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A Résumé of Researches at the Arizona Meteorite Crater

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The fall of a huge fireball that he witnessed in 1923 turned Dr. Nininger from a summertime enthusiast to a full-time geologist. In 1946, with his wife (and co-worker), he opened the American Meteorite Museum on U. S. Highway 66 opposite the great Arizona Crater. Unlike his predecessors, he believed that the crater could best be understood by studying the distribution of meteoritic particles around it rather than by probing its interior. As a result of his extensive investigations in Arizona and elsewhere, he has developed several new hypotheses, which are incorporated in An Introduction to Meteoritics, *soon to appear.*

IT HAS been almost sixty years since the attention of scientists was first called to the strange topographical feature now known variously as Meteor Crater, the Arizona Meteorite Crater, and Barringer Crater. So far as can be learned, A. E. Foote[1] was the first to be attracted to the problem of explaining its origin. After a brief visit to inspect the site of a remarkable concentration of meteorites, he mentioned the fact that the many nickel-iron masses were found near the base of a circular elevation whose center was "occupied by a cavity nearly three-fourths mile in diameter," the bottom of which was far below the surrounding plain. He gave a brief description of the feature, closing with the statement that he was unable to find any volcanic products and was "therefore unable to explain the cause of this remarkable geological phenomenon."

Shortly thereafter, G. K. Gilbert[2] inspected the phenomenon and concluded that it had been the result of a steam explosion, volcanic in nature. This conclusion may seem strange in the light of present knowledge, especially since Gilbert was such an outstanding geologist. But it should be remembered that up to that time meteorite craters had not been known to exist.

It is to D. M. Barringer and his associates that must go the credit for first recognizing and more or less establishing the meteoritic origin of the crater, and to them we are also indebted for a great body of facts regarding the structure and general characteristics of the phenomenon. At great expense of time and money, these men worked intermittently during the first three decades of this century at various types of exploration—chiefly with a view to commercial exploitation, it is true, but in the process they brought to light much useful information concerning the crater. In a monograph[3] read before the autumn meeting of the National Academy of Sciences in 1909, Barringer summarized the results of several years of exploration, and in later papers[4] he recorded additional findings which, he thought, gave further verification of the opinions expressed at that time.

In the present paper frequent references will be made to these reports. Our admiration for the pioneer work of Barringer has been set forth in *A Comet Strikes the Earth*,[5] and, even though our opinions, having been modified by the discovery of several new facts, are not now in full agreement with those of Barringer, our respect for the man's determination and persistence remains unchanged.

The topographical aspects of the crater as determined by Barringer are as follows: Diameter of pit at crest of rim, 4,150 feet; elevation of rim above adjoining plain, 120–168 feet; average elevation of crest above lowest point in present floor, 570 feet; vertical distance from highest point of crest to center of present floor, 600 feet; width of rim entire, inclusive of outlying mounds of ejecta, 1–2 miles, with the bulky portion varying from 1,000 to 2,500 feet in width. As determined by drillings, the extreme depth to undisturbed sediments in the pit is 1,000–1,200 feet below the surrounding plain. Approximately the lower half of the pit is filled with fragmental rock and water, the water level being about 200 feet below the center of the present floor.

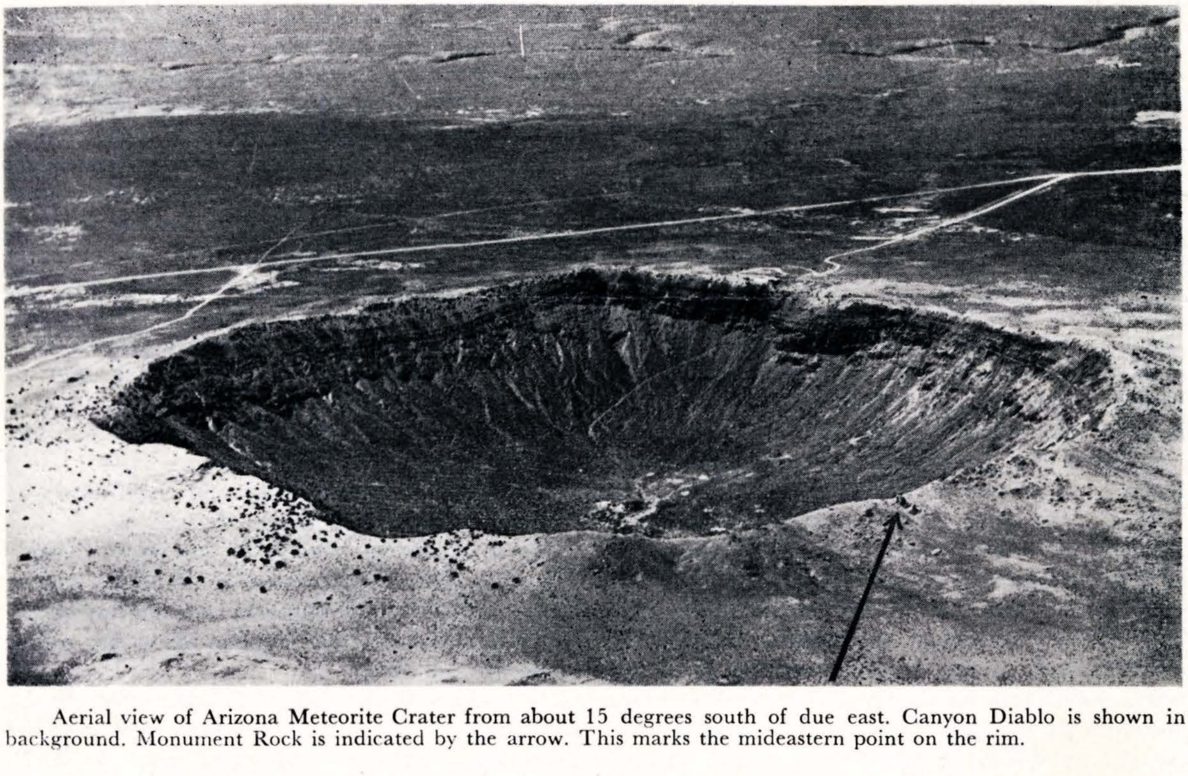
The name "Canyon Diablo" was applied to the meteorites from this area before their relation to the crater was recognized. Their description by A. E. Foote in 1891 was based on a study of the metallic masses first recovered by a prospector and shipped from Canyon Diablo Post Office; hence the name. Such masses were later reported by Barringer as having been found as far as 6 miles distant, on three sides of the pit. These ranged in weight up to several hundred pounds, and a very few even exceeded 1,000 pounds.

