about actually fall but they are either not found or not recognized. After lying in, or upon, the soil for a few years the color of a meteorite usually becomes brownish due to iron-oxide staining. The staining first shows on the surface but eventually penetrates throughout the stone or iron.

What causes the fusion crust on meteorites?

The fusion crust is the result of surface melting caused by friction between the meteorite and the atmosphere and consists of a thin layer of molten material spread over an unheated interior. Meteorites enter the atmosphere at speeds averaging 26.2 miles per second. This is about 76 times the speed of the average .30 caliber rifle bullet. The friction produced by the meteorite's passage through the atmosphere generates heat so violent that the surface melts and is stripped away as soon as it is exposed. When the resistance of the atmosphere has sufficiently checked the speed of the meteorite, the last-formed molten material solidifies upon its surface. This is the dark, slaggy crust found on freshly fallen stony meteorites and the bluish-black crust on the nickel-iron ones. (See Fig. 9)

Why doesn't the entire meteorite become molten?

All of the heat involved results from friction and is therefore surface heat. As the surface of the meteorite is heated, it is torn away by the resisting atmosphere and the underlying layer of cold material is exposed to be heated and torn away. Since, before it entered the atmosphere, the meteorite was traveling in space where the temperature is estimated to be 273° C. below zero (−459° F.), its passage through the atmosphere may be likened to a block of ice placed before a blow-torch: so long as the torch flame plays upon the cake of ice, the surface melts; but if the torch is removed while something solid remains, that solid portion is still ice.

Do terrestrial rocks ever exhibit the kind of fusion crust that is found on meteorites?

No. The thin fusion crust overlying an interior which shows little or no evidence of heat is peculiar to meteorites. However, certain terrestrial rocks which are long exposed in deserts often develop a "desert varnish" which to the untrained eye closely resembles the fusion crust of meteorites. Careful inspection with a hand lens will reveal a definite distinction between the two. Occasionally lightning produces a glazed surface on rocks which resembles somewhat the fusion crust of a meteorite, but it lacks certain features such as pits and flow lines which can nearly always be found on some parts of a meteorite.

Does not lava show such a fusion crust?

No. Lava shows fusion throughout. Lava bombs are sometimes found which superficially resemble the fusion crust of meteorites, but the interiors of such bombs generally evidence the same characteristics as do their exteriors. They

have been molten throughout. Meteorites have been molten only at the surface. There are certain instances where masses of crystalline rock become coated with lava to form a peculiar sort of bomb, but such are generally associated with abundant evidence of recent volcanic activity.

Do meteorites always show a fusion crust?

No. While nearly all meteorites arrive on the soil with more or less of a fusion crust, they in time lose it through weathering. All stones, both terrestrial and accretionery, sooner or later begin to scale or flake away at their surfaces. Alternate warming and cooling, freezing and thawing, eventually bring about the destruction of the most durable rocks. Meteorites are more susceptible because certain of their constituents, metallic iron for example, cannot resist the advances of oxygen. A grain of metal in, or beneath, the fusion crust will swell upon oxidation and tend to pry off a scale of the crust lying over it. All of the older meteorites therefore have lost more or less of this feature.

If such a great percentage of the meteorites on the earth have lost their fusion crust through age and exposure, why is the fusion crust still considered to be an important characteristic by which to identify meteorites?

Those who know meteorites best realize that many of the meteorites exposed on the soil can never be recognized and recovered by any method now in use. Consequently emphasis is placed upon those which are sufficiently well preserved so that recognition may be expected of persons who have received some instruction.

Why do some freshly fallen meteorites show tiny cracks or checks in the fusion crust?

These are *contraction* cracks and have probably resulted from a slight shrinking of the stone after it landed, due to cooling. This does not indicate that any great amount of heat preceded the cooling. Some meteorites arrive on the soil too warm to handle, which may mean no more than a temperature of, say, 150° F. The fusion crust had been formed to fit the size of the stone at that temperature. This crust is quite brittle so that even a small amount of shrinking causes it to crack. It is of interest to note that some stones have this feature very well developed while others of the same shower show none of it. (See Fig. 4)

Are all the cracks on meteorites contraction cracks?

No. Sometimes *pressure* cracks are developed during flight. These are fissures sometimes reaching deep into the body of the stone. In several meteorites, sectioning has revealed that there has been slippage along these pressure cracks. Also, *exfoliation* cracks develop during the process of weathering after a meteorite has landed on the earth. These actually are produced by expansion rather than contraction. When iron or some other constituent of a meteorite oxidizes, it increases in size. As this process goes on all through a stony meteorite its consequent increase in size produces cracks. These are not limited to the very outer skin of the meteorite, as is the case with the contraction cracks in the fusion crust, but may penetrate deeply into the interior of the stone.

How extensive is the weathering process?

The process of weathering never ceases. Exposure to weather always continues to bring about changes of one kind

or another, either chemical or physical, in all rocks, whether accretionery or terrestrial.

At what stage of weathering does a meteorite cease to be classified as a meteorite?

When it no longer can be definitely recognized as distinct from terrestrial rocks.

What is the meaning of the word terrestrialization?

Terrestrialization includes all of the processes of change which a meteorite undergoes after its arrival on the earth until each of its constituents has lost its meteoritical perculiarities and conforms to the standards of the earth's crustal rocks. Much of the earth's crust no doubt consists of completely terrestrialized meteoritic material, but it has been brought into conformity with the rocks of the earth by chemical changes, fractures, and trituration (rubbing together).

Is there no possibility of developing a method for the recognition and recovery of old and weathered meteorites?

Yes. We believe that after our courses in geology have been modified to include an adequate discussion of meteoritics and when meteorites have been placed among the rock specimens which students are required to study in the laboratory, many more meteorites will be recovered than in the past and ways to recognize the older falls will be developed.

Do meteorites show evidences of their rapid atmospheric flight other than their fused surface?

Yes. *Pits* (often called *thumb marks*), *thread lines,* and the *orientation* of these markings are all graphic records of the atmospheric conflict and are called *flight markings.* (See Figs. 10, 11, 12, 13)

What causes the pitting in meteorites?

Pitting takes place at the last instant of the burning flight when the slowing of the meteorite reduces the surface temperature to a point where only certain of the constituents are melting. As the melted material is removed, the void is enlarged by a whirlpool action. Good examples of pitting may be seen in Bruno and Glorieta. (See Figs. 12, 13)

What are thread lines?

As the meteorite is slowed down to the point where friction is no longer severe enough to produce melting, the last of the viscid spray may adhere to the surface and cool into thin hair-like ridges such as are shown in Lafayette and Bruno. (See Figs. 10, 12)

What is meant by orientation?

We say a meteorite shows orientation when all or most of its flight markings have a symmetrical arrangement, one face giving evidence of having borne the brunt of the aerial conflict (this face is sometimes called the *brustseite*), and the opposite face indicating that it was sheltered from the aerial blast. This latter is referred to as the *base* of such a meteorite and often holds an accumulation of slag or fused material swept from the front and sides of the mass. (See Figs. 10, 11, 12, 13)

Do many meteorites show orientation?

No. Only a small percentage of those that have been collected show this feature. However, in some showers of stony

meteorites about half of the individuals are so marked. These have been the more friable varieties, indicating that the parent mass of such falls probably fragmented earlier in its flight while moving at higher velocity, a condition which is thought to favor orientation.

What is the best test that one who is not a scientist can make on a suspected stone to determine whether it is a meteorite?

Take the stone, or a chip from it, to an emery wheel and grind into it slightly. Then examine the ground surface for a content of bright, silver-looking metal. If it is a stony meteorite the metal will appear in the form of irregular grains, usually very small. If it is a metallic meteorite its interior will appear like a piece of steel. If either of these results is obtained then a nickel test is in order. This any good chemist can make.

Of course the most positive way of determining whether or not a suspected object is a meteorite is to send the object, entire if it is not too large, or a sample taken from it, to a meteoritics laboratory for examination. A good meteoritics laboratory will make the tests free of charge (other than postage costs) for the privilege of having a chance to purchase an authenticated meteorite or a portion of it from the owner.

Classification of Meteorites

How are meteorites classified?

Meteorites have been divided into three main classes based upon the prevalence of nickel-iron in the meteorite, without taking into account structural differences or varying mineral content. Each class is subdivided on the basis of structure and composition. About 75 to 80 varieties have thus far been described by various meteoriticists. The characteristics of the three basic classes are:

1. *Stony meteorites (aerolites).* This is the principal and largest group, in which are included the great majority of all known meteorites. It is quite variable, ranging all the way from those consisting entirely of stony matter to those which are abundantly supplied with small grains of nickel-iron. The average aerolite contains from 5 to 15 per cent nickel-iron. However, a meteorite may be entirely without metal or it may contain as much as 25 per cent nickel-iron and still be considered a member of the stony class.

2. *Nickel-iron meteorites (siderites).* These are the meteorites that consist mainly of raw, bright metal. If they have been a long time on the earth they are covered with either a rusty colored or a black oxide crust. If they are new arrivals on the earth they are coated with a very thin, bluish-black fusion crust. Beneath either of these crusts the metal is clean and bright, except as altered by weathering.

3. *Stony-iron meteorites (siderolites).* These contain about as much metal as stone. They show about the same outward appearance as do the nickel-iron group, but inside they are strikingly different. They exhibit two principal types of structure: *Pallasites* show a network of nickel-iron, the meshes of which are filled with crystals of olivine (an olive-green or yellowish mineral composed of iron, magnesium, silicon, and

Fig. 13. Oriented nickel-iron meteorite found near Glorieta, New Mexico, in 1937 and identified as belonging to a fall discovered in 1884. Note the fresh appearance of the pits and flight markings.

