THE BARRINGER (*Arizona*) METEORITE CRATER

by GEORGE E. FOSTER

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By George E. Foster

Fellow, Meteoritical Society

Fellow, American Association for the Advancement of Science

Curator, Museum of the Barringer Meteorite Crater

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To Oscar Monnig,
with the compliments
and sincere regards of
George Foster

DANIEL MOREAU BARRINGER, 1860-1929

Working almost single-handed against the opposition and ridicule of the scientists of his day, he lived to see general acceptance of the crater's meteoritic origin.

The Barringer (Arizona) Meteorite Crater

The Northern Arizona plateau, traversed by U. S. Highway 66, is visited each year by well over a million people from all sections of the United States and most nations of the free world. They find it of great interest, not only for its beauty but also for its difference from the places from which they come. Most populous areas have moderate to heavy rainfall and deep topsoil. Many have been scoured by glaciers within comparatively recent times. They show the Earth's surface at this point in time, with little or no indication of what it was like in the past or how it came to its present state.

This plateau, on the other hand, is an ancient land. It is, and for ages has been, a semi-desert of rock and canyon untouched by glaciers. It is a land of slow erosion, which shows, as few areas do, how the Earth looked in the past and how its crust was formed.

To the east is the Petrified Forest with its acres of logs and fragments, replacements in agate of trees which lived 160 million years ago. Surrounding it and stretching to the northwest along the bank of the Little Colorado River are the buttes and cones of the Painted Desert, residue of vast beds of volcanic ash which buried those ancient trees.

From Holbrook to a point twenty miles west of Winslow are eroded rocks and ridges of still older Mœncopi sandstone, which was deposited as floodwater mud in the bed of a shallow river in Triassic times. West of that may be seen the still more ancient Kaibab limestone, formed of Permian sea-bottom deposits, 200 million years or more ago.

Farther west, around Flagstaff and Williams, these ancient rocks are overlain by volcanic mountains which are comparative babies, the oldest dating back only a few million years. North of these mountains is the Grand Canyon, where erosion has cut to a depth of a mile through all the sedimentary layers to expose the granite which was the Earth's original crust.

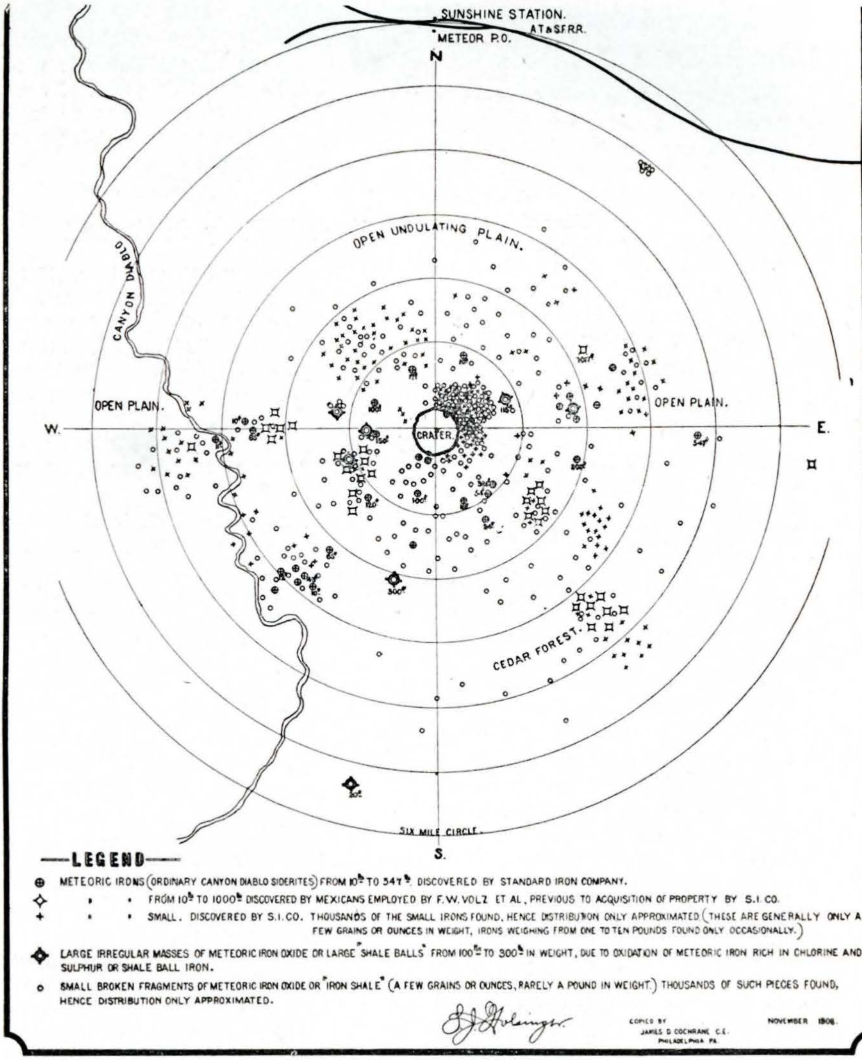
Nature's Study In Contrast

In these great wonders, Nature has demonstrated how slowly, over eons of time, she usually works. Yet, almost in their midst, as though she sought to demonstrate by contrast how fast she can work on a gigantic scale, she has placed another of her great wonders—the Arizona, or Barringer, Meteorite Crater.

This crater, which is the largest accepted by science as of proved meteoritic origin, rises about 150 feet above the plain, between Winslow and Flagstaff, at a point six miles south of Highwayy 66. It may now be reached by a paved access road. It has an average diameter of 4150 feet, a depth of 570 feet, and is 3 miles around the top by footpath. It has been estimated that the rim comprises over 300 million tons of rock and earth and that its original mass was close to 400 million tons. For comparison as to its depth, the Washington monument is 555 feet high.

This crater was known to white men as early as 1871, but it was thought to be just another dead volcano and was given little attention. In 1886 sheepherders found some meteorites near Canyon Diablo, about two miles west of the Crater. Meteorites from the area are still called Canyon Diablo siderites.

In 1891 geologists from the U. S. Geological Survey visited the area. They found no volcanic materials within miles of the Crater; still they concluded that it had been formed by steam or gaseous blowout and that the finding of meteor-



Meteor Crater and surrounding area, showing distribution of meteoritic material. D. M. Barringer, Report to Academy of Sciences, 1909.

ites in the vicinity was pure coincidence. By 1900, although more metallic meteorites had been found there than in all the rest of the world, most authorities still insisted they had no connection with the Crater.

D. M. Barringer, 1903

Then, in 1903, Daniel Moreau Barringer, a Philadelphia mining engineer, arrived on the scene. Careful study convinced him that a meteorite had made the Crater and

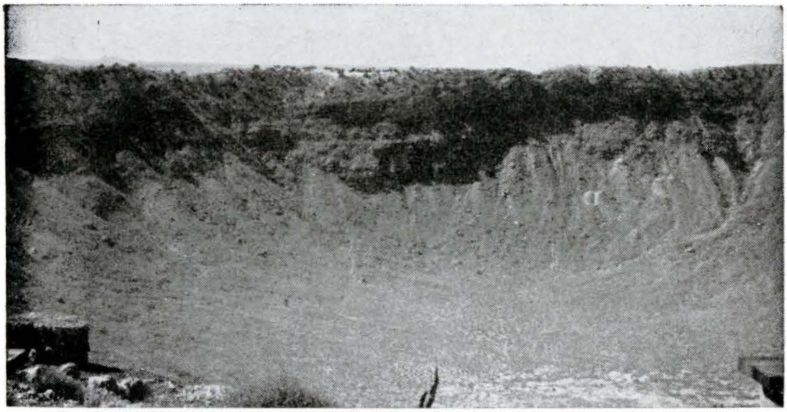
Aerial view of Meteor Crater from the north, showing Museum.

was still buried there, so he acquired the supposedly worthless land and formed a company to mine the metal of the meteorite. He thought he could prove his case to science and make the recovered metal pay the cost.

That is a story of bulldog perseverance and bitter disappointment, of constant struggle to find convincing proof, and of frequent long stops while he raised more funds to continue the work. Finally, after about 25 years, he did achieve recognition of the Crater's meteoritic origin as partial reward for his efforts. Today, as a tribute to his outstanding part in the story, the name "Barringer Meteorite Crater" is in general use among scientists and is officially endorsed by the Meteoritical Society, the International organization of scientists in this field.