Small irons of 5 pounds or less were found in great abundance on the outer slope of the northeastern sector of the rim and less abundantly in several other areas, some as far distant as 2 or 3 miles from the pit. As will be pointed out later, it is probably significant that these outlying scatterings of small irons, with the exception of those on the north-northwest, have been found in association with larger masses, whereas those on the rim slope were not accompanied by masses of more than 10–15 pounds, except for one instance where a mass of approximately 100 pounds was found about midway of the outer rim slope.

Chips and flakes of iron-nickel oxide were found irregularly scattered on all sides of the pit to distances of 3 and 4 miles and in a few areas much farther out. These were usually more abundant in the areas where metallic masses, either large or small, were recovered. Their presence was frequently used by meteorite hunters as a guide to areas likely to yield metallic meteorites.

Another form of iron-nickel oxide that was widely scattered both on the rim and on the plain appeared as nodular masses of various sizes and shapes. These usually displayed deep cracks or fissures, the result of internal expansion as the oxidation of metals proceeded inward from the surface. They were named "shale balls"—rather ineptly, since they are really neither shale nor by any means always ball-shaped. Actually, they exhibit an almost unlimited variety of forms, though they tend to be nodular, with ends, corners, and edges rounded. A considerable percentage do appear more or less rounded, and an even greater proportion somewhat pear- or drop-shaped, often with one side flattish. But some are quite elongated, flattish, and variously contorted in general form. Some of the shale balls have metallic cores, and Barringer at first seemed to think that the shale-ball meteorites represented a distinct variety of individual mass in space. But in view of his study of some that contained metallic cores he seems to have later concluded that all the metallic masses were residual cores left by the flaking away of the "shale-ball iron" that originally enveloped them. With this view we are not in agreement, as will be discussed later.

Particles of nickel-iron oxide were reported recovered from 17 of 31 drill holes in the crater and including one from the crest of the southern rim. According to the drilling logs that were kept, in



Aerial view of Arizona Meteorite Crater from about 15 degrees south of due east. Canyon Diablo is shown in background. Monument Rock is indicated by the arrow. This marks the mideastern point on the rim.

two of the holes drilled in the southwestern quarter of the pit and in the one from the crest of the south rim, impenetrable masses were encountered which, after persistent hammering, were by-passed. After several repetitions of this behavior, the drill bits were lost, probably becoming entangled among such fragments.

Some of the particles of nickel-iron oxide recovered had metallic centers that would not crush in a mortar. Barringer interpreted these as "sparks" stripped from the outside of the mass as it came into contact with the rock strata through which it penetrated. He was not sure whether these "metallic centers" were true nickel-iron or schreibersite.

The Barringer group reported that water was encountered about 200 feet below the floor of the crater and believed that this represented an accumulation of rain water subsequent to the time the pit was produced. When they later tried to sink a shaft outside the pit at a point about 1,000 feet below the crest of the southern rim, they encountered the water at approximately the same level as inside. They believed this was due to shattering of strata beyond the limits of the pit, however, and still thought it possible to lower the water level in the pit by means of pumping, so as to permit mining operations in the bottom. A trial pumping program reportedly lowered the water level somewhat, but the calculated expense of completing the task led to the temporary abandonment of the pumping program (1929). We now know that the water level in the pit is consistent with the general water table of the surrounding country, as revealed by the drilling of several water wells a few miles from the crater.

Barringer also reported large deposits of finely pulverized quartz (produced from the Coconino formation) in the crater pit and in various parts of the rim, and he estimated that it probably amounted to as much as 10–20 per cent of the ejected material. He pointed out that this had been subjected to intense dry heat. On the other hand, in certain parts of the pit, he found deposits of fused quartz pumice that must have been, he indicated, formed in the presence of steam and at higher temperature than is known to be present in volcanoes. He further reported the absence of volcanic deposits other than ash, which had evidently blown in from volcanic craters 15–40 miles to the south and west.

Although several of his findings would have fully justified a conclusion that the meteorite had more or less completely exploded and that only a small remnant remained in the crater, Barringer clung to the idea that the principal mass of the meteorite, or cluster of meteorites, still lay buried in the pit and that it constituted an available source of valuable metals. One of the arguments against the explosion theory which Barringer regarded as incontestable was the fact that no great amount of iron stain was noticeable in the vicinity of the crater. He argued that, if the meteorite had exploded into a large volume of metallic vapor, we should now witness positive evidence of that fact in the form of widespread iron stain in the country rock. We have since learned that this reasoning was fallacious. When the Haviland crater was excavated, we found no evidence of soil staining in the area around the crater where the small nickeliferous pellets, products of vaporization, were found. Only a layer of soil a few inches thick was stained, delineating the bottom of the crater bowl, and only a narrow zone of staining surrounded each of the thousands of specimens removed, usually less than one-fourth inch in thickness.