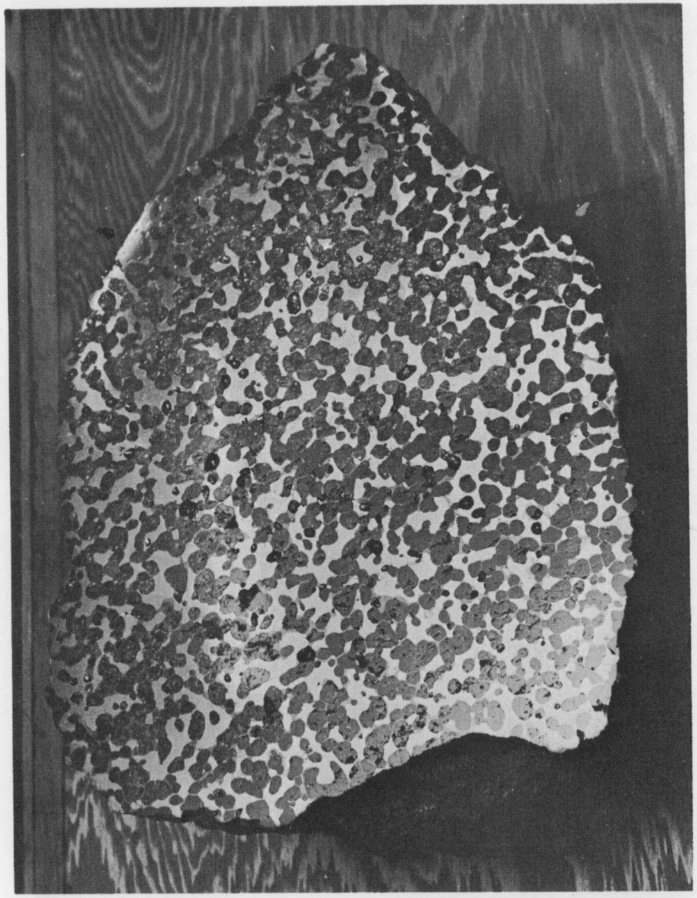

Fig. 14. Polished section of the Brenham, Kansas, pallasite exhibiting a reticular structure of nickel-iron the meshes of which are filled with olivine. This is a fragment of the meteorite which formed the Haviland, Kansas, meteorite crater. **Nininger Collection.**

Fig. 15. Polished slice of the Estherville, Iowa, mesosiderite exhibiting large lumps of nickel-iron. **Photo courtesy of U. S. National Museum.**

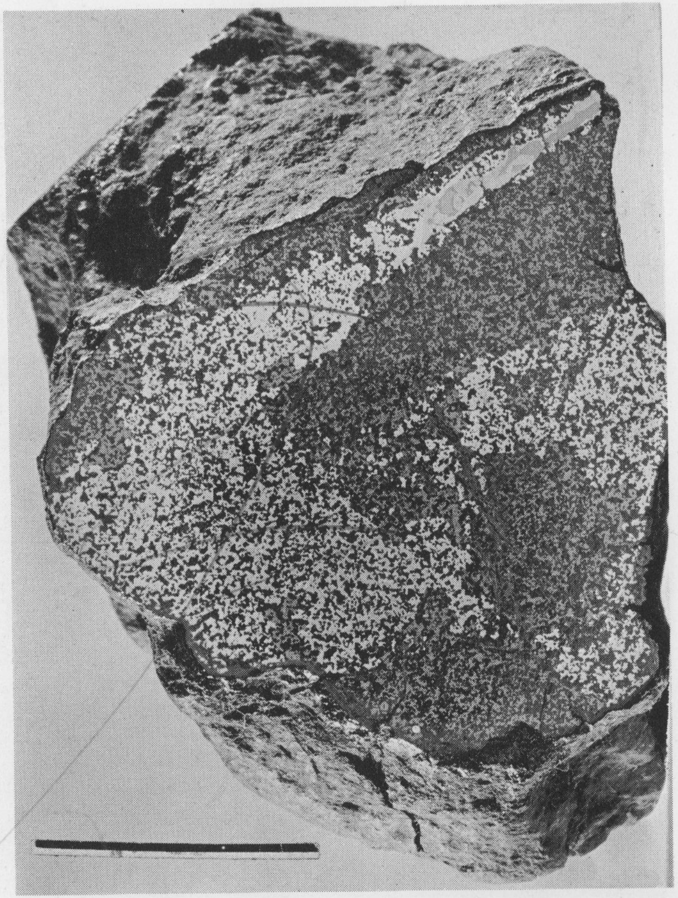

Fig. 16. Polished section of the Enon, Ohio, mesosiderite showing small grains of nickel-iron more or less connected. The darker patches in this unusual meteorite are sulphide. (Bar equals one inch.) **Nininger Collection.**

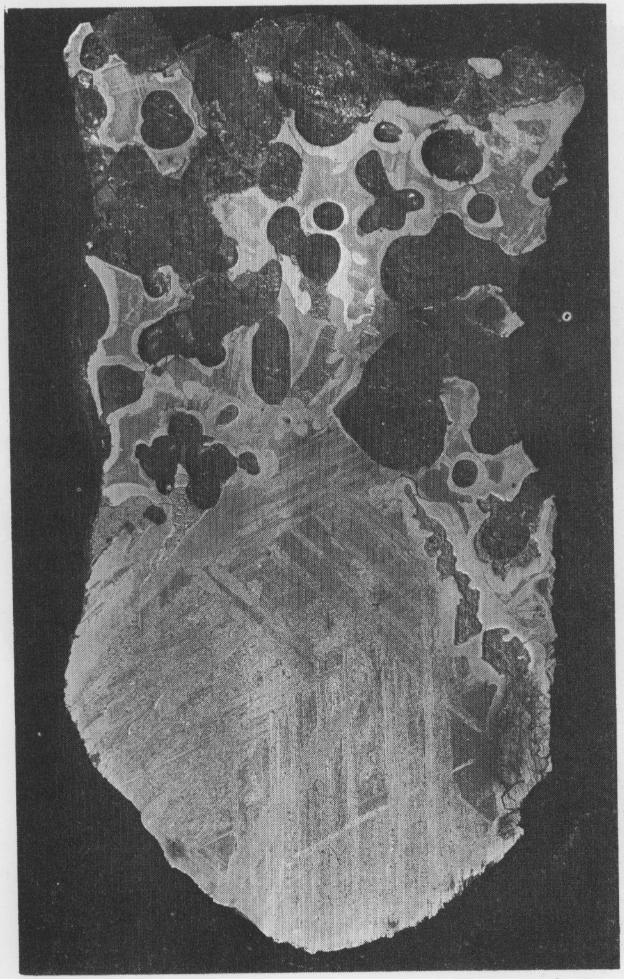

Fig. 17. Polished and etched section of a meteorite of the Brenham, Kansas, fall exhibiting a combination of pallasite and siderite structures. **Photo courtesy American Museum of Natural History, New York.**

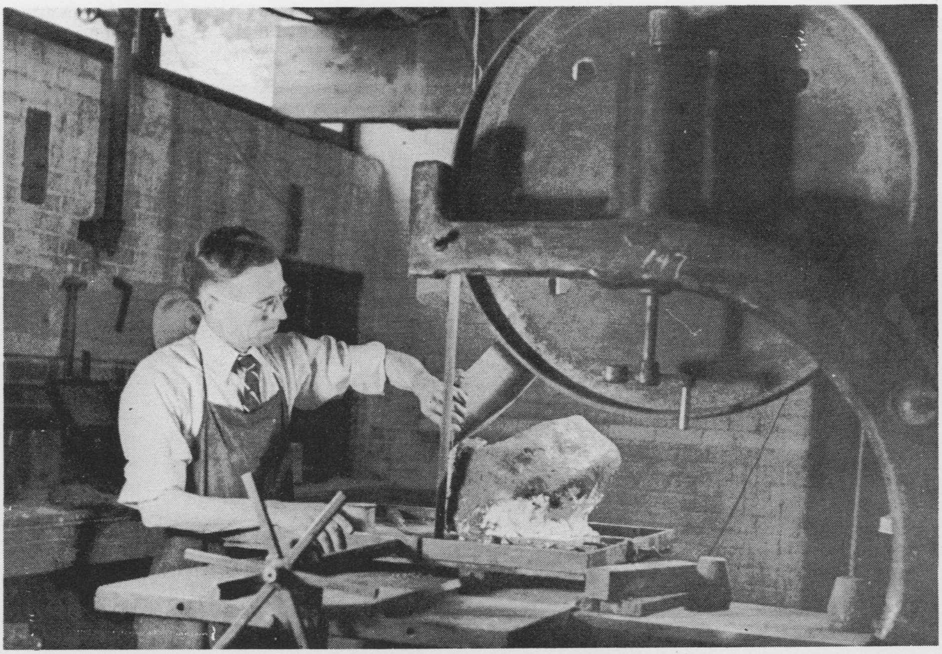

Fig. 18. The meteorite saw constructed and operated by the author in the 1930's.

