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METEOR CRATER
ARIZONA

BY

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METEOR CRATER, ARIZONA

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INTRODUCTION

It is the purpose of this report to summarize some of the various theories which have been advanced, during the past 35 years, to account for the origin of Meteor Crater. To outline some of my observations regarding this phenomena of nature which has attracted scientists from all parts of the earth for many years. Efforts to exploit the meteoric mass by commercial interests in which large sums of money have been expended will be noted. Briefly it is proposed to bring up to date our present knowledge of Meteor Crater for the Park Service records and the possible interest for various members of the staff concerned.

The noted Astronomer, Arrhenius, is said to have declared that Meteor Crater is the most fascinating spot on earth. The interesting fields for investigation in this area are innumerable. Facts may be disclosed which to an astronomer might give concrete evidence as to our theories of origin and the building up of our solar system. Should the crater be definitely proven the result of a meteoric impact, the geologist will be interested to have the evidence to be found in the behavior of rocks under sudden stress, not to mention the later effects of chemical reactions underground. From the point of view of the physicist and chemist the various features prove none the less interesting. The average visitor stands in amazement when the great pit is viewed from the rim for the first time.

LOCATION

Meteor Crater is situated in Coconino County, northeastern Arizona, in the southern portion of the Colorado plateau, amid many National Parks and National Monuments which have been reserved for preservation by the Government. The crater may be reached on U. S. Highway No. 66 by traveling 23 miles west of Winsow and thence seven miles southeast. The loop road south to the crater is taken at the Sunshine station on the main highway. The feature is most accessible to transcontinental tourist travel, being located near one of the main highway routes through the Southwest. Stops may be made and visits arranged for at Winslow or Flagstaff situated on the Santa Fe Railroad.

METEORS AND METEORITES

Very few meteors reach the Earth's surface as meteorites and still fewer meteorites give rise to meteoric craters. Meteorites, as is known from studies of those that have been seen to fall, are bodies which before their striking the Earth were pursuing independent orbits around the Sun, usually in an elongated form similar to comets. Their velocity averages around 26 miles per second and with the Earth moving 18 miles per second in its own orbit, the meteorite can strike at any speed from eight miles per second if it overtakes us, to 44 miles per second if it meets us squarely. At even the lesser speed the meteorite is subject to great friction as soon as it enters the Earth's atmosphere, some 80 to 100 miles distant, which heats the surface of the body and the air about its track. Small meteors appear as shooting stars and large ones as fire-balls.

A few of the most important meteoric craters thus far discovered are listed as of possible interest.

The Texas crater is situated about nine miles southwest of Odessa in Ector county. It is a shallow depression, roughly circular in outline, with an average diameter of 530 feet. The steep inner slopes show the limestone dipping 20° to 30° away from the center. Fragments of meteoric iron have been found and some have been located mixed with the limestone and sandstone debris forming the rim. Although this crater is now generally recognized to be of meteoric origin, various suggestions have been made to account for it; namely, - volcanic explosion, salt dome, expansion by hydration of anhydrite, explosion of gas, etc.

The Henbury craters in central Australia are located about seven miles southwest of Henbury, on the Finke river. Much meteoric iron has been collected from this area and within an area of a half square mile 13 craters have been mapped. The largest crater is 220 yards by 120 yards across, and 50 to 60 feet deep. In this area there must have been not a single mass, but a shower of large masses of iron that formed this group.

The Wabar craters, discovered in 1932, are located in Arabia. Two distinct craters have been ma pped with the indications of others buried in the sand. The larger of the craters is approximately circular in outline, has a diameter of 100 meters, and a depth of around 10 meters. The rims of the craters appear to be built up mainly by silica-glass. A few pieces of meteoric iron have been collected from the outer slopes of the craters. It has been suggested that the reason for the unique occurrence of silica-glass is no doubt that large masses of iron fell on clean desert sand.

The group of craters in Estonia, 20 kilometers northeast of Arensburg, were first described in 1827. They have been considered as being earthworks made by man, to be the result of gas explosions, oozing out of a bed of clay, weathering of limestone, expansion of anhydrite, but recently detailed borings and trenches undertaken by the Inspector of Mines, has resulted in their being identified with the fall of a shower of iron meteorites. The main crater is occupied by a lake, with a diameter of 92 by 110 meters, and depth of 15.5 meters. The steep inside walls show beds of Silurian dolosite dipping from the center of angles of 30° to 40°.

No meteoric iron has been found in the locality and this is explained by the fact that the ground has been tilled since time immemorial.

The Siberian craters are said to be rather disappointing, showing only a series of small pools in a swamp. It is certain that some catastrophic event occurred there on June 30, 1908, but the exact nature remains doubtful. It is stated that a fireball had been seen and that loud explosions were heard over a wide area, blasts of hot air were felt, and earthquakes recorded at several points. Pine trees were felled outwards for a distance of 37 miles from the center. Numerous round depressions have been found in a swamp area but no meteoric iron has been collected, although it is rumored that natives have collected pieces of iron in the central area of the fallen forest.

The Campo del Cielo craters of the Gran Chaco, Argentina, are now considered meteorite craters. Native iron has been known in this district since 1576. Transparent glass has been found. There are no volcanic rocks in the surrounding pampa, and the Andean volcanoes are 500 miles away. One of the craters has a width of 183 feet and a depth of 16 feet.

