METEOR CRATER

(FORMERLY CALLED COON MOUNTAIN OR COON BUTTE)

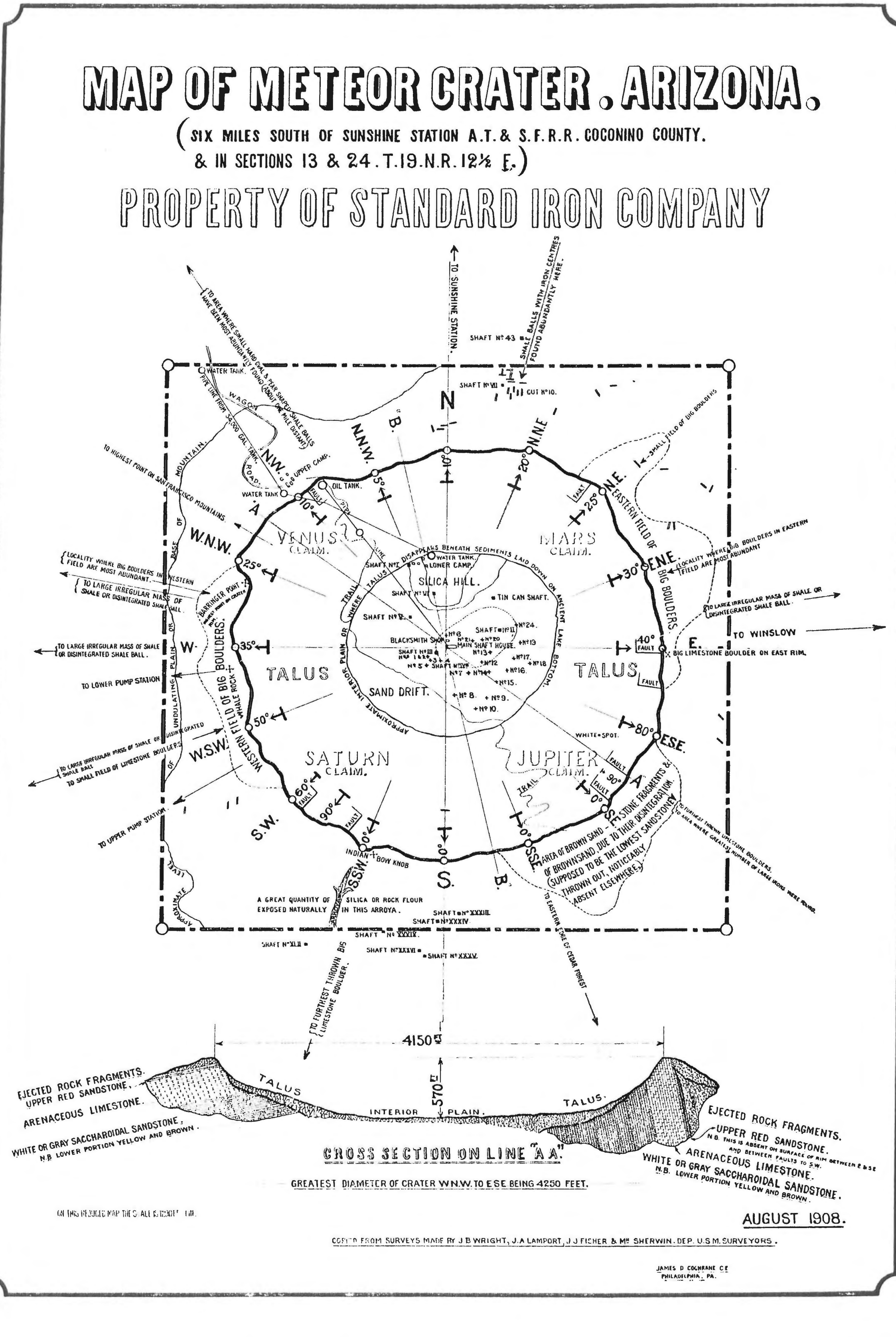
IN

NORTHERN CENTRAL ARIZONA

BY

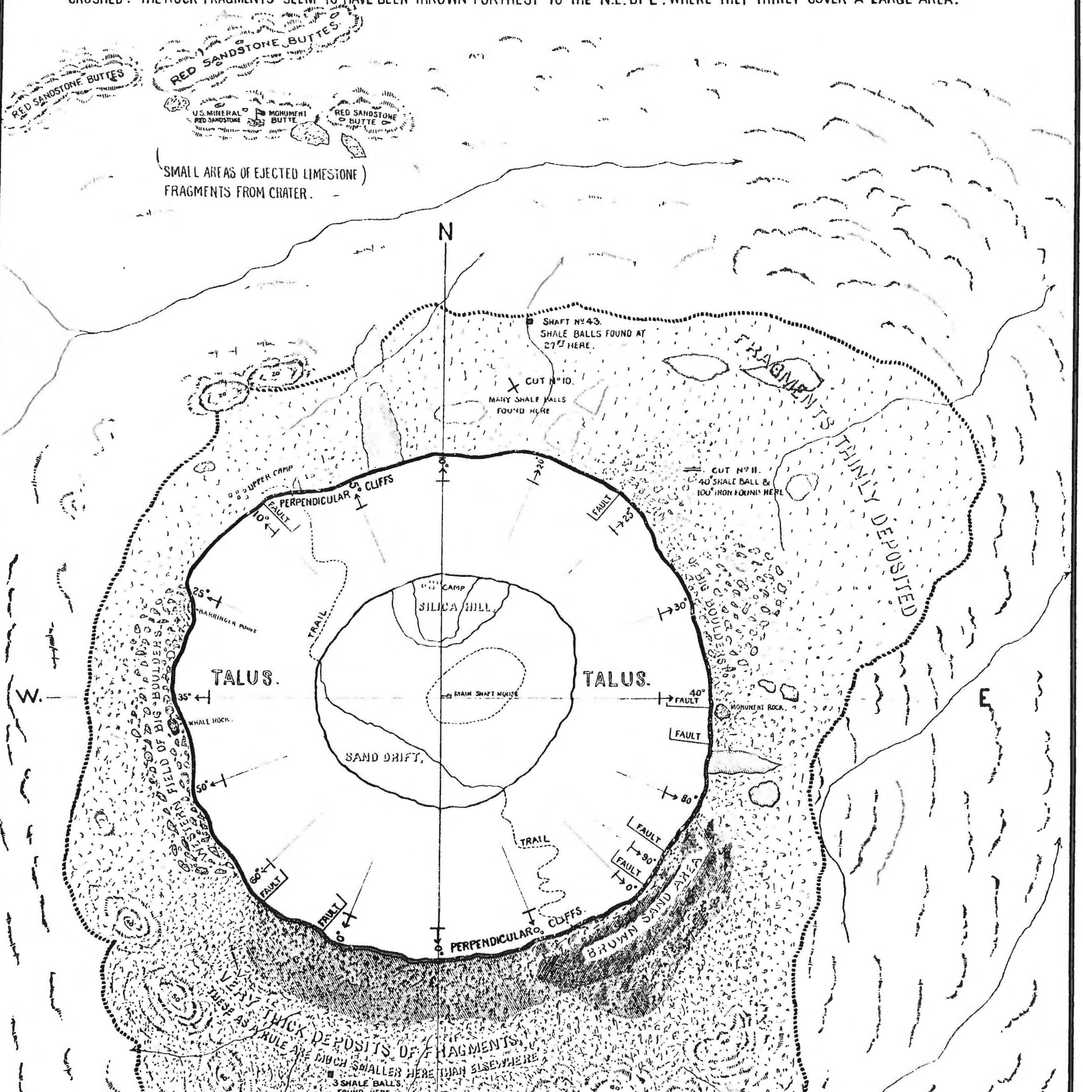
D. M. BARRINGER

This paper was read before the National Academy of Sciences at its Autumn Meeting at Princeton University, November 16th, 1909.