His first work was to dig a series of trenches in the outer slopes of the rim. From them, he removed limestone boulders which had been thrown from the depths of the Crater and found meteorites lying under them. To him, at that time, and to nearly everyone today, that observation seems convincing proof that the meteorites had been falling while the rim was being made; but most of the scientists of that period were unimpressed.

Because the Crater is approximately round, he believed that the meteorite had come straight down, so he sank a shaft in the center of it. The steam-boiler, hoist-engine, and burnt out ruins of that shaft-house are still on the Crater floor. In that shaft he found rocks from all the different strata mixed together. He found much Coconino sandstone, which had been pulverized like flour by the meteorite's impact. He found some, called lechatelierite, which had been popped like popcorn. Apparently this material had been below the water-table at the time of impact and the



Looking across Meteor Crater from the Museum.

terrific heat had instantaneously converted the water into steam, producing this effect. He found many nickel-iron particles, but he found no actual meteorites. At a depth of about 200 feet, that shaft was stopped by underground water and quicksand.

He drilled 28 drillholes and sank more shafts before November, 1909. His drill cores showed up to 90 feet of lake-bottom deposits, which proved that the water-table, at some time since the Crater was made, had been 200 feet or more above its present level. This fact substantiates the belief that the Crater was in existence when the last glacier melted. That ice-sheet did not reach so far south; still a moist climate which raised the water-table might well have resulted when that ice did melt farther north.

Those cores showed rocks from the different strata mixed together to a depth of more than 1,000 feet below the Crater floor, with the Supai sandstone lying in undisturbed layers below that level. This observation proved that the Crater had been made by a force striking from above and not from below. However, he still found no mass of metal, and most scientists were unconvinced.

Rifle Bullet Points Way

He later discovered that a rifle bullet fired into thick mud, even at an angle, would still make a round hole. He already knew that meteorites and oxidized meteorites, which he called "shale-balls", were most heavily distributed on the north rim, as would have been the case if the meteorite had come from the north. He knew that the strata of the south rim arched 105 feet above their normal level but were solid as though they bodily had been lifted vertically, whereas those of the east and west rims were raised still higher but were loosely consolidated, as though they had been shattered and raised by a tremendous force from the direction of the center of the Crater. From this knowledge, the picture became clear to him.

A 6-inch churn-drill was set up near the center of the south rim, directly above the high point in the arched strata. Below 1,000 feet, it struck increasing numbers of meteoritic fragments. Sometimes it worked for hours in one spot, then finally pushed the buried obstacles to one side and went past them, deeply scarring the sides of the steel bits. Occasionally, soft going al-

Meteor Crater Museum and the top of the north rim.

lowed fast headway. More often, the drill log shows such reports as "5 hours to make one foot", "6 hours to make 2 feet", "last foot almost impossible to drill", and "drilling especially hard, finally refusing to advance any further. Drillings looked very black, so samples were taken from the riffles. . . . All gave fine nickel test and were 75% mineral."

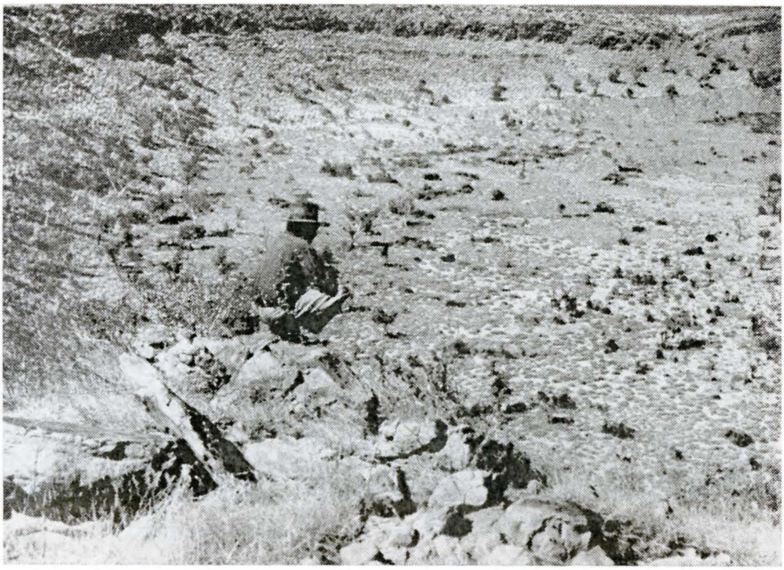
The log then says, "The expert drillman says he has drilled in all sorts of formations but has never encountered anything like this. From the saw-toothed appearance of the dull bits, he says we must be passing through streaks of solid metal," and, finally, "Started reaming at 8 A.M. and at 11 A.M. had reamed only 1 foot. At 11, rotary operating nicely when bit stuck in bottom of hole and stopped rotary."

The rest of the log, which was signed by C. W. Plumb, job superintendent, was devoted to the attempts to free the bit. All were unsuccessful, the cable finally broke, and, in August, 1922, the hole was abandoned after a maximum depth of 1376 feet had been reached.

Shaft Dug To The South

The next step was to start sinking a shaft a little south of the Crater in hopes of avoiding the water and quicksand. When the workers struck the groundwater, they installed pumps and pumped and dug their way down. Here no silica flour was met; still, sand grains from the loosely consolidated Coconino sandstone worked through the pump-screens to chew up the pumps, slowing the work and increasing the cost. Three days of pumping were needed for each day's digging. The operators went down 63 feet below normal ground-water, level, and, then, once more, they were forced to shut down for lack of funds.

Shortly thereafter, the stock market crash of 1929 occurred. Right after that, Daniel Moreau Barringer, who had given 30 years of his life and much of his private capital to the Crater's development, died suddenly at his home in Philadelphia. His family accepted the Crater as a public trust and a monument to his memory and has continued this work to the extent possible.



Wolf Creek Crater, Australia, 3,000 feet across.

Geophysical Studies

In 1930 J. J. Jakosky conducted a geophysical survey covering the geological, magnetic and electric aspects of the Crater. This survey indicated a mass of heavy material lying below the inner talus slope in the southwest sector. It showed also that there were no deep faults through which steam or gas could have come to cause a blowout.

The late George M. Colvocoresses, Arizona mining engineer, then drilled two holes near the center of the indicated area. His rig was light and he had almost continuous difficulty with freezing water-lines, so he had a rugged time. His logs show that he used both stellite and Carboloy bits when in contact with meteorites, but that neither was equal to the task. For example, he made a quarter-inch of seeming progress in 6 hours of drilling only to learn that that amount had been worn from a Carboloy bit. In each hole, he was stopped at a depth of about 675 feet by some impenetrable mass which he could neither drill through nor push aside.

The depression dragged on, followed by the War, to prevent further work on the project. After the War, research work conducted at the Crater by the University of New Mexico's Institute of Meteoritics included the excavation of one of several prehistoric pit-dwellings on the outer south slope of the rim. This dwelling was dated from the 1100's by identification by the researchers of the artifacts found; so a once-suggested idea that the effects of the meteoritic impact may have put an end to the Mesa Verde Culture of Southwestern Colorado is defiinitely disproved.

Late in 1951, a survey with the Worden Gravimeter, sponsored by Princeton University with Roswell Miller III in charge and financed by the Barringer Company, was conducted at the Crater. This survey, which will be discussed more fully later, indicates the presence of a high-gravity mass equivalent to

Destruction of trees to a 20 mile radius around Tunguska Craters made June 30, 1908.

a solid sphere of metal 120 feet in radius and weighing 1.7 million tons *if it is centered 600 feet below the Crater floor* and proportionally greater if it is farther down.

Repeated analyses show that meteorites from this fall have an average content of 91-92% nickel, and from 1% to 2% of minor elements such as silicon, phosphorus, copper and carbon, with small but valuable amounts of platinum and iridium and traces of cobalt, gold and silver. At present prices, this content would give the buried mass a valuation of about $100 a ton; so the day may yet come when Mr. Barringer's dream is realized and the world may see and use the mass of metal that made the Crater. At one time, no economical means of cutting large masses of this metal were available; however, it is now believed that the oxygen torch in use in the steel mills would do so, so that obstacle may have been removed.

Microscopic diamonds and crystals of silicon carbide, the only natural carborundum ever found on Earth, also have been found in these meteorites. Neither has more than a nuisance value, yet they do testify to the heat and pressure under which these meteorites formed.