Recent Discoveries

We believe that recently there has been brought to light sufficient evidence to prove that Barringer's conclusions were in error at several points. We believe it is now evident that there remains no considerable mass of meteoritic material in the crater, but that, rather, the colliding mass was for the most part actually vaporized upon impact. The principle has been demonstrated in experimental gunnery and has been theoretically supported by astronomers, physicists, and mathematicians who have investigated the problem mathematically. Now, new discoveries, we believe, have verified the explosion principle in fact.

With the help of the American Philosophical Society and of certain private individuals, we began seriously to explore the Barringer Crater area in 1939, believing that a thorough study of the distribution of meteoritic material around it would eventually lead to a satisfactory interpretation of the event. We began with a search of selected areas on various sides of the pit within a radial distance of 1–3 miles, using a magnetic rake. This device, attached to an automobile and carried on a small trailer, gathered small masses of an ounce or less in the upper three-quarters inch of soil.

The combing of a total of some 23 acres in many different small areas on various sides of the pit gave results that led to the belief that meteoritic material exhibited a *radial distribution,* with the crater as a center. Subsequently, an inspection of the many holes left by cowboys and others who had recovered large masses 25–1,000 pounds in weight lent further support to the theory of radial distribution.

In 1947, working on a permit from the Standard Iron Company, the American Meteorite Museum systematically searched large areas of the crater rim's outer slope for small masses (10–5,000 g), using an Army surplus mine detector and several other types of metal-finders, effective to depths of about 2 feet on masses of one pound. Here we found further evidence of radial distribution, but by comparing our results with the record made on the Holsinger map published by Barringer in 1909 we were also able to demonstrate a *general distribution of meteorites as to size*—i.e., small sizes near the crest of the rim and larger ones on the plain beyond the rim. An exception to this distribution lies in the fact that on the plains small meteorites were usually associated with the large ones; but on the rim we found no large masses associated with the abundant small ones.

Another peculiarity of distribution has been the almost complete lack of large masses in the northern-northwestern sector of the adjoining plain. This area has, however, yielded many small metallic fragments, mostly less than an ounce in weight. During our magnetic survey of 1939, this sector proved to be the most productive of any large area investigated, but the meteorites collected averaged less than 2 g in weight. The Holsinger map shows an almost complete absence of large masses in a fan-shaped area lying between radii drawn from the center of the crater 30° north of due east and 10° north of due west, but I can find no reference to indicate that any significance was attached to it. It should be noted that according to present evidence the path of the colliding meteorite just about bisected this area, a fact that is believed to be significant.

In 1946, again working with the help of the American Philosophical Society, we began a magnetometer survey to ascertain the distribution of large masses of 40 kg upward which might be buried on the plains around the crater. This program was interrupted by outside interference, but not before we had set up and taken readings on 1,032 stations, covering 23 acres along the base of the crater rim on the north and south. These stations were spaced at 30-foot intervals. Whether meteorites of size were located, we were never permitted to learn, but six very pronounced anomalies were mapped. One lesser anomaly yielded a 12-pound mass of oxide with a 3-pound metallic core, only about 12 inches below the surface.

An important fact to record from this partial survey is that the operator, A. J. Whelan, was not impressed with the possibility of a magnetic mass in the crater, but he did believe that his readings indicated something to the southeast. He later called attention to the report of International Geophysics (which was made in 1930 and detailed radial traverses leading outward from the crater) which showed abnormally high values for stations in the two traverses on the southeast. Jakosky[6] regarded this as due to local disturbances and did not use these data. Whelan suggested that there was a chance of there being a large mass lying southeast of the crater, "but if there is it will be farther out than anyone has looked to date."

We are inclined to interpret the readings in this area as due to buried meteorites near the surface, since more large masses have been found at the surface here than in any other area. We have also suspected the existence of one or more subsidiary craters such as the University of Texas found concealed by surface deposits near the principal Odessa, Texas, crater. We believe further that similar near-surface objects led Helmut Landberg to the seemingly impossible conclusion that large masses had forced themselves under the strata to distances as great as a mile south of the present pit and at depths of 1,000 feet or more.

It seems reasonable that, if large masses of metal (or oxide, which in the earth seems to develop a stronger magnetic field than does metal) existed under the south rim, then surely our east-west traverses along the base of the rim should have given strong indication of such, because those stations along the north rim were an average of about 7,000 feet north of the mid-point on the south rim where Barringer thought he had a huge mass of metal, whereas those on the south were but 2,000 feet south of the same point.

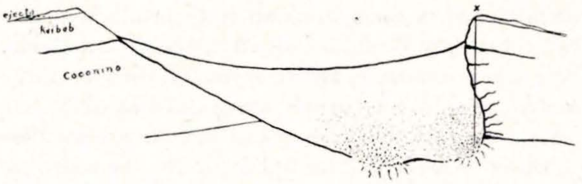
The velocity of meteorites in space at the earth's distance from the sun has been fairly well established as 20–30 miles per second. At such velocity any meteorite would explode upon striking the earth. Consequently, only those that are small enough to be effectually decelerated by the atmosphere can be expected to survive their encounter with the lithosphere. Wylie[7] has shown that iron meteorites of 220 tons or more should explode on hitting the earth. The fact that no mass larger than about 50 tons and only three larger than 30 tons have ever been found suggests that this figure is too high. Also, the excavation of the 80-foot subsidiary crater at Odessa, which plainly evidenced an explosion, and the several excavations in the Henbury craters, all indicate that many meteorites of smaller size than 30 tons actually explode on contact with the rocks of the earth. No considerable-sized mass has yet been found within any crater. A broken mass of 441 pounds was found in a 30-foot crater at Henbury, and three contiguous masses aggregating about 200 pounds were found in the Haviland Crater. The bowl-like bottom of this 36′ × 55′ crater was strewn with thousands of smaller fragments.