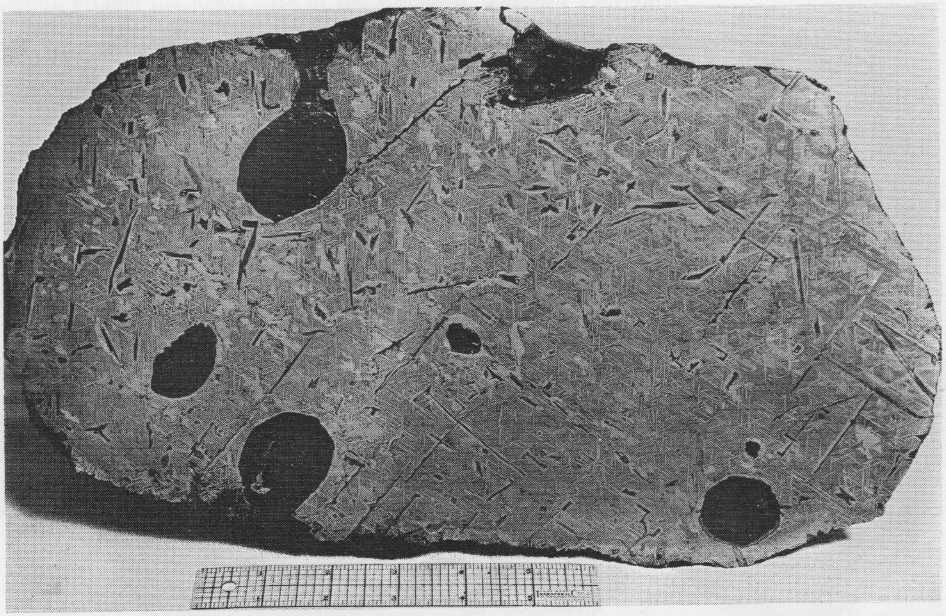

Fig. 19. Polished and etched section of the Bear Creek, Colorado, meteorite exhibiting fine octahedral structure. The bar-like inclusions which interrupt the Widmanstätten pattern are schreibersite. The rounded nodules are troilite. **Nininger Collection.**

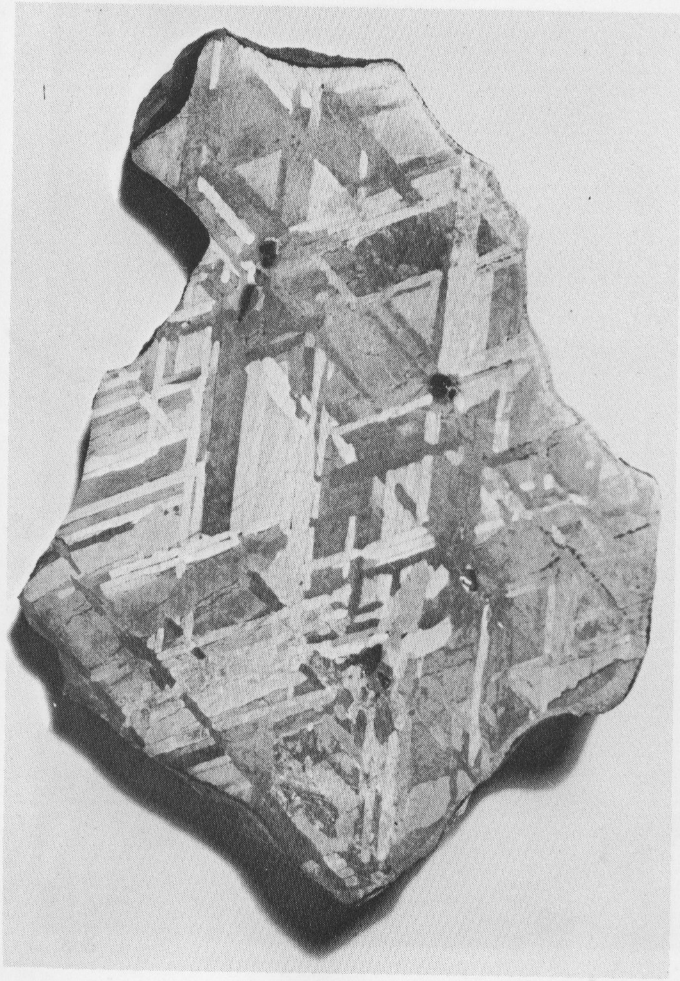

Fig. 20. A polished section of one of the Henbury, Australia, meteorites etched to exhibit the Widmanstätten figures of the medium octahedral structure. Note how heat has altered the structure around the lower edge of the specimen. **Nininger Collection.**

oxygen). (See Fig. 14) *Mesosiderites* show irregular grains of nickel-iron embedded in a stony matrix. Sometimes these grains or lumps are quite large as in Estherville, Iowa, or Crab Orchard, Tennessee. (See Fig. 15) In others, such as Mincy, Missouri; Enon, Ohio; or Hainholz, Germany, they are small and tend to be more or less connected to form a network. (See Fig. 16) Morristown, Tennessee, reveals a combination of the two characteristics.

Can each known meteorite be definitely placed within one of these three groups?

No. There are several meteorites which do not definitely belong to any of the three groups. There are probably all gradations of composition from pure stone to pure nickel-iron and numerous combinations of the various aspects of each. (See Fig. 17)

How are the internal characteristics of meteorites studied?

Meteorites are studied both chemically and microscopically. In order to examine their structure, they are usually cut into sections and the sections are then polished. If the specimen is a metallic meteorite, the sections are etched with acid after polishing.

How are meteorites cut?

Metallic meteorites are usually cut by means of an abrasive saw which consists of a thin band of soft steel to which is applied a continuous small stream or trickle of water carrying an abrasive such as silicon carbide. One could correctly say that such a saw wears its way through the meteorite. (See Fig. 18) Stony meteorites may be cut on a diamond saw such as is used in cutting agates and other gem stones.

What is meant by etching?

The etching of a meteorite is the application of a weak acid solution to the polished surface of its metallic portions in such manner as to cause the crystalline structure to become visible. Etching is possible because in the crystallization process the metal of a meteorite has separated into two principal alloys—one of low nickel content and one of high nickel content. When the acid is applied, it dissolves the different alloys at different rates producing etching pits of various depths in the polished metal.

Can meteorites be classified according to structure?

Yes. There are three structural classifications for nickel-iron meteorites. Those which show an octahedral (eight-sided) type of crystallization in the metallic alloys of which they are composed are known as *octahedrites.* When cut, polished, and treated with etching agents, the octahedrite will generally reveal its octahedral structure in a pattern known as *Widmanstätten figures.* (See Figs. 19, 20)

Hexahedrites are those nickel-iron meteorites which show a cubic or six-sided crystal structure, usually microscopic. Etching agents applied to a hexahedral meteorite reveal a peculiar type of intersecting lines unlike the Widmanstätten pattern. These are known as *Neumann lines.* (See Fig. 21)

Those nickel-iron meteorites which show no distinct crystalline structure are called *ataxites.*

Just what is the nature of the Widmanstätten figures?

The nickel-iron of the octahedral meteorite (the class in which the Widmanstätten pattern is found) exists as two distinct alloys: *kamacite,* in which the ratio of iron to nickel is about 16:1, and *taenite,* in which the ratio of these two metals varies but averages about 3:1. In the commonest

variety (known as medium octahedrites) the kamacite is about six to eight times as abundant as is the taenite.

In crystallizing, these two alloys have arranged themselves in alternate blocks or plates and their arrangement has been such that together they form an eight-sided structure.

When a polished section of such a meteorite is exposed to the action of a chemical, such as a weak solution of nitric acid, the acid attacks the kamacite, slowly dissolving it, but the taenite remains unaffected. This action of the acid is such that the glossy polished surface of the kamacite is changed to a dull gray, while the taenite retains its high polish. The result of such a treatment is a conspicuous lattice-like pattern.

Very slight differences in composition or structure may be revealed by the etching process. There are also many other different chemicals besides nitric acid that can be used as etchants and each one produces a slightly different result. If a scientist is familiar with the different etching agents and their respective actions then he is able to learn much about a meteorite by their use. (See Figs. 19, 20)

Where does the name Widmanstätten come from?

The name derives from Alois Von Widmanstätten, a Viennese scientist who discovered the presence of these figures in 1808.

Just how does the etching pattern reflect the chemical composition of the meteorite?

There is a direct relation between the width of the kamacite bands and the nickel content. Meteorites rich in nickel produce narrow kamacite bands, and taenite appears correspondingly more abundant. When the percentage of nickel reaches more than about 12½ per cent, all of the meteorite is taenite and there is no Widmanstätten pattern. The meteorite is then called a nickel-rich ataxite. On the other hand, with lower nickel content the kamacite forms thicker and thicker plates or blocks and the taenite is correspondingly scarcer until the content of nickel has dropped to about 6 per cent (the composition of kamacite). Then the entire mass is kamacite and again no Widmanstätten pattern is present. We have already stated that kamacite has a nickel content of only 6 per cent. This also is the average composition for hexahedrites. Consequently, a nickel-iron meteorite with not more than 6 per cent nickel crystallizes into cubes and etching reveals only Neumann lines. Or, in some instances meteorites of such composition develop no pattern and are called nickel-poor ataxites. It is believed that such meteorites were once hexahedrites but that during their existence in space they have approached too near the sun and have received heat sufficient to break down their crystalline structure.

How much heat is necessary to break down the crystalline structure in a meteorite?

The amount of heat necessary to alter the structure of a meteorite varies somewhat with the particular meteorite. As a general rule one may say that Neumann lines disappear upon heating to temperatures above 400° C. (752° F.). The Widmanstätten structure is altered at heats of around 800° C. (1472° F.) or higher. Neither temperature approaches the melting point of iron (which is 1533° C.) or of nickel (which is 1453° C.) (See Fig. 20)

If several sections are cut from the same meteorite, will all of them develop the same pattern on etching?

This is only partially true. If the various sections are cut on different planes they will develop correspondingly different patterns. Also, nickel-iron meteorites often contain inclusions

(nodules, etc.) of substances other than nickel-iron which may alter the structure somewhat. Some sections may be cut through such inclusions while others fail to reveal any.

Aside from non-metallic nodules are there any other alloys in the octahedrite meteorites besides kamacite and taenite?

There is another metallic substance known as *plessite.* This is not a true alloy but rather a combination of the two alloys already described. In plessite these alloys apparently have been unable to completely accomplish the normal process of alignment. They, to some extent, reproduce in miniature the general structure which surrounds them. The plessite fields generally appear on the etched surface as three-, four-, or five-sided areas.

Into what categories are stony meteorites subdivided?