Direct observation as to how the larger craters are formed seems to be out of the question. Meteorites which have been seen to fall have been comparatively small in size. They make small holes usually only a few feet in depth. The largest meteorite which has been observed to fall is of the stony type, which weighed 820 pounds, and fell near Paragould, Arkansas, in February 1930. This stone penetrated the soil to a depth of only eight feet. The largest known iron meteorite is the Hoba meteorite, discovered protruding from the surface in Southwest Africa in 1920, and weighing 60 tons. It was not seen to fall and there is no sign of a crater in the vicinity.

GEOLOGY

The surface geology of Meteor Crater and vicinity is comparatively simple. The sediments of the surrounding region lie practically horizontal and as the crater is approached, the beds may be seen to dip away from the center in all directions, at angles of from 10° to 80°. One is astounded by standing on the rim and peering into the high crater for the first time. The irregular rim of up-thrown rocks rises over 150 feet above the surrounding plain. The main portion of the rim is more than 1,000 feet in width with scattered remnants of debris as much as six miles from the crater. The floor of the crater is flat and is approximately 1,500 feet across. The elevation at the cabin on the north rim is 5,860 feet above sea level.

The upturned sediments of the rim consist of from 0 to 60 feet of Moenkopi (Triassic) sandstone; around 250 feet of Kaibab (Permian) limestone; and 150 feet of Coconino (Permian) sandstone. From the drill records a total thickness of the Coconino sandstone is given as 660 feet.

Below the Coconino sandstone is the Supai formation, also Permian in age, and from records of drill holes and sections in surrounding region it is believed to be around 1,000 feet in thickness. It is also assumed from drill hole records that the Supai was apparently not disturbed by the forces responsible for the crater.. The Redwall limestone, of the Mississippian, underlies the Supai formation. For a generalized stratigraphic section see following:

STRATIGRAPHY OF THE METEOR CRATER AREA

ARIZONA

SYSTEM	SERIES	FORMATION	THICKNESS (FEET)	CHARACTER
CENEZOIC	RECENT AND PLEISTOCENE	LAKE BEDS, ETC.	90 to 500	Lake beds containing some lignite, fresh water fossils and thin bed of rhyolitic ash. Talus consisting of sand, gravel and boulders. Limestone and sandstone blocks representing material thrown out of the time of the impact. Some meteoric fragments found in debris.
MESOZOIC	TRIASSIC	MOENKOPI	0 to 60	Chocolate brown sandstone
CARBONIFEROUS	PERMIAN	KAIBAB	250	Grey limestone with some thin sandstone members.
		COCONINO	660	Light colored cross-bedded sandstones.
		SUPAI	1000	Uniformly red to buff sandstone and red sandy shales.
	MISSISSIPPIAN	REDWALL		MASSIVE, Grey, fossiliferous limestone.

The masses of rock which are upturned consist in the main, therefore, of Permian sediments with the exception of a variable thickness of thin

Moenkopi outliers. There is observed on the rim much debris and fragmentary rock materials which have been classified as Quaternary in age. Comprized in this group is the meteoric shale, meteoric rock fragments of the original formation, and metamorphosed masses of Coconino sandstone (rock flour). On the floor of the crater is some recent stratified rocks, consisting mainly of crushed limestone and sandstone fragments, which have been identified as lake beds, indicating that the interior was once occupied by a lake, at a time when the climatic conditions of the region were much humid than at present. These lake beds are around 90 feet in thickness and are considered to be of Pliestocene age. They contain fresh water fossils.

The crater rim is capped by material thrown out of the crater. Land slides along the rim have removed portions of the Kaibab limestone and Coconino sandstone. Limestone and sandstone blocks are present on and surrounding the rim. They range from small fragments and fine dust up to 25 feet or more in thickness. Most of the coarser material is limestone since the sandstone is more easily crushed.

Regionally the rocks lie nearly horizontal with dips of only a few feet to the mile. Angles of dip along the rim of the crater vary from 10° to 80° with an average perhaps of around 30°. The dips are all in rough radical fashion from the center of the crater and has been stated previously, they become increasingly greater from a point on the north rim, until the arched portion of the rim at the south is reached. A dozen or more faults may be seen on the inner walls of the irregular rim but due to the debris they cannot be traced to any extent. The regional structure is broken by Sunshine mountain, 12 miles southeast of the crater.

AGE OF THE CRATER

D. M. Barringer, Jr., has considered briefly the age of the cone. He states that it cannot be less than 700 years old, since a cedar tree with that number of annual rings was found growing on the rim. He also concludes that it cannot be more than 5,000 years old, from the lack of erosion, particularly of the chemical erosion on the limestone blocks, and finally infers that the true age will no doubt be found between these two limits. Mr. Barringer mentions the legends of the Navajo Indians, who are said to have a story about the crater which coincides very closely with what actually occurred. A hole in the ground would not likely stir the imagination of the Indians, since they are familiar with the many volcanic craters of the San Francisco mountains, 50 miles or so away, and attach little importance to them. But about Meteor Crater they are said to have marked superstitious beliefs, and they are supposed to have a legend which describes the descent of one of their gods from the sky, in clouds of fire, to bury himself in that particular spot. I do not attach much weight to such traditions among the Indians since it is generally considered as improbable that legends could be carried down for more than a few centuries by such primitive people. Professor Elihu Thompson (29) mentions these Indian legends which state that a number of their tribe were killed when the body fell and that they now send to the crater and secure the white silica dust to sprinkle around when they have their ghost dances, indicating that they still retain some superstition in regard to this natural phenomena. Mr. Barringer states that the Indians will not carry away any of the iron, however, I have been informed from other sources that there was quite a traffic in this material for many years and that tons of it was collected by the Indians and sold to traders.