MAP OF METEOR CRATER, ARIZONA.
(SIX MILES SOUTH OF SUNSHINE STATION A.T. & S.F.R.R. COCONINO COUNTY.
& IN SECTIONS 13 & 24. T.19.N.R.12½ E.)
PROPERTY OF STANDARD IRON COMPANY
TO SUNSHINE STATION.
SHALE BALLS WITH IRON CENTRES FOUND ABUNDANTLY HERE.
TO AREA WHERE SMALL HARD OVAL & PEAR SHAPED SHALE BALLS HAVE BEEN MOST ABUNDANTLY FOUND (ABOUT ONE MILE DISTANT)
SHAFT Nº 43
SHAFT Nº VII
CUT Nº 10.
WATER TANK.
PIPE LINE FROM 50,000 GAL. TANK.
WAGON ROAD.
UPPER CAMP.
TO HIGHEST POINT ON SAN FRANCISCO MOUNTAINS
BASE OF MOUNTAIN.
N.
N.N.W.
N.N.E.
N.W.
N.E.
W.N.W.
E.N.E.
W.
E.
W.S.W.
E.S.E.
S.W.
S.E.
S.S.W.
S.S.E.
S.
A
B.
OIL TANK.
WATER TANK
VENUS CLAIM.
MARS CLAIM.
SATURN CLAIM.
JUPITER CLAIM.
SMALL FIELD OF BIG BOULDERS
EASTERN FIELD OF BIG BOULDERS.
LOCALITY WHERE BIG BOULDERS IN EASTERN FIELD ARE MOST ABUNDANT
LOCALITY WHERE BIG BOULDERS IN WESTERN FIELD ARE MOST ABUNDANT.
TO LARGE IRREGULAR MASS OF SHALE OR DISINTEGRATED SHALE BALL.
BARRINGER POINT
WESTERN FIELD OF BIG BOULDERS.
WHALE ROCK
TO WINSLOW
BIG LIMESTONE BOULDER ON EAST RIM.
TO LOWER PUMP STATION
TO UPPER PUMP STATION
TO LARGE IRREGULAR MASS OF SHALE OR DISINTEGRATED SHALE BALL
TO SMALL FIELD OF LIMESTONE BOULDERS
UNDULATING PLAIN
APPROXIMATE LEVEL
LINE WHERE TALUS DISAPPEARS BENEATH SEDIMENTS LAID DOWN ON ANCIENT LAKE BOTTOM.
APPROXIMATE INTERIOR PLAIN
TRAIL
WATER TANK.
LOWER CAMP.
SILICA HILL.
TIN CAN SHAFT.
BLACKSMITH SHOP
MAIN SHAFT HOUSE.
SAND DRIFT.
TALUS
FAULT
WHITE SPOT.
AREA OF BROWN SAND-STONE FRAGMENTS & OF BROWN SAND DUE TO THEIR DISINTEGRATION. (SUPPOSED TO BE THE LOWEST SANDSTONE) THROWN OUT, NOTICEABLY ABSENT ELSEWHERE.
TO FURTHEST THROWN LIMESTONE BOULDERS. TO AREA WHERE GREATEST NUMBER OF LARGE IRONS WERE FOUND.
INDIAN BOW KNOB
A GREAT QUANTITY OF SILICA OR ROCK FLOUR EXPOSED NATURALLY IN THIS ARROYA.
SHAFT Nº XXXIII
SHAFT Nº XXXIV
SHAFT Nº XXXIX
SHAFT Nº XLII
SHAFT Nº XXXVI
SHAFT Nº XXXV
TO EASTERN EDGE OF CEDAR FOREST
TO FURTHEST THROWN BIG LIMESTONE BOULDER.
4150 FT
570 FT
TALUS
INTERIOR PLAIN.
EJECTED ROCK FRAGMENTS.
UPPER RED SANDSTONE.
ARENACEOUS LIMESTONE.
WHITE OR GRAY SACCHAROIDAL SANDSTONE. N.B. LOWER PORTION YELLOW AND BROWN.
N.B. THIS IS ABSENT ON SURFACE OF RIM BETWEEN E & SE AND BETWEEN FAULTS TO S.W.
CROSS SECTION ON LINE "A A"
GREATEST DIAMETER OF CRATER W.N.W. TO E.S.E. BEING 4250 FEET.
AUGUST 1908.
COPIED FROM SURVEYS MADE BY J.B. WRIGHT, J.A. LAMPORT, J.J. FISHER & Mr SHERWIN. DEP. U.S.M. SURVEYORS.
JAMES D. COCHRANE C.E. PHILADELPHIA, PA.

ROUGH SKETCH MAP SHOWING DISTRIBUTION OF MAJOR PORTION OF FRAGMENTARY MATERIAL EJECTED FROM METEOR CRATER, ARIZONA.

N.B. SOME ROCK FRAGMENTS HAVE BEEN THROWN AS FAR AS TWO MILES FROM THE CRATER. THIS MAP MERELY SHOWS MANNER OF DISTRIBUTION AND RELATIVE QUANTITY OF MATERIAL NEAR THE CRATER. VERY MUCH MORE MATERIAL HAS BEEN THROWN TO THE SOUTH (GENERALLY SPEAKING) THAN ELSE WHERE, I.E. THE MASS OF ROCK FRAGMENTS IS MUCH THICKER THERE THAN ELSEWHERE AND THE ROCK HAS BEEN MORE FINELY CRUSHED. THE ROCK FRAGMENTS SEEM TO HAVE BEEN THROWN FURTHEST TO THE N.E. BY E. WHERE THEY THINLY COVER A LARGE AREA.



LEGEND.