Stony meteorites may be classified into two principal groups: *chondrites* and *achondrites.*

Chrondrites are meteorites of the stony variety in which *chondrules* are present to a considerable extent. Chondrules are perhaps the most important structural feature of stony meteorites. They are small grain-like bodies of various mineral substances, predominantly spheroidal in form, ranging in size from microscopic to, in rare instances, the size of a marble, with the vast majority being less than two millimeters in diameter. They vary in color from almost white to black, the majority being gray or brown. Chondrules are, for the most part, crystalline, but are generally neither whole crystals nor groups of crystals. Rather, each consists of a part of a crystal or portions of several crystals. They look as if they had once been fragments of crystalline rocks and had been subjected to trituration or to bombardment until all of their corners and sharp angles had been obliterated. (See Fig. 22)

Acondrites are stony meteorites in which no true chondrules are found. They vary greatly in structure. Some consist entirely of ashy or tufaceous substance while others are mainly made up of large crystals. They have been, and still are, rare in collections. But this is probably due to the fact that, until recently, no successful effort had been put forth to trace down newly arrived meteorites. Achondrites are so much like certain terrestrial rocks that they ordinarily escape recognition.

Meteoritic Clouds and Dust

What becomes of the small meteorites which frequently flash in the atmosphere and then vanish?

They are reduced to dust and gases which either settle to the earth or become additions to the atmosphere.

Can the dust from such meteorites be collected and studied?

Yes. On several occasions it has been collected in small quantities. With proper facilities it could no doubt be studied exhaustively.

What is the method of collecting this dust?

Several methods have been used. Many years ago it was collected by melting arctic snow. Various dredging expeditions have brought up from the sea bottoms clays in which were embedded minute globules of magnetic metal. Professor Maud Mackemson of the Department of Astronomy at Vassar College set out a number of large pans on the top of a tower during the Leonid shower of 1931 and collected small globules which were tentatively identified as being of meteoritic origin. The author has collected meteoritic dust from many locations and by several methods, the most successful of which was the placing of magnetic traps at the exits of drain pipes on houses with roofs of non-metallic material in locations free from industrial magnetic dust or sand.

How can meteoritic dust be distinguished from deposits of terrestrial dust and artificial products?

The meteoritic dust collected by use of the last-named method was strongly magnetic and under magnification a large percentage of it was found to consist of perfect, or nearly perfect, spheres which, upon testing, showed the presence of nickel. Tests run on various terrestrial materials and artificial products most nearly resembling meteoritic dust showed no nickel. Coal smoke yields small globules which are about the same shape and size but these are only slightly magnetic and contain no nickel. Successive showers of rain or snow a few days apart washed from the same roof amounts proportionate to the length of time separating the showers.

Could there not be found a more perfect method of collecting and measuring this increment of dust?

A plan has been worked out involving the setting up of a roof-like trap constructed of aluminum, stainless steel, or porcelain-glazed steel, to be placed on an island of coral formation far removed from any granite or volcanic land mass. This trap would be washed down with distilled or filtered water at regular intervals. The run-off would pass through a suitably constructed trap and all of the solids carefully sorted and analyzed. Such a test would extend over a period of several years so that seasonal and other variations could be recognized and measured. To make it still more meaningful the method would be tested in different latitudes so as to learn whether distribution of meteoritic dust materials is uniform over the surface of our planet. To date, this plan has not been put into use.

If the majority of meteorites are stony, why should we expect that meteoritic dust should all be magnetic?

We are quite sure that it is *not* all magnetic. The search was made for the magnetic dust for the reason that it seemed to be the simplest method of carrying out a preliminary test

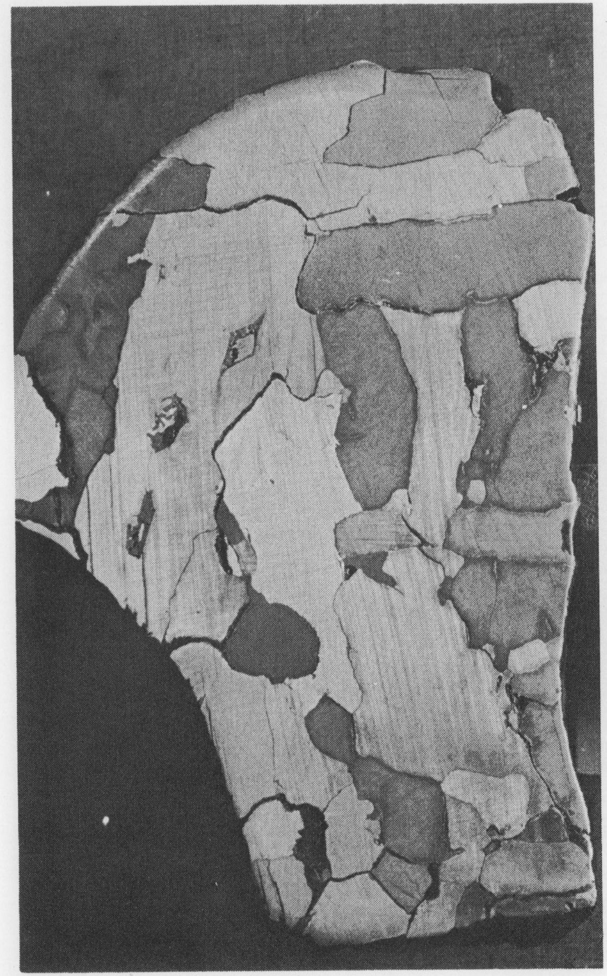

Fig. 21. Polished and etched section of a granular, or brecciated, hexahedrite from Sandia Mountains, New Mexico. Each section or granule represents an independent crystalline aggregate each with its own set of Neumann lines and orientation. Some hexahedrites are made up of a single crystalline aggregate. **Nininger Collection.**

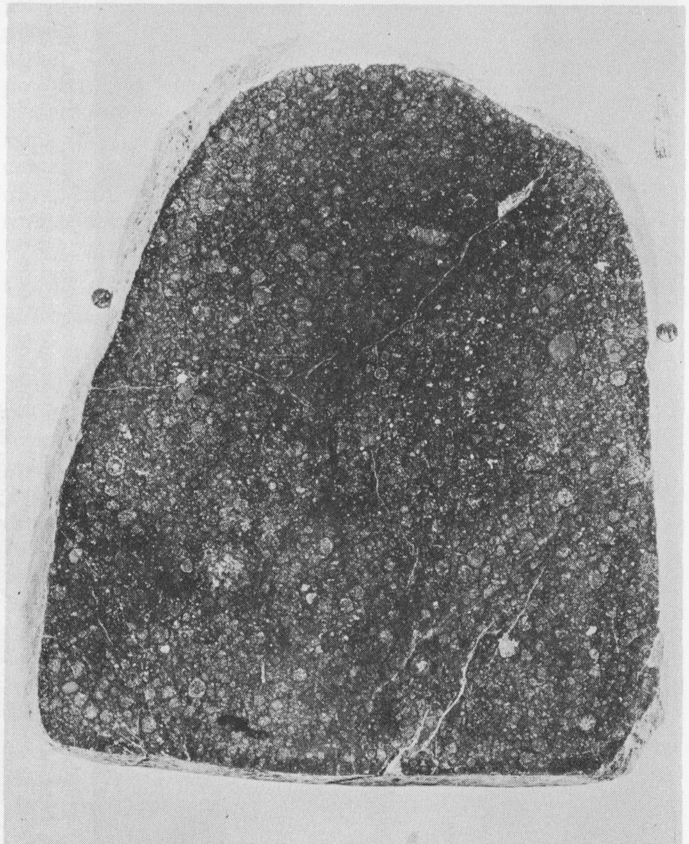

Fig. 22. Polished section of a chondritic aerolite from Coolidge, Kansas, showing both nickel-iron grains and chondrules. **Nininger Collection.**

Fig. 23. Cloud left in the wake of the meteor of March 24, 1933, as seen from Timpas, Colorado, 160 miles to the north. This photo was taken by C. R. West about 15 minutes after the Brown photo (Fig. 2) was taken.

Fig. 24. The Arizona meteorite crater as viewed from the air, looking north. The road in the upper left connects with U. S. Highway 66 to the north. The scars on the crater rim in the foreground are those of the now abandoned silica mining operation. **Photo courtesy U. S. Air Force.**

to prove the existence of such a cosmic rain. Logically, we should expect the great bulk of meteoritic dust to be non-magnetic and the plan outlined above should provide an opportunity for working out a system for the identification of the various types of meteoritic dust.

Is the amount of meteoritic dust arriving on our planet of sufficient significance to warrant extensive investigations?

Any amount, however small, is significant. And from preliminary tests we suspect that there may be deposited over the earth in a thousand years an amount equal to a layer one millimeter thick. This would amount to a layer nearly 200 feet thick since the beginning of Tertiary time. This is, of course, very speculative. Measurements may show it to be only one-tenth as much, or many times greater. The fact that we must be so indefinite is precisely why it is so important that we find out the facts. In 1933 the author estimated that perhaps 50,000 tons of meteoritic material reach the earth daily. Recent studies tend to confirm this estimate.

What are meteoritic clouds?

Many of the meteorites which have been seen to fall have left in their wakes clouds of dust or "smoke." These clouds, which are composed in part of dust from the meteorite, may appear roundish or as long ribbon-like clouds. (See Figs. 5, 23)

What is the importance of studying meteoritic clouds?

If we are to understand the function of meteorites in the solar system and in the history of our planet, a most important problem is to ascertain the total weight of meteoritic matter that is constantly arriving from space. The clouds left in the wake of meteorites constitute a valuable, concentrated source of this material.

How can meteoritic clouds best be studied?