Ballistic experiments have shown that projectiles traveling at velocities above about 4,250 feet per second explode into vapor on striking the target. In the light of present knowledge we may assume that any iron meteorite of larger size than 20–30 tons has small chance of surviving its collision with the lithosphere. There are, however, mitigating circumstances, such as angle of descent, texture and slope of soil encountered, shape and texture of the meteorite, whether it overtakes or collides head-on with the earth, etc. The 36½-ton Cape York iron landed on a 15-degree slope in a latitude where deep snow is the rule. Otherwise it might not have survived. The Hoba iron of perhaps 50 tons presents a problem; but it is of great age and may have arrived when conditions in that area were very different.

In view of these facts it at first seems surprising that any fragments of the great Arizona mass remain. However, a careful consideration of its structure seems to have brought to light a very sound reason for the survival of so many fragments.

We pointed out, in a paper read before the American Astronomical Society in Tucson (December 1949), that the unequal distribution of cohenite and schreibersite and abundant scattered nodules of troilite and graphite are probably responsible. These minerals are all brittle, the first two extremely so. Also, both schreibersite and troilite have low melting points. Concentrations of one of or all these minerals are common in the fragments that have been collected and may very well have been more abundant in areas obliterated in the fragmentation process. Such a condition may have occasioned a superficial shattering of the mass upon its first contact with the lithosphere. Fragments so detached were thrown free and distributed over the surrounding plain, thus escaping the great heat which seconds later reduced most of the remaining mass to vapor.

During 1948 and subsequently, by studying the internal structures of hundreds of small Canyon Diablo irons found on the northeast rim of the crater during the 1947 survey, we were able to demonstrate that a *zonal distribution* existed with regard to heat effects. More than 97 per cent of the regular Canyon Diablo irons from this location appear to have been altered by heat, whereas fragments of comparable size taken from outlying points seldom show such alteration. Barringer and other early investigators had noted that large specimens found on the plain showed beautiful Widmanstätten patterns, whereas the small ones they had sectioned revealed a pattern altered by heat. It was long believed that size was the determining factor in these results. Unfortunately no records were kept as to where these irons had been found, but it is generally assumed that the small ones came from the crater rim, since that is the area from which so many small specimens had been recovered. Our 1948 studies, however, were conducted on meteorites the places of find for which were accurately recorded. It was thus that we were able to demonstrate the relation between heat alteration and *location,* leading to the conclusion that the outlying fragments were thrown free before final vaporization, and that those found on the rim betray by their altered condition the fact that they were not set free until the explosion occurred.



Theoretical section of the present crater. The two concentrations of fragments explain the area of high conductivity located by the electrical survey of International Geophysics in the southwestern quarter of the crater pit and that encountered by the drill as reported by Barringer. *X* shows location of the 1,376-foot drill hole. Looking eastward.

The concentration of these small meteorites on the northeastern sector of the rim and their almost total absence on the western sector can probably best be explained by the fact that the prevailing winds in this area are from the southwest. At high elevations wind velocity often reaches 70 miles per hour. From a depth of 1,000–1,200 feet, surviving fragments thrown aloft several miles could very easily have drifted with the wind in their descent, so that those that did not fall into the pit spread only slightly beyond the rim to leeward. The lesser deposit of similar small masses that Holsinger indicates on the southern rim may have been a product of the initial shattering described earlier. Unfortunately we have no access to any of the fragments from that portion of the rim. Almost certainly some specimens could yet be collected, and the study of such is here suggested.

Barringer's conclusion that all the metallic specimens represent residual cores left from disintegrated shale balls, and that the holes and deep depressions in these irons all were products of the wasting away of shale-ball iron, seems untenable. We have exhumed many irons in beds of large boulders and in various other situations where movements of the irons could not have been possible by erosion. Yet careful inspection revealed no evidence of exfoliation of any considerable amount of oxide. On the other hand, many other irons showed abundant evidence of such oxidation.

We concluded, therefore, that the shale-ball iron and the normal Canyon Diablo irons were not originally two different kinds of meteorites in space but were merely different portions of a common parent mass which in some parts was rich in one accessory mineral and in others another, and that still others were composed of pure nickel-iron. Those fragments which carried a destructive content of chlorine became the shale balls, and those that lacked it survived. There were, of course, those fragments that contained this disintegrating agent in irregular distribution. Such specimens lost their afflicted portions by rapid weathering, and other portions remained more or less immune. They were by this means reduced to all sorts of fantastic shapes, not a few being completely perforated. However, the majority of deep, narrow perforations and pits were undoubtedly due to the dissolution of troilite where the nodules of this mineral were exposed at the surface of the fragment. This has been proved in many instances by the finding of residual troilite at the bottoms of such narrow cavities.

We have found considerable evidence that the shale balls were not the product entirely of their chemical peculiarities, but that their rapid deterioration may have resulted from them, together with their exposure to greater heat than were those regarded as typical Canyon Diablo irons. Those few iron cores from the masses of oxide we have examined all appear to have had the Widmanstätten pattern altered by heat. Laboratory experiments have demonstrated that an iron which contains a trace of chlorine, and which has been resisting oxidation very well, may disintegrate rapidly after being subjected to a temperature sufficient to induce redness. It may be that the large lumps of oxide (shale balls) represent those masses which contained some chlorine and which also received a little more heat than did the average. This is a point on which we feel we have as yet insufficient evidence to justify final conclusions, but our findings seem significant.