Meteorites Defined

Before going farther, it might be well to quote Dr. Frederick C. Leonard's definitions as they appear in *Meteoritics, The Journal of the Meteoritical Society and the Institute of Meteoritics of the University of New Mexico, Vol. 1, No. 1, 1953.* These definitions are accepted by most meteoriticists:

"A *meteorite* is a solid body of subplanetary mass that either is in space or has come thereform, is falling or has fallen as a discrete unit onto the Earth or onto some other astronomical body, and still retains its essential cosmic character; whereas a *meteor* is the luminosity —i.e., the luminous thing—that re-

Edge of 90-foot crater and up-rooted trees, Sikhote-Alin, Siberia, made February 12, 1947.

sults when a meteorite from space penetrates the atmosphere of the Earth, or that of some other astronomical body, and becomes, usually, a falling meteorite. *Meteoritics* may be defined . . . as that branch of astronomy that is concerned with the study of the *solid matter* that comes to the Earth from space; of the solid bodies of subplanetary mass that lie beyond the Earth: and of the phenomena that are associated with such matter or such bodies."

Other Known Meteorite Craters

Since the meteoritic origin of the Barringer Crater has been accepted as proved, other meteoritic craters, all smaller, also have been recognized. Dr. Leonard, of the Department of Astronomy, University of California at Los Angeles, lists 13 more such craters or groups of craters as authenticated. (*A Classification Catalog of the Meteoritic Falls of the World*," University of California Press, 1956, $1.75.) They are, listed alphabetically:

Aouelloul, in French West Africa. 1 crater about 800 feet across, 20 feet deep. Found in 1920, recently accepted as meteoritic. Silica glass analyzing 0.022% nickel oxide, but not meteorites, found there.

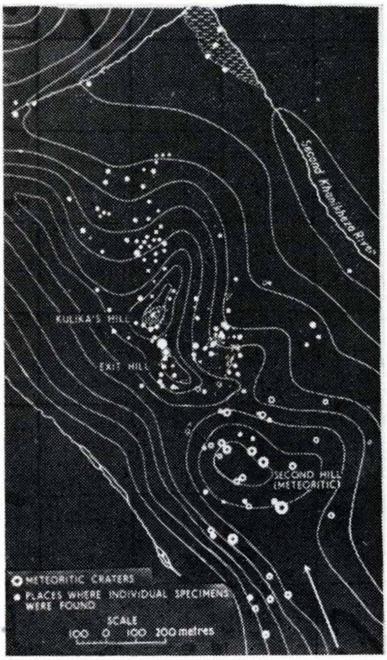
Boxhole, Australia. 1 crater about 550 feet across, 50 feet deep. 1 meteorite weighing about 60 pounds plus numerous "shale balls" have been found there.

Campo del Cielo, Argentina. At least 4 shallow craters, the largest about 230 feet across, 20 feet deep, have been known since 1576. About 20 tons of meteorites plus rock flour and silica glass have also been found there.

Dalgaranga, Western Australia. 1 crater about 230 feet across, 17 feet deep, discovered in 1923 but identified much later. Several iron meteorites were found there.

Haviland, Kansas. 1 crater 50 feet across, 10 feet deep. About 2½ tons of stony-iron meteorites were found there.

Henbury, Australia. 13 craters. The largest, 640 feet long, 340 feet wide, 45 feet deep, was probably formed by two over-lapping craters.



Fall area, Sikhote-Alin.

It was discovered in 1931. Iron meteorites totalling 1400 pounds were found there.

Kaalijaev, Estonia. 6 craters, the largest 300 feet across, with rim rising about 20 feet were identified about 1931. Only 30 small meteorites with combined weight of about an ounce have been found there; but the area has been populated for centuries; so all the larger ones may have been carried off for use.

Mount Darwin, Tasmania. 1 crater. Silica glass only has been found.

Odessa, Texas. 2 craters, the larger about 500 feet across, 20 feet deep, identified in 1926, largely through the efforts of D. Moreau Barringer, Jr. Iron meteorites and "shale balls" have been found there.

Podkamennaya Tunguska, Siberia. 10 craters, the largest 165 feet across, 20 feet deep, more than 100 craterlets, were made in 1908, first investigated in 1927. This fall will be covered more fully later.

Sikhote-Alin, Siberia. Numerous craters, made in 1947 by a cluster of iron meteorites, also will receive detailed coverage later.

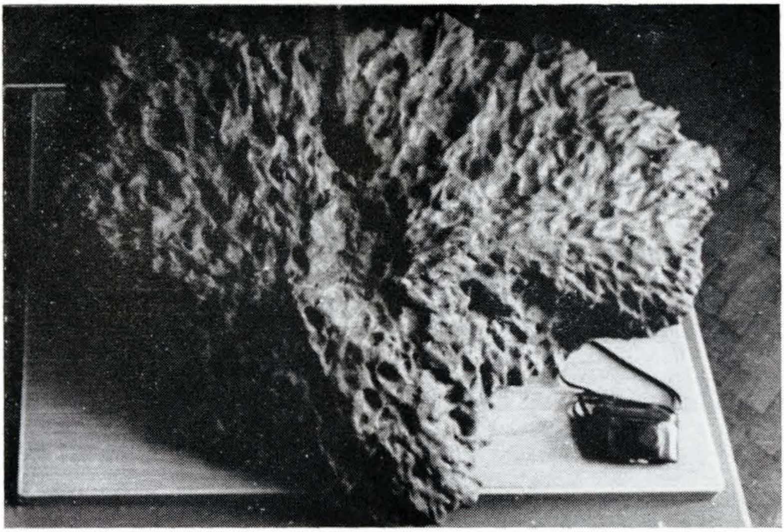
Wabar, Saudi Arabia. 2 craters, the larger about 300 feet across, 38 feet deep, was discovered in 1932. Iron meteorites and silica glass were found there.

Wolf Creek, Australia. 1 crater, about 3,000 feet across, 200 feet deep (next in size to the Barringer Crater) was discovered in 1947. Over 1400 pounds of oxidized meteorites, the largest weighing 352 pounds, were found there. (W. A. Cassidy, *Meteoritics*, Vol. 1, No. 2, 1954, p. 197)

Siberian Craters, 1908

The two Siberian falls, being the only great ones of modern times, are of particular interest because of the positive evidence they give of

Tree shattered by meteorite, Sikhote-Alin.



Largest individual specimen found at Sikhote-Alin, about 3500 pounds.

what happens when huge meteoritic masses strike the Earth.

The Tunguska meteorite fell on the morning of June 30, 1908. Although it was bright daylight, the fireball was seen from a distance of hundreds of miles and the heat was felt for 50 miles. Windows were broken to a distance of 50 miles and the engineer of a train more than 400 miles away stopped his train for fear of derailment. All trees were blown down over a radius of about 20 miles around the fall-point and a herd of 1500 reindeer which was grazing in the area was almost completely destroyed.

I. S. Astapovitsch calculated the velocity of this mass at about 37 miles a second, which, as we shall see later, is near the maximum velocity possible for a projectile that originated in our Solar System. Its mass is not known but it has been estimated at more than a million tons.

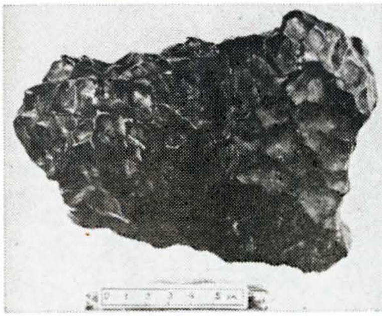
This mass was completely destroyed upon impact. No meteorites have been found around these craters, although Kulik reported finding rock flour and fused silica containing nickel under one of the craters. We do not even know what type of meteorite this was, but at least it has shown us what terrible devastation can result from meteoritic impact.

The Russian scientists cited above both published papers about this fall. Translations of these papers were made available in English, starting in 1935, by Dr. Lincoln LaPaz of the University of New Mexico and its Institute of Meteoritics and his collaborators.

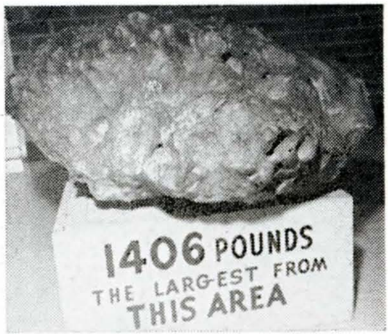
More recently, Dr. Otto Struve of Leuschner Observatory, University of California, ("Meteorites and Their Effects," *Sky and Telescope*, May, 1956) further states that the energy involved in this fall was "comparable to that of a moderately strong earthquake".