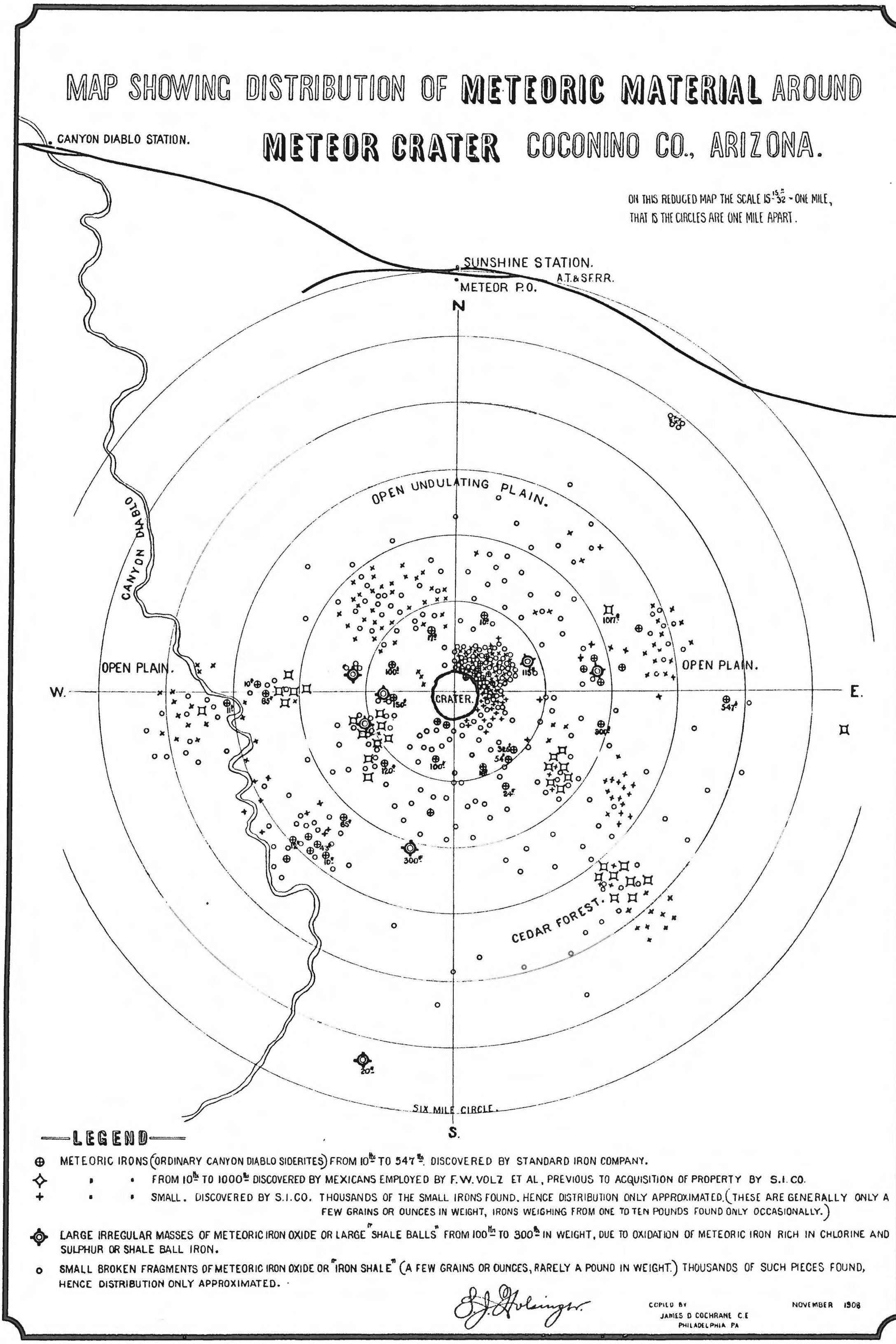
- CRATER RIM.
- LOWER LIMIT OF BULK OF EJECTED MATERIAL WHICH FORMS TO A LARGE EXTENT THE SO CALLED MOUNTAIN. THIS LINE NECESSARILY APPROXIMATE.
- LIMESTONE FRAGMENTS, THE MOST COHERENT ROCK THROWN OUT OF THE CRATER.
- FIELDS OF BIG LIMESTONE BOULDERS ON THE EAST AND WEST SLOPES OF THE MOUNTAIN.
- WHITE OR GRAY SACCHAROIDAL SANDSTONE FRAGMENTS. THESE FREQUENTLY SHOW CROSS BEDDING.
- BROWN SANDSTONE FRAGMENTS & BROWN SAND DUE TO THEIR DISINTEGRATION. MUCH OF THIS SAND HAS BEEN DRIFTED TO THE EASTWARD BY THE PREVAILING WINDS.
- THIN SHEETS OR INDIVIDUAL MASSES OF EJECTED LIMESTONE FAR OUT ON THE PLAIN. THESE SCATTERED FRAGMENTS ARE FOUND 1½ MILES FROM THE CRATER RIM TO N.E.— 1¾ TO 2 MILES EAST AND ABOUT ONE MILE S.E.— MAP TOO SMALL TO SHOW THEIR DISTRIBUTION EXCEPT IN A GENERAL WAY.

ON THIS REDUCED MAP THE SCALE IS 1250 FT = 1 IN.

S. J. Holsinger

COPIED BY JAMES D. COCHRANE C.E. PHILADELPHIA, PA.

NOVEMBER 1909


MAP SHOWING DISTRIBUTION OF METEORIC MATERIAL AROUND
METEOR CRATER COCONINO CO., ARIZONA.
CANYON DIABLO STATION.
ON THIS REDUCED MAP THE SCALE IS 15/32" = ONE MILE,
THAT IS THE CIRCLES ARE ONE MILE APART.
SUNSHINE STATION.
A.T.&S.F.R.R.
METEOR P.O.
N
OPEN UNDULATING PLAIN.
CANYON DIABLO
OPEN PLAIN.
OPEN PLAIN.
W.
E.
CRATER.
CEDAR FOREST.
SIX MILE CIRCLE.
S.
LEGEND
METEORIC IRONS (ORDINARY CANYON DIABLO SIDERITES) FROM 10 lbs TO 547 lbs. DISCOVERED BY STANDARD IRON COMPANY.
" " FROM 10 lbs TO 1000 lbs DISCOVERED BY MEXICANS EMPLOYED BY F. W. VOLZ ET AL, PREVIOUS TO ACQUISITION OF PROPERTY BY S. I. CO.
" " SMALL. DISCOVERED BY S. I. CO. THOUSANDS OF THE SMALL IRONS FOUND. HENCE DISTRIBUTION ONLY APPROXIMATED. (THESE ARE GENERALLY ONLY A FEW GRAINS OR OUNCES IN WEIGHT, IRONS WEIGHING FROM ONE TO TEN POUNDS FOUND ONLY OCCASIONALLY.)
LARGE IRREGULAR MASSES OF METEORIC IRON OXIDE OR LARGE "SHALE BALLS" FROM 100 lbs TO 300 lbs IN WEIGHT, DUE TO OXIDATION OF METEORIC IRON RICH IN CHLORINE AND SULPHUR OR SHALE BALL IRON.
SMALL BROKEN FRAGMENTS OF METEORIC IRON OXIDE OR "IRON SHALE" (A FEW GRAINS OR OUNCES, RARELY A POUND IN WEIGHT.) THOUSANDS OF SUCH PIECES FOUND, HENCE DISTRIBUTION ONLY APPROXIMATED.
COPIED BY
JAMES D. COCHRANE C.E.
PHILADELPHIA PA
NOVEMBER 1908

METEOR CRATER

(FORMERLY CALLED COON MOUNTAIN OR COON BUTTE)

IN NORTHERN CENTRAL ARIZONA.*

It affords me pleasure to attempt to describe briefly some of the features of Meteor Crater, Arizona, the origin of which I have been privileged to be chiefly instrumental in discovering.

I shall subdivide my paper into six headings as follows:

First. Topography and geology of the region immediately surrounding the crater.

Second. Description of the main features of the crater itself, including a description of the ejected rock fragments and of the two kinds of metamorphosed sandstone known to us as "Variety A" and "Variety B."

Third. The kinds of meteoric iron and meteoric iron oxide found on the outside plain and among the ejected rock fragments on the outer slopes of the crater rim.

Fourth. The kinds of meteoric material which have been found to exist in the depths of the crater.

Fifth. Conclusions.

Sixth. What has become of the projectile?

TOPOGRAPHY AND GEOLOGY.