What we believe to be conclusive evidence of the vaporization of the bulk of the meteorite has recently been provided by the discovery of five different forms of particles which evidently constituted the condensation products from an iron vapor cloud. Such a cloud we believe to have been the product of the great impact-explosion. Great quantities of minute spherules and droplets of nickel-iron have been found in an area of more than a hundred square miles with the crater near its center. These have been collected magnetically from many locations and have been quantitatively estimated at several thousand per cubic foot in the topsoil 4 miles due north of the crater rim. They are much more abundant nearer the crater and along the base of the rim, but gradually thin out as one recedes from the crater. These were first identified early in 1948 as an ingredient of the fine, dark-colored debris that so abundantly clings to a magnet when dragged through or over the surface of the soil. That they had eluded all investigators during the past half century is easily explained by their being so greatly overshadowed by the much more abundant particles of basaltic cinders, many of which are also magnetic, and with which they are likely to be confused until critically examined under a lens.

A preliminary account of our discovery of these particles was reported to the American Philosophical Society in 1949. That report dealt only with the two forms of the condensation droplets that were first isolated. The more important ingredient of this metallic rain which is here discussed we only succeeded in separating out in September 1949—too late for incorporation in the 1949 report. This is in the form of a rounded particle, with a more or less lumpy surface, as though it had been produced by the accretion of several smaller droplets during the process of condensation and solidification. A critical examination of the surfaces establishes the fact that at least the larger ones (those measuring 0.3 mm or more) are not residual cores of larger bodies which have oxidized but, rather, are complete individual particles which have not suffered loss of mass since their formation. They have developed a very thin skin of oxide which seems to have been impervious to the forces of weathering, so that the body of the particle is for the most part untarnished metal.

Probably the most difficult problem presented by the discovery of these condensation products is the explanation of their survival. If the crater was formed twenty to fifty thousand years ago, then one should surely not expect such minute bodies of ferrous metal to be still resisting oxidation. Even more amazing is it that they should have escaped being ground to impalpable powder. Yet here they are! We may assume that their resistance to oxidavariation among themselves, and some of those variations, we surmise, would be difficult to distinguish from an altered Canyon Diablo No. 2 or No. 3. However, we have not as yet to our knowledge seen No. 3 in altered form. (We have several problematical specimens laid aside for further study.) The limits of the variations in the normal Canyon Diablo meteorites have been determined by an extensive inspection of many large sections in our own and other large collections, involving careful measurements of the kamacite plates, with critical notes on taenite and other less conspicuous characters. Nothing is regarded as *non*-Canyon Diablo unless it is plainly inconsistent with all the different variations observed in any of these sections. Identifications are difficult, and we had examined at least a hundred sections before we became convinced that the fall was a composite one consisting of two or more components. Even after Canyon Diablo No. 2 was described in 1938, we were not sure but that it may have represented a later fall in the same area. It showed less heat alteration than the typical Canyon Diablo irons with which it had been associated on the rim and could therefore be thought of as a chance overlapping of a subsequent fall. However, when in 1947 and 1948 we discovered two additional types it seemed entirely unreasonable to assume that so many falls of nickel-iron meteorites should be recovered from so small an area. Besides, we had by this time found several more of Canyon Diablo No. 2, and some that showed heat alteration similar to what had been suffered by typical Canyon Diablo fragments on this same portion of the crater rim that we suspect of being Canyon Diablo No. 2.

We were now wholly convinced of the multiple nature of the impact and we strongly suspected that we had been missing the identity of specimens which represented the components of this multiple system, or swarm, in instances where the latter had suffered heat alteration. We are still more convinced of this error since becoming conscious of the existence of these various components among the heat-altered specimens. We have now learned how to distinguish them even when the Widmanstätten pattern has been largely obliterated. In one instance, 2 specimens of Canyon Diablo No. 2 were recognized among 30 specimens cut. Both were free from heat alteration. In another lot of 24 irons, 5 were non-Canyon Diablo components, 2 of which had been altered by heat. Two other lots of 15 and 7 irons all proved to be of the typical Canyon Diablo. These four lots are typical of our recent investigations of crater material.

A, Etched section of typical Canyon Diablo meteorite showing Widmanstätten pattern and nodules of troilite and graphite surrounded by narrow borders of schreibersite. Several cohenite inclusions near lower edge. × ½.
B, Another typical Canyon Diablo section; here heat has largely obliterated the Widmanstätten pattern. This also contains abundant cohenite, which conforms to the original pattern. × ½.
C, Etched section of Canyon Diablo No. 3. Note much greater prominence of taenite separating the kamacite bands. × 1.3.
D, Etched section of Canyon Diablo No. 2. In this specimen the structure is deformed but still quite distinct. × ½.

Present Interpretation

Barringer's final conclusion was that the crater was formed by a closely packed swarm of small meteorites. Moulton[10] admitted such a possibility and always made allowance for this condition in his calculations; but he found some serious difficulties in explaining all the facts on this basis. Jakosky always referred to "the meteorite or swarm of meteorites." Our recent finds give positive evidence that the encounter was a multiple one, but we think they with equal positiveness argue against tion has been due to the formation of a thin, impervious layer of oxide while the droplets were in the liquid stage and during solidification. This protective film was similar to that found on the best-protected areas of a freshly fallen metallic meteorite. We recovered two masses of the Glorieta meteorite fifty-three years after the discovery of that iron, whose date of fall is unknown. These masses still exhibited patches of the original fusion crust unstained by rust. They were quite as fresh-looking as those that had been placed in museums in 1884. This find gives evidence that a fusion crust of oxide may be an extremely effective protection for ferrous alloys.

As to their escaping destruction by trituration, it should be noted that the best locations in which to search for them is on the leeward (northeastern) side of boulders or clumps of vegetation. In such situations they might rest undisturbed for long periods and, since the topsoil is dry most of the time, their being covered would protect them from moisture.

The recent reports on the great cosmo-terrestrial encounter near Novopokrovka in southeastern Siberia in 1947 give point not only to the discovery of this metallic rain but also to other aspects of the theory of explosion of large meteorites on contact with our planet. It was with no small satisfaction that we read in Otto Struve's[8] translation of the Russian report on this great meteorite the account of the "rain of iron," the Arizona counterpart of which we had been investigating for the past two years.