On the basis of the effects of erosion Tilghman favored an age of not more than 10,000 years and probably less than 5,000 years for the crater.

According to the geologist attached to the geophysical survey the age of the crater is estimated at 50,000 years. This figure was arrived at upon consideration of the sedimentary deposits, conditions for deposition of same in arid climatic regions, is recognized as an extremely slow process. The proof of a very considerable period of erosion.

The most exhaustive study of the age of the crater which has come to my attention was made by Professor Eliot Blackwelder (7) in 1930. He lists five factors which have a bearing on the determination of the age of the crater as follows:

(1) - The lake deposits at the bottom of the crater, shown by drilling to be from 70 to 90 feet thick, comprise stratified sand and quartz flour with many lacustrine gastropod sheels and diatom frustules. This is interbedded with platy fresh-water limestone, lignitic beds, diatomite and a single layer of rhyolitic ash $\frac{1}{4}$ to 3 inches thick (12). The characteristics of the deposit are such as to indicate a body of water of many years duration, rather than a seasonal pond of playa. This in turn suggests a climate distinctly cooler or more humid than the present one, for there has been no pond in the crater since it first became known to white men. At present the water table is about 200 feet below the floor of the pit, whereas during the presence of the lake it must have been somewhat above it.

(2) - The bed of volcanic ash is plainly the record of an explosive eruption in the southwestern arid region. No such eruption (rhyolitic ash) is known to have occurred since late glacial or Pleistocene times.

(3) - Both upon and beneath the lake beds are wedge shaped alluvial deposits built out by streamlets descending the crater slopes. The lower fans are said by Tilghman (3) to extend under the lake deposits, although not to the center of the crater, as indicated by exploration in shafts and drill holes.

(4) - Most of the limestone blocks upon the parapet are deeply cavernous and corroded by the effects of solution. As this process works rather slowly in an arid climate, the advanced stage of solution pitting indicates a long period of time. A study of the ravines and graded valleys on the parapet indicates that the latter has suffered more erosion than the latest (Tioga) glacial moraines, but hardly so much as those of an older epoch.

(5) - As a fifth source of evidence, the present condition of the talus slopes within the crater affords instructive suggestions regarding the physiogrphic history. A close scrutiny of the talus shows that it is no longer growing but has extensively eroded into a series of ravines between which a few wedge-shaped remnants of the talus still remain. The talus is therefore the product of an earlier age, long since past. It is a well known fact that talus formations is particularly favored by the wedge work of ice (frost action) and that aridity tends to prevent it.

Dr. Blackwelder summarizes his points by stating that it seems very significant that the evidence along these five independent lines points to a long period of atmospheric action and also rather definitely to climatic changes from warmer and drier to colder and moister and back to dry again. From these considerations he is led to suspect that the crater was made during the last interglacial (or Post-Tahoe) epoch, perhaps 40,000 to 75,000 years ago. He concludes that no finality can be claimed for this estimate, but as a counterbalance for the current view, that the crater is only a few thousand years old, it has considerable value.

CANYON DIABLO METEORITES

It has been stated by Mr. Barringer that a far greater number of iron meteorites have been collected from the debris around the crater rim and a short distance from it than have been found in all the rest of the Earth's surface. By looking over a map showing the distribution of some of the material collected up to 1908 one cannot fail to be impressed with the concentration of meteorites as the rim is approached. This fact alone, it seems to me, presents some evidence that there is a connection between the meteoric material and the crater.

But how do we know that this is meteoric iron? All of the meteorites collected give what is known as the Wiedmanstatem figures, that is if they are etched, they will show after smoothing a peculiar internal crystalline structure which is characteristic of those iron meteorites which have actually been seen to fall upon the earth's surface. Iron meteorites are so unlike the normal rocks of the Earth's crust that they are easily recognized.