The topography immediately around the crater is that of a more or less level rocky plain with a very thin covering of soil. In places the soil is entirely absent, owing largely to the violent winds which prevail at certain seasons of the year. There are no trees on this plain except many stunted cedars on a rather large area, several miles to the south, and except a sparse growth of cottonwoods and walnuts along the water courses. The water flows in torrents through the deep box canyons in the flood season, but for the rest of the year there is little or no water in them, owing to the lack of rain. The slightly rolling plain is sparsely covered by the usual sage brush and grass characteristic of this desert region. Portions of the plain, as in the case of the exact location of the crater, were covered at the time it was made, probably in historical times, as now, by a thin bed of purplish red sandstone having in places a shaly structure. This stratum of sandstone, like all the undisturbed strata underneath it, is horizontal. Other portions of the plain, especially to the westward of the crater, are marked by the outcroppings of the uppermost layers of the underlying Aubrey (Carboniferous) limestone, which is well shown not only in the crater walls, but in the neighboring gorge of Canyon Diablo, two and one-half miles distant to the west. Dotted here and there over the plain, as accidents of erosion, are many small, isolated buttes of the purplish red sandstone showing the contact between it and the limestone. There are no eruptive rocks of any sort nearer than Sunset Mountain some nine miles distant. This is formed by an old volcano and the lava which flowed from it. To the northwest and west some forty odd miles are the San Francisco Mountains, with their numerous craters and the great

---

**This paper was read before the National Academy of Sciences November 16th, 1909.*

flows of lava which poured out from them over the surrounding area of level sedimentary rocks.

The rocks with which we are immediately concerned are, generally speaking, the Grand Canyon series, and are as follows: First, some 40 or 50 feet of the purplish red shaly sandstone above referred to. Underneath this 250 to 300 feet of a yellowish gray, arenaceous limestone. Underneath this there is a stratum of about 1000 feet in thickness (as nearly as we can estimate it) of what we know as the white or gray saccharoidal sandstone, in places cross bedded. This stratum is beautifully shown in the walls of the Grand Canyon of the Colorado some 70 miles distant, and is known there as the White Wall or Cross Bedded sandstone.

As at the Grand Canyon this white or gray sandstone is underlaid by a dark red sandstone stratum, known as the Red Beds or the Red Sands, of about one thousand feet in thickness at the Grand Canyon and of unknown thickness at Meteor Crater.

One point to which I wish particularly to call attention is that we know from our drilling and from the ejected rock fragments that the lower two hundred feet of the white or gray saccharoidal sandstone (which for the greater part of its thickness is a sandstone which is singularly white and of exceptional purity) is largely composed of sand grains of yellowish, and finally immediately above the Red Beds of brownish red color. This point is of importance, as will be seen later. The whole stratum is a loose textured, incoherent sandstone, and this is particularly true, so far as we know, of its lower portions just referred to.

With the much more compact Red Beds sandstone immediately underneath this stratum we are not immediately concerned, for no piece of this stratum has been thrown out to form a part of the great mass of ejected rock fragments comprising in a large measure the elevation formerly known as Coon Mountain or Coon Butte. Our drill, however, has penetrated these Red Beds in a number of places. I have with me samples of the drill cores and a complete log of all the drilling. This sandstone has been found to be in place, to be unaltered and to be occupying a horizontal position. These facts are indisputably shown by the cores brought up by the drill. In short it is, so far as we now know, practically certain that this Red Beds stratum was not particularly affected when the crater was made, certainly not to the extent of having been thrown out, violently disturbed, or having been metamorphosed. In my paper read before the Academy of Natural Sciences of Philadelphia four years ago I made the mistake, owing to the similarity in color, of thinking that a portion of the Red Beds had been thrown out. I now know that the brownish red fragments are from what we term the brown sandstone, above referred to, which overlies the Red Beds.

The drilling of some twenty five holes in the generally central portion of the floor of the crater has absolutely demonstrated the general correctness of the above statements. I should add that no piece of igneous or eruptive rock has been encountered by us in connection with our work, or exists in place within less than nine miles of the crater.

GENERAL DESCRIPTION OF THE CRATER AND OF THE EJECTED ROCK FRAGMENTS.

It should be remembered that the word crater is used simply for want of a better term to describe a great basin like hole in the originally horizontal strata, and because in shape it is not at all unlike a volcanic crater. We now definitely know, and I think I shall be able to show you, that it was not produced by any volcanic agency.

I have had a very accurate map made of the crater, as well as a necessarily more or less rough sketch showing the distribution of the ejected rock fragments. I have also had made a much more accurate map showing the distribution of the meteoric material concentrically surrounding the crater. A careful study of these maps, which are printed herewith, should be made by those who are interested in the various questions which will be discussed in this paper.

The crater, as will be seen by referring to the map, is nearly round and is, roughly speaking, about 4000 feet, or something over three-quarters of a mile, in diameter. It is of an average depth from the rim to the interior central plain, or more or less level floor, of about 570 feet. The limestone and sandstone strata exposed in the walls dip away from the center of the crater at varying angles, as shown on the map. The fact that the strata are uplifted in this way of course contributes to form the rim and the elevation heretofore known as Coon Mountain or Coon Butte. The compact limestone bed is very prominent in the crater walls, and where it is nearly horizontal causes the cliffs to be nearly perpendicular. A very interesting feature in the southern portion of the crater is that for a distance of half a mile, measuring around the rim, this limestone and the underlying sandstone have been vertically lifted as a mass more than one hundred feet out of their original position. Careful aneroid measurements show that the uplift of this great mass of rock is 105 feet. I mean measuring from the top of the perfectly level limestone bed, where we know it to be in place on the outside level plain, to the top of the same limestone bed, where we know it to be out of place in the south wall of the crater, but where it is also lying level. The cause of the uplift of this tremendous weight of rock (probably some 20 to 30 million tons) may be found in the fact of the meteoric mass having wedged itself underneath, or in the development underneath it of a vast amount of shattered rock, or by the formation beneath it of great quantities of what we know as Variety A and Variety B of the metamorphosed sandstone. Directly opposite in the northern rim of the crater, between W. N. W. and N. W. to N. N. E. (the line "B—B" on the map passes nearly through the center of it) there is to be seen, when the observer approaches from the north, a very noticeable low place or depression in the crater rim. Attention is called to the fact that this is not only opposite to but that it corresponds quite closely in length with the great vertical uplift of the strata in the southern wall. It has been suggested that the inrush of the air accompanying the projectile may have produced this low place in the northern rim. It is partly shown in one of the general views of the crater. The southern cliffs are also fairly well shown in these photographs.

