



1. CRATER RIM FROM NORTHEAST



2. CRATER RIM FROM SOUTH

THE METEOR CRATER OF CANYON DIABLO, ARIZONA;
ITS HISTORY, ORIGIN, AND ASSOCIATED METEORIC
IRONS

BY GEORGE P. MERRILL

HEAD CURATOR OF GEOLOGY, U. S. NATIONAL MUSEUM

(With 15 plates)

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INTRODUCTION

Interest in the question of the possible meteoric origin of the remarkable crater-form depression lying a few miles south of the Santa Fé Railroad and not far from Canyon Diablo, in Coconino County, Arizona, has lately been revived by development work carried on under the direction of the Standard Iron Company of Philadelphia, and the publication of preliminary results and conclusions in the

Proceedings of the Philadelphia Academy of Sciences.¹ Such an origin was considered by Mr. G. K. Gilbert in his paper on the "Origin of Hypotheses," published in 1896, but the facts then available failed, in his opinion, to substantiate so startling a conclusion. The later developments and the interpretations put upon them have reopened the question and in the minds of many proven the correctness of the meteoric hypothesis.²

The mere existence of a crater some three-fourths of a mile in diameter and 500 feet in depth in a region of undisturbed sedimentary rocks and remote from volcanoes is in itself enough to invite scientific inquiry, while even the plausible suggestion that such might be due to the impact of a stellar body is of so unusual a nature as to warrant the fullest investigation. Consultation with the authors of the paper above noted impressed the writer with the desirability of a re-study of the problem in the light of the new evidence. The matter was therefore laid before Secretary Walcott, of the Smithsonian Institution. He promptly approved of the general plan of the work, and in May of the present year the writer spent several days on the ground, and has since been in frequent consultation and correspondence with Messrs. D. M. Barringer and B. C. Tilghman, the prime movers in the development work. The results are given in the following pages. The closing down of the works at this time, owing to the approach of winter, furnishes a convenient halting place in the investigation.

II. GEOLOGY AND PHYSIOGRAPHY OF REGION

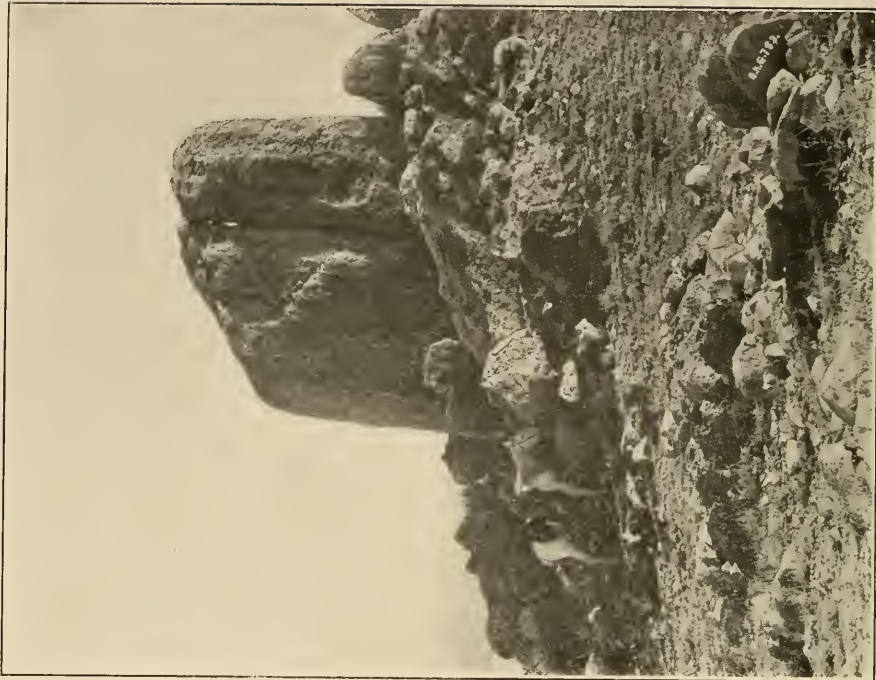
The region about Canyon Diablo is an elevated and nearly level sandy plain, the floor of which is composed in the main of a buff-colored arenaceous limestone known as the Aubrey (Carboniferous) limestone. This is capped here and there by low, elongated flat-topped mesas of red sandstone, which are but residuals from a one-time continuous stratum that covered the entire area. The limestone is underlaid by a highly siliceous sandstone of a gray or faintly buff tinge (also Carboniferous), and this in turn by a yellow, merging into red, sandstone. The exact thickness at this point of any of these beds can not be given. The U. S. Geological Survey, basing their estimates on results of well borings at Winona, some 30 miles distant,

¹ Coon Mountain and Its Crater, by D. M. Barringer, and Coon Butte, by B. C. Tilghman, Proc. Acad. of Sciences of Philadelphia, 1906, pp. 861-914.

² At the December, 1906, meeting of the Geological Society of America, in New York, Prof. H. L. Fairchild, of Rochester, submitted some lantern slides of the crater and announced his acceptance of this hypothesis.



1. OUTER SLOPE OF EAST RIM OF CRATER



2. LIMESTONE BOULDER ON OUTER SLOPE OF CRATER

give the Aubrey limestone at Canyon Diablo as probably not far from 300 feet in thickness, the gray sandstone 400 to 500 feet in thickness, and the still lower yellow-red sandstone about 1,000 feet in thickness.¹ The residual overlying red sandstone in the mesas is rarely over 15 to 20 feet in thickness, never, according to Mr. Barringer, over 50 feet. These beds all lie approximately horizontally, and almost as little disturbed by orographic movements and other dynamic agencies than those of erosion as when first laid down. The country is arid, the average annual rainfall being but 8 inches. The dryness of the soil consequent upon this slight precipitation is increased by numerous deep canyons and even earth cracks,² which quickly drain off all surface water. The country is essentially a desert, though affording at certain seasons of the year good pasturage for numerous flocks of sheep. Viewed from a slight elevation, and particularly when the sun is approaching the horizon, these great stretches of gray plain, with their scanty vegetation and occasional streaks of red from the residual sandstone mesas, are fascinating in the extreme and well merit the descriptive name of "Painted Desert," as applied by the early explorers of the region to the northwest, of which they are but a continuation.

III. THE CRATER

Historical References.—The occurrence of a peculiar crater-form depression within an elevated rim of limestone and sandstone, some 5 miles south of the railroad and 12 miles southeast of Canyon Diablo, has been known for several years, but was first brought prominently before the scientific world by A. E. Foote³ in 1891, and through the later writings of G. K. Gilbert,⁴ D. M. Barringer, B. C. Tilghman,⁵ and others.

This crater, through a singularly inappropriate use of terms, has become known in the literature as *Coon Mountain*, or *Coon Butte*, although occurring in a region where raccoons are rarely known

¹The record at Wimona, where the limestone had been very considerably eroded, was: Aubrey limestone, 185 feet; light gray sandstone, 456 feet; red sandstone, 16 + feet. (Darton.)

²The Canyon Diablo, the Canyon of the Little Colorado, the Grand Canyon of the Colorado, and the earthquake cracks described by Gilbert (*Science*, vol. II, 1895, p. 117) are sufficient examples of these.

³*American Journal of Science*, vol. XLII, 1891, p. 413.

⁴Presidential Address, *Geol. Soc. of Washington*, 1896; also *Science*, vol. III, 1896, p. 1.

⁵*Coon Mountain and Its Crater*, *Proc. Acad. Natural Sciences*, March, 1906, p. 861.

and partaking of the nature neither of a mountain nor butte. At best, the elevation is but a low, circular ridge, and in the existing condition of our knowledge might be well renamed Meteor Crater.

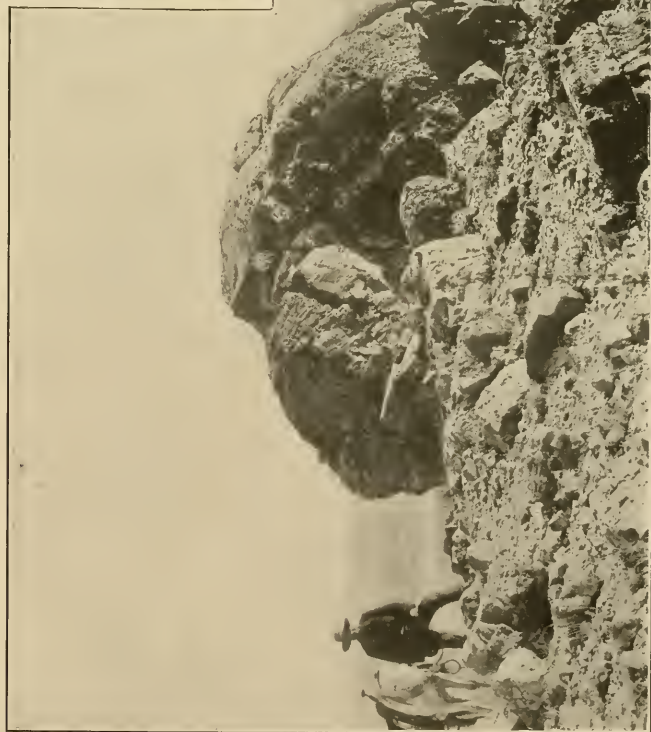
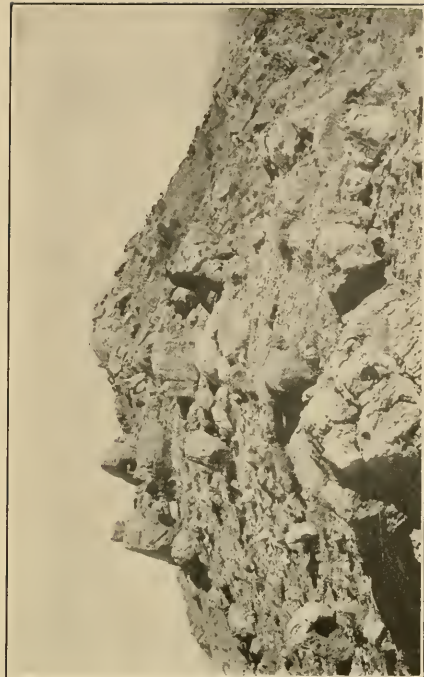
External Appearance.—As seen from the railroad and other points within a few miles, the crater rim rises above the level of the plain in the form of a low hill with peculiarities of contour and surface configuration that at once catch the eye of the observant and serve to differentiate it from the surrounding mesas. Its appearance, as viewed from the northeast and from the south, is shown in plate LXI. East and west views differ in detail, which, though of importance in connection with the origin of the crater itself, are not sufficiently conspicuous in the photographs to warrant reproduction.

A near view shows the mass of the crater rim (as the hill proves to be) to be composed, so far as visible, of loose, unconsolidated material in fragments of all sizes from microscopic dust to blocks weighing hundreds of tons (pl. LXII). The jagged nature of the ridge increases until the summit (pl. LXIII) is reached, where a full view of the phenomenon and its surroundings is obtained (see pl. LXIV, figs. 1 and 2)¹. From this point it is seen that the crater walls are composed of the crushed, broken, and bent strata of the limestone and sandstone forming the floor of the surrounding plain (pl. LXV), and which dip away from it in all directions. In other words, the structure is that which is known as quaquaversal. The crater rim is at its highest point 160 feet above the plain, according to Mr. Barringer, and at its lowest 120 feet. In outline the crater is itself nearly circular, though showing numerous minor deformations (see contour map, pl. LXVI). The diameter along an east to west line is given as 3,808 feet; along a north and south line as 3,654 feet.² and the depth as approximately 600 feet from the crest of the rim, though, as will be noted, this is considerably short of the original depth.

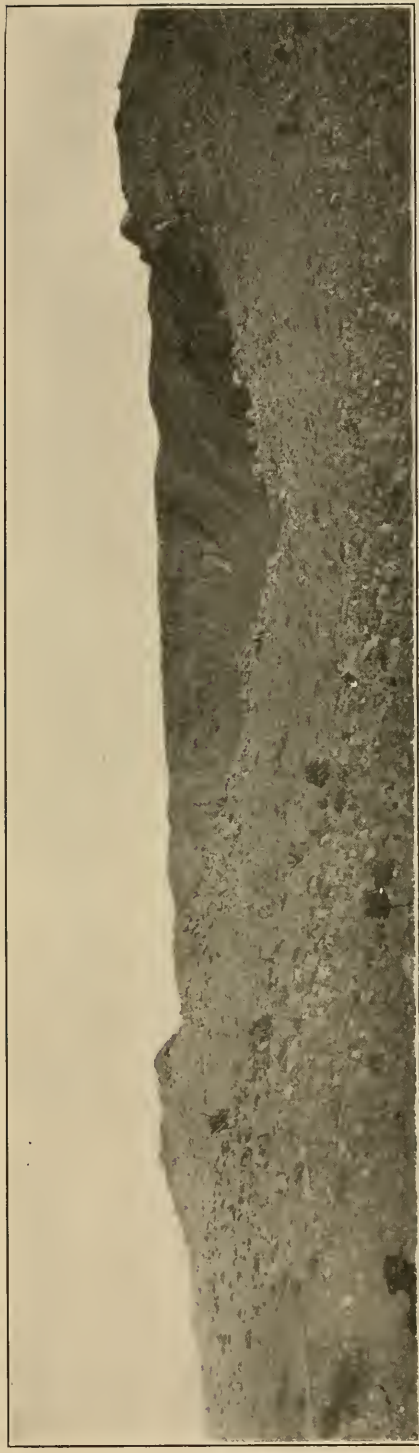
Details of Structure.—As already noted, the crater rim is composed exteriorly, so far as exposed to view, of loosely consolidated fragmental material, for the most part angular, and beyond ques-

¹The view from this point, particularly about sundown or by moonlight, is weird and impressive in the extreme. The inwardly steep and even overhanging walls, profoundly shattered, surrounding on every side a broad, deep pit, accessible only by the steepest of trails, barren of all but the scantiest of vegetable life and gashed by torrential action, present a picture which, when one reflects on its probable origin, is never to be forgotten.

