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NATURE AND FATE OF THE METEOR CRATER BOLIDE

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THE impact origin of Meteor Crater, Arizona, is an accepted fact. The fate or disposition of the colliding body is yet undetermined, and a very interesting problem in cosmic science.

Through many years of exploration, with large expense, the Barringers, father and sons, have collected and published a mass of surprising facts about the crater and its associated meteoric materials. The data, however, have not been marshaled to attack the question of what has become of the greater part of the meteor, except to sustain the theory that the mass lies buried under the south wall of the crater.[1]

The problem of the fate of the meteor involves not only the physical and chemical properties of the discovered meteor fragments but the nature of other meteorites. There are also involved most of the features of the crater and the characters of the rock strata which were disrupted.

CANYON DIABLO SIDEROLITES

The meteoric irons known as Canyon Diablo, from the near-by creek and canyon, have been gathered from the desert plain about the crater to the number of thousands and distributed to institutions all over the world. Because of their number and wide distribution, their inclusion of minute diamonds, their genetic relation to the unique crater and their remarkable chemical and physical characters they are the most interesting and instructive of known meteorites. The facts concerning these irons should give some clue to the character and fate of the giant bolide of which they were a part.

The typical C. D. irons were scattered over the des-

[1] See article by D. M. Barringer, Jr., in the *Scientific American* of July, August and September, 1927. A list of the more important writings is given in SCIENCE, 69: 485–487, 1929.

ert in a radius of four miles and have also been found in the ejecta on the rim of the crater. The largest one weighed about 1,400 pounds. The total weight of all the discovered irons can be only several tons, and they are certainly only a small percentage of the giant bolide. On the supposition that the meteor was wholly nickeliferous iron ballistic calculations have suggested a diameter of about 400 feet and a weight of some ten million tons. The velocity factor, against which the mass must be computed, is unknown. The facts to be described below do not favor a meteor composed wholly of iron.

EXPLORATION—THE ROCK STRATA

The early exploration of the crater assumed that the meteor lay buried under the ninety feet of lacustrine sediment in the floor of the crater and in the subjacent rock débris. After a shaft was found impracticable, because of the copious ground water, drilling was done during the years 1905–1908. Only particles of nickel-iron and some green stain of nickel were found by the drills. But an important discovery was that the deeper rock strata were in continuous and undisturbed position. This ruled out any idea of a volcanic vent or chimney.

The rocks of the region belong in the Grand Canyon Series. They are as follows, in descending order.

(1) On the desert plain, some remnants of the red Triassic sandstone, called Moencopie.

(2) The topmost continuous stratum is the Kaibab, a Permian limestone, 250 feet in thickness.

(3) A white, saccharoidal sandstone, the Coconino; 1,000 feet; also of Permian age. The basal beds of the Coconino carry some yellow and brown color.

(4) Hard, red sandstone, known as the Red Beds, or Supai formation, of undetermined depth in that region.

The central area of the crater was probed by seventeen drill holes, even to the depth of 1,000 feet, or 1,450 feet below the surface of the surrounding plain. This probing passed entirely through the white Coconino sandstone, and penetrated 200 feet into the Red Beds. Seven of the drill holes entered the Red Beds, which were found in place and unchanged. This lowest formation is not represented in the ejected materials composing the crater rim, but samples of the yellow-brown basal rock of the Coconino are found in the ejecta on the southern rim.

During later years, from 1920, exploration has been made on the south border of the crater, on the theory that the bolide fell slantingly from the north and that much of it lies deep under the south wall. This section of the uptilted surrounding rim has been raised about 100 feet higher than elsewhere. The drillers reported meteoric iron from the depth of 1,200 feet down to 1,376 feet, where the drill was stuck and abandoned. Recently a shaft at the locality was a failure because of water and the shattered condition of the rocks. Further exploration is anticipated.

It appears highly improbable, if not impossible, that the mass of the bolide could penetrate to the depth reported for meteoric material. It would have to slantingly traverse some 2,000 feet of rock. And the uplift of the surface should be more than 100 feet. And it is difficult to visualize the mechanics by which detached fragments could reach to the great depth.

IMPACT EFFECTS ON THE ROCK STRATA

The kinetic energy resident in the meteor was instantly expended in several direct effects, as follows:

(1) Crushing of the rocks beneath the locus of impact. The Kaibab limestone which lay immediately beneath the area of impact must have been pulverized to dust and largely swept away in the steam and dust cloud from the violent explosion described below. The underlying Coconino sandrock was shivered to microscopic dust, and much of it was poured out over the crater rim to help form the encircling hills, also described below.