Besides the spherules above described we have isolated and identified the following condensation products: (1) Metal-centered pellets which are minute globules of bright nickel-iron encased in a few layers of soil and sand grains. (2) Reticulated pellets consisting of soil and sand particles bound together by a reticulum of nickel-iron oxides. These often are flattened on one side as if the metal had landed in liquid form and incorporated the soil particles within the liquid droplet. (3) Near-perfect spheres of nickel-iron oxide which apparently condensed from those portions of the vapor cloud exposed to oxygen and which oxidized previous to or during solidification. (4) Globules of silica glass coated with oxides as if a droplet of silica had cooled and subsequently received a deposit of metallic condensation before reaching the soil. This form of silica glass resembles that described by L. J. Spencer and M. H. Hey[9] in connection with the Henbury craters in Australia. Details of the nature and varieties of the metallic particles deposited at Novopokrovka are not available. It will be interesting to note what subsequent reports reveal on this point.

In addition to the little silica-glass droplets, we found a small amount of the better-known form of silica glass, which had never previously been reported from the Arizona Crater. This is a transparent glass with a greenish-yellow tint and contains minute metallic spheres, or droplets. Black and brown varieties were found in abundance at the Henbury craters and a clear white variety at the Wabar craters, all described by Spencer and Hey. The Arizona find was in the form of small angular blocks and shreds up to one-half inch in greatest dimension. It was found on the north rim of the crater about halfway up the outer slope and was gathered by means of a magnet while searching for the metallic droplets.

The structural studies of the Canyon Diablo meteorites that we have been conducting during the past few years have revealed further important evidence concerning the nature of the meteoritic encounter that produced the Arizona Crater. The American Meteorite Laboratory began sectioning the small Canyon Diablo meteorites in the 1930s and in 1938 encountered one that exhibited good Widmanstätten figures but of a pattern that did not conform to the well-known Canyon Diablo structure. Subsequently, two other small irons were cut that conformed to this new type, which was described as Canyon Diablo No. 2.

Later, two more new types were studied and catalogued as Canyon Diablo No. 3 and as Monument Rock (the latter so named from its nearness to the huge boulder on the crest of the east rim of the crater, to which Barringer gave that name). Canyon Diablo No. 3, like No. 2, has been found in duplicate, but so far only one group of fragments (evidently from a single mass) of the Monument Rock find has been recovered. In view of the fact that all these three new types have been gathered from the crater rim, and the further fact that they were found among but about 200 specimens critically examined, we regard them as very good evidence that the crater-forming mass was accompanied by more or less of a swarm. In other words, this appears to have been a multiple fall. We estimate that 40,000 small specimens have been collected from the crater rim since its discovery. Assuming the same ratio as our studies have yielded, we should expect quite a number more of non-Canyon Diablo types to have been among these. We here suggest that those who have irons from the crater might do well to section and study them.

The normal Canyon Diablo irons show great the kind of swarm indicated by these men. We believe that the many widely scattered masses on the plains around the crater, which show the same range of structures, and which have come to be recognized as the Canyon Diablo meteorites, have been derived from one large mass. We refer to both those that show heat alteration and those that do not, so long as they compare favorably as to widths of kamacite plates, arrangement of taenite and plessite, and their inclusions of carbide, phosphide, troilite, and graphite.

We believe that the comparative scarceness of Canyon Diablo No. 3 and of Monument Rock indicates that these represent very minor masses that were satellites of the Canyon Diablo body. But the greater abundance of Canyon Diablo No. 2, and the fact that it occurs in both the unaltered and heat-altered conditions, indicate that it represents a second large mass that underwent considerable fragmentation before it finally disintegrated upon impact. These facts may best be explained by assuming two large masses constituting a sort of miniature earth-moon system, accompanied by a family of smaller masses.

Jakosky assumed an angle of incidence of about 70° from the horizontal, but did not submit any special reason for selecting that angle. For several reasons, we have chosen to assume a much flatter trajectory, of about 30° with the horizontal. This is chosen because: (1) It seems to better explain the shape and structure of the crater. (2) The great majority of observed meteorite encounters have been at angles less than 40° with the horizontal. We refer here, of course, to the trajectories of the fireball stage of meteorites, not the much steeper angle at which ordinary meteorites strike the soil. Certainly crater-forming meteorites would be checked but little by atmospheric friction and would therefore arrive at the lithosphere at approximately the same angle of descent as marked their encounter with the atmosphere. (3) The lower angle of approach better fits the distribution of meteoritic material around the crater. (4) The reported concentration of meteoritic material under the southern rim suggests a flat trajectory.

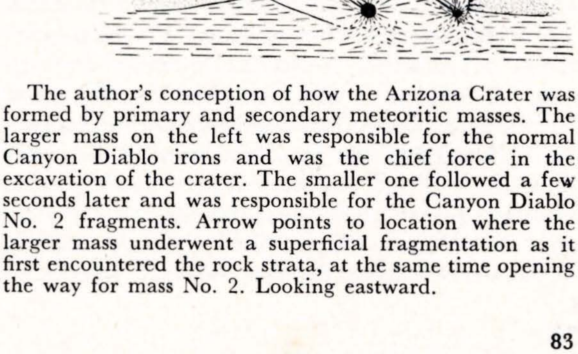
We assume that on its very first contact with the lithosphere, the principal colliding mass shattered in certain weak outer portions. The fragments thus set free were thrown with great force but were spared any great heat penetration, the heat being restricted largely to the shearing planes. These were naturally thrown forward, laterally, and upward from the exposed areas of the meteorite's surface. That portion of the surface which made the initial contact with solid sediments was vaporized instantly, as quickly as it came into contact with the sediments, and set free no sizable fragments. The discharge from this portion was in the form of gases and very small shreds, and constituted a backfire from the missile. This would seem to offer the best explanation for the lack of large fragments in the segment of the plains adjoining the crater on the north-northwest, which, as has been pointed out, was the direction from which the meteorite approached.