²Later measurements by Mr. Lombard, of Flagstaff, give the major diameter as 3,950 feet and the lesser 3,850 feet.



1, 2. LOOKING NORTHWARD ALONG CREST OF WEST RIM OF CRATER



1. LOOKING ACROSS THE CRATER FROM NORTHERN RIM



2. LOOKING ACROSS AND INTO THE CRATER FROM THE SOUTH

tion derived from what is now the crater interior. Masses of sandstone and limestone, from the finest rock-flour to those weighing hundreds and even thousands of tons, are scattered about in the wildest profusion (see pls. LXII and LXIII). The larger blocks are of limestone, but this, as noted by Gilbert, is due to the rapid disintegration of the sandstone under atmospheric influences. They are most abundant on the east and west slopes, and lie on or near the crest of the rim, from which the debris spreads out in gradually diminishing quantities for distances varying from one-fourth of a mile to nearly a mile, or in some instances, according to Gilbert, to a distance of $3\frac{1}{2}$ miles. The block shown in figure 12 of Mr. Gilbert's paper is described as 10 feet in height and as lying some half a mile outside of the crater rim. Perhaps the most significant feature of the ejectamenta is the occurrence of enormous masses of the sandstone which have undergone a partial metamorphism through crushing and heat in a manner to be described when speaking of the materials found inside of the crater. It is sufficient to state here that this material must have come from a depth of at least 300 feet below the original surface. In this connection may be mentioned also the rock-flour ("silica" of Mr. Barringer's paper), which, while occurring on nearly all sides of the crater, is particularly conspicuous on the southern slope, where it has been cut through by a dry "wash," and is exposed for a distance of hundreds of feet to a depth in some cases of upward of 10 feet (see pl. LXVII, fig. 1). This is of a chalky white color, has a sharp, gritty feeling when rubbed between the thumb and fingers, and, as shown by the microscope, is composed of the shattered grains of the gray sandstone. It will also be described in detail later.

At various points along the lower margin of the crater, and particularly toward the north, are many low, rounded, moraine-like deposits composed of the same material as the rim, but for the most part in a comparatively fine state of disaggregation (see pl. LXVIII, fig. 1). In pits and trenches, sunk in these, are found fragments of all the rocks indigenous to the crater, and, what is of still greater interest, many of the shale-ball irons described elsewhere¹ and first brought to notice by Mr. Barringer. The occurrence of these is fully described by Mr. Barringer, and subsequent excavations made in the writer's presence corroborated his description in every

¹ See also Contributions to the Study of the Canyon Diablo Meteorites by George P. Merrill and Wirt Tassin, Smith. Misc. Collections (Quarterly Issue), vol. 50, p. 203, September, 1907.

detail. The position they occupy is such as can be accounted for only on the supposition that all the material composing the deposit was in the air at the same moment of time and was deposited "pell mell," wholly without order or reference to gravity, as it fell to the ground. Mr. Barringer speaks of one mass of the iron, found some 6 feet beneath the surface, embedded mainly in the fine white rock-flour ("silica") and directly beneath an angular fragment of red sandstone several feet in diameter, overlying which was a piece of limestone, and over this again one of sandstone.

The rim of the crater is, as stated, at its highest point some 160 feet above the surface of the plain, with a very conspicuous low place (see pl. LXIV) on its northern side. The 5,800-foot contour line (see pl. LXVI) passes along this crest, and it is seen that on the north, and for the most part on the east and south, this is a mere ridge (pl. LXIII, fig. 2) sloping away abruptly on either hand. To the west and southwest the 5,800-foot contour includes two long and comparatively broad areas, near the middle of the southwestern of which are found the highest points on the rim—5,860 and 5,863 feet. The supposed significance of these features of the crest will be noted later.

A glance at the interior walls of the crater shows at once its nature, if not origin (see pls. LXV and LXIX). The details have been given very fully by Messrs. Barringer and Tilghman and less so by Gilbert. They consist of strata, principally of the limestone, but locally of sandstone also, "crushed and shattered to an extraordinary degree" and dipping away (*i. e.*, outward) on all sides at angles of from 10° to 80° , or, in one instance, with an overturn of at least 10° from the vertical. The walls are steep and often overhanging, for hundreds of feet accessible but to birds, and of so loose and friable a character as to make exploration dangerous. A single false step may set tons of loose material slipping and plunging down the steep slope. The illustrations utterly fail to convey an idea of their impressive as well as dangerous character. The typical sections here given were made by Mr. Tilghman, to whom I am indebted for the privilege of utilizing them. It will be noted that at Station 5 (see diagram, figs. 124 and 125) the crater wall is composed, below the surface debris, of (1) a thin bed of red sandstone, and (2) the Aubrey limestone, dipping southwesterly 35° , the cliff face sloping inward at an average angle of 34° . The underlying white sandstone does not show at this point, being obscured by talus fallen from the cliffs above and the sedimentary beds formed in the bottom of the crater. The "typical east rim" section (Station 18, fig. 125),



1. INTERIOR WALL OF CRATER, LOOKING NORTHWARD



2. LOOKING ACROSS CRATER FROM NORTH, SHOWING FAULTING (BENEATH ARROW) IN SOUTHERN RIM

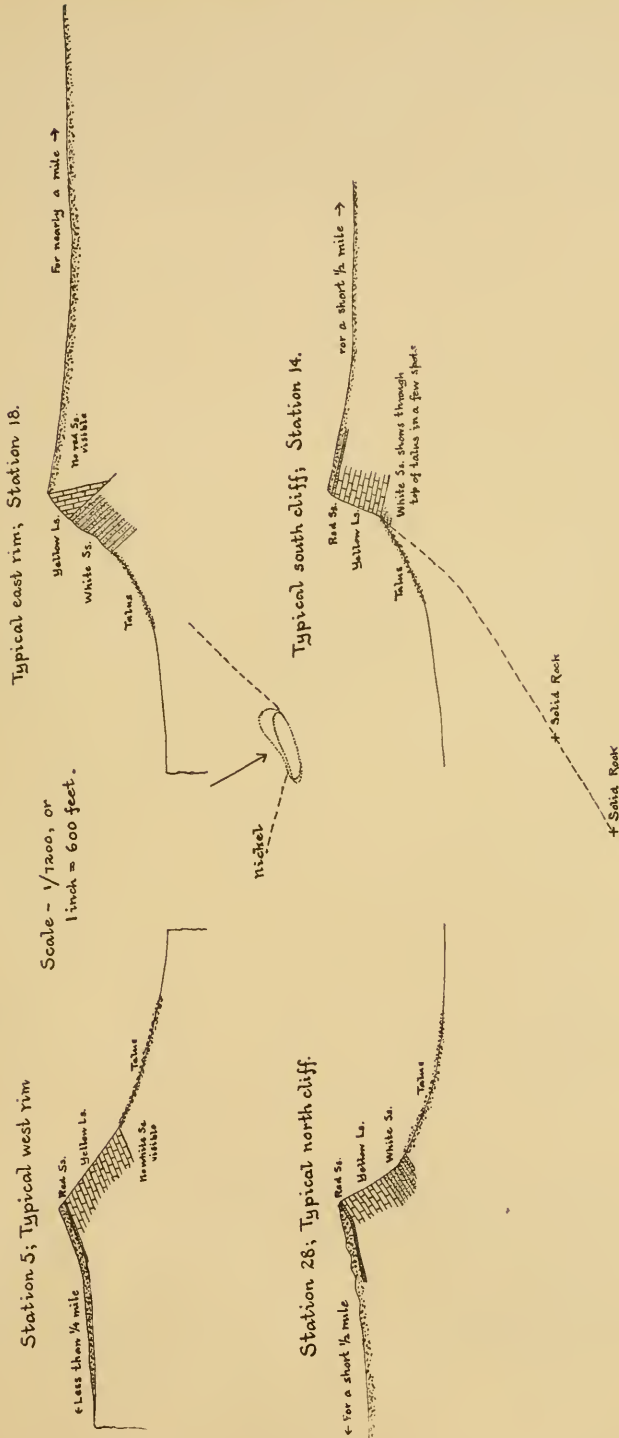


FIG. 124.—Cross-sections of Crater. From drawings of Mr. Tilghman.

is by far the most striking and suggestive of the series. No red sandstone is here visible. The limestone is shattered and turned up at an angle of 80° , the cliff face having an average slope of about 46° . Immediately beneath this appears the white sandstone, at first crushed to powder, but beneath gradually assuming a more solid form, until at the bottom of the outcrop it is nearly normal in ex-

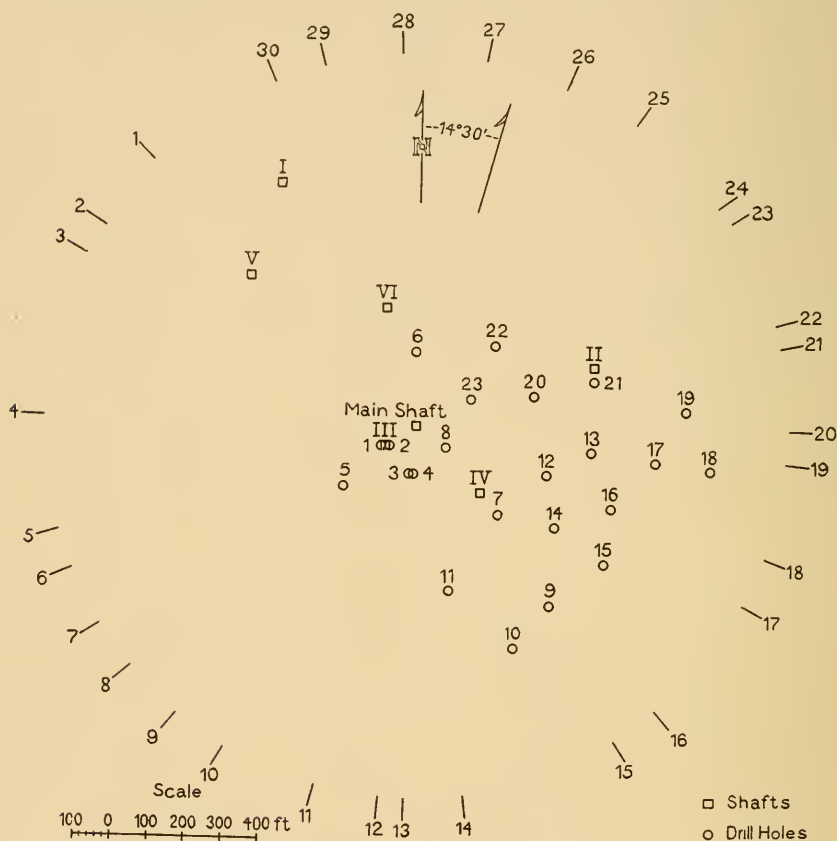
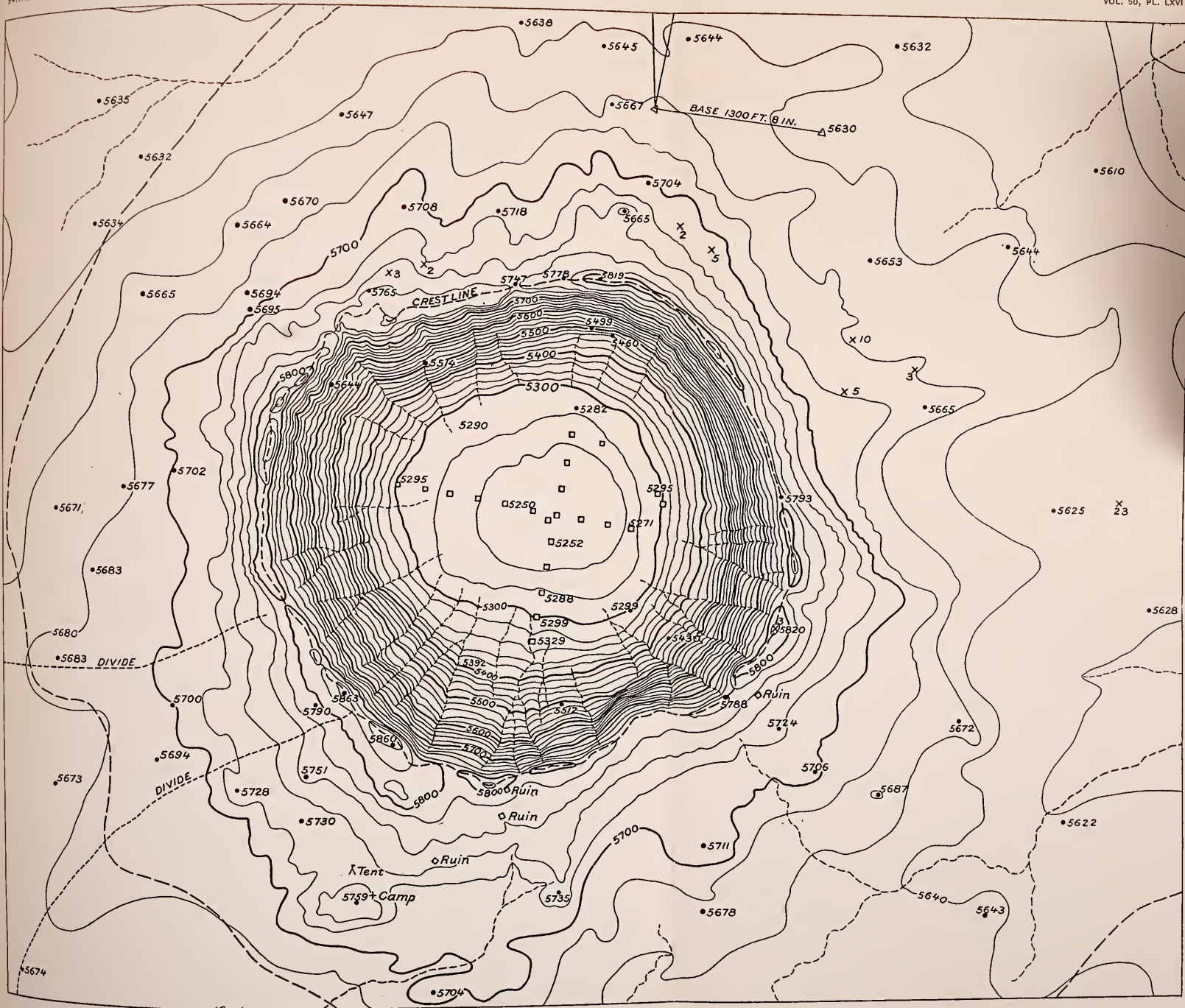