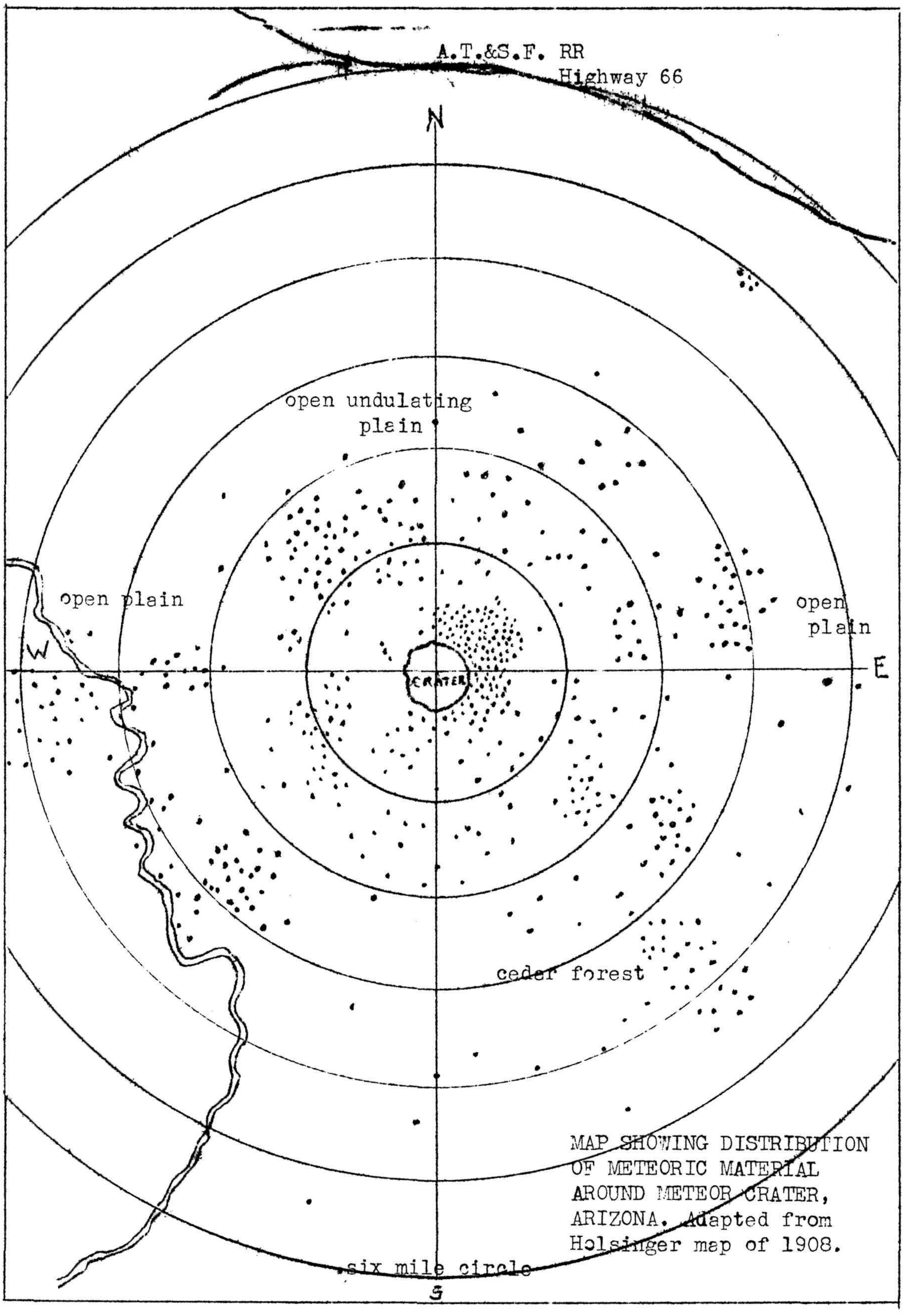
Mr. Barringer gives this description of the meteoric material found at or near the surface in the vicinity of Meteor Crater. The chunks of solid nickel-iron, known as Canyon Diablo meteorites and which may be observed in most of the large museums, are irregular shaped fragments of metallic nickel-iron, with the surface, which is characteristic of many iron meteorites, looking as though thum-prints had been made all over it when it was soft. When cut they reveal a bright, silvery surface, which will rust only very slowly if at all. If the surface is etched, the so-called Wiedmanstatom figures of crystallization may be plainly seen. The composition of the unoxidized fragments is roughly as follows: iron, 92%; nickel, 6%; carbon, (both crystalline and amorphous) phosphorus etc., 2%; cobalt, copper, etc., traces; platinum, iridium, palladium, etc., about four-tenths of an ounce per ton. The pieces so far discovered range in weight from less than an ounce to about 1,400 pounds.

Dr. L. J. Spencer (26) considers a point of interest about the Canyon Diablo irons in the presence in some of the masses of small diamonds, both black and white; and it is stated that doubtless this observation suggested to H. Moissan his experiments on the artificial production of diamonds. Moissan also detected in the iron the presence of native carborundum (silicon carbide), which as a meteoric mineral has been named moissanite. Other rare constituents of this meteoric iron are platinum metals. One assay yielded platinum 3.65 and iridium 14,95 grams per metric ton, but some other later trials gave negative results.

There has been much speculation as to the magnitude of the meteor which would be required to form a crater of this size. One of the first methods of calculation used by the Barringer interests and suggested in an old handbook of artillery, was to a formula for computing the probable effect of bombarding masonry with round-shot. This formula stated that where the diameter of the shot was 1, the depth of the hole would be about 2, and the diameter of the hole about 7. Applying this to the observed features of the crater it was estimated that the diameter for the projectile would be around 550 feet.

Tilghman (3) has calculated that the debris now represented in the parapet would, if replaced in the crater, fall short by millions of cubic yards, of filling the cavity. The difference may well have been removed by erosion. Gilbert (16) has estimated the capacity of the crater at 82 million cubic yards. Dr. Elihu Thompson and Dean Magie of Princeton have made a number of calculations, considering the speed of the projectile, the amount of work involved in throwing out of the hole some 350,000,000 tons of rock, and arrived at a somewhat smaller figure for the diameter of the projectile than that calculated by Barringer. The latter concluded that a sphere about four hundred feet in diameter, which is probably a conservative estimate, would weigh in the vicinity of 10,000,000 tons.

Professor Thompson (29) makes the following calculations, - assuming that one ton of material in the meteor was capable of displacing thirty tons of rock when it struck, then the mass of the meteor should have been



MAP SHOWING DISTRIBUTION OF METEORIC MATERIAL AROUND METEOR CRATER, ARIZONA. Adapted from Holsinger map of 1908.

approximately at a low estimate, say, five million tons. By using a figure of six-tenths of an ounce of platinum and iridium per ton, with an estimate of three million ounces, at a value of $30 to $35 per ounce, the total value would be in the vicinity of $100,000,000. Various estimates of this type have been made and there is little wonder that extensive exploration work has been undertaken to locate the ore body, for this would represent only one of the valuable constituents of the mass, as indicated by assays.