It is on either side of this axis that the crater walls are most steeply upturned, and the fields of large boulders lie on the outer slopes of these steeply dipping strata. It is also at the distal end of this line of flight that the magnetometer survey of Jakosky indicated a concentration of metalliferous material.

The southern rim is somewhat arched, but dips only slightly away from the pit. These features were interpreted by Barringer as indicating a large meteoritic mass wedged under the rim. Jakosky, however, has pointed out that this southern section of the rim is stratigraphically lower than the sections on either side of it, so that it is quite as important to explain the positions of these latter as it is to explain the southern section.

Several forces combined to form the crater:

1) The impact splash in itself was sufficient to produce the present surface dimensions. A high-velocity bullet fired into packed dry sand forms a crater twenty to thirty times the diameter of the projectile. As Alfred Wegener long since pointed out, the coherent strength of the target material is of no great consequence when forces of such magnitude as is represented by impacts of large meteorites are involved; sand behaves about the same as the toughest rock.



The author's conception of how the Arizona Crater was formed by primary and secondary meteoritic masses. The larger mass on the left was responsible for the normal Canyon Diablo irons and was the chief force in the excavation of the crater. The smaller one followed a few seconds later and was responsible for the Canyon Diablo No. 2 fragments. Arrow points to location where the larger mass underwent a superficial fragmentation as it first encountered the rock strata, at the same time opening the way for mass No. 2. Looking eastward.

2) Closely related—in fact, one aspect of the impact force, but producing a special kind of result—was the plowing or burrowing action, the lateral and upward displacement of rock strata which were torn free from their axial moorings. We here refer to the tilting of strata, a part of which was the result of impact and part a result of forces yet to be considered.

3) The expansion of highly compressed air that had been captured on the front of the moving projectile as it traversed the atmosphere was another of the factors. The magnitude of this force would depend upon the angle at which the passage was accomplished. Descending vertically, the pocket of air should be the equivalent of a layer of rock about 14 feet thick, according to Moulton, but coming in at an angle of 40 degrees or less it could be very much greater. It should also be borne in mind that the dimensions of this air cap would be much greater than the diameter of the meteorite, because each layer of impacted air becomes a trap for more, and so the cap grew in lateral as well as in axial dimensions. This superheated block of air operated as a powerful explosive laterally and upward as it made its escape from the trap into which it was being driven between the projectile and solidly bedded rock. It wreaked havoc in the porous sandstone of the Coconino.

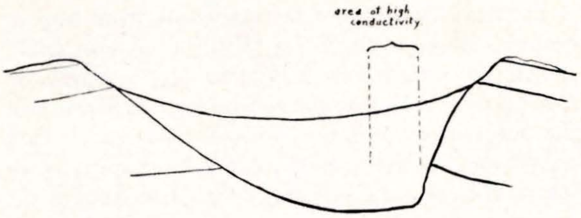
4) The fourth factor was steam. The pores of the lower Coconino sandstone were filled with water, and this was heated both by impact and by compression. The resulting violent rise in temperature transformed the water into steam under conditions of pressure which rendered it an extremely powerful explosive. Already distributed among the sand grains of the formation, the entire mass, as far as the heat and pressure effects were sufficiently felt, disintegrated in a mighty blast. This blast was a protracted one, the superheated steam becoming active as the pressure and temperature conditions reached the critical levels; i.e., as that portion of the rock near the source of heat was removed, the pressure was reduced in deeper layers, thus allowing more of the superheated fluid to participate in the distintegrating process.

5) Finally came the greatest explosion of all, when the internal temperature of the nickel-iron mass had reached the critical point where the mass was suddenly transformed into metallic vapor. This was a blast of mountain-shattering proportions. It was this that gave final form to the crater in all its principal outlines. It was this explosion also that propelled skyward the gigantic metallic-vapor cloud from which rained down the millions of condensed-vapor droplets recently discovered in the field. At the same instant the thousands of small fragments that survived the blast were released. Since they were shot aloft from the depths of the pit before the crater vent had fully formed, they had but a narrow distribution. Obviously, nothing very large escaped from this final blast, which accounts for the absence of sizable fragments on the rim.

No mass of metal, however, as heterogeneous as that represented by the Canyon Diablo meteorites, could possibly explode completely. With its several included minerals, some of which have low melting points, together with the highly crystalline character of the nickel-iron, certain portions would certainly absorb more than their due share of the heat and disrupt the mass while certain other portions were at a safe temperature for survival. But, as we know the structure of the meteorite from a study of hundreds of samples, it is certainly not to be expected that any great masses survived. In all probability those that have been collected (many thousands in number) around the pit are entirely representative in size of whatever are buried in it.

This final explosion had much to do with the ultimate shaping of the crater. It removed a roughly circular, conical block of the overlying Coconino and Kaibab, and its downward thrust also excavated some of the underlying red beds. The side walls, whose uptilting had already begun as a result of the plowing action, lifted in degrees proportional to their nearness to the explosive force. The south wall, which had been somewhat arched by the tunneling action, was uplifted by this most powerful thrust of all. The compressed Coconino, together with meteorite fragments, was wedged into the gap. At the same time the steam action was ripping out the support for this uplifted block on either side, where escape was provided by major faults and by the upedged side walls. The uplifted overhanging south wall was sheared off by the upward thrust of the blast. The anchored portion dropped back into place as nearly as the underwedging permitted. The steam action adjacent to the faults at either end undercut this block, allowing its east and west edges to slump and thus accentuating the arching effect.