The ejected sharply angular rock fragments are of all sizes and shapes, from great masses of limestone weighing perhaps in excess of 4000 tons, down to microscopic particles of crystalline quartz which we know as "silica" or rock flour, as it has been aptly called. There are a great many million tons of this latter material. It probably forms fifteen or twenty per cent. or more of the entire material thrown out of the crater. It is absolutely certain that this rock flour is pulverized sandstone. In no case are the little microscopic, sharply angular, particles of crystalline quartz larger than one of the very small, water worn grains of quartz which compose the white or gray sandstone. A very large proportion, if not most of it, will pass through a 200 mesh screen, the finest of all wire screens. It is very interesting material, and in my opinion cannot have been formed, much less distributed as it is at present, by any other agency than by the impact of a body or a group of bodies falling out of space, and moving at high speed. It fills in a large degree, with the included rock fragments great and small and the metamorphosed sandstone which will be described, the lower portion of the crater, and is the material which forms in a large degree the outer slopes of the rim, where in places it is admixed with the larger angular limestone and sandstone fragments very abundantly. In other places it is comparatively free from them. In some places it looks as if it had welled out of the crater like flour out of a barrel. In places great quantities of the metamorphosed sandstone (principally Variety A) have been expelled from the crater and have disintegrated into this silica or rock flour. We have specimens of this metamorphosed or partly metamorphosed sandstone showing a gradation from the almost unaltered white or gray sandstone down to this rock flour. Some are coherent, others are incoherent, some contain a large percentage of unbroken water-worn quartz grains; there are others in which it is impossible to find a single unbroken sand grain. These specimens must be seen to be appreciated. Time does not permit me to emphasize the fact that these in themselves, and entirely apart from the great amount of other proof, present incontrovertible proof that this crater could not have been produced in any other way than by the impact of a projectile falling out of space and moving at high speed. The rock flour is exposed by erosion in a number of places on the south rim, that is to say, the south slopes of the "mountain." At one place in particular there is an arroya some two or three hundred yards long and some ten to twelve feet deep, where this very white rock flour is naturally exposed. In analysis it often shows upwards of 98 and 99 per cent. silica.

The amount of rock dislodged and partly thrown out of the crater has been estimated at over three hundred million tons. A vast amount of the surrounding rock in addition has been violently disturbed. (In passing it should be noted that it is practically impossible to estimate accurately the amount of work done or energy expended; almost as impossible as it is to estimate the speed at which the projectile was moving when it struck. Therefore it becomes extremely difficult to make a reliable estimate as to the weight of the projectile. As it seems to me, all that we can know with certainty is that its weight must have been very great.) It is very difficult, if not impossible, to form a correct estimate of the amount of the dislodged and ejected material. I think that this can be clearly shown to any one who will visit the locality. In the first place, it is next to impossible to know without innumerable shafts just how deep it is to rock in place, frequently tilted and broken strata, on the outside of the rim. Again it is impossible to know without most complete exploration what the shape of the invisible true bottom of the crater is, inasmuch as it is filled for about one-half of its depth with the rock fragments which have rolled back into it and with some 70 to 90 feet of lacustrine or lake sediments formed at a time when the bottom of the crater was the bed of a small lake.* Nor is it possible to estimate the amount of talus at the base of the limestone cliffs. Finally there can be no doubt that enormous quantities of the finely divided rock flour have been blown away from the slopes of the so-called mountain by the violent winds that rage in the locality.

Some of the rock fragments have been ejected to an extreme distance of about one and one-half to two miles from the crater. These are pieces of compact limestone weighing from fifty to several hundred pounds. The larger fragments, and especially the very large fragments, are distributed rather closely around the crater, say not to exceed a quarter of a mile from the rim. As will be seen from the map, there are two remarkable fields of big boulders, as they are locally termed, or very large angular limestone fragments, weighing hundreds and even thousands of tons, opposite to each other, one on the eastern side and one on the western side of the crater. The symmetry which is seen in the walls of the crater and in the ejected rock fragments is very remarkable and furnishes in itself one of the many proofs against a volcanic origin of the crater. By consulting the map you will notice that not only are these very large rock fragments on the outside distributed more or less symmetrically, but that, commencing at a point which we will name as north northwest, the strata exposed in the walls of the crater gradually increase in dip as you go around the crater in either direction to the south, from 5 degrees up to vertical and in one place they are slightly overturned. The greatest amount of ejected material lies on the south slopes of the mountain, where it is also more comminuted than elsewhere. This symmetry along the line "B—B" shown on the map is not accidental and would be impossible if a steam explosion had caused the crater. Then there are several interesting spurts or jets of rock fragments to be observed on the outside rim from N. N. W. to E. S. E., which are composed entirely of white sandstone fragments overlying limestone fragments. These jets of sandstone fragments are of great interest. It does not seem probable to me that they could have been made in any other way than by the impact of a projectile. They can be duplicated by such an impact, that is to say, by a rifle bullet fired out of a high power rifle, but they cannot be duplicated by any sort of a gas explosion. Any one who is familiar with the action of explosives will, I think, bear me out in this when he has visited the locality. An explosion from beneath (such as the Hell Gate explosion or the explosions employed to break up the "nitrate" in Chile) separates and scatters the material in a very different and characteristic way. The spurts or jets of rock fragments could not, it seems to me, have been produced by an explosion from beneath. Again, the rock fragments on the outside rim, while often intimately admixed over small areas, always lie, when considered in a large way, in the reverse order of their geological occurrence when undisturbed. That is, the limestone fragments are on top of the purplish red sandstone, and the white

---

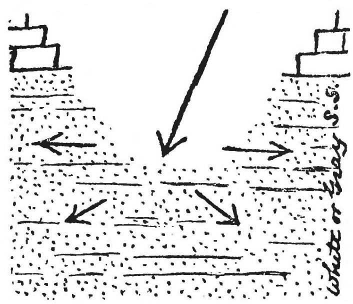
**Dr. W. H. Dall will soon examine the fossil shells found in these sediments with the object of determining as nearly as possible the age of the sediments.*

sandstone fragments are on top of the limestone fragments; all of which is strongly suggestive of the ploughing effect of a projectile. In this connection there are on the surface of the southeast rim thousands of tons of brown sandstone fragments, or brown sand due to their disintegration. As above stated, we know by our drilling that this brown sandstone is found only in the lower portion of the white or gray saccharoidal sandstone stratum. Petrographically, as Dr. G. P. Merrill has pointed out, it is the same rock and is different from the somewhat darker and much more compact sandstone of the underlying Red Beds. The fact that this very large amount of brown sand and brown sandstone fragments, stratigraphically the lowest of all the rocks ejected, is found in quantity at this particular locality on the rim and nowhere else, and is on top of the other ejected material, is significant, and it should not be forgotten is in absolute accord with the symmetry above referred to. These brown sandstone fragments could not, it is argued, lie on top of the white sandstone fragments, and they in turn could not lie on top of the limestone fragments if a steam explosion had caused the crater.

I have the permission of Professor William F. Magie to state that the map of the crater which has recently been made is as correct as it has been possible to make it, and that it has not been distorted in any way in order to fit any theory. I am glad to say that Professor Magie was able to spend two weeks at the crater with me this summer and to examine very carefully all the phenomena in connection therewith many of which the space of this paper will not permit me to dwell upon.

THE METAMORPHOSED SANDSTONE.

The metamorphosed sandstone is of peculiar and of great interest. It is of two varieties. What we have termed Variety A consists of angular fragments of undoubtedly original sandstone, still showing the bedding planes, but often with strongly marked slaty structure at more or less right angles to the bedding planes, which slaty structure can be due only to the exercise of very great lateral or perhaps radial pressure. Dr. J. W. Mallet was the first to assure me that this rock was certainly of terrestrial origin. I had submitted one of the first specimens found in the main shaft, which we attempted to sink in the center of the crater, to him for examination, since I had never seen a rock like it. The utter destruction of the individual sand grains and the superinducing of this more or less vertical slaty structure by pressure before the rock was dislodged and thrown out, is simply unexplainable on any other theory than that of terrific and sudden shock, with waves of concussion and pressure radiating outwardly; all of which is again absolutely opposed, of course, to the steam explosion theory of origin. That this rock was heated highly there can be no doubt, but that it was quite dry at the time it was metamorphosed there also seems to be no doubt. While I have found it to contain now and then some unbroken sand grains, it is composed almost entirely of minute fragments of crystalline quartz, each of them smaller than one of the original sand grains of which the rock was composed. The bedding planes are still well shown, and an interesting fact is that they are not always at right angles, but are frequently at different oblique angles, to the slaty structure above referred to. This fact alone practically necessitates this metamorphosed rock having been made by a projectile advancing through the rock strata of which these are fragments. The following simple diagram will show what is meant.