Siberian Craters, 1947

The second great fall of this century occurred at 10:38 A.M., February 12, 1947, in the Sikhote-Alin mountain range, several hundred



Individual specimen, Sikhote-Alin. Scale in centimeters.



Largest meteorite found at Barringer Crater. Note surface similarity.

miles north of Vladivostok. Four field parties from the Committee on Meteorites, USSR Academy of Sciences, worked there for a total of 19 months between April, 1948, and 1950 and it was 1955 before the data had been fully analyzed. E. Krinov wrote a detailed account of this fall, a translation of which, with critical summary, by LaPaz and Dr. W. A. Boedyreff, appeared in Contributions to the Meteoritical Society.

A translation of a short account, "The Siberian Fall of February, 1947," appeared in *Sky and Telescope*, May, 1956. The latter article states, "The bolide was so bright that it blinded the eyes of people who watched it, and it cast moving shadows. In its wake, there remained a wide band of dust, which was seen for several hours." The total mass of the fall was calculated as about 70 tons, of which about 23 tons were collected and shipped to Moscow for study. The velocity in the upper atmosphere was calculated to be about 9 miles per second, which is near the minimum velocity possible for a wanderer from our Solar System.

As Krinov has pointed out, the meteorite exploded in the atmosphere into fragments weighing from fractions of a gram to several tons and the largest of these broke further on striking the rocky ground. "Smaller fragments, so-called individual specimens, fell to Earth intact," he said. "These differ from the other fragments in being covered by a fused crust of dark-gray color, and on their surfaces are peculiar round pittings caused during their descent through the atmosphere." (See photograph, above) These pittings, called piezoglyphs, will be discussed later.

The Russian expeditions located 122 craters or impact pits, having diameters ranging upward from 1½ feet, the largest being 90 feet across and 20 feet deep. They found 78 additional smaller holes and collected 175 small specimens on the surface of the ground. All of the craters, holes and locations of finds occurred in an elliptical area with the large craters in the southern part and the small specimens in the northern part. (Map p. 11) This fact is explained by the circumstance that the smaller pieces were more greatly retarded by atmospheric resistance and lagged behind, since the meteorites moved from north to south.

On the surface of many specimens were molten drops of congealed nickel-iron. Vast numbers of these drops, with diameters of tenths or hundredths of a millimeter, formed the dust trail which settled to the ground after the meteorite struck. (See photomicrograph, p. 25) This dust was collected with a magnet from the earth in the craters and the surrounding area.

These meteorites show a chemical analysis of 93.5% iron, 5.27% nickel, 0.47% cobalt, 0.20% phosphorus , 0.06% sulphur and tiny quantities of other elements.

Aouelloul Crater

An interesting story, wide open to controversy, is connected with the Aouelloul Crater in French West Africa. [See "The Adrar (Chinguetti), Mauritania, French West Africa, Meteorite," by Lincoln LaPaz and Jean LaPaz, *Meteoritics*, Vol. 1, No. 2, 1954.]

In 1916, a French government official, M. Ripert, reported seeing a metallic mass measuring 100 meters on a side and rising 40 meters above the desert dune sand, at a point about 45 km. southwest of the oasis of Chinguetti. Several more blocks of the same material lay around the great mass and one, which weighed about 9 pounds, was on top of it. The latter was sent to Paris and proved to be a nickel-iron meteorite.

Although a mass of this metal having those dimensions would weigh of the order of a million metric tons, it has never been relocated. Still, the fact that the Aouelloul Crater has recently been found and authenticated at a point only four miles from the approximate location given by Ripert lends some credence to the story. The region specified by Ripert is an "unmapped, wind-blasted" desert area "with constantly changing topography", further harrassed, at present, by political unrest; but detailed study is certainly called for when times become more propitious.

Possible "Fossil" Meteorite Craters

It has been suggested that, in addition to the meteorite craters which can be proved by the finding of meteorites or other meteoritical evidence of the sort described above, there may be many more which cannot be so proved. The 60% of the Moon's surface which is visible to us is heavily pitted with craters, some of stupendous size. There is some difference of opinion as to how many were caused by meteoritic impact; still there is agreement that at least the ray-craters had such an origin. That being the case, there is no reason to doubt that the Earth underwent a similar bombardment at the same period of time.

If this meteoritic bombardment took place long ago, as is probable, meteoritic materials would long since have disappeared or become unrecognizable and the craters themselves would have been filled by glaciation or other sedimantation. The name "fossil" meteorite craters has been suggested for them, in case proof of their origin is established.

At present, five features in Canada are under close study by the Dominion Observatory at Ottawa, with Dr. C. S. Beals in charge and Dr. M. J. S. Innes as head of the Gravity Department. No meteoritic materials have been found at any of these craters, although drill-cores at one showed a bare trace of nickel.

All these craters are in the Pre-Cambrian Canadian shield formation, which dates back at least a half billion years. Three of them have been so nearly filled with sediments that they were completely unrecognizable except in aerial photographs. Stereoscopic examination, which greatly exaggerates relief, has been of great help in this work. Sediments in these craters

Norton County, Kansas, stony meteorite in its funnel. Dr. Lincoln LaPaz on ladder.

have been judged to be at least 75 million, and perhaps as much as 400 million years old.

Largest of these craters is at Deep Bay in northern Saskatchewan. It is about 8 miles in diameter and 250 feet deep, includes lakes and swampland.

In 1951, study of an aerial photograph revealed an interesting circular depression, 2 miles in diameter, near Brent, Ontario. (*Sky and Telescope*, May 1956.) Geophysical studies and drilling showed that a crater in Pre-Cambrian rock had been nearly filled with Paleozoic sedimentary deposits. Extensive studies of this feature's cross-section and contours have been made by the Dominion Observatory and indicate close similarity to those of proven meteorite craters. Publication of these studies is awaited with interest.

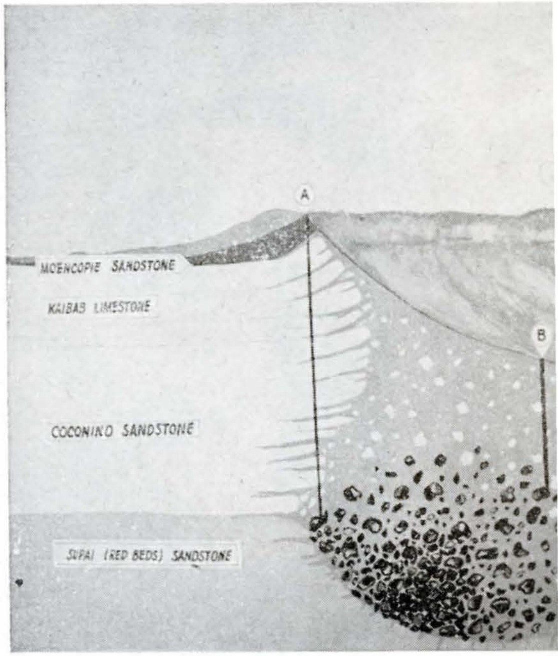
In 1955, further studies of aerial photographs revealed another such circular feature at Holleford, Ontario. It is a depression about 1¼ miles across and 100 feet deep, which includes part of the village of Holleford. This depression in Pre-Cambrian rock is filled with Ordovician deposits.

Drill-cores from deep below this depression show a fine-grained greenish-gray rock which may have evolved from rock-flour which has been subjected to tremendous pressure over millions of years.

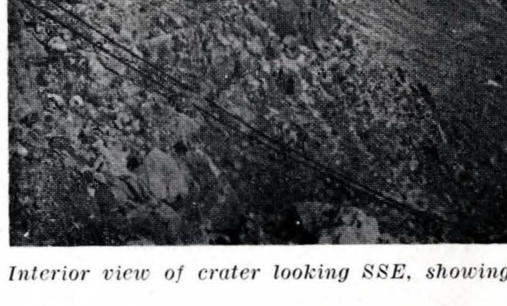
The Dominion Observatory in conjunction with the Geological Survey of Canada is continuing these studies. While this booklet was in preparation, Dr. Innes spent a day at the Barringer Crater, studying what he called, "the classic example of a meteorite crater." It was the writer's pleasure to be his guide, pointing out features which might be helpful in his studies. He and Dr. Beals carry with them my every good wish for success in this important work.