(2) Shattering of the rocks laterally, with expulsion of the rock strata surrounding the impact area. This is attested by the great volume, with huge blocks, of firm limestone which constitutes a large part of the ring of débris.

(3) Vibratory motion which shivered the sand grains of the Coconino sandstone. This is a most interesting feature which has not been sufficiently emphasized. The elevated rim of the crater, averaging 120 feet high above the plain, appearing from a distance and from the Sante Fe Railroad as a range of low hills, consists of the dislodged Kaibab limestone and the crushed Coconino sandstone. This lower formation was affected to its base and largely reduced to dust. Some portion of the kinetic energy in the colliding body was suddenly changed to short-wave vibrations which shattered the individual sand grains. The resulting dust, of angular, crystalline quartz, is of such microscopic fineness that 55 per cent. will pass a 200-mesh sieve. Masses of the rock which to the eye appear as firm sandstone will crush to powder under hand pressure.

(4) If the meteor was largely brittle material, as will be claimed below, it was also shivered. The matter of temperature applies here; also noted later.

(5) Production of intense heat. Theoretically this was inevitable. Clear evidence is found in masses of the Coconino sandstone altered by fusion to "silica glass" or lechatelierite. This required a temperature of 1,400 to 1,800 degrees Centigrade.[2]

[2] See article by A. F. Rogers, *Amer. Jour. Science*, March, 1930.

Further proof is found in rock fragments that carry brown and green stain from vaporized nickel-iron.

REACTION AND EXPLOSIVE EFFECTS

The huge crater was the product of mechanical reaction. The expulsion of rock was partly by the elastic reaction of the compressed strata with its included air, but largely from water expansion.

The sudden compression of the rock strata to a depth of 1,250 feet involved the air which was in the upper strata and the water which saturated the deeper strata.

Standing water deposits, ninety feet thick in the crater floor, consist of marl and peat of organic origin and sand and clay washed in from the basin walls by the "cloud-burst" precipitation of the desert climate. The height of the standing water in the basin shows that the strata were filled with air and water to the depth of 450 feet and below that were entirely saturated with water. As disruption of the rock reached to the base of the Coconino sandstone, 1,250 feet below the land surface, it follows that 800 feet of the porous sandrock, the affected thickness below the later lake level, supplied water for the steam explosion.

In his examination of the crater in 1892 Mr. Gilbert recognized the explosion phenomena, but interpreted them as volcanic. It may be noted that if the explosion had been from subterranean heat this would have involved the porous strata far and wide, and hot-water or fumarolic phenomena would have subsequently occurred for, perhaps, centuries.

The elastic rebound of the compressed rocks and the included air, and the explosive expansion of the suddenly generated steam produced enormous mass movement. This was the expulsion of the meteor itself and of rock material to the depth of 540 feet and over an area three fourths of a mile in diameter.

The size of the crater does not directly indicate the size of the bolide. It is a problem of two indeterminate factors, mass and velocity.

PHYSICAL STATE OF THE METEOR

The temperature of the meteor is a factor of some importance. To the degree that its internal temperature was low the mass was correspondingly brittle, whether iron or mostly stone. If the body had suddenly arrived from extra-solar space, as a casual visitor to our planetary system, it probably had very high velocity, and was intensely cold. And even if it had been aimlessly wandering with some relation to the sun it probably had very low temperature and a velocity not less than that of the observed meteors.

The violent impact which produced so great effect on the earth must have shattered the bolide, whatever its velocity, temperature and substance. If it was largely stony material, as all the facts appear to indicate, the stone was shivered to dust and swept away in a cloud of vapor, in which case only the included, nodular masses of iron-alloy are the existing remnants.

The walls of the crater have receded somewhat under the storm-wash of many centuries, and the débris has produced the talus slopes, giving the concave profile to the basin. The talus and the ninety feet of water deposits have buried any meteor fragments which fell into the basin. But many fragments of the hydrated iron, to be described, have been found in the ring of débris topping the walls. And Brandon Barringer writes that it has been found beneath the talus and against the south wall.

RELATION OF THE IRONS TO THE PARENT BODY

There is no doubt that the thousands of nickeliferous irons found over the desert were associated with the huge bolide. The question is—how did they acquire such dispersion? Were they detached companions of the main body, or are they projected fragments of the disrupted mass?