FIG. 125.—Diagram Showing Position of Drill Holes and Shafts in Bottom of Crater.

ternal appearance. This, too, dips away at a high but smaller angle than the limestone, which is undoubtedly faulted against it, as shown in the sketch. An almost equally interesting point in the rim is that at Station 16 (S. 56° E.), where the sandstone in the face of the cliff is faulted up so as to abut squarely against the limestone, the beds to the northeast having a dip of 44° – 54° , while those to the southwest lie at angles of but 6° – 20° . This vertical fault is shown





CONTOUR MAP OF CRATER, CANYON DIABLO, ARIZONA

somewhat indistinctly at the point directly beneath the arrow in fig. 2, pl. LXV.

The "typical North Cliff" section (Station 28) shows again a thin bed of red sandstone underlying the surface debris, dipping outward at an angle of 36° , under which is the yellow limestone lying nearly at the same angle, and beneath this again the white sandstone. The slope of the cliff facing the crater is here 49° to 60° . The "typical South Cliff" (Station 14) shows likewise the red sandstone and yellow limestone dipping at angles of 12° to 14° , with the angle of slope of the interior wall standing as high as 76° . A very little white sandstone shows through the top of the talus beneath the limestone.

These examples are sufficient to convey an idea of the remarkable character of the crater walls. The following table from Mr. Tilghman's notes is, however, inserted (compare fig. 125):

Sta. 1,	north 60° W.,	dip;	red sandstone,	15° ;	limestone,	inaccess. cliff,	76° , av.
" 2,	" 73° W.,	" "	" "	30° ;	" "	19° "	50° , "
" 3,	" 78° W.,	" "	" "	...	" "	... slope,	40° , "
" 4,	south 76° W.,	" "	" "	...	" "	35° "	35° , "
" 5,	" 58° W.,	" "	" "	...	" "	35° "	34° , "
" 6,	" 52° W.,	" "	" "	17° ;	" "	20° "	34° , "
" 7,	" 42° W.,	" "	" covered up;	" "	" "	54° "	34° , "
" 8,	" 34° W.,	" "	" "	...	broken,	{ 75° 85° 95° }	" 50° , "
" 9,	" 24° W.,	" "	" "	7° ;	" "
" 10,	" 15° W.,	" "	" "	10° ;	" "	16° "	41° , "
" 11,	" 0° W.,	" "	" "	13° ;	" "	15° "	37° , "
" 12,	" 10° E.,	" "	" "	16° ;	" "	28° "	44° , "
" 13,	" 14° E.,	" "	" "	10° ;	" "	8° cliff,	66° , "
" 14,	" 23° E.,	" "	" "	12° ;	" "	14° "	76° , "
" 15,	" 48° E.,	" "	" "	3° ;	" "	-3° "	...
" 16,	" 56° E.,	fault { west of fault east of fault	" "	none;	" "	{ $6^\circ-20^\circ$ $44^\circ-54^\circ$ }	slope, 33° , "
" 17,	" 77° E.,	" "	" "	none;	" "	$45^\circ-80^\circ$ "	40° , "
" 18,	" 85° E.,	all broken up—no red sandstone,	about 80° ,	" "	" "	60° "	46° , "
" 19,	north 80° E.,	too broken to measure;	limestone,	" "	" "	60° "	43° , "
" 20,	" 75° E.,	dip; red sandstone,	$9^\circ-12^\circ$;	" "	" "	28° "	50° , "
" 21,	" 62° E.,	" "	" "	28° ;	" "	45° "	54° , "
" Ext.,	" within few feet;	" "	" "	" "	" "	$75^\circ-90^\circ$ "	...
" 22,	" 58° E.,	dip;	" "	53° ;	" "	50° "	41° , "
" 23,	" 42° E.,	" "	" "	...	" "	33° "	46° , "
" 24,	" 38° E.,	" "	" "	28° ;	" "	36° "	46° , "
" 25,	" 20° E.,	dip; red sandstone,	14° ;	" "	" "	26° "	44° , "
" 26,	" 5° E.,	" "	" "	20° ;	" "	34° "	40° , "
" 27,	" 5° W.,	" "	" "	44° ;	" "	42° "	42° , "
" 28,	" 18° W.,	" "	" "	36° ;	" "	37° { cliff,	60° , "
" 29,	" 30° W.,	" "	" "	36° ;	" "	29° { slope,	49° , "
" 30,	" 38° W.,	" "	" "	6° ;	" "	{ " $50^\circ-52^\circ$,	70° , "
						{ cliff,	71° , "
						{ " "	60° , "
						{ slope,	60° , "

IV. THE CRATER FLOOR

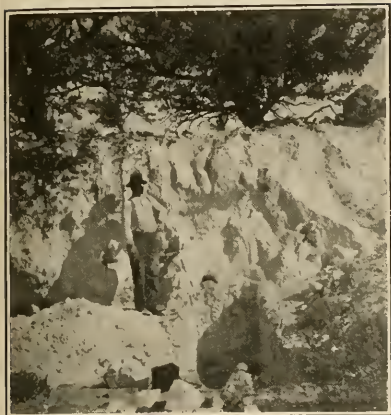
Physiography.—As already noted, the crater has at present a maximum depth of 600 feet, measured from the crest of the rim, or about 440 feet below the level of the plain. Beyond the fringing reef of talus the floor presents a nearly level plain of over 300 acres in extent, surrounded on all sides by well-nigh inaccessible cliffs (see pls. LXIX and LXX). It needs but a glance, however, to show that a large amount of material has fallen from the interior walls through the action of gravity, water, and frost (pl. LXVIII, fig. 2), and that the original depth must have been considerably greater. How much greater could be only guessed at until the borings incident to the development work of Messrs. Barringer and Tilghman were undertaken. A number of drill-holes have now been sunk to depths up to 1,100 feet, and from the results thus obtained we are enabled to gain a record entirely inaccessible at the time Mr. Gilbert made his studies, and which throws such light upon the subject as to justify us in reverting once more to the original hypothesis, as set out in Mr. Gilbert's paper and advocated by Messrs. Barringer and Tilghman—that of an origin through impact of a giant meteorite.

Results of Borings.—Below are given the results of one of these borings (hole No. 17), situated 600 feet south, 84° east (true) of the center of the crater and starting on a surface 540 feet below the rim, or 400 feet below the level of the plain. (See fig. 125.)

	Feet.
(1) Surface material, soil, sand, and wash from cliffs.....	0- 27
(2) Lake-bed formations, lying horizontally and containing diatoms, shells of mollusks, and abundant gypsum crystals.....	27- 88
(3) A sand which gives reaction for nickel and iron and contains fragments of metamorphosed sandstone, sandstone pumice, etc.	85-220
(4) Sand and rock, sand grains crushed slightly, if any, and not metamorphosed, barren of meteoric material.....	220-520
(5) Sand and "silica" (rock-flour), with abundant slag-like material containing iron and nickel, and metamorphosed sandstone.	520-600
(6) Fine silica powder (rock-flour) and sand, no meteoric material..	600-620
(7) Bed-rock, a grayish sandstone rapidly becoming yellow and harder, not metamorphosed	620-720

A less detailed record of hole No. 12 is as follows :

(1) Surface soil, blown sand, etc.....	0- 30
(2) Lake-bed deposits	30- 90
(3) Sand (rock-flour), sandstone in part metamorphosed.....	90-630
(4) Rock, at first soft and shattered, but becoming gradually harder as greater depths were reached.....	630-830



1. DRY WASH, SOUTH SIDE OF OUTER RIM



2. WHALE ROCK ON WEST RIM



3. BOULDER ON RIM OF CRATER, WEST SIDE



1. MORaine-LIKE HILLS ON NORTHERN RIM OF CRATER



2. INTERIOR WALLS OF CRATER, WITH TALUS AND ALLUVIAL FANS FROM CLIFFS

The yellow to red sandstone, which seems everywhere to form the floor of the crater, was first struck at a depth of 820 feet. Meteoric material—*i. e.*, material reacting for nickel and iron—was first encountered at a depth of 180 feet, and continued with few exceptions in all samples down to 600 feet.

A like record of other holes is as below :

No. 7	yielded material reacting for nickel at depths of	450-550 feet.
No. 12	“ “ “ “ “ “ “ “	595-640 “
No. 13	“ “ “ “ “ “ “ “	598-660 “
No. 14	“ “ “ “ “ “ “ “	540-620 “
No. 15	“ “ “ “ “ “ “ “	590-600 “
No. 16	“ “ “ “ “ “ “ “	540-620 “
No. 17	“ “ “ “ “ “ “ “	520-580 “
No. 20	“ “ “ “ “ “ “ “	640-680 “
No. 21	“ “ “ “ “ “ “ “	620-640 “
No. 22	“ “ “ “ “ “ “ “	600-620 “
No. 23	“ “ “ “ “ “ “ “	520-620 “
No. 24	“ “ “ “ “ “ “ “	550-650 “

The following table in connection with figures 124 and 125 is instructive as showing the condition of the deeper lying beds and the varying depths at which what could be unmistakably identified as the underlying red beds were reached :

Hole No.	Red beds found at depths of—	Total depth of hole.	Remarks.
5	885 feet	1,003 feet.....	
6	890 feet	1,059 feet.....	Solid cores obtained below 1,030 feet.
7	905 feet	960 feet.....	
8	900 feet	1,085 feet 7 in..	Solid cores obtained below 1,030 feet.
9	Not reached ...	670 feet.....	
10	“ “ ...	745 feet.....	Solid rock below 640 feet.
11	830 feet.....	830 feet.....	“ “ “ 640 feet.
12	875 feet.....	881 feet.....	“ “ “ 700 feet.
13	Not reached ...	740 feet.....	“ “ “ 640 feet.
14	“ “ ...	780 feet.....	“ “ “ 670 feet.
15	“ “ ...	750 feet.....	“ “ “ 650 feet.
16	“ “ ...	750 feet.....	“ “ “ 640 feet.
17	“ “ ...	720 feet.....	“ “ “ 600 feet.
18	“ “ ...	660 feet.....	“ “ “ 630 feet.
19	“ “ ...	680 feet.....	“ “ “ 620 feet.
20	“ “ ...	780 feet.....	“ “ “ 720 feet.
21	“ “ ...	760 feet.....	“ “ “ 660 feet.
22	860 feet	860 feet.....	“ “ “ 650 feet.
23	Not reached ...	800 feet.....	“ “ “ 660 feet.