Talemzane Crater, 1¼ miles across and 200 feet deep, in Southern Alegria, also has been under study as a possible "fossil" meteorite crater. (See "*The Meteorite Crater of Talemzane in Southern Algeria*," by Ramon Karpoff, *Meteoritics*, Vol. 1, No. 1, 1953.) An expedition there in 1951-52 found that the rocks of the area are late Cretaceous or early Eocene and that the crater was formed in the late Pliocene or early Quaternary, with no volcanic indications in the region. Rocks of the rim are sharply tilted, as at the Barringer Crater. Prolonged study failed to show either magnatic anomaly or meteoritic materials.

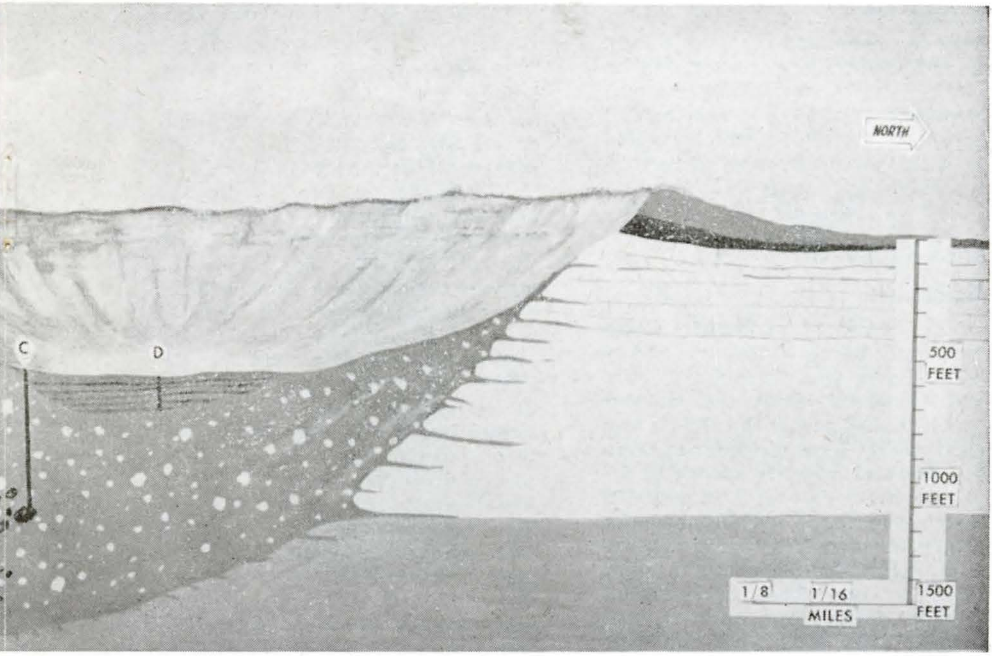
A meteoritic origin has also been suggested for the New Quebec, or Chubb, crater in Ungava, Northern



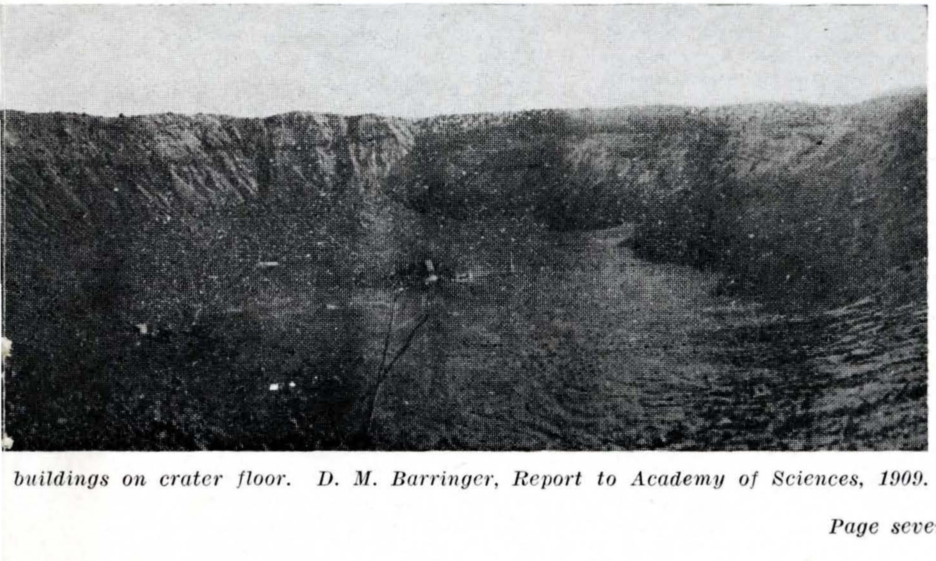
North-south cr



Interior view of crater looking SSE, showing



oss-section of Barringer Crater. North is to the right.



buildings on crater floor. D. M. Barringer, Report to Academy of Sciences, 1909.

Quebec. It is about 2 miles across, 1300 feet deep, and contains a lake. It has undergone glaciation, but its rim still rises high above the surrounding terrain. A group, headed by Dr. V. Ben Meen, which studied it in 1951 found no proof of meteoritic origin.

Brief History Of Meteoritics

The science of meteoritics dates back only about a century and a half. Early man undoubtedly saw and wondered about the meteors which flashed across the sky on any clear night. Some pictographs made by primitive man are known to depict such events and it is probable that others do. A drawing made by paleolithic man in a cavern at Altamira, Spain, may be a case in point. (See p. 19) This is doubtful, though, that these early men thought them to be more than local phenomena, like lightning. The ancient Greeks named them *meteors*, which meant *things in the air* and included clouds and whirlwinds.

In 1794, E. F. F. Chladni published a paper about an iron meteorite which had been found in Siberia in 1749. He had already studied fireballs and their orbits and had conconcluded that they could descend to the Earth's surface; so he recognized that this was the kind of body that would, in passing through the atmosphere, produce such a phenomenon.

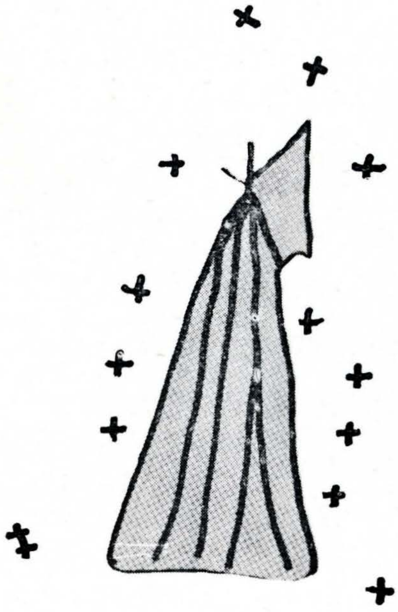
In 1798, two German students realized that they had seen the same meteors, although from points miles apart and from entirely different angles. They continued the study and were able, by triangulation, to compute heights and rates of travel. The results showed them that meteors, instead of being nearby, were appearing at heights of at least 50 miles above the Earth and were traveling at speeds of at least several miles a second. (See "*Between the Planets*," F. G. Watson, Harvard University Press, 1956, $5.00)

These studies received little attention until 1833. Then, on the night of November 12, a great shower of meteors, called the Leonids because it seemed to originate in the constellation Leo, lit up the heavens. It started shortly before midnight and increased in intensity until just before dawn when the meteors seemed thick as snowflakes and a single observer saw about 20 in a second. People leaped to the conclusion that the "end of the world" had come. Indians marked the event on their calendars. Their lasting memory of that shower was once demonstrated by an old Apache who visited the Barringer Crater. After long study of an artist's drawing depicting that shower, he said, "My grandmother told me about when I was a little boy."

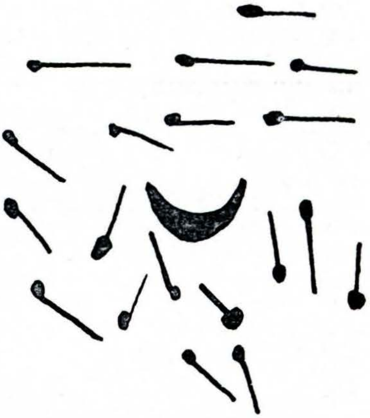
All returned to normal after that night, but the science of meteoritics grew out of the interest created by that shower.

Meteorites are celestial debris that has traveled through space, probably through ages of time, until finally they strike the Earth's atmosphere. Heat generated by collision with the molecules of the atmosphere vaporizes these particles, and molton material is swept off to make the fiery train we see. Generally, since most of the invading particles range in size from a few grains to a fraction of an ounce, vaporization is complete and the flash disappears, in an instant of time. A comparative few of greater size survive that dash, at least in part, and strike the Earth to supply the only material "from out of this world" that we may see and touch. Dr. Watson estimates that this happens about 5 or 6 times a day; which would be equivalent to about one for each 10 square miles of the Earth's surface since our world was formed.