HISTORY OF EXPLORATION "METEOR CRATER"

Army scouts first visited the site of Meteor Crater in 1871 and called it "Franklin's Hole". It was 15 years later that Mexican sheep herders gathered some of the metal and gave it to railroad contractors, who in turn sent it east, where it was identified as meteoric iron. Thus the first known example of a supposedly meteoric crater was discovered. Thousands of specimens of the meteoric iron were collected and shipped to museums in all parts of the world as well as to other interested parties. "Canyon Diablo" meteorites, as these fragments have been called, range in weight from a few grains up to 1,400 pounds. It has been stated that more iron meteorites have been found in this locality than have been discovered thus far in all of the remainder of the Earth's surface. The circular ridge forming the crater rim, which may be observed as a range of low-lying hills for miles around, had been referred to as "Coon Butte", "Crater Mound", "Meteor Butte", "Crater Mountain", but it is now generally called "Meteor Crater". The meteoric iron which is supposed to exist beneath the crater, and which has been found in large quantities in the vicinity, has been called the "Canyon Diablo meteorite", from the Canyon Diablo nearby, and also the "Barringer meteorite" from the Barringer family, who have been interested in exploration for many years.

In 1903 Mr. D. M. Barringer, of Philadelphia, became interested in the commercial prospects of the locality, and was among the first to advocate the theory of meteoric origin. Briefly Mr. Barringer and his associates reasoned as follows, - as one approached the crater the amount of meteoric iron became greater and it was also noted that the size of the fragments increased in this direction; that the fragments of metallic iron and pieces of iron oxide (which by their structure and composition was considered to have been derived from terrestrial oxidation) were found to be intimately admixed with the material excavated from the hole - the conclusion being that the excavated material and the meteorites got there at the same time. They likewise assumed that the hole was made by a meteorite or a cluster of meteorites, or else the juxtaposition of the hole and the meteorites was accidental. If accidental, there remained the coincidence of an unprecedented fall of meteorites hitting the same spot on which suddenly appeared an unprecedented crater in the sedimentary rocks, and hitting it at the same instant of time in which the crater was made. Prominent scientists who critically examined the locality and agreed to the meteoric origin as advanced by Mr. Barringer were Professor Elihu Thompson, of Boston, and Dean William F. Magie, of Princeton.

Mr. Barringer interests at first reasoned that since the hole was round, the meteorite must have fallen vertically, and therefore the main mass must be in the center of the hole. On this assumption they started a shaft at the center and expected to run radial drifts, like the spokes of a wheel, after reaching the required depth and until such time as they encountered the main mass. They assumed that the meteorite had not penetrated more than 1,300 feet below the surface of the plain since none of the fragments of Red Beds, which lie around this depth, had been thrown out of the crater. At 200 feet they encountered soft Coconino sandstone, which had been so shattered by the impact as to be in the form of fine white dust, so fine that 55% of it would pass through a 200 mesh screen. This silica dust had become mixed with water from the rather large catchment area of the crater and formed a quicksand through which they were unable to drive their shaft.

They next proceeded to sink drill holes in the bowl of the crater in an effort to locate the meteoric mass. The central portion was explored by this method to a depth of 1,000 feet. Although they failed in the main purpose of the work some interesting facts regarding the crater were ascertained. To a depth of some 90 feet there occurred stratified lacustrine sediments. Below this depth and for a distance of six or eight hundred feet there was encountered a jumble of large and small fragments of limestone and sandstone (unstratified), which was considered to be material thrown into the air at the time of the impact, immediately falling back into the hole. Two types of metamorphosed Coconino sandstone were found in the drill holes. The first type, which is also found on the rim of the crater, appeared like unaltered sandstone. Upon close examination, however, it was found that nearly every individual sand grain had been cracked and shattered so that it could be rubbed to dust between the fingers. The conclusion was that a shock wave, of sufficient intensity to crack the sand grains, ran through the solid rock ahead of the impacting meteorite. The second type of metamorphosed sandstone was considered to be due to heat caused by the friction of the advancing meteorite. The heat was so intense as to fuse the silica and it was stated that the only other case known in nature of pure silica being melted without a flux, occurs when lightening strikes a bed of sand, producing folgurite glass.

According to the Barringer interests the two types of meta morphosed sandstone presented additional proofs of the meteoric theory. The shattered sand grains show the effect of a sudden terrific blow, rather than the effect of any volcanic explosion. The millions of tons of finely pulvarized sandstone (rock flour) which is found abundantly on the rim in the crater and in the drill holes could not have been produced by a steam explosion. Likewise it is stated that no volcanic action has ever been known to fuse pure silica.

At depths of around 800 feet the drill holes were said to have encountered unaltered "Red Beds" sandstone. This gave them a clew as to the maximum depth at which the meteorite must lie buried and also presented additional proof that whatever caused the crater came from above and not below. The work was suspended in 1908, since the drill holes failed to locate the whereabouts of the meteorite, and most of the funds available for the search at this time had been exhausted.