Dr. O. C. Farrington writes that some specimens of the C. D. irons in the Field Museum have surface features which prove that they fell as individual units. This would indicate that the great bolide did have some free associates, as might be expected. But the fact that the great majority of C. D. irons have irregular forms, with no surficial features produced by atmospheric friction and heat, argues for their inclusion in other material, either as detachments or as an integral part of the great meteor.

If the C. D. irons found over the desert, through a radial distance of four miles, were loose adherents of the central mass, or if they had become detached by the resistance of the earth's atmosphere, then they formed a group some eight miles in diameter. And as distinct units, with original velocity like that of the parent body, the larger ones, with weight of many hundred pounds, should have produced individual craters or pittings in the ground surface. Furthermore, if the typical C. D. irons were only non-oxidizable portions of once larger masses (as some of them certainly are) such larger bodies would have had even greater energy for production of individual craters. If the great bolide buried itself under 1,400 feet of solid rock then the detached units should have behaved in similar manner. But no such pittings of the desert have been noted. Of course, in time the "cloud-burst" storms and high winds of the desert region would obliterate the pittings by filling and such irons as were imbedded would be entirely or partially buried. But all information is to the effect that all the thousands of collected irons lay exposed on the open surface of the desert.

In this dilemma one suggestion is that the detached units did not imbed themselves but rebounded from their craters.

The iron nodules which were inclusions in the disrupted bolide, and were projected by the explosive reaction, had momentum only sufficient to carry them, like a shot from a mortar, to their positions on the plain. Fragments of the disrupted rocks are reported to lie two miles from the crater. Unfortunately, no facts are available as to the characters of the irons in relation to their distance from the crater.

PHYSICAL AND CHEMICAL CHARACTERS OF THE IRONS

The most interesting and important element in this study is the chemical constitution of the irons. Along with the typical C. D. irons there is at least one other variety. The C. D. type is the unoxidizable and resistant irons which have lain on the desert for a great length of time. They are clearly of nodular character. They generally bear no evidence of frictional passage through the air, but do have the surface features, the irregular shapes and the cavities and perforations of nuclei or enclosed accretions. They are the unoxidized and undecomposed segregations out of larger masses of vanished material. The only doubt is whether the enclosing mineral was decomposable iron or was a stony matrix.

The composition of the permanent, D. C. irons is, by percentage: Iron, 92; nickel, 6; some carbon, with minute diamonds; and small amounts of platinum, iridium, palladium, phosphorus, cobalt and copper.

Associated with the easily recognized meteoric irons was a considerable amount of limonite or hydrated iron. During early exploration this was neglected, under supposition that it was derived from the limestone of the desert surface. Barringer noted that larger fragments had a laminated structure and he called it "iron shale." Later, subspherical masses with concentric lamination were found, especially in excavations in hills of débris, and he called these "shale balls." Then it was observed that some of these masses had a green stain, and chemical examination revealed that they contained the nickel and rare elements of the C. D. irons, and, in addition, chlorine.

A specimen of the meteoric iron, supposed to be the typical C. D., in the Meteor Crater exhibit in the University of Rochester Museum in the course of years disintegrated to powder. If this is another variety of the decomposable iron or if it would have produced the "iron shale" form had it been exposed to open weather is unknown. But it emphasizes the perishable nature of some of the meteorites.

Another important discovery is that nodules of the unchangeable or typical C. D. iron are found in the shale balls. Also, that the decomposable, chlorine-bearing iron is occasionally found in the C. D. irons.

The intimate association of decomposable and of permanent iron clearly explains the cavities, holes and perforations in many specimens of the C. D. meteorites. And a similar cause is suggested for the cavities and perforations in the iron meteorites of other finds, for example, the great Willamette, in the American Museum.

THE ARIZONA BOLIDE A STONY METEOR

The doubt concerning the Meteor Crater visitor is whether it was wholly meteoric iron or was a larger body of stony composition, with iron-alloy inclusions, in other words, was the meteor of iron, with smaller size, of high density and with high velocity, or a larger body of stony substance with iron inclusions, of less density and perhaps with less velocity.

Our ignorance as to the source of meteors and comets does not justify the assumption that great masses of iron alloys, up to 400 feet in dimensions, could not exist, or are not formed in some planetary bodies or in dead suns, or that they may not exist deep within our globe. However, present knowledge of terrestrial and cosmic processes does not suggest the formation of such massive metallic bodies.

The early suggestion that the mass of the bolide might have been mostly stone, instead of metal, has been ignored because no stony material foreign to the local rocks has ever been found, although diligently sought by S. J. Holsinger, who conducted the early studies. But when we recognize the perishable nature of stony meteorites any such material should not have been expected.