All of this was recognized almost as soon as these peculiar rock specimens were found, and was discussed at the time in correspondence with Dr. Mallet. A specimen of Variety A, however, to which Dr. J. C. Branner called attention when he was at the crater several years ago, includes small areas of what we have known as Variety B, which is a vesicular metamorphosed rock, looking not unlike pumice stone, in which by far the greater part of the metamorphosed quartz is amorphous and not crystalline. Many angular fragments of this interesting metamorphosed sandstone have been found. When examined under the polariscope these vesicular pieces of Variety B show little particles of crystalline quartz scattered now and then throughout the mass of amorphous quartz, of which the rock is almost wholly composed.

There is, so far as we know, vastly more of Variety A than of Variety B, but much of the former, since it was expelled from the crater, has disintegrated into what we know as silica or rock flour, and we have only been able to get good specimens, especially those showing the slaty structure, from the bottom of the main shaft which we attempted to sink in the middle of the crater. One of the drill holes (No. 7), however, showed some fifty-odd feet of Variety A at the depth of from 530 to 584 feet.

In passing I should say that it was found impossible to sink our main shaft more than 222 feet, or about 25 feet below water level, because of the peculiar quicksand, formed by the water saturated silica, which we encountered; also that, in my judgment, it will be impossible to properly explore the depths of the central portion of the crater until we shall have removed the water which we now know fills its lower portion. Fortunately this part of the crater has been fairly well prospected by the drill. The water seems to be held in the quicksand above referred to and to be confined to the crater, from the catchment area of which it is probably derived. It does not seem to exist in quantity in the surrounding undisturbed sandstone. It is probable that a shaft can be sunk in the crater through the talus and close to the walls, where we know the rock fragments to be much larger than in the central portion, and where there is also much less silica or rock flour.

In one of the small prospecting shafts in the bottom of the crater which was carried down only to water level, and subsequently also quite far down on the outer slopes of the rim, we have found a few remarkable specimens of what we know as Variety B of the metamorphosed sandstone. These certainly represent aqueo-igneous fusion, as Dr. Mallet was the first to point out. As in the case of Variety A the lines of sedimentation are still more or less distinctly preserved in this peculiar vesicular metamorphosed rock. The bedding planes, however, are distorted and are frequently lifted up one from the other, with minute filaments of amorphous quartz connecting the two. The whole appearance of this very white rock is not unlike that of very light, spongy bread. As shown by the drill, it is often sparingly admixed in the depths of the crater with bluish opalescent quartz, and in one specimen, secured from No. 2 prospecting shaft, a mass of Variety B shows on its outside a very considerable quantity of this opalescent quartz, which has apparently been liquid. Now Variety B, I assume, was not heated much more highly than Variety A, but, owing to the presence of water, semi-fusion, or, as in the case of the opalescent quartz, complete fusion could take place, which was impossible in the case of Variety A. It is very wonderful to think how this vesicular metamorphosed rock was formed in a small fraction of a second and was afterwards hurled to the outside plain, as has occurred in a few cases. Practically all of the pieces of Variety B which have been thrown out of the crater have been found between the spurts of white or gray sandstone, and have been confined to a rather small area about 1200 feet from the rim to the E. N. E. Variety B might be considered to be quite similar to geyserite were it not for two things —first, as Professor S. L. Penfield showed, while almost wholly composed of amorphous quartz, it undoubtedly contains some of the crystalline fragments of which Variety A is practically wholly composed, and second, it is now and then smeared with or otherwise associated with the bluish opalescent quartz, which undoubtedly represents more perfect fusion of the original sandstone. There is reason to think that portions of Variety A and Variety B were formed close to the advancing projectile, since fragments have been found which are stained with the oxides of iron and nickel. They also represent the rock which was most highly heated and seems to have been subjected to the greatest pressure.

The specimens of Variety B, which are often so light as to float on water, must be seen to be appreciated. When they are studied carefully they, like the specimens of Variety A, will be found to constitute an irrefutable argument against any volcanic or steam explosion theory of origin of the crater.

I should perhaps add at this point that I have failed to see any evidence of the action of steam except in a very small way in forming Variety B. It is not necessary to presuppose an explosion on a large scale of any sort. As I read them, the facts are all against any explosion except those represented by small and relatively unimportant puffs of steam where there was water in the sandstone.

THE KINDS OF METEORIC IRON AND IRON OXIDE FOUND OUTSIDE OF THE CRATER.

The ordinary Canyon Diablo iron meteorites and their composition (about 91 to 92 per cent. iron and about 8 per cent. nickel) are well known to the scientific world; also the fact that they contain microscopic diamonds. We were the first to show that they contain platinum and iridium to the extent of from ½ an ounce to ¾ of an ounce per ton of iron. No description of the specimens of this class of meteoric iron is necessary, except to point out that they are not readily oxidizable. Hundreds of such pieces had been shipped from the region in the vicinity of the crater to museums all over the world before we secured possession of the property. Before then, and before we had proved the simultaneity in time between the fall of this and the other class of meteoric iron, hereafter described, and the formation of the crater, it was not known, however, that the crater was practically in the exact center of an area on which lay many more meteoric iron specimens than have ever been found on all the rest of the world's surface. Literally, many thousands of such specimens have been found. The map which shows the distribution of the meteoric material will bring out this remarkable fact. This map has been carefully made and may be considered as accurate as such a general map can be.

It will show that no meteoric material has been found further than five and one-half miles away from the crater—over twice as far as the ejected rock fragments are found—and that it increases in abundance as one draws near to the crater. It is practically proved, as will be seen, that most of the individuals of this so-called "shower" do not represent the effect of the bursting in the atmosphere of an enormous siderite, as is commonly supposed.