An intensive study of the physical features of the crater was then undertaken by the Barringer interests with the hope of finding some clue as to the direction of approach of the meteorite, since from the results obtained by explorations to this date, the evidence seemed to point that the meteor had not fallen vertically at all. They observed that by firing a rifle into mud an excellent replica of the crater could be made, that the rifle need not be fired in a vertical direction downward, but that it might be held at an angle even less than 45 degrees from the horizontal. A detailed study of the walls of the crater finally revealed what was considered an important fact. The rocks exposed in the walls were seen to dip radially away from the hole and it was observed upon plotting these dips that their magnitude increased rapidly until a point on the south rim was reached. They then reasoned that as the southern portion of the rim was approached the projectile was plowing deeper and had therefore bent back the rocks more steeply on either side, with its lifting force eventually spent, the mass was lodged in the southern sector. Factors tending to strengthen this theory were given as follows, - the north rim is lower than the south, which is due in part to the lower dip of the strata, but chiefly due to the fact that far less volume of excavated material has been deposited on the north; the amount of ejected material increases progressively towards the south, on both sides, until the greatest volume is found on the southern rim, where the greatest arching and uplifted strata appears.

Due to lack of funds, the theory of oblique approach of the meteorite, was not acted upon until 1920. A churn-drill hole was then sunk on the southern rim, as near as possible to the center of the great southern arch, and after many difficulties the drill eventually reached a depth of 1,376 feet where it became permanently stuck. At a depth of around 1,200 feet it was stated that small fragments of oxidized meteoric material were found mixed with the shattered sandstone. As the hole was drilled deeper this material increased rapidly in quantity until it composed about 75% of the mass and in all respects it answered the description of the oxidized meteoric iron found at or near the surface. It was assumed that it would have been impossible for a small amount of this material to drive itself to this depth in the rocks had not a much larger mass have plowed the way for it. It was considered almost certain that the drill had at last encountered the main mass of the meteorite. Since the mining company had greatly exceeded the estimated cost of drilling the hole and were unwilling to go to further expense, they abandoned their lease at the termination of the drilling in 1924.

Besides the interest of the Barringer family in exploration up to this time the Standard Iron Company, the United States Smelting and Refining Company, the Mining Exploration Company had been ass ociated with various projects to discover the meteorite. In 1927 another company, the Meteor Crater Exploration and Mining Company was organized, obtaining a long-term lease on the 2,369 acres formerly owned in fee by the Standard Iron Company.

GEOPHYSICAL SURVEY

The Meteor Crater Exploration and Mining Company who I am told now own the lease, instigated a geophysical survey of the area by the International Geophysicists, Incorporated, of Los Angeles, in October, 1930. It was stipulated that independent surveys were to be made by three different groups of their staff and that separate reports were to be submitted by each group. A geologist examined some 1,000 acres at Meteor Crater and vicinity; the Magnetometer party, consisting of three members, surveyed some 5,000 acres; and the electrical survey party, of two members, reported on 700 acres. The details of the various surveys was presented in a paper by Mr. J. J. Jakosky (17) at a meeting of the American Institute of Mining and Metallurgical Engineers in New Y ork City. While I have not had an opportunity as yet to review this paper, Mr. George M. Colvocoresees, general manager of the Meteor Crater Mining and Exploration Company, of Phoenix, Arizona, kindly permitted me to read a copy of their formal report. The objective of the geophysical survey was to obtain information about the origin of the crater, the advisibility of continuing with exploration work, and if the latter was to be undertaken the location where such exploration w ork should be directed.

The factors governing the choice of geophysical methods were as follows: (2) The electrical conductivity of the unoxidized meteoric material was over a million times greater than the surrounding country rock. If sufficient quantities of this material existed underground the electrical studies would indicate its presence (assuming no other electrically complicating factors) by a decrease in the effective resistivity. (b) The magnetic permeability of the unoxidized meteoric material was also over a million times greater than the surrounding sedimentary series and should cause a magnetic anomaly if the material existed in sufficient amount at its depth, and again assuming no complicating magnetic factors.

In the magnetometer survey two factors were watched closely, - (1) anomalies which would indicate presence of meteoric materials; (2) anomalies which would be caused by an igneous intrusion or any change in the basement complex. This data was later desirable in connection with the possibility of a steam explosion being the cause. Should such a steam explosion have occurred, its origin and source would probably be indicated, by magnetic anomalies associated with deeper structural effects.

From a study of the results obtained in the magnetometer survey it was concluded that the crater is of meteoric origin in view of the following:

(1) Magnetometer work does not show a change of regional gradient which would account for a buried igneous mass from which the steam might have emanated. (2) If the steam explosion were the cause one would expect some evidence of hydrothermal action which is not in evidence. (3) It is doubtful that, in a steam explosion, temperatores, sufficient to account for the formation of Le Chatelierite (1625° Centigrade) would obtain. (4) The intimate association of meteoric fragments with the ejected debris is undisputable evidence. (5) The fact that previous magnetometer surveys did not show anomalies due to the buried meteoric material has long been cited by those favoring the steam explosion theory. This was because their instruments w ere not sufficiently sensative and also because such work was not carried out in sufficient detail to allow differentiation between regional gradient, increases anomalies due to a buried mass, decreased anomalies due to pulverizing and shattering of the fill material, and topographic attitude effect.

The results of the electrical work were as follows: (1) The water level inside the crater (about 180 feet beneath the present dry lakebed) and level outside the crater about 550 feet below the level of the plateau are of the same elevation. (2) A well defined electrically conductive area occurs in the southwest quadrant of the crater. This calculated to be caused by two factors, (a) a deeper fragmatized or shattered zone underneath the area, and (b) such meteoric fragments as may be mixed with the field material in this zone. This zone is the area wherein all future exploration efforts should be directed. (3) No such area exists in any other part of the crater. (4) Sub-surface structural conditions are quite uniform through the crater area. (5) The crater is undoubtedly of meteoric origin. (6) The electrical effect would be classed as moderate to fair.