The stony meteorites are exceedingly varied and complex in both composition and structure and subject to easy decay by atmospheric agencies. In consequence of this the "finds" of stony meteorites, or their discovery apart from visible "falls," are exceedingly rare. The "finds" are practically all of resistant nickel-iron. In his book on "Meteorites" (1915), Dr. O. C. Farrington states that of 350 falls only ten were of iron. But if the stony meteorites are thirty-five times as numerous as the iron, and yet quite wanting among the finds, it clearly shows their perishable nature. It may also be possible that some of the ten irons included in the 350 falls had quickly lost their brittle and ephemeral matrix before they were located.

The Arizona visitor arrived centuries and perhaps thousands of years ago, and time has been amply sufficient to destroy all the mass except the imperishable iron nodules and some of the chlorine-bearing iron.

It should also be noted that the spasmodic precipitation of the arid region has favored the washing-away of the products of decay, even if this was not all soluble. Doubtless a great quantity of pulverized rock, both limestone and sandstone, was spread widely over the plain. But this has been removed by solution and storm-wash of the torrential rains. The elevated rim of the crater prevented inwash from the surrounding desert.

All the facts concerning the C. D. irons clearly indicate that they were inclusions or nodules of resistant nature, inclosed in some kind of perishable material. And some of that matrix was chlorine-bearing iron.

The rotund or globular form of some of the "shale balls," the decomposable irons, strongly suggests that they also were only concretionary masses in a matrix of other substance. That substance could have been only the stony materials of which most known meteorites are composed. It may not be claimed that because of its greater size the Meteor Crater meteorite was entirely different in source and nature from all other celestial immigrants.

All the facts relating to meteorites in general, and the Meteor Crater bolide in particular, along with the theoretic probabilities, support the view that the Arizona visitor was a very large stony mass with metallic inclusions.

The stony matrix was brittle, even if without very low temperature, and it was shivered by the impact mostly or wholly to dust. And this was thrown high in air, and borne by the steam cloud it was disseminated far and wide, and any large fragments were quickly destroyed by decomposition and hydration.

This conclusion regarding the C. D. irons may imply that many other, if not all, of the known iron meteorites, even the largest, were originally inclusions in perishable matrix. The irregular, angular forms, perforations and characterless surfaces were probably produced by their imbedding as nodules or accretions in other materials. Only the irons which have traversed our atmosphere after losing their protective covering exhibit some frictional and flowage surfaces.

In the above study no estimate has been made as to the kinetic energy resident in the bolide, and the explosive effect has been attributed mainly to the water and air held in the rocks. But if the meteor was large, with high velocity and high density, the impact might have produced sufficient heat to vaporize both the meteor and the crushed rock. And more probably such would have been the case if the bolide was wholly or largely nickel-iron.

In such case the metallic vapor, with terrific expansion in all directions, should have coated all the surviving rocks with a green stain. The absence of such stain is another argument for a stony meteor.

If the meteor was dissipated in vapor then the thousands of C. D. irons found on the desert could not have been part of the main body. With or without enclosing matrix they had become detached from the central mass by atmospheric friction, and so far separated, and perhaps laggard, that they escaped the grand smash-up.

MICROPHONIC ACTION IN TELEPHONE TRANSMITTERS

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A MICROPHONE may be defined as a transmitter which makes use of the resistance variation of one of its elements in changing a pressure wave into an electrical one. That element, in the case of our commercial carbon transmitter, is an aggregate of loosely packed carbon granules, which is compressed between the diaphragm and the wall of a cavity in which the granules are held. Other types of transmitters operate in accordance with other principles. Bell's original transmitter, for instance, reversed the action of the present-day receiver and was electromagnetic in its action. The condenser transmitter, now used extensively in the sound picture industry, depends, on the other hand, on changes in capacitance. Neither of these types has the advantage of amplification and high energy output characteristic of the carbon transmitter, and for this reason the latter is used almost exclusively in our present-day telephone system.

Microphonic action as applied to our commercial transmitters has to do then with those physical changes responsible for variations in resistance which take place in the aggregate of granules when this is subjected to variations of stress at audible frequencies. This process is complex, and as yet there has been no experimental demonstration of the precise nature of the changes involved.

HISTORICAL

An attempt at a quantitative theory of microphonic action was made by Professor P. O. Pedersen.[1] He assumed that microphonic action occurs as a conse-

[1] *Electrician*, February 4, 1916.