First they should be measured. Photographs should be taken from as many different points as possible to obtain dimensional information. Equally important is the question of density and constitution. Both of these aspects are now possible to attack successfully. With modern fast planes, the sampling of meteorite clouds is definitely possible. Vacuum jars, with suitable devices for opening and re-sealing, could be kept in readiness and dispatched via our fastest planes or on pilotless craft instantly on the appearance of a meteoritic cloud. These clouds often endure for half an hour and sometimes for several hours. From an air base at a distance as great as a hundred miles, worthwhile attempts could be made. In cases where equipment chances to be within a few miles, not only could samples be taken of the cloud itself, but air samples from below the cloud could be taken as well.

Of what use would samples from below the clouds be?

On several occasions persons residing under these clouds or in locations favored by air currents have experienced a showering of "gravel" or "sand." Prompt and accurate sampling of the air below the clouds could capture enough of this material before it reached the soil to provide valuable information regarding the mass of material that is rained on the earth from such clouds.

Have we now any clues as to the masses of these clouds?

We know that some have deposited considerable showers of dust and gravel. We also know that the volume of many of these clouds is of the order of 10 to 50 cubic miles and in some cases photographs have proven them to be as great as 1,000 cubic miles. At levels at which these clouds appear, the atmosphere, though quite rarified, still weighs 1,000 to 50,000 tons per cubic mile and it is not inconceivable that the clouds of dust are at least of the same order of mass.

How long would it take for particles to reach the soil from a cloud 10 miles high?

The larger particles would begin arriving in a few minutes, but smaller particles would settle at rates inversely proportional to their sizes. The smallest of these particles suitable for study might require hours, or even days, to settle.

What are the chances of collecting these particles after they reach the ground?

This is an important consideration and it is more difficult than would at first appear. Any such showering must be expected to scatter over quite a large territory—at least 10 to 12 square miles. Unless meteorite fragments are found to serve as a guide, it would be difficult to localize the area within a territory smaller than several times this area.

How can a search for such particles best be made?

If the terrain is suitable, probably the most promising method is to drag the soil with large magnets suspended from the bumper of an automobile.

What quantity of small particles might be collected in this manner?

Let us imagine the arrival in our atmosphere of a stony meteorite weighing one ton, 10 per cent of which consists of nickel-iron and sulphide grains. We shall assume that this mass finishes its fiery descent at an elevation of 12 miles where it undergoes the usual disintegration which characterizes arriving meteorites.

We may assume that at this point 75 per cent of the mass is reduced to particles of cloud-forming size. These will drift considerable distances before settling. They are mainly non-magnetic and are un-recoverable. We may further assume that 5 per cent, or 100 pounds, survives in masses of pebble and cobblestone size such as we see in museums. Perhaps one chunk of 40 to 60 pounds buries itself in the subsoil. Smaller cobblestones and pebbles already referred to are scattered over perhaps 8 or 10 square miles, the smaller ones resting on top of the ground, others partly or completely buried.

The remaining 20 per cent, or 400 pounds, of the one-ton mass we shall assume is reduced to particles of the kind we are now interested in recovering. Let us say they average about the size of wheat grains. These weigh about 70 milligrams each so that it requires about 6,500 to weigh a pound, and they are drifted by wind so that they spread out over at least 10 square miles. Only about half of these particles will contain enough metal to be readily picked up by a magnet; and experience has shown that on the average workable terrain, not more than one-third of the magnetic particles passed over by a magnetic rake can be expected to adhere to the apparatus. Consequently, only about one-sixth of what are passed over in our search can be collected. This amounts to 67 pounds and is distributed over at least 10 square miles of territory.

Let us keep in mind the fact that the above description was imaginary; but let us also remember that there are good reasons for believing that some of the large noisy fireballs which are recorded every year actually represent just such events as we have depicted. In the past none of these has been investigated and we now propose to undertake hypothetically such an investigation.

We shall use a magnetic device, drawn behind an automobile or truck, which effectively covers a strip three feet wide. For maximum effectiveness we shall have to travel at not more than about two miles per hour. This means that in order to cover one per cent of the designated area we shall have to drive 144 miles, consuming 72 hours of driving time. If our assumptions have been correct this survey should yield about 4,350 particles, weighing altogether 10½ ounces.

We have gone to a lot of trouble and expense for such a small amount of material but the significance of such a survey may be very great.

Just what is the objective that would justify such an expensive operation for the recovery of so small an amount of material?

We are here dealing with the fundamental question of how much matter is reaching the earth from space. A fall such as we have imagined would, by methods used in the past, probably not be listed in the records at all because nothing would have been recovered. In the rare event that one or more stones were collected we could not reasonably expect a recovery of more than two or three pounds. Thus, any scientist attempting to deal with the problem of measuring the quantity of meteoritic material reaching the earth would probably miscalculate by something like 99½ per cent!

If successful collecting of particles can be accomplished on the ground, is there still reason for collecting samples of the clouds themselves?

Since 1803, when meteorites were first officially recognized by scientists, new varieties of meteorite have been discovered at the average rate of one every 22 months. This suggests that we are as yet unacquainted with the over-all picture of the meteorite population in space. Furthermore, an eminent astronomer has recently suggested that many of the meteorites which fail to deposit fragments on the earth are of very volatile materials, quite different from the meteorites with which we have come in contact. Investigations of meteoritic clouds may, among other things, prove or disprove this suggestion.

Can a layman be of any service to scientists in determining the dimensions of a meteoritic cloud?

Definitely. Very useful observations can be made. For example, the apparent dimensions of the cloud can be compared with the diameter of a full moon. If the moon is not visible, one can still make fair comparisons from memory. Another practical method is to hold a pencil or any similar object at arm's length and compare the apparent diameter and length of the cloud. Or a comparison can be made with one or more fingers of the hand held at arm's length.

How may one know whether a meteoritic cloud is large enough to be important?

Any visible cloud left by a meteorite is important enough to measure and report. It should be remembered that such clouds float at altitudes of 10 to 50 miles. Ordinary cumulus clouds are on the average only two to three miles above sea level. A meteoritic cloud which appears the diameter of a

full moon may well be more than 100 miles away from the observer. Viewed at a distance of 115 miles a cloud slightly more than a mile in diameter would still appear no larger than does the full moon when seen overhead. The same cloud, if seen from a distance of four miles, would appear to be nearly 29 times as wide. Meteoritic clouds are usually 10 to 30 times as long as they are wide, so that their total apparent size depends largely upon the angle from which the observer sees them. Such clouds may represent enormous weight of material, all of which is added to the earth in one form or another.

Meteorite Craters

What is a meteorite crater?

A meteorite crater is a bowl-like depression in the earth which is formed by the impact of a large meteorite. It will tend to be circular in shape (although some are elliptical), the pit floor is lower than the surrounding terrain, the pit is surrounded by a prominent collar or uplifted rim, the strata in this rim dip sharply away from the vertical axis of the pit, and there is no evidence of the extrusion of lava in any of the known craters. (See Fig. 24)

How are meteorite craters formed?

Meteorite craters are formed by huge meteorites which, by reason of their size or structure, avoid aerial breakup and reach the earth still traveling at high rates of speed. Craters larger than about 90 feet in diameter are usually formed by the explosive disruption of the forming meteorites which were traveling at speeds somewhat in excess of one mile per second at the time of impact and exploded with tremendous force to blast the crater. Such craters tend to be circular, or sometimes somewhat square, and the remaining fragments of the meteorite which has made them are mainly scattered about over the terrain outside of the crater pit. Meteorites which explode to form craters are the only ones believed to reach the earth in blazing condition.

Craters under 90 feet in diameter are normally formed by meteorites traveling at speeds below those at which impact-explosion occurs. These craters are formed by the force of the impact and fragmentation alone and tend to be somewhat elliptical in shape. The larger part of the meteorite which forms this type of crater will be found within the pit, there having been no explosion to remove it therefrom.

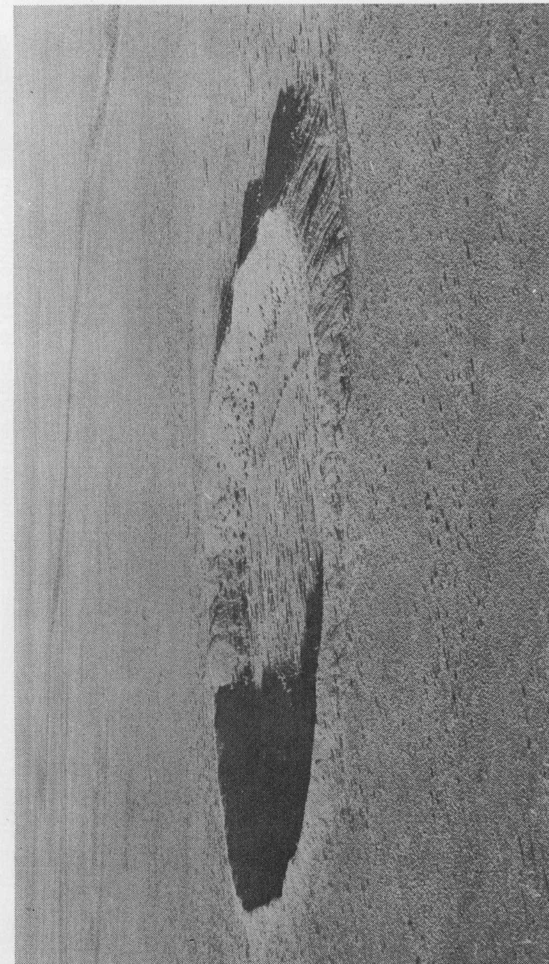

Fig. 25. Wolf Creek crater, near Halls Creek, Western Australia, with Wolf Creek in background. Diameter 2800 feet, depth 160 feet, height of rim about 80 feet.