These records are sufficiently characteristic to serve our purpose. It is evident that the bottom of the crater was occupied at one time by a shallow lake, in which lived diatoms and fresh-water mollusks,

¹Traces only.

and on the bottom of which accumulated, during periods of drought, the deposits of carbonate of lime and gypsum so characteristic of the playa lakes of the West. This naturally thins out along the margin where it overlaps the fragmental material from the steep slopes. None of this needs attention in the discussion of the present problems. The crushed and metamorphosed white sandstone under-

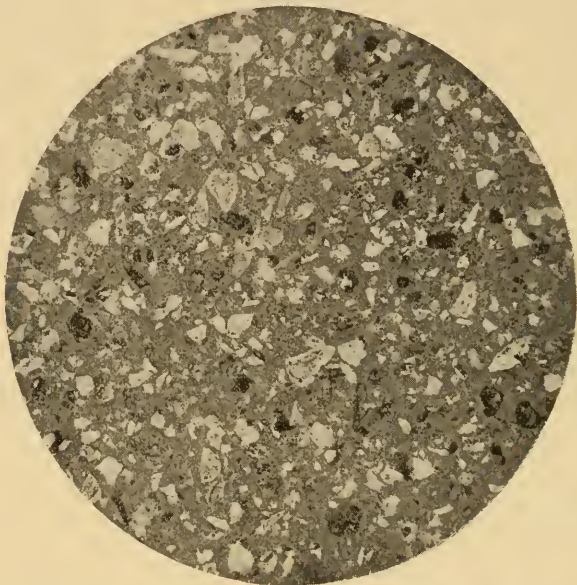


FIG. 126.—Showing the Microstructure of the Rock Flour. The angular particles are all of quartz.

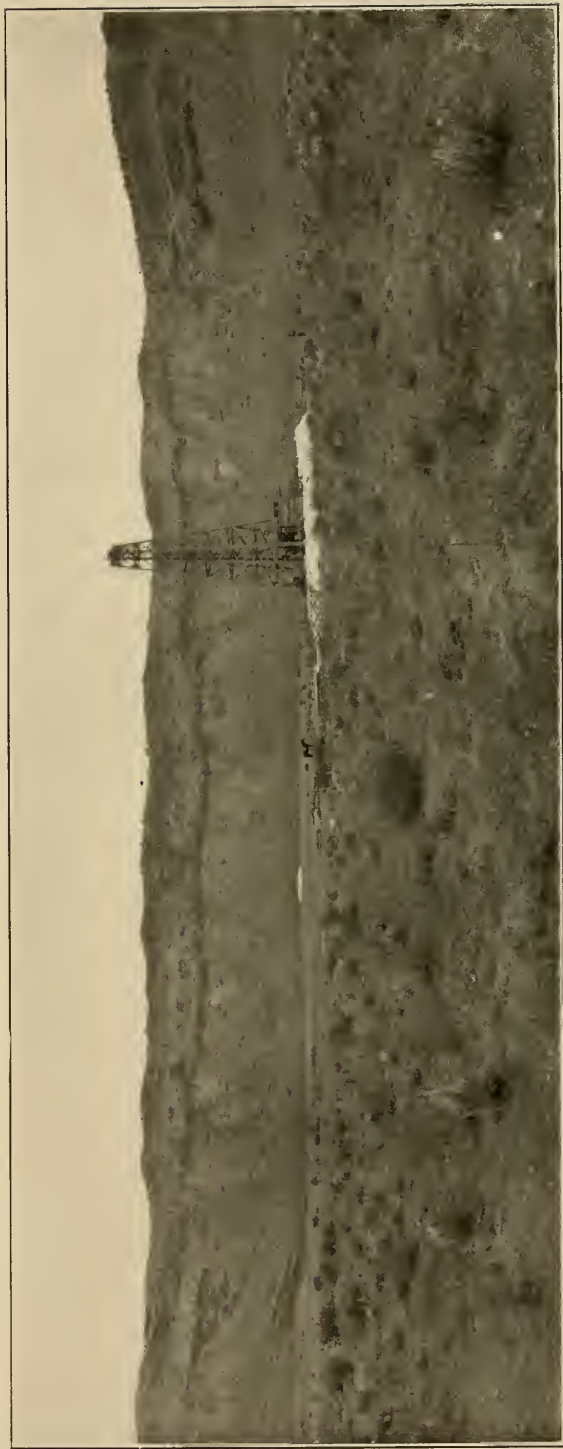
lying it needs, however, careful consideration. This has been already the subject of brief notice by the writer,¹ but is of sufficient importance, as bearing upon the matter of origin of the crater, to be elaborated here.

Petrographic Description of Rock Products.—The unaltered gray sandstone, which has already been referred to as underlying the limestone and having an approximate thickness of 400 or 500 feet, is in its typical form of a very light gray or nearly white color, and is composed wholly of well-rounded, clear, colorless grains of quartz sand, with an occasional fragment of feldspar. A photomicrograph of this is given in figure 1, plate LXXI. This rock, as shown in the borings and as noted in the description of the crater walls, is often much shattered and crushed and is found in

¹On a Peculiar Form of Metamorphism in Siliceous Sandstone, Proc. U. S. Nat. Mus., vol. XXXII, 1907, pp. 547-550.



INTERIOR OF CRATER, SHOWING NEARLY LEVEL FLOOR, LOOKING SOUTH



INTERIOR OF CRATER SHOWING NEAR VIEW OF SOUTH WALL

all gradations, from that just described to the white, almost dust-like powder designated as "silica" by Messrs. Barringer and Tilghman, but which the writer of this paper will refer to as rock-flour. This, interspersed with more or less firm material, occupies a large portion of the crater from the 85- or 90-foot level down to the underlying red bed, a distance in round numbers of 500 feet. It is found also wherever pits have been sunk on the exterior margin of the rim and in deposits comprising the thousands of tons of material shown in figure 1 of plates LXVII and LXVIII. Between the thumb and fingers this material, notwithstanding its fineness, has a sharp gritty feeling, and under the microscope is seen to be composed wholly of the sharply angular bits of quartz derived from the shattering of the individual grains of sand (see fig. 126). It has been unquestionably derived from the sandstone, and that, too, not by simple disintegration, but through some dynamic agency acting like a sharp and tremendously powerful blow.

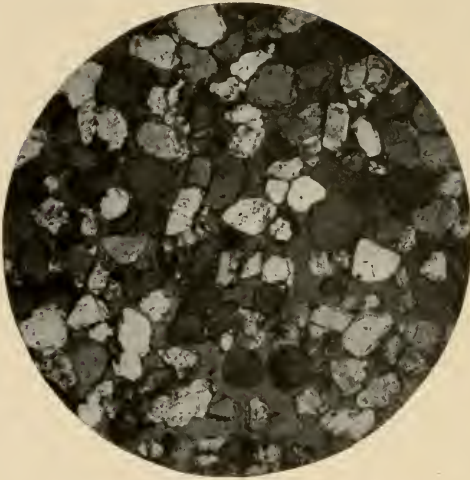
Commingled with this material in the bottom of the crater (as shown by shafts), and to a less extent around the margin and in scattered masses outside of the rim, are fragments of what is plainly sandstone, but of an almost snow-white color, and so friable as to be readily crushed between the thumb and fingers (locally known as *ghost sandstone*). With these, but less abundant, are more compact, but platy forms, almost devoid of appreciable granular structure, but which were yet recognized by Messrs. Barringer and Tilghman as sandstone derivatives, and, more rarely yet, some coarsely and finely pumiceous forms, the exact nature of which was uncertain. These last were examined by Mr. Diller and reported upon to Mr. Gilbert at the time he was making his studies, but the results were not published.

The following is an amended description of these crushed and otherwise altered forms as given by the author in his paper above referred to:

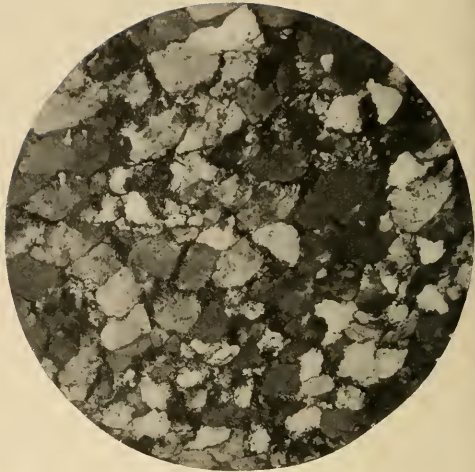
The sandstone (Cat. No. 76,834, U. S. N. M.) in its original and prevailing type is of a light-gray color, distinctly saccharoidal and, in the walls of the crater, very friable, being in small masses easily disintegrated in the hands. Under the microscope it is found to be composed of well-rounded quartz granules, with an occasional grain of a plagioclase feldspar, and a little dust-like material in the interstices, but the amount of interstitial material of any kind is very small. The general structure of the stone is shown in figure 1, plate LXXI. This type passes into what may be called the first phase of the metamorphism, an almost chalky white rock (Cat. No.

76,835, U. S. N. M.), still retaining the granular character and much of the original structure of the sandstone, but crushing readily between the thumb and fingers. Under the microscope this type shows interesting structural changes which are only in part brought out by the photomicrograph reproduced in figure 2, plate LXXXI. A portion of the quartz granules retain their original characteristics. A larger portion are crushed and more or less distorted, though retaining their limpidity and high polarization colors. In many instances two adjacent granules are crushed and fractured at point of contact, as though they had been struck a sharp blow with a hammer. This crushing has at times been carried so far that the rock is reduced to a fine sand or flour (Cat. No. 76,840, U. S. N. M.), each particle of which is as sharply angular as though disintegrated by a blast of dynamite (see fig. 126). Of greater significance from the present standpoint is the presence in the still firm rock of a large number of granules which are so completely changed as to give rise to forms at first glance scarcely recognizable as quartzes at all. A description of these is given in the discussion of the next or second phase of the metamorphism.

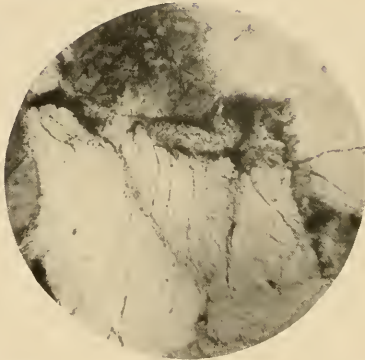
In this second and very complete phase the original granular structure of the sandstone has almost wholly disappeared. The rock (Cat. No. 76,837, U. S. N. M.; fig. 1, pl. LXXXII) is chalk white to cream yellow in color, quite hard, though in thin fragments readily broken between the thumb and fingers, and lacks entirely the arenaceous structure. It resembles the decomposed chert quarried at Seneca, Missouri, under the name of tripoli, more than any other rock that the writer can call to mind, although on casual inspection it might readily pass for an old siliceous or calcareous sinter. This material, Mr. Tilghman writes, occurs sporadically throughout the pulverulent material, of which it constitutes some 2 per cent in bulk, and in fragments from the fraction of an inch to 10 or 12 feet in diameter. In one instance the drill passed through a body of it some 50 feet in thickness at a depth of 500 feet below the surface. In the mass this variety shows an uneven platy structure extending across the original, almost obliterated, lines of bedding. The general structure as seen in thin-sections is shown in figure 3, plate LXXXI. At first glance such would be pronounced to be a holocrystalline rock. It is in fact an aggregate of closely interlocking quartz granules with low and very uniform relief, dull colors of polarization, and in the majority of instances a marked rhombohedral cleavage. So striking are these features that at first the true nature of the mineral was not recognized. Extinctions are often undulatory, indicating a condition



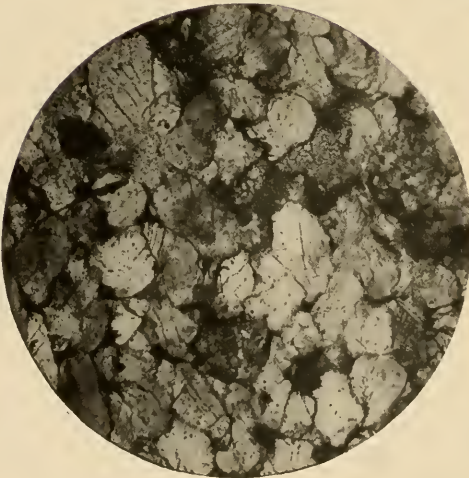
1



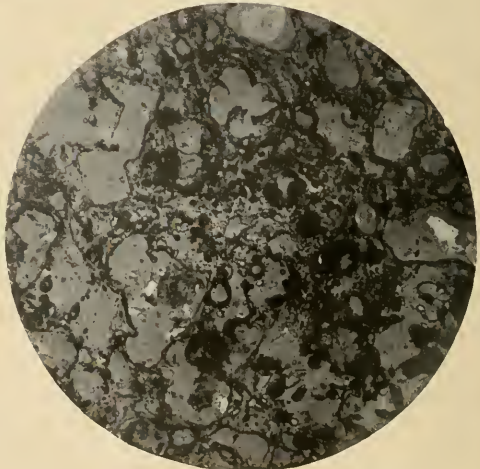
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5



3



4

MICROSTRUCTURE OF GRAY SANDSTONE
See explanation of plates, page 498

of molecular strain, and the cleavage lines are themselves at times more or less wavy (fig. 5, pl. LXXI). The appearance indeed is such as to suggest that the granules have been subjected to pressure while in an almost putty-like or plastic condition. With a high power and between crossed nicols the rock is seen to be not holocrystalline, but to contain comparatively small colorless interstitial areas, showing by ordinary light a fibrous, scaly structure, but which are for the most part completely isotropic between crossed nicols and which the chemical analysis suggests may be opal. From this condition the rock passes through more or less vesicular (fig. 2, pl. LXXII) to highly pumiceous forms (Cat. Nos. 76,839 and 76,840, U. S. N. M.), showing to the unaided eye all the features of an obsidian pumice, but of a white color (figs. 3 and 4, pl. LXXII). This under the microscope is resolved into a colorless vesicular glass, more or less muddied through dust-like material (fig. 4, pl. LXXI), and showing here and there residual particles of unaltered quartz. The glass does not, however, resemble the glass of a pumice, nor is it like that obtained by the artificial fusion of quartz in the geophysical laboratories of the Carnegie Institution. So far as the writer's observations go, it more closely resembles fulgurite glass, formed by the lightning striking in siliceous sand. It is evident that the original molten material was in a highly viscous, almost dough-like condition. The cavity walls are stringy rather than smooth, as in ordinary pumice, and rough fibers or strings of true quartz glass stretch from wall to wall, as shown somewhat indistinctly in figure 3 of plate LXXI. This form, it is well to note, is not abundant and is the material first met with in what Mr. Barringer has designated as shaft No. 2 and at a depth of 130 feet below the crater floor. A few small pieces were found in digging the open cuts outside of the crater, and others lying out on the surface.