The above would seem to account for such a crater as was depicted by Jakosky (a sketch of which is presented herewith), but it still fails to explain the reported encounter by the churn drill of numerous sizable fragments under the southern rim at depths of 1,191–1,376 feet, as we have interpreted the log of that hole. Poorly kept as that log seems to have been, our study of it did not allow any alternative to the assumption of numer-



Longitudinal section of Arizona Crater as conceived by Jakosky after the surveys of International Geophysics, 1930. Looking eastward.

ous fragments at the depths indicated. We were equally convinced that there was no large mass encountered.

The Jakosky survey pointed to a magnetic high some 800–1,200 feet northwest from this drill hole, namely, in the southwestern quarter of the pit. This location may be assumed to be that marking the resting place of the remnants of the mass which we have followed to its explosive demise, its path being a curved one because of the earth's rotation during the period consumed by its traversal of some 1,800 feet of rock formations. But still to be accounted for is the concentration of fragments encountered by the drill under the south rim.

As stated above, we have found positive evidence that this was a multiple fall, that there were several (perhaps many) components involved in the encounter. Recent studies show that at least one of these (Canyon Diablo No. 2) contributed to the abundant deposit of small, heat-altered fragments that are collected from the crater rim. Our incomplete quantitative studies on this point indicate that perhaps 10 per cent of the fragments collected from the rim were contributed by non-Canyon Diablo components, at least one of which underwent an explosive treatment similar to that of the principal mass.

We shall therefore postulate a satellite of the main mass, which reached the earth slightly later than its principle. It was trailing its principle and was describing an orbit averaging some 800 feet from the line of flight of the main mass, and struck before the south wall had settled into place. Upon impact it repeated the last act described for the larger mass but on a smaller scale. Its remnants were for the most part trapped under the southern rim, but an easy path of escape allowed certain of them to escape to the northward through the opening made by its leader.

Future Researches

The cosmo-terrestrial encounter that has been responsible for this great crater was probably far more complicated than the above effort at visualization depicts, but at least this would seem to be an outline of what may have taken place. No doubt a better interpretation can be arrived at by a more complete examination of the surviving fragments. Ours has been the first attempt to relate the various structural features of the meteorites to their distribution around the crater. It appears now that this method of approach, if followed to its logical conclusion and carefully correlated to geophysical, topographical, and geological features, may eventually lead to an adequate understanding of this outstanding landmark.

It is suggested that various university groups could address themselves to different aspects of the phenomenon (offhand, at least twenty problems come to mind, each worthy of several years' effort) and in time make this phenomenon yield as valuable a body of data as does a well-equipped observatory or the field program of any department of geology. For example, since we now have positive proof of the existence of non-Canyon Diablo irons among the small specimens found on the rim, a critical study of the largest possible number of these should be made to ascertain how many different species composed the swarm. In addition, our proposed magnetometer search of the surrounding plain for the larger members of the assumed swarm should be regarded as vital by astronomers who seek further information regarding comets.

Again, we have no satisfactory evidence of the diameter of that swarm. We cannot be certain that various reports of irons being found 7, 10, 17, and 30 miles from the crater were actually deposited in these locations from the swarm that belonged to the crater-forming mass, but these reports cannot be ignored in any adequate survey. On the other hand, we cannot be justified in assuming that there are not many more outliers to be recovered and studied.

Only comparatively few of the several hundred large masses that have been collected in the vicinity of the crater were ever sectioned and studied so as to determine their identity. We have seen at least one of these whose structure appeared to represent a different meteorite. Perhaps a study of 50 or more would reveal the multiple character of these widely scattered masses.

Barringer reported the finding of meteorites in some of the excavations on the crater rim, thus proving that their presence was not limited to the surface. But no quantitative estimate was attempted as to the amount of material thus concealed in the ejecta. In 1948 we recovered 68 meteorites from a few cubic yards of the diggings that the Barringer party had excavated from certain trenches on the northeast sector of the rim. A careful search of several measured sections completely through the blanket of ejecta should be made to determine with some degree of accuracy the vertical distribution and the approximate quantity of meteoritic material.

Assuming that the deposit of meteorites on and in the outer rim slope has resulted from an explosive action in the pit, it seems inevitable that similar material should have been deposited on the inner slope against the upturned wall of the pit. Excavations into and through the talus that conceals the lower portions of this wall, accompanied by the use of electronic detectors, should throw more light on the nature of the crater-forming process.

The extent and distribution of the fused silica, lechatelierite, in the pit should be determined.

Samples could be recovered from the meteoritic masses encountered by the drill under the south rim and examined for trace elements to determine their possible identity with normal Canyon Diablo, or with Canyon Diablo No. 2. Harrison Brown, of the Institute for Nuclear Studies at the University of Chicago, found these two to be readily distinguishable by his recently developed technique.

An extensive reconnaissance should be carried out north-northwest of the crater to a distance of 20 miles or so to ascertain if strippings representing the fiery trail of the colliding comet's course through the atmosphere can be found. The terrain is very favorable for such a search, being almost entirely free from contamination by human industry.

In brief, this greatest of reasonably fresh impact craters, fresh enough for fruitful investigation, should be regarded as a top item for research on the part of both geologists and astronomers. For the latter it can supply a body of facts which may constitute a much-needed anchor in material substance for certain theories. For the former it is the major example of a process in cosmo-dynamic geology which has doubtless played an important role in the history of our planet. The fact that it represents a process that operates intermittently and at remote intervals makes it doubly important that this one prime example be thoroughly understood. Such an understanding will doubtless lead to the recognition and useful interpretation of many larger scars of impact, such as that recently described by Reginald Daly[11] in Africa. Without doubt cosmic impact is a process that must find a more prominent place in future geological theory.

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