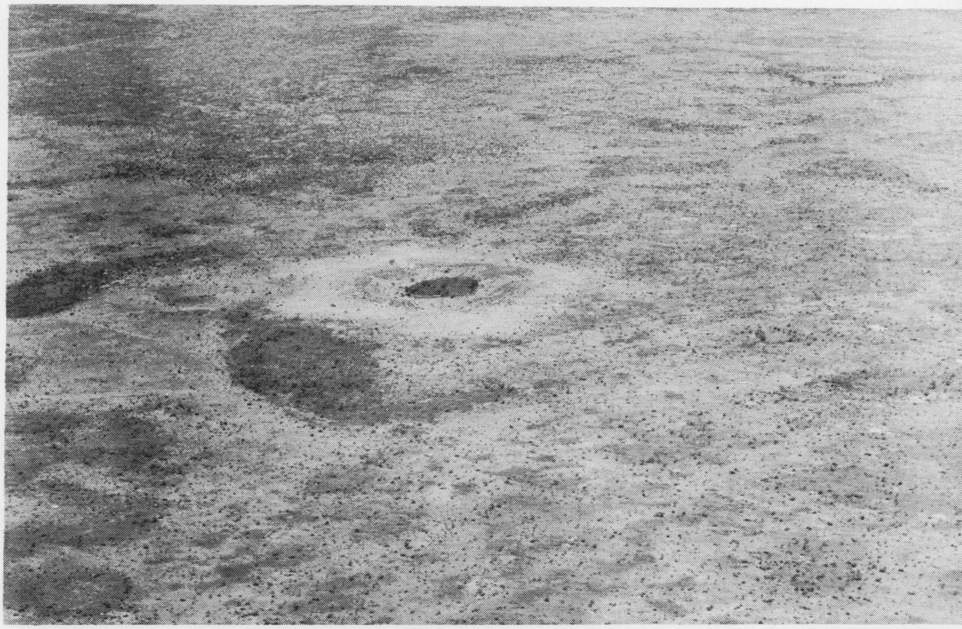

Fig. 26. The largest of the Odessa, Texas, craters. Diameter 530 feet, depth 18 feet, height of rim 3 to 4 feet. The light material surrounding the crater is the outthrown limestone resulting from the crater's formation.

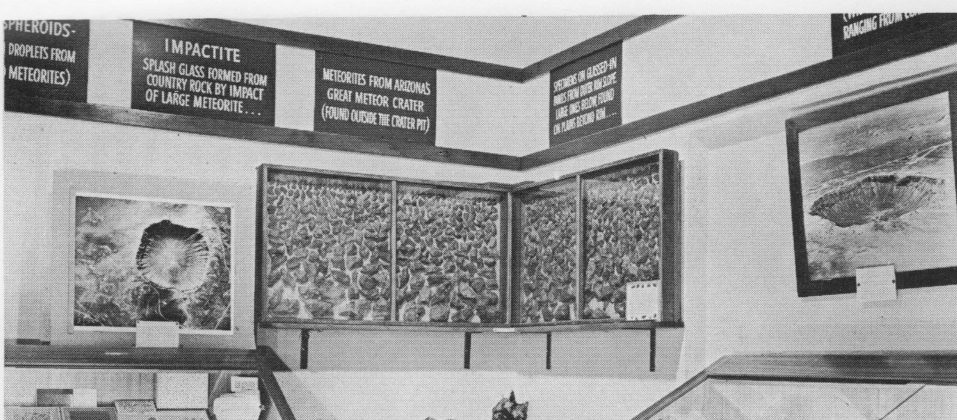

Fig. 27. Meteoritic material recovered from the vicinity of the Arizona crater as displayed in the American Meteorite Museum. **Nininger Collection. Photo by Margaret B. Bennett.**

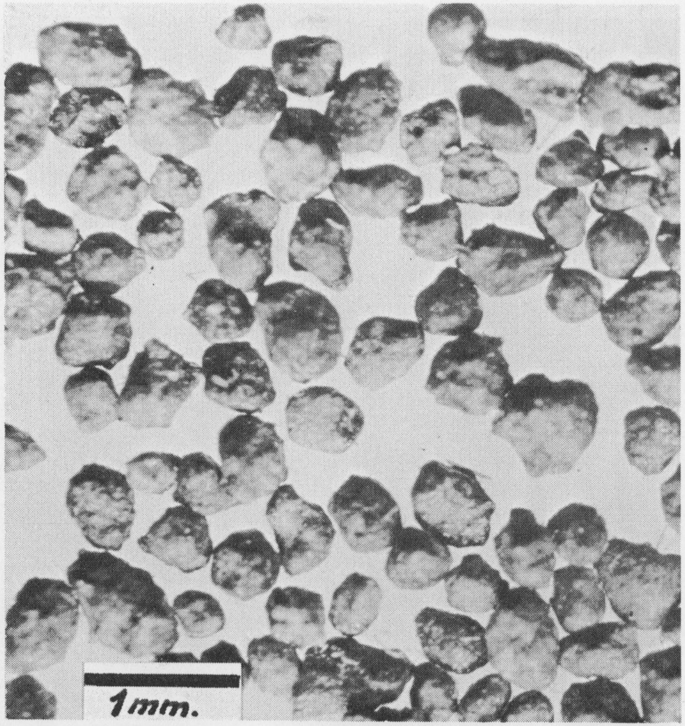

Fig. 28. Metallic spheroids, the condensation droplets of a vaporized meteorite (enlarged to show detail) were discovered by the author at the Arizona meteorite crater in 1949.

Do all meteorites form craters?

By no means. Less than one percent of the 1,600 meteorite falls which have been collected in all the history of the science have been connected with meteorite craters.

Is Crater Lake in Oregon a meteorite crater?

No. Crater Lake is regarded as an extinct volcanic crater as are the Ubahebe crater in Death Valley, the Ludlow crater in California, the Capulin crater in New Mexico, and the Elegante crater in Sonora, Mexico.

What are the differences between meteorite craters and volcanic craters?

A meteorite crater is a bowl-like pit in the earth surrounded by an uptilted rim of country rock. The floor of a meteorite crater is usually much lower than the surrounding terrain. A volcanic crater is usually a funnel-like depression in the top of a lava mountain. However, in some cases, volcanic forces produce what is called a blowout crater where super-heated steam or other gases have been trapped under sediments or volcanic flows. When a sufficient pressure has developed, such gases may break through to the surface in an explosion which produces something very much like a meteorite crater in general appearance.

Is there a way of distinguishing between explosion-type meteorite craters and the explosion-type volcanic crater?

It has been traditional to consider it essential that in order to positively identify a meteorite crater some remnants of the meteorite responsible for it should be recovered. In the cases of extremely old craters, where it is assumed that all remnants of the meteorite would have disappeared, their identification must depend on structural features and their relation, or lack of relation, to adjacent formations; but such identifications are more or less problematical.

Recently a newly discovered mineral called *coesite* has been found in connection with explosion-type meteorite craters. Coesite, the high-pressure polymorph of silica, is believed to be created only under conditions of high temperature and high pressures such as prevail when a meteorite crater is explosively formed in siliceous rock. Other than its occurrence in large meteorite craters and at test sites for atomic bombs, coesite has not been found in nature.

Are there any other features which are likely to be mistaken for meteorite craters?

Yes, sink holes and collapse craters. Sinkholes or subsidence craters are produced by the dissolution of some soluble formation, such as limestone, gypsum, or salt, and its removal to form a large cavity or underground cavern. When a sufficiently large area has been thus undermined a slight earthquake or other disturbance causes the roof of the cavern to fall in. The result is a pit of diameter and depth corresponding to the size of the cavern.

Another such crater is sometimes produced in a lava formation where volcanic bubbles have formed during the cooling of the lava and subsequent cracking of the hardened lava prepares the way for a collapse to form a crater similar to the sinkhole just described.

How can these be distinguished from meteorite craters?

The most evident difference between these two subsidence pits and meteorite craters is that they lack rims of uplift and

outthrown debris which always mark all but very ancient impact craters. Any crater formation which has a rim around it should be investigated by an expert.

Then any pit with a rim around it is a meteorite crater?

No, not necessarily. In areas of predominantly sandy soil where the wind blows largely from one direction, there are developed wind blowout craters which somewhat resemble true meteorite craters. This type of crater is formed when the grass in a small area has been destroyed and the prevailing winds excavate a pit piling the excavated sandy soil around its edges to form a rim. There are several ways to recognize these blowout pits. They usually occur in groups which are elongated in the direction of the prevailing wind with their leeward rims built to a conspicuously higher level than the others. The rims of blowout craters are made up of only sand and light gravel, the larger stones, because of their greater weight, being left in the bottom of the pit when the lighter material was blown out to form the rim. However, an expert should investigate any crater formation which has a rim around it to positively determine the true nature of the formation.

How far down in a crater are meteorite fragments to be looked for?

Meteorite fragments are much more likely to be found *outside* large meteorite craters scattered about on, or near, the surface rather than in the crater pit.

Have no large meteorites been found in craters?

No large meteorites have ever been recovered from inside meteorite craters, but small pieces have been found within the pits of small craters.

Why do not larger craters yield larger meteorites?

The answer to this question is found in the consideration of air resistance. The atmospheric blanket surrounding the earth is equivalent to a layer of rock 14 feet thick which is sufficient to check the speed of most meteorites, cushioning their impacts. But the weight of a very large meteorite is so great in proportion to its surface that the air fails to check its speed very much; therefore it strikes the soil with such tremendous force that the heat of impact is sufficient to explode it. The explosion produces a crater but the meteorite itself is for the most part reduced to gases.

Why, then, have meteorites been found around several of the large craters?

The explosion of a meteorite could hardly be complete. Because of its structure, a certain amount of shattering precedes and accompanies the explosion, thus setting free fragments which are scattered in all directions. Some of these may even be deposited in the depths of the crater.

Where is the best example of a meteorite crater?