Chemical tests on (I), the unaltered sandstone; (II), what may be called the crystalline variety, the finely laminated stone compared to a decomposed chert, and (III), the pumice, gave Mr. Tassin results as below:

(I) Unaltered sandstone.....	{	SiO ₂	99.29
		Undet.	0.71
			<hr/>
			100.00
(II) Altered sandstone.....	{	SiO ₂	98.63
		Al ₂ O ₃	0.18
		Fe ₂ O ₃	0.10
		Ign	0.99
		Loss at 100°.....	0.30
			<hr/>
			100.20

(III) Pumiceous variety.....	{	SiO ₂	95.22
		Al ₂ O ₃	0.59
		Fe ₂ O ₃	0.19
		CaO	1.99
		Ign	1.20
		Loss at 100°.....	0.40
			99.59

The lime in analysis III was there as a mechanically admixed carbonate. The high ignition (0.99) in II would suggest that a part of the silica is in the condition of opal, as already noted. Eliminating the ignition and the free calcium carbonate in III, it is evident that there is no essential chemical difference in the three samples. They vary as little as would probably three independent analyses of any one of the types from slightly different sources.¹

The distribution about the crater of this altered sandstone is of primary importance. The occurrence of the silica powder (rock-flour) in the dry wash on the south side has been already referred to. Mr. Barringer states that the same material is met with almost anywhere in digging on the outside of the rim, and the shafts and trenches sunk show it to extend to a depth of at least 48 feet, commingled with fragments of limestone and sandstone, both unaltered and in the white, pulverulent condition. As described, it has "evidently welled out of the crater almost like liquid mud, or, perhaps more accurately, like flour when it is poured out of a barrel" (p. 870).

The present writer dug fragments of the altered, white, friable sandstone from trenches on the north side, and the same material from the floor of the low place in the north crest of the rim. The finely pumiceous, almost wholly glassy material, the rarest of all, has been found only in shafts sunk from the bottom of the crater, but the coarser material was found in small quantities well out on the lower slopes to the south. The chemical and petrographic work of Messrs. Melville and Diller, elsewhere referred to, was done on material found on the surface and outside of the crater rim.

The work of boring, as carried on in the interior of the crater, was done with a toothed, hardened steel bit, giving a 2½-inch core. Throughout the 500 feet of crushed sandstone a large portion of the material was washed up by a current of water in the form of loose

¹At the time Mr. Gilbert was making his investigations a chemical analysis was made by W. H. Melville of the vesicular variety (No. III). This Mr. Gilbert has placed in my hands. It is as follows: SiO₂, 89.71; Al₂O₃, 1.20; FeO, 0.34; CaO, 4.22; MgO, 0.22; K₂O, 0.15; Na₂O, 0.24; Co₂, 3.25; Ign., 0.74; loss at 100°, 0.20; total, 100.27.

sand. A part of this was nickel-bearing, as noted in the record given of the borings, and in some instances, notably holes No. 16 and 20 (Fig. 125), carried metallic particles. The presence of this nickel-bearing sand was naturally of great significance, and attempts were made to isolate the nickeliferous mineral in order to ascertain its possible meteoric character. The white sand showed numerous slag-like granules, which, in the section, were found to be composed of sand grains cemented by iron oxides, and larger granules ($\frac{1}{2}$ mm.) of a greenish color, the nickel reaction being limited to the latter. Examined under the microscope, these proved to be aggregates of fine angular bits of the quartz sand, stained by a greenish, amorphous material, concerning the true nature of which the microscope revealed nothing.

Hole No. 17 yielded at a depth of 520 feet abundant sand grains stained brown-red by iron oxides and commingled with it occasional minute—perhaps 1 mm. in diameter—thin metallic scales, which it was at first thought might have come from the drill, but which Mr. Tassin's tests showed to consist of phosphide of iron and to be unquestionably schreibersite and of meteoric origin. Small scales of nickel-iron were also found,¹ and in one instance (hole No. 16) a number of chromite and fayalite (?) granules. The source of these last is conjectural, since neither mineral has thus far been identified in the meteoric iron, though Derby gives a trace of chromium in the analysis noted later. Careful search was made for anything in the nature of a silico-ferruginous slag, such as it was conceived might result from the mutual fusion of sand grains and meteoric iron. Nothing was found that could be thus positively identified until hole No. 20 was reached, though some of the particles showed in thin-section a very deep green or brownish, blebby glass which it was at first thought might be particles of the volcanic sand common to the region. A comparison of the two materials did not substantiate this view, and it would seem that such must be in some way connected with the meteoric phenomena, though it was not possible to correlate them absolutely with the nickeliferous granules. Hole No. 20 yielded a quantity of dark brownish particles from 1 to 3 mm. in diameter, which in thin sections showed a ground of radiating, imperfectly differentiated crystals of a gray color and undetermined

¹Analyses by Mr. Tassin of the metallic particles, freed from siliceous matter as much as possible by hand picking and the magnet, yielded: SiO_2 , 12.75 per cent; Fe, 68.17 per cent; NiCo, 12.14 per cent; P, 5.07 per cent; total, 98.93 per cent. The SiO_2 was in form of free quartz.

nature, enclosing some amorphous matter, numerous shattered and more or less altered quartz granules, and an occasional black, highly lustrous particle, assumed from its association to be chromite. This material gave a strong qualitative reaction for nickel.

The underlying red sandstone, met with at depths of approximately 800 feet from the surface and referred to as forming the "floor" of the crater, was brought up from time to time in the form of short sections of drill cores. These were examined in thin sections, and in no instance did they show any signs whatever of the shattering, fusion, or metamorphism so characteristic of the overlying white sandstone¹ (fig. 127).

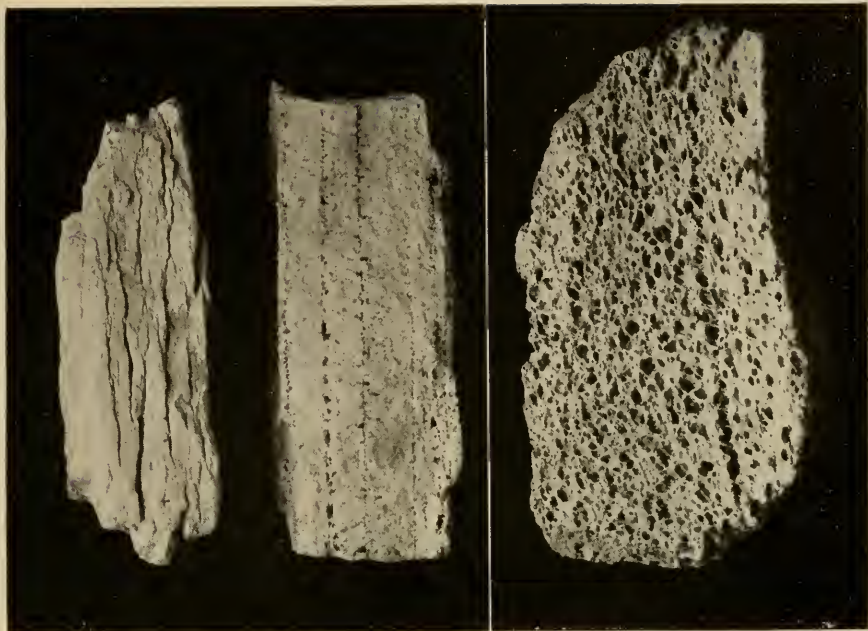


FIG. 127.—Showing Microstructure and Unaltered Character of Sandstone Underlying Crater.

V. THE METEORIC IRONS

History of Early Finds.—The first public announcement of the finding of meteoric irons near Canyon Diablo was that made by Mr. A. E. Foote at the Washington meeting of the American Association for the Advancement of Science, August 20, 1891. In this paper,

¹ Cores were not available from as many holes as could have been desired. Those examined were of sandstone of a distinctly red hue and from holes Nos. 4, 6, 7, and 8 (see diagram, fig. 125), No. 6 being from a depth of 1,065 feet and No. 8 from 1,080 feet below the crater bottom.



1

2

3



4

ALTERED SANDSTONE FROM SHAFTS INSIDE OF CRATER

(See explanation of plates.)



TYPICAL FORMS OF CANYON METEORIC IRONS

which was published in both the proceedings of the Association and the American Journal of Science,¹ Mr. Foote stated that, at that time, nearly all of the small fragments had been found at a point about 10 miles southeast from Canyon Diablo and near the base of a circular elevation locally known as Crater Mountain, but the origin of which he was unable to explain. Mr. Foote's interest lay largely with the meteoric irons, of which he reported that over 137 fragments had been found, the largest of which weighed 201 pounds (91.171 kilograms). He also noted the occurrence at the base of the crater of many oxidized and sulphureted (*sic*) fragments, some of which showed a greenish stain, resulting probably from the oxidation of the nickel. This oxidized material he regarded as identical with an incrustation which covered the surface of some of the iron or filled the pits in the same. With the aid of analyses by Dr. G. A. König, Foote was able to announce the iron to contain (1) small diamonds, both black and white; (2) carbon in the form of a pulverulent iron carbide, the precise nature of which was not made out; (3) sulphur; (4) phosphorus; (5) nickel; (6) cobalt, and (7) silicon.

Naturally this announcement was received with great interest by members of the Association and others—an interest which was kept up for a long period by the rapidly accumulating evidence and final proof of the presence of minute diamond crystals in the iron, and also by the large number of irons and their oxidation products subsequently found.

The exact number of independent masses of the iron that the locality has yielded and their aggregate weight can never be known, owing to the many comparatively small pieces carried away by visitors or purchased from Mr. Voltz, an Indian trader in the neighborhood who has made it a matter of business to search for them, even hiring men and boys and plowing the ground over certain areas. An estimate of the total weight, which can be considered little more than a guess, is 20 tons, while the numbers run up into thousands, weighing from not over a gram to 460 kilograms (1,013 pounds) each, the latter weight being that of the large specimen in the Field Museum at Chicago. The irons are characterized by deep concave and convex surfaces and peculiar pittings or holes, an inch or more in diameter, which sometimes extend through the mass (see pl. LXXIII), and are commonly regarded as due to the oxidation and crumbling away of nodules of iron sulphide (troilite). Each iron seems to form a complete individual, with no visible signs

¹ Vol. 42, 1891, pp. 413-417.

of rupture from a parent mass, nor fusion and flow structure from its flight through the atmosphere. The probable significance of this is mentioned later.

Distribution of the Irons.—These irons, it should be stated, have been found scattered without determinable order over an area of several square miles about the crater. It is unfortunate also that the even approximately exact distribution of the larger masses can not be given, the collecting having been done largely by irresponsible parties, who were interested merely from a commercial standpoint.

Mr. Gilbert in 1896¹ stated that "no iron has been found within the crater, but a great number of fragments were obtained from the outer slopes, where they rested on the mantle of loose blocks. Many others were obtained from the plain within the region of scattered débris, and others, though a smaller number, from the outer plain. One large piece was discovered 8 miles east of the crater, or almost twice as distant as any fragments of the ejected limestone. Another was long ago discovered 20 miles to the southward, but what became of it is not known and it has not been definitely identified as a member of the same meteoric shower."

Mr. Tilghman, writing ten years later (1906), and after the work of development had been some time under way, says: "In the last two years the author and the men in his and Mr. Barringer's employ have picked up more than 2,000 such irons, ranging in weight from 200 pounds down to a small fraction of an ounce, and have platted the position of these finds upon a chart, which shows plainly that the principal locality for such finds is in the shape of a crescent surrounding the hole and strictly concentric therewith, and embracing its edges from the northwest to the east, and having its line of greatest density about midway between these two points."