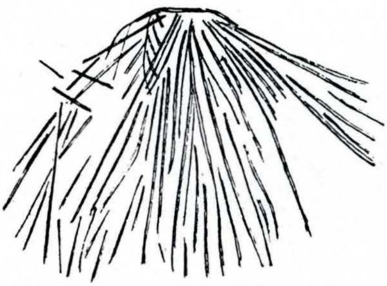
From each of most of these bodies, the Earth gains by only a



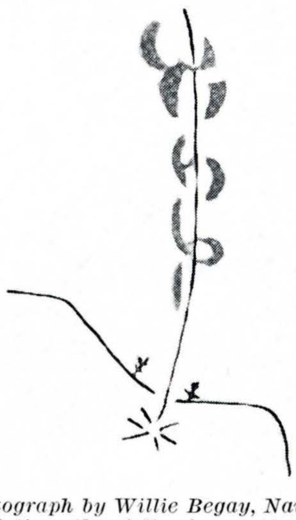
"Storm-of-stars winter." 1833-34, following great Leonid Shower.



"Many stars fell—Dakotas much terrified." Leonid Shower (Nov. 12-13, 1833.)



Radiate Structure which may depict a meteor shower, made by paleolithic man in a cavern at Altamira, Spain. (Breuil and Cartailhac)



Pictograph by Willie Begay, Navajo, depicting the fall of a meteorite, Oct. 30, 1947. Courtesy Institute of Meteoritics, University of New Mexico.

Drawings by primitive man which are known or believed to depict meteor showers.

few congealed droplets; yet many billions reach the atmosphere each day; so it is believed that our Earth may be gaining by an average of about 1,000 to 10,000 tons a day from this source. However, there is no need for alarm. The Earth has a mass of 6600 billion billion tons; so it could gain at the maximum rate just cited for a billion years and the total increase would amount only to one part in 1.8 million over its present weight.

Meteorites And Space Travel

With increasing probability that man will some day travel into the stratosphere and beyond, meteoritics and the problems of this continuous bombardment from space have taken on new importance.

In November, 1951, a meeting sponsored jointly by the USAF School of Aviation Medicine and the Lovelace Foundation for Medical Education and Research, was held at San Antonio, Texas, to discuss the problems of such travel. At this meeting, reports were made by leading authorities covering all phases of the subject. The reports and proceedings have been arranged by the Lovelace Foundation and published by the University of New Mexico Press. (*Physics and Medicine of the Upper Atmosphere,* $10.50.) Two of these papers were by leading meteoriticists, Dr. Fred L. Whipple, Harvard College Observatory, and Dr. Lincoln LaPaz, Department of Mathematics and Astronomy and the Institute of Meteoritics, University of New Mexico. They dealt with the probable frequency and effects of collision with swiftly moving bodies in the upper atmosphere and beyond.

Dr. Whipple cites about 7 miles a second in relation to the Earth as the minimum speed for meteorites to enter our atmosphere, about 41 miles per second as the maximum, 25 miles per second as the probable average. He cites reports of small crater pits in polished surfaces of rockets that have been exposed to altitudes above 18.1 miles. He recommends a thin outer skin for the vehicle to absorb the impacts of small meteorites, devices to warn of drops in air pressure so that repairs can be made in the brief interval before the crew "blacks out", protection of all optical glass when not in use against sand-blasting by "star-dust".

He feels that care should be taken to "avoid the orbits of comets, known meteor streams, and the fundamental plane of the Solar System, particularly between Mars and Jupiter." He concludes that "for short (less than 24 hours) excursions above 62.1 miles . . . the danger of meteoritic penetration is minor or negligible in comparison to the other hazards of such flights . . . but that . . . the hazard is a serious one for a satellite vehicle or for general space travel."

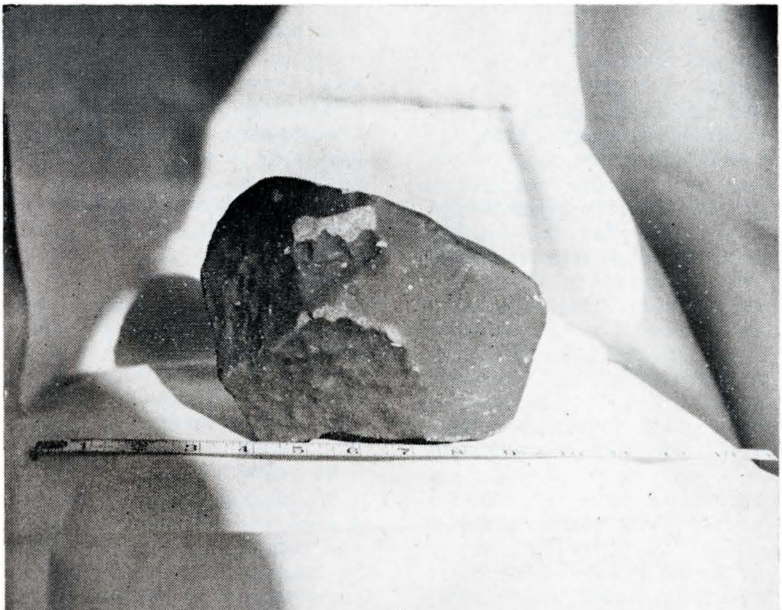
Scientists Disagree

Dr. LaPaz feels that Dr. Whipple's velocities may be correct for photographed meteoroids (minute meteoritic bodies of low density and fragile nature) but that much other matter in space is moving at far higher speeds.

Scientists agree that about 26 miles per second in relation to the Sun is the critical velocity for meteoritic bodies. Below that, the body is said to be traveling at elliptical speed, on a "closed orbit" and would remain within our Solar System. At that speed, the velocity is parabolic; at greater speeds, it is hyperbolic; in either case, the body is moving too fast to be held by the Sun's gravity, and, barring collision, is certain to escape into outer space.

Since these speeds are relative to the Sun and the Earth moves at a speed of about 18.5 miles per second in its orbit around the Sun, they could be decreased or increas-

House in Sylacauga, Alabama, where Mrs. E. Hulitt Hodges was struck by meteorite. Circle marks fall-point.



Nine-pound stony meteorite which struck Mrs. Hodges. These photographs through courtesy of Drs. George W. Swindel, Jr., and Walter B. Jones.

ed by 18.5 miles per second if the colliding body were moving in the same or opposite directions as the Earth.

Much valuable research in the photography of meteors, which has been done under the Harvard Meteor Program, inclines Whipple to minimize the value of non-photographic results and to feel that most or all meteoritic material is moving in closed orbits and at comparatively low speeds. LaPaz, however, believes that an appreciable part of meteoritic material comes from interstellar space and at speeds which would cause it to strike with much greater impact. He says, ". . . at extreme altitudes . . . there exists" a "quite possibly large amount of a high-speed component . . . possessing a far from negligible ballistic potential."

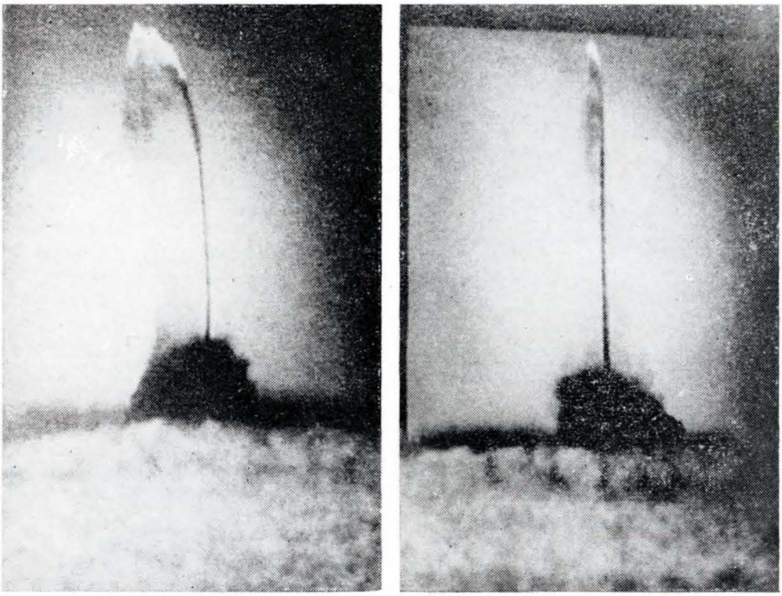
Dr. Charles P. Olivier, of the Department of Astronomy of the University of Pennsylvania, and President of the American Meteor Society, sheds some light on this subject in a paper on "The Velocities of Sporadic Meteors" (*Meteoritics*, Vol. 1, No. 4, 1956.) He says, regarding his reference book, "Meteors", which appeared in 1925, "At that time the best evidence seemed to point to hyperbolic velocities as being quite usual for sporadic meteors and many fireballs, and the writer did not hesitate to state that this was his opinion."