Without doubt the best example of a meteorite crater in the United States is that known as the Arizona meteorite crater near Winslow, Arizona. It also goes under the following names: "Meteor Crater," "Canyon Diablo Crater," "Barringer Crater," "Coon Butte," and "Crater Mound." This crater consists of a giant parapet or collar of uptilted strata rising 150 to 200 feet above the surrounding plain and enclosing a bowl-like pit approximately 4,100 feet in diameter and about 600 feet deep. (See Fig. 24)

Did the meteorite which fell in Siberia in 1908 form a large crater?

The original investigations of the area of the fall which were conducted in 1928, 20 years after the event, indicated that a number of small craters had been created in swampy land. The atmospheric disturbance was extremely great, almost completely devastating an area of forest some 40 miles in diameter, uprooting the trees and flattening them radially outward from the central area, and burning the bark and smaller branches from those within a 10 to 12 mile diameter. Impressive sounds were heard by persons as far away as 300 to 350 miles. And barigraphs as far distant as London recorded the aerial pressure wave from the blast. Recent investigations, made by members of the Committee on Meteorites of the U.S.S.R. Academy of Sciences in light of present-day knowledge of meteorite craters, indicate that the meteorite which fell here almost completely demolished itself by exploding in the air without reaching the ground. The formations which were formerly believed to be craters have been subjected to deep and repeated excavations and are thought to be the result of frost and water action, which the Russian investigators state is a common occurrence in that swampy arctic terrain. The meteorite is hypothesized by the Russians as being one composed of very light materials so that little was left of it following the explosion.

Have other meteorite craters been discovered?

Yes. In Australia there is a group of 13 craters, known as the Henbury craters, which range in size from 10 to 220 yards in diameter and around which have been found scattered fragments of nickel-iron meteorites. A geophysical survey indicated the presence of meteoritic fragments in the depths of the smaller craters but not in the larger ones. Excavation of one of the smallest yielded about 500 pounds of meteoritic material in the form of fragments.

There are three other single craters known in Australia. The largest of these, the Wolf Creek crater, is more than one-half mile in diameter. (See Fig. 25) Meteorites have been found in connection with all of them. There are also groups of craters in Arabia, Estonia, Argentina, and near Odessa, Texas. (See Fig. 26) A single small crater was found near Haviland, Kansas.

A systematic program of discovery and evaluation of possible meteorite craters has been underway in Canada for several years with rather amazing results. At this writing there are 10 crater formations under investigation by the Department of Mines and Special Surveys of Canada ranging in size from 650 feet to nearly 300 miles in diameter. Five of these are considered proven meteorite impact craters (the largest about 8 miles in diameter) and the other five are awaiting completion of more definitive studies.

Have meteorites been found in connection with the Odessa, Texas, and the Haviland, Kansas, craters?

Yes. At the Odessa, Texas, group of three craters, nickel-iron meteorites have been found abundantly scattered around the craters, and some weighing in the neighborhood of a hundred pounds have been found in the smaller craters; but the main crater, with a diameter of about 600 feet, has yielded no meteorites even though extensive explorations were carried out.

The Haviland, Kansas, crater, which was small (36′x55′x 11½′ deep), was completely excavated and yielded about 1,200 pounds of fragments, the largest of which weighed about 85 pounds. Scattered around the crater were found many masses weighing from a few ounces to 1,000 pounds. A total of about four tons was recovered from the whole fall.

Have the meteorites so far found associated with craters all been of the nickel-iron variety?

No. The Haviland, Kansas, crater was formed by a meteorite of the pallasite variety. (See Fig. 14) The Dalgaranga crater of Western Australia (diameter about 70 feet) is believed to have been formed by a stony meteorite in which were embedded lumps as well as small grains of nickel-iron. In this respect, the meteorite may have looked very much like the Estherville, Iowa, meteorite. (See Fig. 15)

What is known about the meteorite which formed the famous Arizona meteorite crater?

The meteorite which formed the Arizona meteorite crater was of the nickel-iron variety, containing about 7 per cent nickel and 90 per cent iron. It also contained large nodules of graphitic carbon and of troilite—iron sulphide (FeS)—as well as abundant schreibersite—nickel-iron phosphide $(Fe\ Ni\ Co)_3P$—and cohenite—nickel-iron carbide $(Fe\ Ni\ Co)_3C$. In portions of the meteorite which were heated by the crater-forming explosion, some of the carbon has been changed by the heat and pressure into diamond.

It is estimated that from 30 to 35 tons of metallic fragments ranging from less than one ounce to more than 1,400 pounds have been collected from the plains within a radius of five to six miles around the crater. (See Fig. 27) Meteoritic oxide, mostly in the form of small chips, is abundantly scattered over the area; and what appeared to be fragments of the meteorite were encountered by a drill several hundred feet below the present crater floor, though no meteorites have ever been recovered from the crater pit.

The bulk of the crater-forming mass, however, is not in the form of fragments but in the form of minute droplets which condensed from the vapor cloud which resulted from the explosion of the meteorite upon impact with the earth. These droplets, which have been named *metallic spheroids,* are found mixed with the topsoil around the crater and in the crevices of the inner walls in amounts estimated at from 4,000 to 8,000 tons. (See Fig. 28)

How do their structure and composition prove that the metallic spheroids are not merely the particles of a pulverized meteorite?

Particles resulting from the pulverization of a meteorite should be angular, corresponding to the granular structure of the original meteorite which we know from a study of the fragments found in the area. Small angular particles called *sluglets* have been recovered in the crater area which are without doubt the pulverization products but they differ both chemically and structurally from the metallic spheroids. Laboratory studies of the spheroids show their form to be that of a droplet which has been formed from a vaporous state by the accretion of material around a central core. In chemical composition the metallic spheroids are much richer in nickel, cobalt, and platinum than are fragments of the original meteorite. Such enrichment can be explained only by assuming that the parent meteorite passed into a vaporous state from which the droplets formed by condensation. The sluglets, on the other hand, compare favorably with the larger masses of the meteorite which have been found.

Has any other explosion product been discovered at the Arizona crater?

Yes. *Impactite* was discovered by the author at the Arizona crater in 1953. Impactite is the name given to the native, or

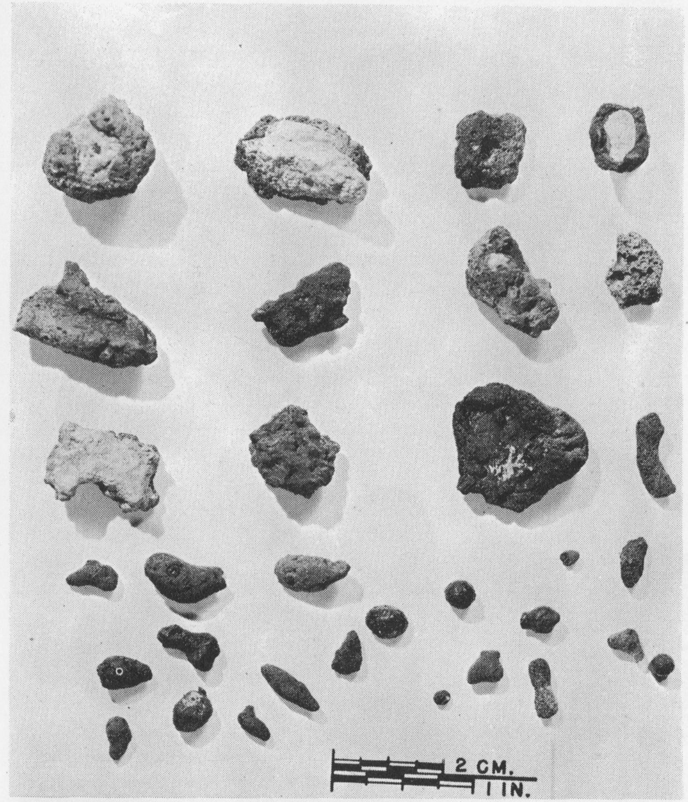

Fig. 29. Impactite bombs of various shapes and sizes, from the Arizona meteorite crater. The light colored cores of the bombs in the top row are composed of sandstone and contain the impact-induced pseudomorph of quartz, coesite. **Photo by U. S. National Museum.**

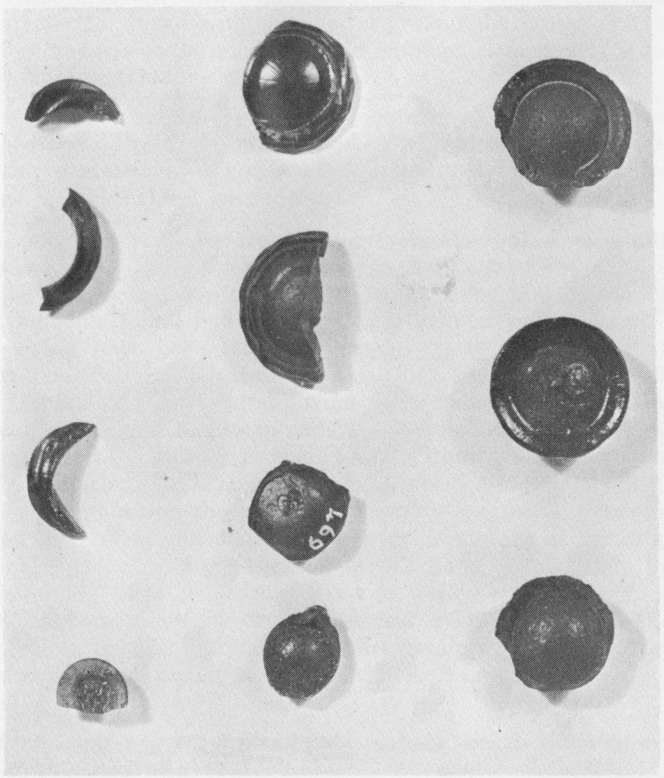

Fig. 30. Australites, tektites from Australia, tend to have either a button shape, as shown above, or a dumbbell shape; however, most do not have the flange around the outside, as shown here, and are referred to as cores or lenses. **Nininger Collection.**