Mr. Barringer, in the same publication, states that four irons, weighing from 3 to 4 pounds each, have been found on the interior of the crater, and "so far as I know, these are the only iron specimens which have been found inside the crater."

It is obvious, from a consideration of these statements, that nothing regarding the direction of the flight of the meteors can be gained from a study of their present distribution, it being a well-known fact that in all recorded showers the larger members have been carried the farthest, so that a gradual assortment in sizes takes place along the line of flight.²

The evidence of the crater walls, however, seems to at least sug-

¹ Op. cit., p. 16.

² It may be well to state that a 960-pound mass in the National Museum, purchased in 1893 from parties at Winslow, Arizona, was reported as having

gest that if due to impact of a bolide, the same came from a direction a little north of west, though at a very high angle, perhaps not less than 70° . Proof of this lies in the greater amount of shattering and upturning shown by the beds in the eastern wall of the crater (see typical east and west section, station 18), and in the greater distance to which débris has been thrown to the east as compared with that in any other direction.

These irons it should be stated, have all been found near, and in many cases actually on, the surface. At most they have been buried scarcely enough to cover, and in the case of most of those found have been in part uncovered by wind or water erosion. It is the writer's opinion, based upon an examination on the ground, that a very large proportion of them were buried to a slight depth, and are being gradually brought to the surface through the action of the wind blowing away the finer and lighter material from around them, or, on the slopes of the crater in particular, by the rush of water from the spasmodic rains. As found, but a small portion of an iron projects above the surface, and, being of a rusty brown gray color, is easily passed over by any one not experienced in hunting them. When embedded they are covered with but a slight coating of oxide, though usually more or less incrustated, particularly on the lower sides and edges, with carbonate of lime. A cut section of what may be called the typical iron is shown in plate LXXIV. It is characterized, as long since noted by Brezina,¹ by a coarsely lamellar structure composed of broad plates of kamacite with very little tænite and occasional nodules or troilite.

Chemical and Mineralogical Properties.—The chemical, physical, and mineralogical properties of the iron have been discussed by several workers, the chief interest naturally centering around the occurrence of the diamond. Foote in his paper announced that the iron contained (1) small diamonds, both black and white; (2) carbon in the form of pulverulent iron carbide, the precise nature of which was not made out; (3) sulphur; (4) phosphorus; (5) nickel; (6) cobalt, and (7) silicon. Huntington, the year following, described somewhat briefly, and in 1894² more in detail, the methods and re-

been found in a canyon at Peach Springs. This statement I have not been able to substantiate, not being able to get into communication with the parties mentioned. Peach Springs is at least 100 miles west of the crater. Knowing what he does of the conditions existing at the time the iron was purchased, the writer feels justified in believing the source as given to be erroneous, and that the iron actually came from near the crater.

¹ Wien Sammlung, 1895, p. 288.

² Proc. American Acad. Boston, vol. 29, 1894, p. 209.

sults obtained by him in isolating small colorless octahedral diamonds and also yellow and black particles having the hardness of diamond. Other papers by Mallard,¹ Daubree,² Friedel,³ and Moissan⁴ were all confirmatory and corroborative of Huntington's results.

Brezina,⁵ in 1893, noted the finding of the iron (which he wrongly located as in *New Mexico*), and called attention to its crystallographic structure and occurrence about the crater—a fact which raised in his mind the question of the latter being incidental or consequent. In 1895⁶ he returned to the subject, described the external appearance of the iron as found, and noted that natural etched surfaces showed the iron to be composed principally of kamacite plates without appreciable tænite. He noted also the presence of cohenite and troilite-graphite nodules, and that the tænite residues lying parallel with the octahedral faces were as strongly marked as in the freshly etched iron.

Derby, in 1895,⁷ published the results of investigations upon the chemical and mineralogical nature of the iron, and reported the occurrence of tænite, schreibersite (and rhabdite), cohenite, diamonds (probably), and amorphous carbon, with traces of chromium and a relatively high percentage of copper. Analyses of the tænite and schreibersite were given. The form of the irons (see pl. LXXIII), he suggested might be due to their having been "small irregular metallic masses scattered through the stone matrix of a mesosiderite," and he ventured the hypothesis that the mass on arriving in our atmosphere, as a mesosiderite, contained unusually large metallic nodules that became separated by the explosion attending the fall, and probably also by consequent decay and disaggregation of the stony matrix.

Cohen, in 1900 (*Meteoreisen Studien*, XI), made similar examinations with results confirmatory of Derby.

Moissan, in 1904,⁸ published important chemical contributions, giving analyses of the iron and the included troilite nodules, and announced the finding of carbon in three forms—amorphous, as graphite, and the diamond. He also announced the finding in his insoluble residues from the iron of a green mineral in the form of

¹ *Comptes Rendus*, vol. 114, 1892, p. 812.

² *Ibid.*, vol. 114, 1892, p. 812, and vol. 116, 1893, p. 345.

³ *Ibid.*, vol. 115, 1892, p. 1037, and 116, 1893, p. 290.

⁴ *Ibid.*, vol. 116, 1893, p. 288.

⁵ *Ueber Neue Meteoreisen*, 1893.

⁶ *Wien Sammlung*, 1895, p. 288.

⁷ *American Jour. Sci.*, vol. 49, 1895, p. 101.

⁸ *Comptes Rendus*, vol. 139, 1904, p. 773.



ETCHED SECTION OF CANYON DIABLO IRON

hexagonal plates which analysis showed to be a silicide of carbon. Kunz later proposed that this mineral be named *Moissanite*, in honor of its discoverer.

The complete mineralogical composition of the meteorite as given by these various writers, including Mr. Tassin, is, then, as follows:

Nickel iron:

- (1) Kamacite.
- (2) Plessite.
- (3) Tænite.

Phosphide of iron:

- (1) Schreibersite.
- (2) Rhabdite.
- (3) A black phosphide, unidentified.

Carbide of iron:

- (1) Cohenite.
- (2) Graphitic iron (?)

Sulphide of iron:

- (1) Troilite.

Chloride of iron:

- (1) Lawrencite.

Silicide of carbon:

- (1) Moissanite (Moissan).

Carbon:

- (1) Diamonds, colorless, yellow and black.
- (2) Cliftonite.
- (3) Amorphous.
- (4) Graphite.

Silicon (Tassin).

Platinum (Mallett).

Copper (Derby).

Olivine (very rare) (Tassin).

Chromite (Tassin).

Fayalite (?) (Tassin).

Daubreelite (Foote and Derby).

Of the several partial and complete analyses of the iron that have been published, the following are selected, No. 1 being by Moissan, No. 2 by Booth, Garrett, and Blair, and Nos. 3 and 4 by Wirt Tassin, No. 4 being that of a shale-ball iron next to be described:

Constituents.	1.	2.	3.	4.
Fe	95.370	91.396	93.510	94.030
Ni.....	3.945	7.940	5.600	5.320
Co.....			0.044	0.020
Cu.....			Trace.	0.010
P.....	0.144	0.179	0.156	0.235
S.....	Trace.	0.004	0.010	0.005
C.....		0.417	0.512	0.121
Si.....	Trace.	0.047	0.050	0.020
Cl.....			0.000	0.120
Insol.....	0.260			
Total.....	99.719	99.983	99.882	99.881

VI. THE IRON SHALE AND SHALE BALLS

Occurrence, Composition, and Origin.—Scattered over the surface of the plain, and practically coextensive with the iron, are abundant fragments and nodules of brown iron oxide, sometimes stained greenish from the presence of a nickel hydroxide. These, as a rule, have a somewhat shaly or platy structure, the plates sometimes slightly



FIG. 128.

curved, or again, and more rarely, are in the form of flattened ovals sometimes pear-shaped, and invariably deeply cracked and fissured (fig. 128). These shale fragments were noted by Foote in 1891 and their probable connection with the iron suggested. The oval "shale balls" were, however, first noted by Mr. Barringer. That

both have the same origin would seem most probable. Foote described the material as "identical in appearance with an incrustation which covered the surface of some of the irons or filled the pittings in the same." Its occurrence in such large quantities he though indicated that an extraordinarily large mass, of probably 500 or 600 pounds weight (!), had become oxidized while passing through the air, and so weakened that it burst into pieces not long before reaching the earth. It is needless to state that Foote's estimate of the size of the meteoric mass was at least conservative.

Derby, writing in 1895, advocated the idea of the origin of the schistose masses by secondary alteration—*i. e.*, terrestrial weathering. This view was generally accepted, but the question was opened up again through the publication of Messrs. Barringer and Tilghman, the first named, after noting the distribution of the material as coextensive with the iron, stating his belief that it was produced by the heat generated from friction while the meteor passed through the earth's atmosphere. And again (p. 877): "We have assumed that these small particles (*i. e.*, of shale in form of fragments and spherules) once constituted a portion of the great luminous tail of the meteoric body."

Mr. Tilghman puts the matter a little more definitely in stating that it "is fused and massive and at the same time stratified and laminated and in general appearance different from any terrestrial magnetite known, and closely resembles what would be thought, *a priori*, to be the appearance of such a product of iron melted and burned on the surface of a great meteorite in its passage through the air."

In explanation of the term "magnetite" as used by Mr. Tilghman, it may be said that the particles are almost invariably somewhat magnetic—more so, in fact, according to Mr. Barringer, than are the irons themselves. This has led to the assumption that they are composed, in part at least, of iron in the form of magnetite. Nichol's analyses, as given by Farrington,¹ showed the material to consist mainly of iron in the form of FeO and Fe₂O₃ with smaller amounts of the other constituents characteristic of the unaltered material. From these analyses Farrington made the calculation of the constitution of the shale as below:

Limonite	52.99
Magnetite	42.39
Schreibersite	0.64
Graphite	0.15

¹ American Journal Science, vol. xxii, 1906, p. 303.

Lawrencite	0.14
Aragonite	0.80
Andradite	2.45
Quartz	0.21

99.77

The work of Tassin, next to be referred to, throws doubt upon these conclusions, it being claimed that the magnetic character of the shale is due to the minute particles of unaltered schreibersite, already noted. The origin attributed to this oxide, either in the form of fragments or the oval and pear-shaped masses, by the writer is given below in the consideration of—

The Shale Balls.—In the publication by Mr. Barringer reference is made to the finding, principally in pits and open trenches on the north side of the crater rim, of numerous nodular masses of more or less oxidized meteoric material, to which the name “shale balls” was given. These were studied by Merrill and Tassin,¹ the conclusion reached being that such represented chloride-sulphide rich masses of the iron which, through the protective action of the earth, had escaped complete oxidation and afforded an opportunity for the observation of the transition stages (pl. LXXIV). In short, that the iron shale was, as surmised by Derby and others, but a product of natural oxidation, after reaching the ground, of a peculiarly susceptible phase of the iron. Such an origin seemed absolutely proven in cases where a cross-section showed the plates of unoxidized iron phosphide still retaining their original orientation, although the nickel iron had all gone over to the condition of limonite. In many of the smaller blebs no such transition could be observed, and their like origin is assumed from analogy only. It is to be noted that the contention of Messrs. Barringer and Tilghman apparently finds support from Lockyer.²

The relationship of the shale-ball irons to the typical irons is expressed as follows:

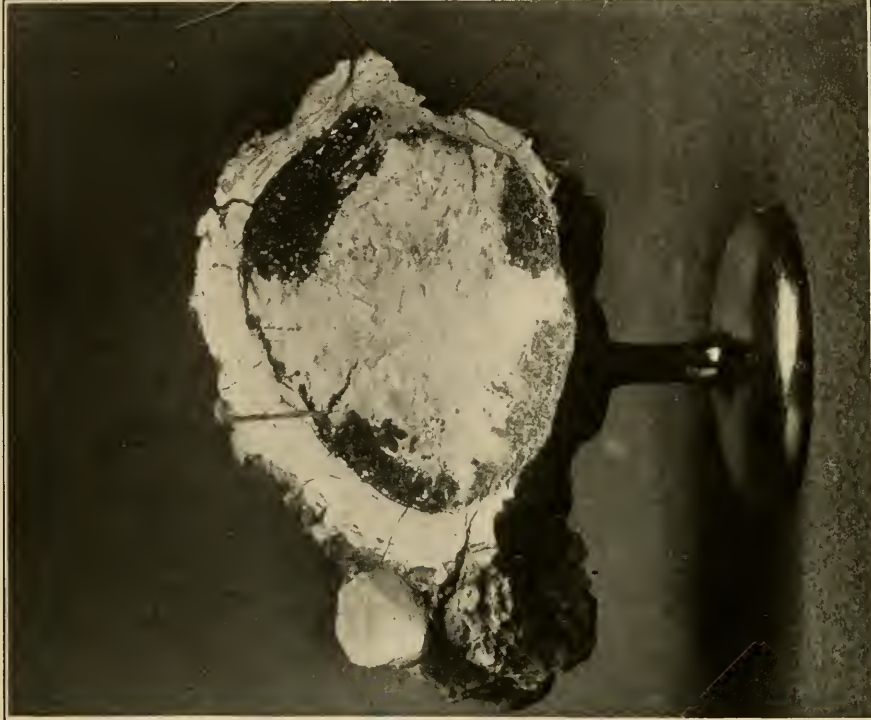
We have therefore come to the conception of a large heterogeneous mass of nickel-iron with segregation masses rich in chlorides, phosphides, and sulphides. Such would naturally rupture most readily along the line of contact with the more homogeneous portions, and, moreover, the results of at-

¹ Smith. Misc. Collections (Quarterly Issue), vol. 50, 1907, p. 203.