He says that observation by radar in England has led to the conclusion that not more than 1% of the observed falls could have hyperbolic velocities; that in similar studies in Canada, "this work has been done not only for the principal showers but also for great numbers of sporadic meteors", with the result that "the Canadian observers seem rather positive that few, if any, of the thousands observed could be hyperbolic"; and that Whipple "concludes that no certain cases of hyperbolic velocities occur in the very many doubly observed meteors". He adds, "Therefore to date, the great preponderance of radar and photographic results are against hyperbolic velocities for meteors."

Dr. Lincoln LaPaz, University of New Mexico and Institute of Meteoritics.

On the other hand, Olivier says that recent important papers by Hoffmeister, LaPaz, and Opik give arguments to support the reality of hyperbolic velocities. The first two "point out that radar . . . may not be able to detect small bodies of great velocities in higher strata." Opik contends "that fainter telescopic meteors give higher velocities". LaPaz gives arguments that "many small bodies with hyperbolic velocities are destroyed at heights too great for radar detection." Hoffmeister "has revised his work . . . . and confirms that, for sporadic meteors, large numbers have hyperbolic velocities.

Olivier concludes, in part, "At present, then, it must be admitted that the proponderance of mechanical evidence is that nearly all the meteors *that these methods can detect*" (his italics) "originate within the Solar System. But do these methods really reach all types of



Photographs of high-speed (armor-piercing) jets which reached speeds of the meteoritic order. Taken at Carnegie Institute of Technology, they led to the conclusion that a mass of between 2.6 and 7.8 million tons was required to make Barringer Crater.

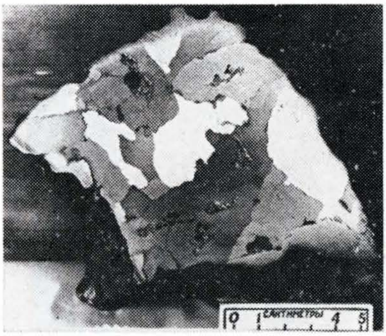
meteoritic phenomena?" And, "Meantime . . . everyone will await with great interest publication of further data, secured by all known methods, and perhaps the development of even more powerful ones that may aid in the solution of the problems involved."

It is possible that the satellite program scheduled for the International Geophysical year may furnish fresh evidence on this subject.

Classifications Of Meteorites

Dr. Leonard's "Classificational Catalog", mentioned previously, lists and classifies 1563 meteoritic falls that are authentic. They are divided into 3 divisions, 7 classes, and some 30 sub-classes, according to their internal structure and mineral composition. Here we shall discuss only the three divisions. They are: the stones, of which there are 946; the stony-irons, of which there are 62; and the irons, of which there are 555.

The stones vary from as hard as granite to so soft that they may be scratched with the finger-nail, as is the case with the Norton Aerolite. The largest stony meteorite that has been recovered anywhere in the world, this aerolite fell in Norton County, Kansas, and Furnas County, Nebraska, February 18, 1948. It exploded aboveground, terrifying people over a wide area. The largest piece recovered, weighing 2300 pounds, was dug up from 10 feet below ground level and may be seen at the Institute of Meteoritics, University of New Mexico, at Albuquerque. It was unusually soft, so weathering would have destroyed all proof of its origin if it had not been found soon after it fell, as the



Etched meteorite from Sikhote-Alin Craters showing crystalline structure.

result of systematic field search conducted by the Institute.

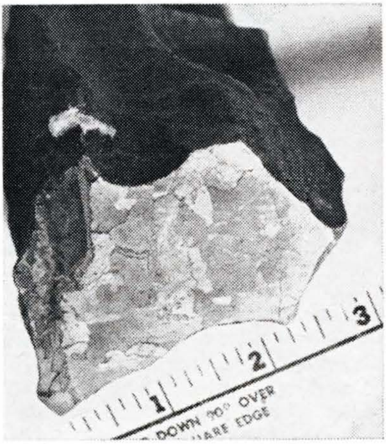
The stony-irons consist mostly of nickel-iron networks, the openings of which are filled with silicate minerals, like metal sponges filled with stone (olivine) instead of water.

The nickel-irons are almost wholly metallic, being chiefly iron, with nickel ranging from about 5% to, rarely, more than 30% in the various falls, and with a wide variety of related elements in very small amounts. The purest are comparable to armor-plate steel, and the first stainless steel was developed as the result of their study. Contrary to popular belief, no elements

Etched meteorite from Barringer Crater showing evidences of having been heated to a high temperature.

otherwise unknown on Earth have been found in them.

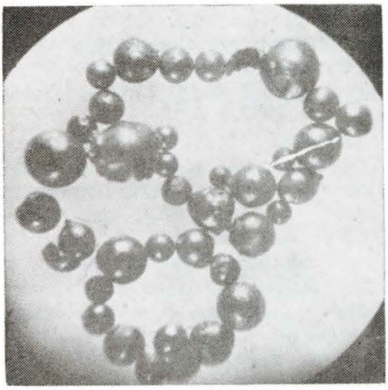
All of the largest meteorites known are irons. The Hoba West meteorite, probably the largest single meteorite found to date, still lies where it fell in Southwest Africa. It lay half aboveground and was left there after partial excavation permitted an estimate of its mass as at least 50 tons. The second largest, which weighs about 34 tons, was brought from Greenland by Admiral Peary and may be seen in the American Museum of Natural History in New York City.



Etched meteorite from Barringer Crater. Note similarity to one above.

The largest found in the United States, weighing about 15¾ tons, was discovered in Oregon's Willamette Valley and also is in the American Museum of Natural History. O. C. Farrington's "Meteorites" and Watson's "Between the Planets" give added information about these and many other interesting meteorites.

Since 1790 there have been 22 authenticated cases of meteorites that have struck and damaged buildings. (For a chart describing 21 of these, see *Physics and Medicine*



Photomicrograph showing nickel-iron droplets which formed the dust-train of the Sikhote-Alin meteorite.

of the Upper Atmosphere, cited previously.) Until 1954 there had been no fully authenticated case of a human being's having been struck by a meteorite, although 6 unverified cases had been reported, and Dr. LaPaz had calculated that the chances were nearly 1 in 3 that someone would be struck in the course of this century.

However, on November 30 of that year, a stony meteorite penetrated the roof of a house in Sylacauga, Alabama, and struck Mrs. E. Hulitt Hodges. (Photograph, p. 21) She was lying d o w n, covered by two quilts; the 9-pound stone ricocheted off the walls, consequently she incurred no more than a large bruise on her hip. (See "The Sylacauga, Talladega County, Alabama, Aerolite: A Recent Meteoritic Fall That Injured a Human Being", by Dr. George W. Swindel, Jr., Geologist, U. S. Geological Survey; and Dr. Walter B. Jones, Geological Survey of Alabama, published in *Meteoritics*, Vol. 1, No. 2, 1954.)

Newspaper stories to the effect that this meteorite was worth a considerable sum led to threats of a law-suit for its possession; but the stone, which was awarded to Mrs. Hodges, has been donated by her to the University of Alabama. A smaller fragment of this stone fell several miles away, on the farm of J. K. McKinney, and is now in the United States National Museum, Washington, cut and polished.

Characteristics Of Meteorites

Surface indentations called piezoglyphs or "thumb-marks" are common to all newly fallen meteorites. In many cases they look as if a thumb had been pressed into putty or hot wax. They are believed to have been caused by the melting away of the softer materials under the heat and pressure which attended passage through the atmosphere. Stony meteorites also have a black or brownish surface glaze. Weathering soon erases these surface features from the stones, but they remain on the irons until oxidation is far advanced.