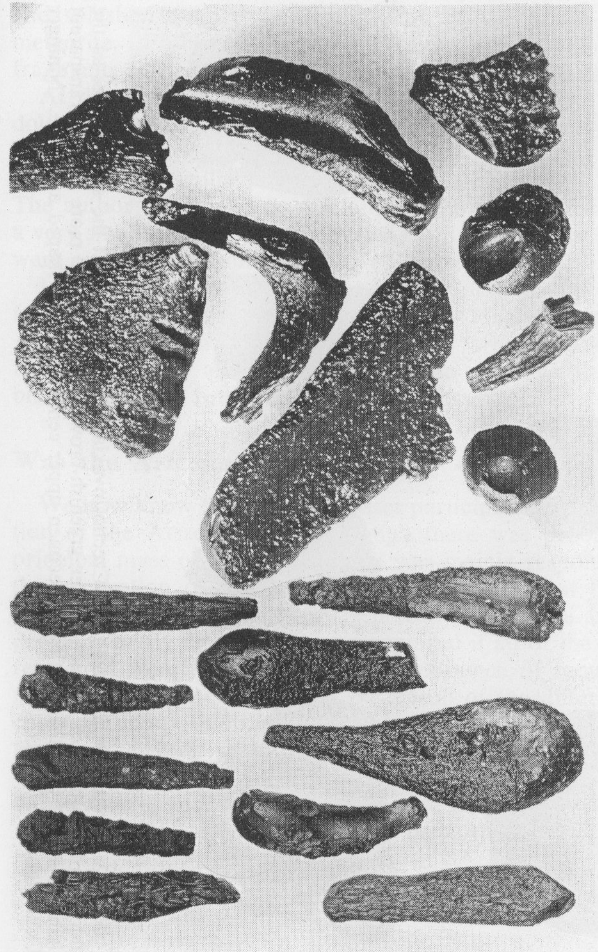

Fig. 31. Indo-chinites, tektites from South Viet Nam, tend to have an elongate drop shape or a discoidal shape when whole. They show evidence of long weathering, violent breakage, and subsequent long weathering, however, and are more likely to be fragmental than tektites from other areas. **Nininger Collection.**

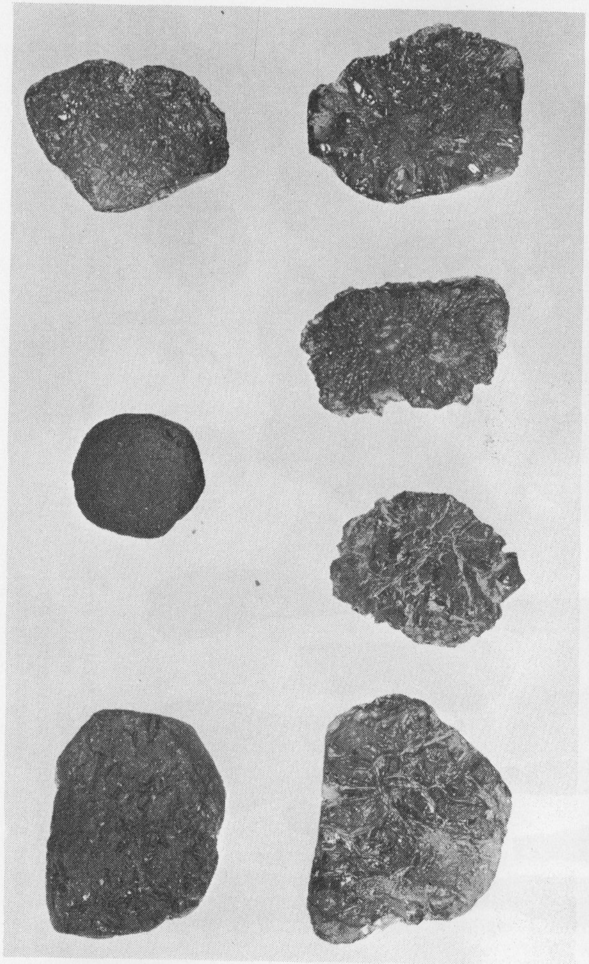

Fig. 32. Moldavites, tektites from Czechoslovakia, exhibit somewhat the same shapes as the indo-chinites but are of a much lighter greenish-brown color and are more nearly transparent than are any of the other tektites. Specimen upper center is a core-shaped australite. **Nininger Collection.**

country, rock which is invaded, partially or wholly melted, and splashed about by the explosion of the crater-forming meteorite. Embedded in it are found small spheres and fragments of bright meteoritic metal.

At the Arizona crater the impactite is a slag composed of dolomite and silica, formed principally from the dolomite limestone beds through which the meteorite had to pass as it penetrated the sediments of the Arizona desert. (See Fig. 29) The author also found on the north rim of the Arizona crater a very small quantity of a yellowish transparent glass in which were embedded minute droplets of metal.

Impactite may be expected to vary in accordance with the formations of the local terrain. At the Henbury craters in Australia impactite material, some of which looked like furnace clinkers and some in the form of silica fused into black glass, was found in considerable quantity.

Was the Arizona crater made by one mass?

We now know that several masses participated in the formation of the Arizona crater although there was probably one principal mass of great size which was mainly responsible for the excavation of the hole. Fragments of at least five, and probably of six, masses have been recovered in the area; and probably many more would be recognized if all of the material recovered were to be studied. The existence of remnants of more than one mass is known by reason of the differences in chemical composition and physical structure which have been found in a very small percentage of the many fragments which have been studied. Each meteorite has its own individual structure, and, usually, a distinctive chemical structure by which it can be differentiated from meteorites of other falls.

How many meteorite fragments have been collected from around the Arizona meteorite crater?

No complete record has been kept, but the following figures are at least approximate:

One mass of 1,406 pounds.

About a dozen masses ranging from 500 to 1,000 pounds.

Several hundred masses ranging from one ounce to 400 pounds.

Many thousands of smaller masses under an ounce in weight.

The several organizations with which the author has been associated have recovered an estimated 43,000 specimens of the latter size range. Some of these weigh less than 1/10 gram (1/283 ounce). A survey conducted by the author in 1939 indicated that some three million of these small fragments were yet in the soil within a radius of three miles from the crater.

Tektites

Are meteorites the only objects which come to earth from space?

No, there are objects called *tektites* which are believed to come from outside the earth's atmosphere.

What are tektites?

Tektites are the small, dark glass objects which are found distributed over several large areas of the earth's surface and which seem to bear no relationship to the terrains on which they are found. The name *tektite* is derived from the Greek word *tektos,* meaning molten, and was chosen because of unmistakable evidence that these glassy particles were shaped while in plastic condition.

Are tektites meteorites?

Not in the opinion of this author. They differ in all respects from meteorites, except that they seem to come from outside the earth's atmosphere as do meteorites. Their form, surface markings, and distribution all bear testimony to the fact that they have come from a source different from that of meteorites and that they have arrived at the earth's atmosphere at speeds much lower than those of meteorites.

Tektites are composed principally of silica in the form of glass, and, although silicates (combined forms of silica) are present in meteorites, silica, particularly in the form of glass, is practically never present.

Tektites lack the peculiar fusion crust of meteorites which is a thin slag-like coating overlying an interior which shows little or no evidence of heating. Tektites show unquestionable evidence of having been melted throughout.

Tektites lack both metallic nickel-iron and chondrules which are the two most common features of meteoritic structure.

Tektites are of lower specific gravity (of less weight for their size) than even stony meteorites, except in very rare cases; and those few meteorites of low specific gravity in no way resemble tektites.

The range in size is far greater in meteorites than in tektites.

Tektite distribution differs in two important respects from meteorites: A deposit of tektites which seems to represent a single fall will be spread over an area many times larger than that encompassed by any known meteorite fall. Although tektite areas are large, they are far fewer in number than are known meteorite falls. The known tektite deposits which may be reasonably assumed to represent separate falls scarcely equal in number one per cent of the number of known meteorite falls; yet, these few deposits contain a larger number of individual tektites than the total of known meteorites from a hundred times as many falls.

In short, it may be said that tektites differ from all known meteorites in all respects except that they are assumed to have come to the earth from outside of our atmosphere.

Where are the known tektite deposits?

So far, tektites have been identified and collected from the following nine locations: Australia; Indo-China; Luzon, Philippine Islands; Czechoslovakia; Malay Peninsula and nearby islands; Java and nearby islands; Ivory Coast, Africa; and Texas and Georgia in the United States.

How are the tektites of the various deposits differentiated one from another?

Tektites differ from one another in size, shape and color,

and yet, in internal structure and composition they closely resemble each other no matter where found. Specimens found in a given locality have certain characteristics in common which generally set them apart from those of other areas. So conspicuous are these group differences that tektites from the various localities have received special names. Those from Indo-China are called indo-chinites. Those from south Australia are called australites. Those from the Moldau River Valley in Czechoslovakia are called moldavites. The tektites found in Texas have been given the name bediasites. Those found in the Philippine Islands were named rizalites. And the distinctive type found on Billiton Island are called billitonites.

If tektites come from outside the atmosphere, but do not come from the same source as meteorites, then from whence do they come?

The best supported theory of origin is that they are bits of moon-rock (lunite) which have been blasted off the moon by exploding meteorites. Since there is no atmosphere to protect the moon, all meteorites probably explode upon striking its surface; and since the gravitation of the moon is weak (only 1/6 that of the earth) some of the spray of fragments resulting from the impact-explosion of large meteorites may very well leave the moon never to return. Those spurts of fragments which chance to be properly directed may reach the earth to give us our tektites.