Until we acquired possession of the property and until we began to sink shafts and make cuts in the silica and rock fragments on the slopes of the mountain, it was not known that this ejected material contained meteoric iron. This exploration work discovered another variety of meteoric iron, previously unknown, which is represented by what are now known as "shale balls." These (and there can be no doubt of this) are generally rounded or globular disintegrating masses of meteoric iron and nickel oxide, many of them containing solid nickel iron centers. With others, I had at first thought that the iron and nickel oxide of which these shale balls are sometimes entirely composed, and with which they are always covered when they have an iron center, was due to the burning of these meteorites in their passage through the earth's atmosphere. Professor O. C. Farrington was the first to take issue with me on this point, and I am now convinced that he was right. In fact, it is now proved that this iron oxide or shale (the name was given to it because of the peculiar shaly structure so often noticed in this material) is due to terrestrial oxidation of this peculiar shale ball iron, which it must be understood is chemically different from the ordinary Canyon Diablo siderites in that it contains very small quantities of chlorine, which is practically absent in the latter. Otherwise in chemical analysis they are quite similar. They also contain microscopic diamonds and, I assume, a small amount of platinum and iridium. We have encountered in our shafts and cuts on the outer slopes of the mountain more than a hundred of these so-called shale balls. I call attention again to the remarkable fact that they are never angular, but as stated, always seem to be rounded, and globular or oval in shape. Sometimes they are pear or almond shaped. They are frequently found on the outside plain entirely converted by terrestrial decomposition into iron shale, yet retaining the general outline of their original shape. When sawed in two these specimens are very interesting. What appear to be Widmanstatten figures can still be dimly seen in some of them. The iron shale with which they are covered is often exactly similar, even to the characteristic roughly triangular shape, to many of the thousands of pieces of iron shale which are strewn over the plain. The largest shale ball with an iron center which we have so far found weighed some forty odd pounds. Those with iron centers have been found in the rock fragments and silica on the slopes of the mountain, where they have been protected from complete oxidation, but they have not been found at any considerable depth in these ejected fragments so far. They are usually found in the upper portion of the ejected material. The deepest found was at 27 feet. It is interesting that they are overlaid in no particular order by limestone and white and red sandstone fragments which come from the adjacent crater, and it is certain that they and the rock fragments overlying and underlying them have not been moved appreciably since the time they came to rest in their present surroundings. Where they lie in the almost snow white silica they have in decomposing stained it for only a few inches around each specimen. The evidence is all against their rounded or globular shape being due to terrestrial decomposition. It is interesting that so far no piece of the ordinary unoxidizable Canyon Diablo iron has yet been found deeply embedded in the silica on the slopes of the mountain, but always on top of it, that is on or very near the surface, where many hundreds of specimens have been found. I have no completely satisfactory explanation to offer for this fact.

An interesting discovery was made in making a trench for the pipe line from our reservoir in Canyon Diablo. A piece of iron was found, one end of which was composed of the shale ball variety of iron and the other end of the ordinary Canyon Diablo siderite variety. Other specimens show the same thing on a smaller scale. One has been found with quite a large amount of iron shale adhering to it; others with a less quantity. It is therefore certain that these two classes of irons have frequently formed part of the same mass, probably grading one into the other. It is certain that what we know as the shale ball variety of iron frequently disintegrates or oxidizes with remarkable rapidity, probably in proportion to the percentage of chlorine which it contains. For example, a solid iron center which we dug out of the silica and rock fragments on the outer slopes of the crater rim three years ago, so solid that it could not be more than dented with a heavy sledge when placed on an anvil, is to-day represented by a lot of iron dust or rust, some of which is the so-called iron shale, and a few pieces of iron.

Most of these shale balls, when exposed to the action of the atmosphere, have a tendency to disappear rapidly, or to oxidize into hard compact iron shale, but when not so exposed, as when embedded in the silica, they oxidize very slowly. It is very likely, from the association of the pieces of the so-called iron shale, which is found in great abundance on the plain for several miles on all sides of the crater, and from the fact that this hard, compact iron shale often shows more or less curvature (indicating that it in all probability had been once a part of an unoxidized shale ball iron meteorite), that the surrounding plain was strewn with perhaps thousands of these unoxidized shale ball iron meteorites a few minutes after the impact. It is also very nearly proved that at least most of the small Canyon Diablo irons represent the residual unoxidizable portions of such shale ball iron meteorites, the oxidizable portion having been converted either into iron shale or rust, which rust was probably blown away almost as fast as it formed by the violent sand carrying winds of the region, wherever such meteorites were exposed to their action. You will note that the map shows that a discovery was made some time ago, nearly five miles from the crater, of a number of pieces of iron shale and a number of ordinary very small Canyon Diablo siderites grouped together. This means that a shale ball meteorite of probably considerable size fell on this spot and that the shale and the iron, as represented on the map, are all that remains of it. This peculiar association of the two, iron shale and small iron meteorites, is too marked here and in other instances to admit of any other explanation.

I am willing to admit that the finding of many, and especially the great pieces of ordinary Canyon Diablo meteoric iron, weighing frequently over 300 and in one specimen over 1000 pounds, which are not now surrounded by any iron shale, does not seem to be in agreement with this theory. Again, one of these large iron meteorites, with no shale surrounding it, was found slightly embedded, but with a point protruding, in the silica and rock fragments on the northeast slope of the mountain, and almost immediately beneath it within a few feet, there was found a large shale ball meteorite with a solid iron center. It is certain that neither had been moved appreciably since they came to rest in the silica and ejected rock fragments. Possibly these large, deeply pitted, and many of the small meteorites, both of which we know as ordinary Canyon Diablo siderites, were individual meteorites trailing behind the cluster. It has been suggested that they are fragments due to the bursting in the atmosphere of a larger mass. Their shape, however, does not indicate this. It has also been suggested that they were hurled out of the crater at the time of the impact, but this seems to me improbable. The characteristic pittings of the large Canyon Diablo siderites strongly suggest the idea that these cavities were once filled with globular masses of shale ball iron, which have disintegrated upon exposure to the action of the earth's atmosphere. But we have no proof of this. I am also willing to admit that a few very large irregular masses of iron shale, as shown on the map, have been found which by their present shape would indicate that the iron meteorite, from which they are certainly derived, may not have been as globular as the vast majority of the shale balls which we have found. We have not yet found any characteristic Canyon Diablo siderites among the remains of the shale balls which have disintegrated since they have been in our possession. Nor have we found them in any of the disintegrated shale balls which have oxidized *in situ* in the silica on the outer slopes of the mountain. Notwithstanding these facts, the evidence is quite strongly confirmatory of the theory that many of the smaller, and especially the very small, Canyon Diablo siderites have been derived from the disintegration of shale ball meteorites great and small. There is a characteristic shape among many of them which points to a common origin and is opposed to the theory that they are fragments due to the rending of a large mass of iron; at least after it entered the earth's atmosphere. Less than a dozen specimens, varying from a few grains or ounces to several pounds in weight, have been found, however, in which there are small cracks suggestive of the fact that the iron has been subjected to a certain amount of strain and rending. These cracks are so small and have been so seldom observed that I do not think importance should be attached to them in this connection.