Briefly the geological report considered the crater to be formed by the impact of a meteor or a swarm of meteoric material. The possibility of a steam explosion is not probable. The age is estimated at 50,000 years. The latter figure is arrived at since there is a series of sedimentary deposits originating in arid climatic conditions, under which conditions of sedimentation is recognized as an extremely slow process. The record in these beds of a volcanic disturbance in the vicinity, probably at Sunshine mountains. The proof of a very considerable period of erosion. From a geological study of the crater there appears to be foreign material in the southern portion of the crater.

By way of summary the magnetic survey pointed to the presence of an area of continuous magnetic material in the southern portion of the crater, at depths of 200 feet and more, with concentration probably increasing with depth. By this method it was regarded that the mineralized area appeared to be as much as 600 feet in length and possessing appreciable depth and breadth. The electrical survey indicated the presence of an area of high conductivity in the southwest quadrant, between the center and the rim of the cone, at a depth of approximately 700 feet. That the original and altered material found in the area indicated that the zone of higher conductivity cannot be due to rocks in place, or to their products, or to fill material. The conclusion advanced by this group infer that the material is almost certainly of metallic character. The geologist observed that the regional conditions are more or less simple, with flat sedimentary beds lacking in igenous intrusions or structural deformation, except local faulting caused by the impact. It was concluded that the absence of such complicated factors were indicative of the presence of meteoric material. Evidence warrants drill-hole exploration and five tests are recommended. The general location of the areas within which magnetic highs was located, agrees with the locations obtained in the electrical surveys, wherein a higher conductive zone was found. The magnetic high is also in the same general area as the location obtained from geologic data.

The results of the geophysical work are not considered sufficiently definite, in view of the complicated factors involved, to warrant calculations or predictions regarding the tonnage or mass of material which may be present. The chief result of the work has been to definitely delineate the area wherein future development work should be concentrated.

DRILLING OPERATIONS

Many trial shafts, six or more in number, and some 25 test holes have been put down in an effort to locate the meteorite. The results obtained in the deepest test hole, which reached a depth of 1,376 feet, have been described. Mainly upon the recommendations of the geophysical survey, the present management, the Meteor Crater Exploration and Mining Company, in the last few years made another attempt to locate the supposedly buried mass. Since considerable difficulty had been encountered in previous tests due to pulverized material and debris it was decided to sink a 1,500 foot compartment shaft, on the south rim of the crater, outside of the crater and then cross-cut to the location of the main mass as determined by geophysical methods. This shaft reached a depth of 713 feet. Large amounts of water, 1,000,000 gallons per day, were encountered at around 650 feet from cracks and fissures in the Coconino sandstone, and the operation had to be abandoned at the above depth. Some have suggested that it might be possible to cut an underground tunnel for the transportation of this water to the Salt River valley some hundred miles to the south, however, we are interested to know that work on this venture has not started as yet. It is stated that approximately $600,000 have been expended in efforts to exploit Meteor Crater up to the present time. No work is being carried on at present. The Mining Company has a custodian of the crater to show visitors around for which a fee of 25 cents is charged. An observation tower has been erected on Highway 66 recently and is called the Meteor Crater Observatory. True little can be observed from this point.

THEORIES AS TO ORIGIN

As may be seen from the partial bibliography at the end of this report, the literature has contained many articles on Meteor Crater during the past 35 years. While I do not mean to imply that I have read all of these references I have perused many of the more recent ones and there seems to be only two real theories as to origin, namely, meteoric or volcanic. The limestone sink idea has been well disproven as will be noted from the following page.

Meteoric Theory of Origin

The Meteoric theory for the origin of the crater which was first propounded by Ballinger has since been agreed to by G. P. Merrill (19); J. J. Jakoski (17); Elihu Thompson (29); L. J. Spencer (27); C. L. Longwell (18); Eliot Blackwelder (7); H. N. Russell (25); C. O. Lampland (30); H. S. Colton (31); and others. Some have argued that the meteorite was in the form of a single projectile and others that it was a swarm of meteoric material but all consider the crater the result of a meteoric impact of some sort. There has also been some disagreement among the above writers as to whether there was an explosion accompanying the impact. Most of the authors seem to favor the idea of an explosion.

Some of the main ideas advanced which tend to prove this supposition are as follows:

1. The actual presence in the debris around the rim and for miles around of much meteoric iron. The fact that concentration of this material increases as the center of the cone is approached. That the meteorites, admixed with the debris, must have had something to do with the formation of the crater or else they must be assumed to have fallen at exactly the same time and precisely the same spot on which a crater was being moulded, however formed. Such a double coincidence they contend would be next to a physical impossibility.

2. No evidence whatsoever of volcanic activity has been noted in the immediate vicinity of the crater.

3. Borings show that the crater is filled to a depth of about 700 feet with debris shattered by the original disturbance. The sandstone has been crushed to powder or "rock-flour" and some has undergone fusion, indicating a temperature of around 1,500° Centigrade. The temperature of a steam explosion which may have accompanied a volcanic intrusion, as inferred by the opponents of meteoric origin, would not be high enough to produce the silica-glass.

4. The structural features of the crater, the dip of the strata, with notable increase in dip towards the arch on the south rim, seems to be of considerable significance, with such an arrangement not probable.

under volcanic origin.

5. The results of the geophysical survey as conducted by three independent parties have been detailed on the preceding pages and they all point to a meteoric impact.