Many iron and stony-iron meteorites can be identified also by the crystalline structure of the metal. When cut, polished and etched with acid, they show a crystallographic pattern, called Widmanstatten figures, which is not found elsewhere in Nature. Metallurgists can duplicate these figures, but only on a microscopic scale. When the meteorite is roasted for a considerable time at 850 degrees, Centigrade, these figures disappear permanently. The accepted hypothesis is that the cooling of this meteoritic metal was prolonged over a period of millions of years, during which the molecules formed the huge nickel-steel crystals.

An Exploded Planet?

This crystal structure leads to the commonly-held hypothesis that many of the meteorites may be parts of a disrupted planet which may have once traveled on an orbit situated between those of Mars and Jupiter.

Late in the 18th century, the German astronomer, Bode, devised a scheme for estimating the mean distances of the planets from the Sun. The outermost pair, Neptune and Pluto, do not conform to Bode's Rule; the rest fit fairly closely, except that one which should exist between the orbits of Mars and Jupiter, has never been found. However, more than 1500 minor planets or planetoids, the largest being Ceres with a diameter of nearly 500 miles have been found to move on orbits the average mean distance for which approximate that predicted for the missing planet by Bode's Rule. So it is possible that such a planet may once have existed but have been torn to pieces by some cosmic cataclysm.

It is believed that the core of our Earth, some 4,000 miles in diameter, is composed of iron, nickel, and related metals; so it may be that the metallic meteorites are from the core of this former planet, that the stony meteorites are from its crust, and that the stony-irons are from the intermediate region between the core and the crust.

Age Of The Barringer Crater

There has been much study and conjecture as to the probable age of the Barringer Crater. As has been stated, a hypothesis once suggested that it is only 700 years old has been definitely disproved by the finding of ruins of a pit-dwelling, built on the south rim in the 1100's.

The most exhaustive study of the Crater's probable age was made by Dr. Eliot Blackwelder, Professor Emeritus of Geology at Stanford University. He based his research chiefly on the weathering of the rocks on the Crater rim. He found that they showed more weathering than similar rocks in Utah that were known to have been exposed by the last glacier, and less than similar rocks in California that were known to have been exposed by the previous glacier; so he concluded that the Crater was made probably during the last interglacial period, 40,000 to 75,000 years ago.

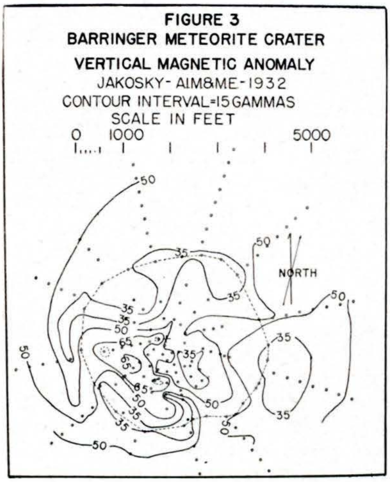
Evidence from the drill cores, that the water-table has at some time stood 200 feet above its present level, bears out that conclusion. Except for local ice-sheets on the San Francisco Peaks, no glaciation has reached the area around the Crater. However, it seems logical to assume that glaciation a few hundred miles north would have caused a moist climate which might have raised the water-table.

The finding of evidences of only one lake bed adds further support to this belief, since there should be evidence of two such lake beds if the Crater had been made before the previous glacier. If further research should bring to light either shells contemporary with this lake bed or carbon-bearing material contemporary with the formation of the Crater, modern dating methods could settle this question of the Crater's age with more positive assurance.

How Big Was The Meteorite?

One of the most intriguing questions about the Crater, "How big was the mass that made it?" is still unanswered and open to disagreement. All indications are that the meteorite struck from the north. If it struck at a time when the Earth was moving in that direction, the impact velocity would have been increased by the amount of the Earth's orbital speed around the Sun, about 18.5 miles a second; if it struck when the Earth were moving in the opposite direction, rolling with the punch, as it were, the impact velocity would have been decreased by that amount; so any studies of this subject must allow for this difference.

The first of four studies of this



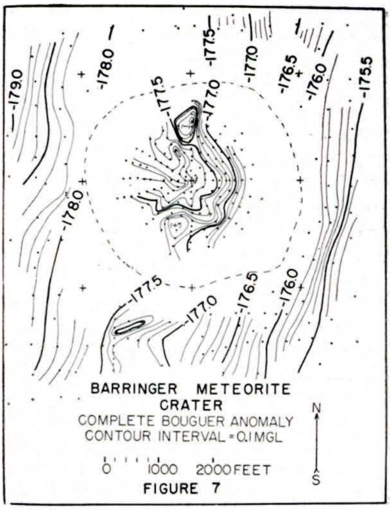
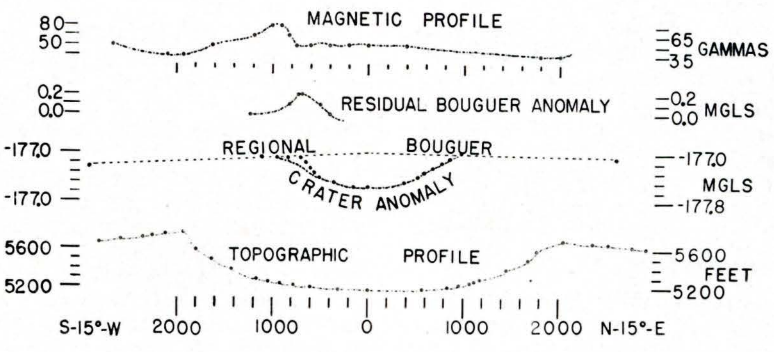


FIGURE 10
BARRINGER METEORITE CRATER
COMPARATIVE PROFILES



Drawings mentioned on next page, showing results of geophysical studies made at the Barringer Crater.

of the crater of about 45 gammas. (See Figs. 3 and 10.) Although we do not know the exact magnetic characteristics of a large meteorite, its net magnetic effect should be larger than the surrounding sediments.

3. Roswell Miller and I obtained a residual gravity high of about 0.20 milligal in the southwest quadrant of the crater. (See Figs. 7 and 10.) This indicates the presence of a body of material with a density higher than the surrounding rocks. An iron-nickel meteorite would have a density of 7.4 as compared to a density of about 2.4 for the surrounding sediments. It would require about 1,000,000 tons of meteoritic materials to produce a gravity effect of 0.20 milligal at a depth of 500 feet. This is equal to a spherical mass of meteorite 100 feet in radius.

4. The shift to the south of the magnetic anomaly relative to the gravity anomaly is in the right direction and amount for the affect to have a common origin at a depth shallower than 600 feet."

This letter and these drawings, which are on permanent display at the Museum of the Barringer Meteorite Crater, would seem to indicate that a quite considerable mass of meteoritic metal still lies buried below the crater floor.

Policy Of The Barringer Company

The Barringer Crater Company, successor to the Standard Iron Company, which was founded by D. M. Barringer in 1903, still owns the Crater, with most of its stock held by members of the Barringer family. Those of the present generation regard it as a public trust, and it is one of their chief aims to instill the same feeling in the succeeding generation.

It is their policy to present and to explain the Crater to visitors in the best manner possible. That this aim is being accomplished is proved by the fact that The Meteoritical Society, international organization of scientists in the field of meteoritics, passed by unanimous vote at its meeting in Albuquerque, in September, 1955, a resolution praising the manner of that presentation and opposing any attempts to make this natural wonder a national or state park as long as it continues to be maintained in its present manner.

It is their policy to return any profits from the tourist traffic into research, with the ultimate aim of proving to science and mankind how large a mass of metal from space was required to make such a crater. It is their hope to realize their father's belief that the recovery of the metal will eventually reimburse the investment, now past the half-million-dollar mark, made by private enterprise in that research. It is their pledge that any actual attempts to mine the metal will be so made as not to deface the Crater for generations still unborn.

The tourist concession at the crater is operated, under a long-term lease, by Meteor Crater Enterprises, Inc., a subsidiary corporation of Bar-T-Bar Ranch, Inc., which surrounds the Crater. Under the terms of that lease, The Barringer Company holds editorial power over the manner of the Crater's presentation, as a guarantee that it will be held to a high level. The concessionaire has veto power over any mining attempts which might tend to deface the Crater from the standpoint of the tourist or student. These checks and balances will protect the public interest under the administration of future generations of stockholders.

Meanwhile, The Barringer Meteorite Crater will remain the spectacle it was when Svante Arrhenius, the great Swedish scientist, stood on its rim and said, "This is the most interesting spot on Earth."

ACKNOWLEDGEMENTS

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