² Meteoric Hypothesis, p. 69. He says: “It is natural to suppose that meteors in their passage through the air break into fragments; that incandescent particles of their constituents, including nickel-iron, manganese, and the various silicates, are thrown off, and that these, or the products of their combustion, eventually fall to the surface as almost impalpable dust, among which must be magnetic oxides of iron more or less completely fused.”



1



SHALE-BALL IRONS FROM TRENCHES ON NORTH RIM OF CRATER

2

mospheric frictional heat would ignite and burn away the sulphide portions. Even where the heterogeneous masses of considerable size fall to the earth, it is possible that these susceptible portions would oxidize and wholly disappear, leaving the more refractory to be found later. This would account for the almost constant association of shale and irons of the type shown in plate LXXIII at various points out on the plain.

The occurrence of the still incompletely oxidized forms—shale balls—as described, is due to the protective action of the dry soil in a region of great aridity, the annual precipitation, as recorded by the Weather Bureau, being but about 8 inches. It has been shown that under such conditions soils rarely or never become saturated with moisture for more than a few inches below the surface, and that this moisture is brought back by capillarity and evaporated rather than drained off at lower levels, as in more humid regions. An iron thus buried, even though rich in chloride and sulphide, would endure for a long period.

The connection of the shale balls with the embedding material is noted on page 465.

Analyses of the new variety of the iron and of the shale are given on page 484; those of the three iron phosphides¹ and of cohenite have not been reproduced.

VII. ORIGIN OF THE CRATER

Opinions for and against the Meteoric Hypothesis.—The origin of the crater has been discussed or suggested from time to time by various authors. So far as I am aware or as shown by the literature, the first hypothesis that need be taken seriously is that put forward by Mr. W. D. Johnson,² who concluded from a somewhat superficial study that “in some way, probably by volcanic heat, a body of steam was produced at a depth of some hundreds or thousands of feet, and the explosion of this steam produced the crater.” In this view the occurrence of the meteoric irons was of course merely a coincidence.

Mr. Gilbert, at whose request Mr. Johnson had made the preliminary studies, acknowledged himself as not quite satisfied with these conclusions, and in the summer of 1892 undertook, in coöperation with the late Marcus Baker, a more detailed study of the region. In connection with these studies there was prepared by Mr. Baker the topographic map, a copy of which is here reproduced.³ An excellent series of photographs were also taken, a part of which is here utilized,

¹ Derby thought to find three forms in the typical iron also.

² See Gilbert, *op. cit.*, p. 9.

³ For a redrawing of this map from a reduced photographic copy I am indebted to the U. S. Geological Survey.

and several petrographic and chemical analyses made, all of which have been put at my disposal. Mr. Gilbert, in the systematic and conservative manner for which he is noted, considered the problem from various standpoints, and particularly with reference to the theories of its having been formed by the (1) "collision and penetration of a stellar body"—*i. e.*, by a meteorite, and (2) by steam explosion. In the light of the evidence then available, Mr. Gilbert did not feel justified in adopting the meteoric hypothesis, and, as the only available alternative, was forced to adopt the second mentioned above, though those who know Mr. Gilbert thought to read in his report a strong leaning toward the first mentioned, abandoned only because not borne out, so far as he could see, by the facts. His failure to recognize the tendency of Mr. Diller's studies is not so strange when it is recalled that but a few fragments of the fused material had then been found scattered over the plain, and with no certain connection with the crater. It was not until more was discovered in the work of prospecting, at a depth of several hundred feet below the surface, that its full significance was realized.

Though a matter of frequent discussion among those more or less conversant with the facts, nothing of value relating to the subject appeared until 1905, when Messrs. D. M. Barringer and B. C. Tilghman presented their results before the Philadelphia Academy of Science.¹ Mr. Barringer described the crater and the character of the ejectamenta in great detail, laying particular stress upon the "silica," or pulverized sand grains (rock-flour), derived from the sandstone. He reviewed the work of Gilbert and thought to prove (p. 885): (1) that a great meteor, wholly or in part metallic, fell to the earth at this locality, and (2) that the crater was made by and at the instant of time of the fall of this meteor. Mr. Tilghman dis-

¹ Coon Mountain and Its Crater, by Daniel Morean Barringer; Coon Butte, Arizona, by Benjamin Chew Tilghman. Proc. Acad. Nat. Science of Phila., December, 1905. Issued March 1, 1906, pp. 861-914. It may be well to state in this connection that Mr. Barringer is a well-known and successful mining engineer and joint author with J. S. Adams of a work on Laws of Mines and Mining in the United States. Mr. Tilghman, on the other hand, is a high authority on velocity and impact of projectiles. These gentlemen, basing their preliminary operations upon reports of Mr. S. J. Holsinger, took the necessary steps to locate the "mountain" under the U. S. mining and land laws, and proceeded to bore and sink shafts in and about the crater, with a view of locating the fallen body, which they believed to lie there, desiring to exploit it as a source of nickel, iron, and platinum. The conclusions regarding the origin of the crater, now arrived at, are based, so far as the present writer is concerned, almost wholly upon results obtained in these mining operations.

cussed the physical aspects of the crater with reference to its similarity to those produced by projectiles, and also discussed Mr. Gilbert's hypothesis, the distribution of the iron and magnetic oxide about the hole, the crater rim and interior, and the disintegrated sandstone. His conclusions were that (p. 910): (1) at this locality there is a great hole or crater corresponding in all respects except size with impact craters formed by projectiles of considerable size moving at considerable velocities; (2) that in and about the hole and to a distance of over 1,400 feet below the present surface of the plain "every indication of either volcanic or hot-spring action was positively absent;" (3) that all signs which might be expected of the impact of a great projectile were present; (4 and 5) that the meteoric material scattered about the hole and over the plain was deposited at the same instant of time at which the hole was made; (6) that in and around the hole is a quantity of material such as could be produced only by a violent blow; and, finally, that all the attendant minor phenomena observed can be explained upon the theory of the impact of a great projectile and none can be satisfactorily explained upon any other theory. In view of these facts, Mr. Tilghman felt himself justified in announcing that the formation of the crater "is due to the impact of a meteor of enormous and hitherto-unprecedented size."

With these conclusions the present writer freely confesses he was not at first inclined to agree. In several minor matters, as that relating to the origin of the iron shale and shale balls, he is still at variance with them; but after going over the ground with both gentlemen, noting the results of the borings, and restudying the problem from all standpoints, he gives the following summary of his conclusions:

VIII. SUMMARY

Consideration of Evidence.—So far as shape is concerned, the crater could have been formed equally well by blow-out or impact.

The character of a portion of the ejected material points, however, strongly to an origin by impact. It is difficult, if not impossible, to conceive of the smashing and metamorphism of the sandstone on any other ground. The sand grains are crushed in a manner that could be brought about only by some sudden shock, such as might possibly be imparted by an explosion of dynamite, but certainly not by steam. The secondary foliation at an angle with the bedding and the condition of molecular strain of the altered quartz indicates pressure, while the fused quartz indicates great heat. The latter

might be due either to impact or to vulcanism. The association of the fused pumiceous masses with the smashed material, together with the transition of one form into another, is such as to suggest a common origin for both.

The slightly disturbed and unchanged condition of the deeper-lying sandstone seems to prove the superficial character of the phenomena. Where disturbed, the beds apparently dip downward, as though forced out of position by some power acting from above. This apparently prohibits the consideration of a deep-seated cause. There being nothing in the beds themselves to bring about such results, one is forced to the consideration of an extraneous source; and, if extraneous, I can conceive of but two—the electric and meteoric. Of these, only the latter seems worthy of serious consideration.

Velocity of Meteorites and Possible Depth of Penetration.—Unfortunately we have little to guide us in estimating the speed at which a meteorite reaches the earth and its consequent power of penetration. The velocities as given by various observers vary between 2 and 45 miles per second. These last, however, are the initial velocities, the velocities possessed by the meteors on entering our atmosphere and while still at considerable altitudes—in some instances 50 or 60 miles—and which become very materially reduced by atmospheric friction long before reaching the earth. Indeed, from the calculations of Schiaparelli and others, it is commonly assumed that a meteorite reaches the surface at the speed of an ordinary falling body. A. Herschell, as quoted by Flight,¹ calculated the velocity of the Yorkshire (England) meteorite at the time it reached the ground as but 412 feet a second. The Guernsey, Ohio, meteorite was estimated by Prof. E. W. Evans² to have reached the earth while traveling at a speed of 3 or 4 miles a second; that of Weston, Connecticut, while at a height of some 18 miles, was estimated by Professor Bowditch³ to have a velocity of 3 miles per second. Newton⁴ calculated the speed of the fire-balls which passed over the Ohio and Mississippi Valley in August, 1860, as 30 to 35 miles per second, and stated⁵ that the Stannern, Moravia, stone came into our atmosphere with a velocity of 45 miles per second. These higher velocities are

¹ A Chapter on the History of Meteorites, p. 219.

² Amer. Jour. Science, vol. 33, 1861, p. 30.

³ Mem. Amer. Acad. Arts and Sci., vol. 3, 1815, p. 213.

⁴ Amer. Jour. Sci., vol. 33, 1862, p. 338.

⁵ Amer. Jour. Sci., vol. 36, 1888, p. 11.

doubtless those of bodies pursuing a retrograde course about the sun.

The evidence afforded by actual falls and impacts is extremely contradictory. Thus Nordenskiöld¹ states that, in the case of the Hessle fall, stones so friable as to be readily broken if simply thrown against a hard surface were not broken or even scarred on striking the frozen ground. Stones weighing several pounds which struck on ice a few inches in thickness rebounded without breaking the ice or being themselves broken. The 70-pound stone that fell at Allegan, Michigan, in 1899 penetrated the sandy soil to a depth of about 18 inches and was itself considerably shattered. Like that of Hessle, this was an unusually friable stone. It is evident that its speed did not exceed that of a projectile from an old-time piece of heavy ordnance. The 260-pound stone that fell at Ensisheim, Germany, in 1492 is reported to have buried itself to a depth of 5 feet.

The greatest depth of penetration of a meteoric stone which has come under the writer's observation is that of Knyahinya, Hungary, as described by Haidinger.² In this instance a 660-pound stone, striking the ground at an angle of some 27° from the vertical, penetrated to a depth of eleven feet. The hole was nearly circular in outline, and fragments from the interior were thrown back and scattered to a distance of some 180 feet (dreiszig Kläfter). The stone was found broken in three pieces and the earth beneath it compacted to stony hardness, but nothing in the description as given indicates that any traces of metamorphism, either in the ground or mass of the stone, had taken place. On the other hand, still heavier masses have been found under such conditions as to lead one to infer they scarcely buried themselves.

Peary's giant Cape York iron, weighing 37½ tons, was found only partially covered; but, as it lay on a bed of gneissic boulders, this is not strange. It should be remarked, however, that an examination of the iron reveals no such abrasions of surface as might be expected had it fallen with a speed of miles per second, or, indeed, any abrasions whatever that can be ascribed to such a cause. It is, of course, possible that this fall took place when the ground was

¹Kongl. Svenska Vetenskaps-Akademiens Handlingar, B. 8, No. 9, 1870.

²Sitz. d. k. Akad. d. Wiss, II Abth. B. LIV, 1866. This occurrence illustrates on a small scale so perfectly what is supposed to have happened at the meteor crater that I feel justified in giving here a photographic reproduction (fig. 129) of page 20 of Haidinger's paper. The description, beginning with the seventh line from the top, refers to figures 5 and 6.

deeply covered with ice and snow, and its speed was thus checked before coming in contact with the stony matter.¹

The Williamette iron, weighing 15.6 tons, seemingly lay without question as it originally fell, and in a region of no appreciable erosion—rather, one of organic deposition, for it was found lying in a primeval forest; yet the mass was scarcely buried, a small projecting portion leading to its discovery.