6. The argument that to date no meteoric mass of any size sufficient to have produced the crater has been located and that therefore it could not be meteoric in origin, means no more than the assumption that there are no oil pools in certain areas because of the fact that many dry holes have been drilled, or that there are no commercial ore deposits in certain localities since much prospecting has been undertaken.

7. If the crater were formed by a steam explosion from hot solutions or gases coming from underneath the present sedimentary strata then there should be evidence of hydrothermal action. Also from the results of borings and geophysical work it was observed that the underlying Supai red beds are in undisturbed position.

Volcanic Theory of Origin

The theory that the crater was produced by a volcanic steam explosion in the Coconino sandstone was first advanced by Gilbert (16). He arrived at this conclusion since the feature is in the midst of an area of volcanic activity, with many recent volcanic cinder cones at no great distance, and its similarity to these latter features. But there is no evidence of volcanic activity at Meteor Crater such as is present at these other localities. I have been informed that Mr. Gilbert leaned toward the theory of meteoric origin prior to his death although he refrained from publishing anything in this regard. Darton (10) has been one of the few prominent scientists in recent years to hold to the theory of volcanic origin and the writer is frank to admit that he does not present much evidence in support of same. It is most certainly difficult to conceive of huge chunks of limestone being blown for miles around the crater, and to visualize the force involved in such a blast, with no semblance of volcanic rocks left behind. I might add also that the surrounding countryside has been pretty well looked over in search for meteorities.

LIMESTONE SINK THEORY

In Science, Jan. 9, 1931, Mr. F. S. Dellenbaugh (11) suggests that the great pit of Meteor Butte is a sink formed by ground water solution in the Kaibab limestone. The geologic facts as enumerated by Mr. Chester H. Longwell (18) disprove Mr. Dellenbach's theory conclusively. The former agrees that the Kaibab limestone of this region contains many sinks, which receive much of the drainage of the Kaibab plateau, but states that it would be a wonder indeed to find in a semi-arid country a sink, almost circular in plan and nearly a mile in diameter, occupying the entire top of a hill, where the only water available for solution consists of the scanty rain that falls directly on the area of the pit. Meteor Butte is a hill with the ground sloping away from the very edge of the rim on all sides and hence no outside drainage can enter the depression. Mr. Longwell mentions further the following points which are considered sufficient to remove the sink hypothesis from consideration, -

1. A limestone sink does not reach deeper than the base of the soluable formation in which it is formed. The Kaibab limestone here forms less than half the height of the walls. Beneath the Kaibab is the Coconino sandstone which is one of the most insoluable rock formations known. Any suggestion that the Coconino sandstone may have been caved owing to solution directly beneath it is ruled out, because the sandstones rest on red shales and sandstones many hundreds of feet in thickness.

2. At the top of the pit the slopes on all sides are littered with fragments of the Coconino sandstone. These fragments range in size from minute bits of broken sand grains to blocks of large size; and they are mixed with similar debris derived from the Kaibab limestone. How were these pieces brought up from their normal position hundreds of feet below? Obviously by a great force that acted upward and was explosive in character.

3. Although the rock strata are practically horizontal beneath a wide surrounding area, in the walls of the crater these strata are tilted and otherwise disturbed. On the south side, where the wall is steepest, the beds dip directly into the wall, at a high angle. There is no haphazard arrangement, such as would be expected if the disturbance were due to slumping into a solution pit. The tilt is consistent in direction and indicates that a powerful lifting force acted inside the pit, with concentrated action on the south side.

4. In places the quartz sand in the Coconino sandstone forming the lower part of the walls has been fused to glass (lechatelierite). This is astonishing in view of the high melting point of quartz (nearly 1500° Centigrade). Evidently the crater has been subjected to intense heat, such as could be generated only in an exceptional way.

Mr. Dellenbaugh sees support for his hypothesis in the fact that both inside and outside slopes of the crater show effects of erosion. Whatever its origin, the crater has been outdoors since its formation, and modification of its slopes by erosion has been inevitable, the fate it shares with every other landscape feature.

CONCLUSIONS

The writer has conversed with numerous geologists, astronomers, mining engineers, and has communicated with geophysicists who are familiar with and have examined Meteor Crater. After reviewing many of the various theories advanced to account for the origin of the crater and after studying the situation on the ground I can see no other solution than that it was formed by a meteoric impact. I was skeptical at first due to the fact that to date, despite many years of work in exploration, no large mass of meteoric material has been found buried in the crater. But this does not alter the fact that more meteorites have been found outside of the crater than have been discovered to date in all the rest of the earth's surface. As the crater is approached the meteorites are more concentrated and some of them have been found mixed with the debris on the rim; therefore, if the crater is due to some cause other than meteoric impact it must have been formed at the identical moment that a mass of meteorites struck the spot. With the world for a target and in consideration of the time element it does seem that such a double coincidence would be improbable. Than there is the matter of intense heat which fused the sandstone, the large blocks of limestone scattered for miles around the crater, the arrangement of dips along the rim becoming increasingly greater at a point on the south, not to mention the general form of the crater with no evidence of volcanic activity it now appears that practically all of the real evidence points to meteoric origin. The concensus of opinion of most of the leading scientists is that the crater is the result of a fall of a meteorite.

Regardless of the origin, however, the crater contains much in the way of inspirational appeal, and would doubtless make a most important addition to the National Park Service chain of monuments throughout this region. Due to the fact that considerable sums of money have been spent in exploration it is not known if satisfactory arra ngements could be made in this regard. If the cone is the result of an impact of a meteor, as is now generally conceived, it is the largest known crater in the world formed by such a phenomena.

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