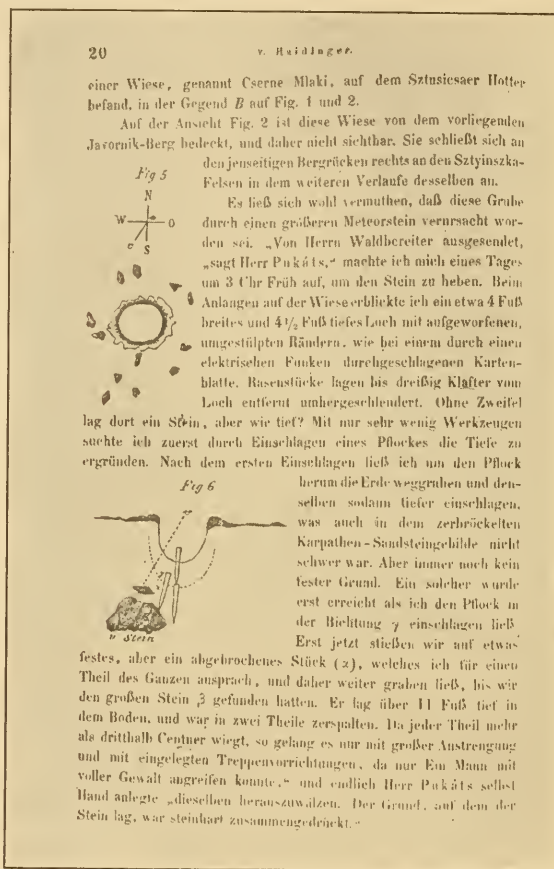


FIG. 129.—Page from von Haidinger's description of Knyahinya meteorite. Shows formation of small crater. See footnote, p. 491.

The Bacubirito iron, weighing at a rough estimate 20 tons, lay in a soft soil, with its surface but little below the general surface of the field around it.

¹Mr. Tilghman informs me that lead bullets from a modern rifle may be completely checked in traversing a few feet of light snow, and this, too, without the slightest appreciable deformation or surface abrasion.

These illustrations are sufficient to show the contradictory nature of the evidence. Such contradictions can be partially explained by taking into consideration the varying angles at which the meteorites come in contact with the earth and the direction of their flight. One falling from a great height almost vertically would naturally have a greater power of penetration than one coming at a low angle. More important yet is the direction of flight of the meteor with reference to the earth. If following the earth in its course about the sun, the apparent speed would be but differential. Thus a meteorite with a velocity of 25 miles per second overtaking the earth traveling at the rate of 19 miles per second would enter our atmosphere with an initial speed of but 6 miles per second, and this through atmospheric friction would be so far reduced as to give the lower figures above mentioned, or the speed of an ordinary falling body. In the case of a meteorite pursuing a retrograde course, conditions are greatly exaggerated. With a velocity of 25 miles a second, it meets the earth traveling in the opposite direction at the rate of 19 miles per second, and hence enters our atmosphere with an initial velocity of 44 miles per second. Here, as before, the retarding effect of the earth's air cushion must be considered. With such a velocity, friction must be tremendous, and even in the few seconds occupied in its transit large quantities of its material must be dissipated. That such is the case we have unquestionable proof in the luminous trains of meteors, and H. E. Wimperis¹ has calculated that "no iron meteor the original weight of which was less than 10 to 20 pounds reaches the earth's surface," being entirely consumed in its passage.

Schiaparelli, as quoted by Fletcher,² has shown that if a ball 8 inches in diameter and of $32\frac{1}{2}$ pounds in weight enters our atmosphere with a velocity of $44\frac{3}{4}$ miles per second, its velocity on arriving at a point where the barometric pressure is still but $1/760$ of that at the earth's surface will have been already reduced to $3\frac{1}{2}$ miles a second—figures which correspond fairly well with the estimates made on the flight of the Weston and Guernsey stones.

Dr. R. S. Woodward, as quoted by Mr. Gilbert,³ has calculated that a body reaching the surface of the moon with a velocity of $1\frac{1}{2}$

¹ Nature, vol. 71, 1904-'05, p. 82. The writer well remarks: "I am aware that the whole structure of the investigation (*i. e.*, his calculations) rests on the evil principle of extrapolation, but until man is capable of experimenting with velocities of 10 or 20 miles per second, and surviving thereafter to record his results, no other manner of investigation seems possible."

² Introduction to the Study of Meteorites, 1896, p. 26.

³ The Moon's Face, Bull. Philosophical Soc. of Washington, vol. xii, 1893, p. 258.

miles per second would, if all the equivalent energy were converted into heat and all stored in the mass of the falling body, suffice to raise its temperature, supposing it to consist of ordinary volcanic rock, through 3,500 degrees of the Fahrenheit scale, or within 400 degrees of the temperature necessary to fuse quartz. How far these results are applicable to the case in hand is problematical, since, as Huxley has remarked, "what one gets out of the mathematical mill will depend upon what is put in it," and in this particular case both the size and velocity of the body must be assumed, and to a certain extent its composition as well. We have, however, unquestionable proof of a force of impact sufficient to crush a mass of limestone 300 feet in thickness, which has been shown by tests on cubes of but one inch in diameter to possess an average crushing strength of 12,595 pounds per square inch of surface, and of sandstone 500 feet in thickness capable of withstanding a pressure of 6,350 pounds;¹ and this, too, with a production of heat equivalent to the 3,900°, or fusing point of quartz, above noted. It is well-nigh impossible, however, that a force so great, and applied, as is apparent, in an instant of time, should not have been productive of an amount of heat so vastly greater than 3,900° that its expression in figures would be utterly meaningless and incomprehensible, and in the writer's mind the greatest difficulty in accepting the meteoric hypothesis lies in the absence of sufficient evidences of such extreme temperatures. There are no volatilization products and but slight evidence of slags among the products thus far brought to light. Only the fused quartz remains as a tangible proof.

The formation of the crater rim and the presence of the enormous blocks of stone therein may, as above noted, be explained on either the blow-out or impact hypothesis. The presence in this rim of blocks of the altered sandstone, both pumiceous and of the white or "ghost," variety, and the presence of the shale-ball irons embedded in the heterogeneous mass of rock detritus to a depth in some cases of upward of 20 feet, can not be satisfactorily accounted for on the blow-out hypothesis. To explain these phenomena, the following is presented:

Hypothetical Considerations and Conclusion.—Let one conceive of a spheroidal mass of meteoric iron, perhaps 500 feet in diameter, falling upon the earth at a speed of 5 miles per second. The superficial rocks are crushed and thrown back upon the plain in an amount more than equal to the bulk of the meteorite. Mr. Tilgh-

¹ For these determinations I am indebted to Mr. L. W. Page, of the Bureau of Roads, Department of Agriculture.

man, an authority on impact of projectiles from heavy ordnance, has estimated that in rocks as brittle as those of this particular vicinity the crater formed would be eight to ten times the diameter of the projectile; that is, with a 500-foot projectile the crater might be 4,000 feet in diameter, which is approximately that of the existing crater. As depths below the surface increased, the upward escape of material around the mass would be impeded, and that directly in its path and, to a less extent, that on either side would become enormously compacted. The heat generated by the sudden downward plunge of the body would produce fusion and probably a partial volatilization, and where sufficient moisture was present, other conditions being favorable, would give rise to the pumiceous structure found in the altered sandstone. But certain after-effects must be taken into consideration. That there was moisture is evident by the existence of the pumice. The effect of the impact would be to convert almost instantly this moisture into steam with an enormous explosive power. As a result, quantities—the amount being dependent upon the amount of water—of débris, including even portions of the meteoric fall itself would be ejected and thrown back above the crater rim and scattered widely over the plain. It would seemingly be safe to assume a temporary pseudovolcanic condition.

To this cause the writer would ascribe the formation of the peculiar moraine-like mounds shown in plate LXVIII, figure 1, and indeed all those heterogeneous deposits, composed of rockflour and fragments of limestone and sandstone (a portion of the latter metamorphosed), in which the shale-ball irons are embedded. It is impossible to account for the position of these last in any other way than to assume that they fell at the same period of time as the material in which they lie embedded. The difference in specific gravity of the various materials is such that it is inconceivable that they should have traveled together for any great distance. Their association may be best explained on the assumption that all were poured out together over the crater rim, perhaps in the condition of mud, during this pseudo-volcanic stage. Only on this ground likewise is it possible to explain the presence in these deposits of masses of the altered sandstone. These, seemingly, must have been formed by heat and pressure well down toward the bottom of the crater, and have been brought back to the surface through explosive action, which took place some little time after the meteor came to rest. What proportion of the irons scattered over the plains are the result of this secondary effect one can only surmise. The fact that there is seemingly no regularity in their distribution—as is almost universally the case in

meteoric showers, and, in addition, no gradation in size along the supposed line of flight, nor evidence of atmospheric friction upon their surfaces—favors the idea that *all* were thrown out, and it is not impossible that practically the entire mass not dissipated by volatilization was thus ejected. It should be remarked, in this connection, that a most liberal estimate of the material carried away by collectors or still remaining as shale on the plain would scarcely account for a thousandth part of a mass sufficient to form the crater.

The failure thus far to find a large intact mass within the crater might be further explained on the ground that a considerable portion of it was volatilized by the intense heat generated at the moment of striking the surface, and the comparatively small residual remaining has largely succumbed to oxidation. It must be remembered, however, that the method of borings, whereby the materials are brought to the surface by a stream of water forced downward through the drill-pipe is such as to practically preclude the securing of particles of metallic iron of any but the smallest sizes. Even if permitted by the dimensions of the hole, their high specific gravity would cause them to be left behind, and only the lighter sand grains and more minute particles would be brought to the surface.

The work thus far done does not, therefore, disprove the presence of a large quantity of fragmental iron, although tending to show that no large mass lies there buried. It is possible, too, that the estimated size of the body making the crater is an exaggeration, since if, as seems probable, volatilization of a considerable portion followed immediately upon striking the ground, the outrush of vapor due to the enormous expansion in passing from the solid to the gaseous condition would certainly have served to tear away the rock and increase the diameter to an extent that we have no means of estimating.

ACKNOWLEDGMENTS

This investigation detailed above has been rendered possible only through the generous and hearty coöperation of Messrs. Barringer and Tilghman, to whom reference has been made so repeatedly that further allusion seems almost superfluous. To Mr. G. K. Gilbert the writer is also indebted for notes, maps, and other materials collected at the time of his studies. To the U. S. Geological Survey he is indebted for prints from Mr. Gilbert's negatives, for a re-drawing of the contour map, and for the photomicrographs reproduced in plate LXX. Mr. Holsinger, manager at the crater, has kindly forwarded material as requested and furnished photographs

and important data, and Mr. Tassin, of the Division of Mineralogy, has allowed the use of his unpublished chemical notes.

The investigations in the field were conducted under the auspices of the Smithsonian Institution. A set of specimens of the meteoric irons, altered sandstones, and associated products has been deposited by Messrs. Barringer and Tilghman in the U. S. National Museum, where it is now on exhibition.

U. S. NATIONAL MUSEUM, *November, 1907.*

EXPLANATION OF PLATES

PLATE LXI

- FIG. 1. View of crater rim from the northeast.
2. View of crater rim from the south.

PLATE LXII

- FIG. 1. View on outer slope of east rim of crater, looking southward.
2. A limestone boulder on outer slope of east rim of crater. Dimensions, 148 feet in circumference at the ground, 23 feet high on west side, 30 feet high on east side. Approximate weight, 3,000 tons.

PLATE LXIII

- FIG. 1. View looking northward along crest of west rim of crater.
2. View looking northward along crest of west rim of crater, showing width of crest.

PLATE LXIV

- FIG. 1. View looking across the crater; from low place in northern side of rim.
2. View looking across and into the crater; from the south.

PLATE LXV

- FIG. 1. Near view of interior wall of crater, looking northward.
2. View looking across the crater from the north and showing the faulting (directly beneath arrow) in southern rim.

PLATE LXVI

Contour map of crater

PLATE LXVII

- FIG. 1. Dry wash on south side of outer rim, showing seven-foot bank of rock-flour.
2. Whale Rock, a limestone boulder on outside of west rim. Dimensions, 88 feet in circumference at the ground and 38 feet in maximum height. Approximate weight, 1,500 tons.
3. Largest boulder on rim of crater, west side.

PLATE LXVIII

- FIG. 1. Moraine-like hills on outer slope of northern rim of crater.
 2. Near view of interior walls of crater, with talus and alluvial fans from the cliffs.

PLATE LXIX

View in interior of crater showing nearly level floor; looking south.

PLATE LXX

View in interior of crater showing a near view of south wall.

PLATE LXXI

Microstructure of gray sandstone

- FIG. 1. The unaltered sandstone.
 2. First and partial phase of alteration.
 3. Completely metamorphosed sandstone.
 4. Quartz glass formed by fusion of sandstone.
 5. A highly magnified portion of No. 3, showing curved cleavage lines.

PLATE LXXII

Altered sandstone from shafts inside of crater

- FIG. 1. Completely metamorphosed sandstone, with secondary platy structure at right angles to bedding.
 2. Fused and slightly pumiceous sandstone, almost wholly glass.
 3. Pumiceous sandstone, almost wholly glass.
 4. Coarsely pumiceous sandstone, almost wholly glass.

PLATE LXXIII

Typical forms of Canyon Diablo meteoric irons

PLATE LXXIV

Etched section of Canyon Diablo iron

PLATE LXXV

Shale-ball irons from trenches on north rim of crater

- FIG. 1. Ball consisting of residual nucleus of metallic iron, with adhering fragments of sandstone and limestone.
 2. Shale ball cut in halves and showing metallic nucleus, with its crust of iron shale.

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