A conclusion which we can deduce from these facts and those which will be hereafter stated, is that the crater was not made by a single giant meteorite, but rather by a compact cluster or swarm of many thousands of shale ball meteorites and also possibly of other iron meteorites, as explained above, traveling together as the head, or part of the head, of a small comet. Those which fell outside of the crater, on this theory, were probably stripped off from the cluster in its passage through the atmosphere, or perhaps they had been trailing behind it in space, or had been traveling with it concentrically surrounding it, yet separated from it by considerable distances. They would, of course, have been much more retarded by the resistance of the earth's atmosphere than the main mass or central cluster, and would have reached the earth after it did, possibly while it was forming the crater. The concentric distribution of the many thousand pieces of shale (certainly derived from shale ball meteorites) around the crater for a distance of five and one-half miles, is in accord with this theory. I do not think it is probable that the majority, if any, of these globular masses of nickel iron were thrown out of the crater at the time of the impact. They in no wise resemble angular fragments torn from a solid mass. Again, many small ones have been found twice as far from the crater as any of the ejected rock fragments have been found. The evidence to my mind is in favor of the large majority of them having fallen out of the sky upon the plain or upon the crater rim at or near the places where they or their remains have been found. The iron centers, when sawed in two and etched, show the Widmanstatten figures beautifully, as do the ordinary Canyon Diablo siderites wherever found, and this, I am told by those who have made the experiment, they would not do if they had been heated beyond 700 degrees or 800 degrees Centigrade. If they were hurled out of the crater by the force of the impact with sufficient violence to have been thrown a number of miles, it would seem that they would have been more highly heated than this. And this appears all the more reasonable when one remembers the evidence of high temperature in the rocks immediately adjacent to the advancing projectile, for it would seem that the projectile would have been as highly heated, especially in its outer portions, and these, it would seem, are the very portions which would have been hurled out of the crater by the force of the impact, if any portions of it were expelled. On the other hand, if shale ball meteorites were stripped off the outside of the cluster in the upper atmosphere they would have been retarded in their subsequent passage through it and would have reached the earth a fraction of a second, or a few seconds perhaps, later than the main body or cluster, and possibly, as suggested above, while the fragments of rock were pouring out of the crater or settling on the outer slopes of the rim. On this theory they would not have been very hot when they fell upon the earth. It is easily conceivable that because of air resistance they might not only have been retarded, but might have taken a slightly divergent course from that of the main body. It is also easily conceivable that members of the swarm were trailing some distance behind the main cluster, or perhaps were surrounding it in space. But even admitting that some of them were thrown out at the time of the impact, for example those embedded in the silica and rock fragments on the crater rim, it is only another argument in favor of the crater having been made by a dense cluster of shale ball and possibly other iron meteorites.

If the crater was made by a single giant iron meteorite it is very hard for me to realize, remembering the toughness of this nickel iron, and remembering the fact which Professor Magie was the first to point out to me, that the temperature of such a meteorite traveling in space would not be very low, how it should have broken up into a great number of very small pieces. If it did not break up in this manner the dip needle should indicate its presence in the depths of the crater. It is clear, as we shall see, that there is not nearly sufficient evidence of heat inside or outside of the crater to warrant the conclusion that it went into the form of vapor or of fine metallic mist when it struck. The absence of staining by iron and nickel oxides on a grand scale is absolutely opposed to such a theory. It should be stated also that there is not the slightest evidence, either inside or outside of the crater, to warrant the conclusion that the projectile was composed of anything but nickel iron; unless the finding by me of a single small aërolite about one and one-half miles N. W. of the crater, several years ago, may be regarded as such. As stated in my former paper, there is fairly good reason to believe that this aërolite was seen to fall in the winter of 1904-5.* It is recognized, however, that it may have been a member of the swarm, the central or probably the most advanced portion of which, when it struck the earth, was the projectile which made the crater, and which, from all the evidence, was almost wholly composed of iron meteorites. From this point of view the finding of an aërolite lends support to the theory that the crater was made by a compact cluster of meteorites. No other aërolite and no piece of meteoric stone has been found in the crater or in the vicinity of it. Surely in all our exploration and constant search during six years we would have found some additional evidence of the fact had the crater been made by the impact of a stony meteorite or a cluster formed in large part of stony meteorites. We have searched very diligently for such evidence, both inside and outside of the crater. If it was in part a stony meteorite or a cluster composed largely of stony meteorites, it seems certain that we would have found some small pieces of meteoric stony material in the shafts, in the drill holes, or attached to the many thousands of pieces of nickel iron or nickel iron oxide which we have found. The finding of the remains of shale balls in the talus on the inside slopes of the crater, as described below, furnishes additional support to the theory that the crater was made by the impact of a compact cluster of meteorites.

Professor Magie checked during the past summer the observations of Mr. Marcus Baker, of the United States Coast and Geodetic Survey, which were made in behalf of the United States Geological Survey, when the latter made an examination of the crater in 1891. Like Mr. Baker, Professor Magie finds no systematic variations of the magnetic declination or the magnetic dip in different parts of the floor of the crater, such as one would expect if there were a large mass of iron buried beneath it; I mean a mass of the size which was

---

**Coon Mountain and Its Crater, Proceedings of the Academy of Natural Sciences of Philadelphia, December, 1905, pp. 883-884; American Journal of Science, Vol. XXI, May, 1906, pp. 347-355.*

necessary to produce the crater. From preliminary tests the shale ball irons and the ordinary Canyon Diablo irons seem to possess a low magnetic permeability. If this is the case, and if the mass exists in many fragments or as separate shale ball meteorites and possibly ordinary Canyon Diablo siderites, the lack of any magnetic indications of their presence may be accounted for.

Professor Magie intends to examine the magnetic properties of the iron in the near future.

THE METEORIC IRON AND MORE PARTICULARLY NICKEL IRON OXIDES FOUND IN THE BOTTOM OF THE CRATER BY THE DRILL.

Before describing the meteoric material brought up by the drill from the depths of the crater I should not neglect to state that the remains of one or more shale balls were found in a tunnel driven in the talus at the base of the limestone cliffs on the northern side of the crater, not very far above the level of the central plain which forms its visible floor. Also that one or two ordinary Canyon Diablo iron meteorites have been found high up on the inner slopes of the crater and just inside the rim.

Our drilling has disclosed at a number of places in the depths of the crater the existence of undoubted meteoric material admixed with the rock fragments. It is usually found where we find considerable quantities of Variety A or of Variety B of the metamorphosed sandstone, but it is also found scattered through the silica and other rock fragments 600 and odd feet below the floor of the crater. This meteoric material is often in the form of small specks of nickel iron oxide, some of which seem to have minute metallic centres (possibly schreibersite). These are obtained by grinding the little specks of oxidized material in an agate mortar. This meteoric material, which invariably reacts strongly for nickel, was found in places quite abundantly, admixed with the fragmentary material filling the bottom of the crater. The discovery of a number of pieces of Variety B last summer in the fragmentary material underneath the lake sediments, or at a depth of about 100 feet below the crater floor (supposed to represent at least approximately the original visible floor of the crater an hour after the impact), which specimens were locally covered with a film or stain of, or abundantly studded with, little specks of exactly the same oxidized meteoric material which we had previously brought up with our drill from the depths of the crater, probably shows us just what it is that we have been bringing up with the drill, namely, original sparks (bits of once burning metal) or the result of the flame produced by vaporized metallic iron and nickel. There can be no doubt that the drill, when cutting through similar fragments of Variety B and of Variety A liberated many of these small particles or specks of meteoric material, which, as I think can be safely assumed, represent flame and sparks due to friction. That there must have been a great deal of such flame and vast numbers of big and little sparks is certain, just as we have seen there was a certain amount of fusion of the rocks which were penetrated by the meteorite or cluster of meteorites. The vaporization or fusion of the metal composing the projectile was, however, as I think, confined to its outer portions, or (as in the case of the rock affected) to a *very* small portion of the entire mass; that is to say, to the portions which were actually in contact with the rock which was being penetrated. This vaporized metal and the sparks or bits of fusing metal have, when admixed with the silica, as would naturally be expected, combined with it and formed a somewhat slag like and often vesicular material (iron nickel silicate I assume) containing minute cavities or bubbles showing the action of escaping gases.

This slaglike material also always reacts strongly for nickel, and it must be remembered that the rocks of the region do not contain a trace of this metal. Wherever it is found in this locality it is certainly due to the presence of portions of the meteorite or meteorites which fell at the time the crater was made.

It must always be borne in mind that if the projectile struck so hard as to be totally vaporized, not only, in my opinion, would there have been a very shallow crater and greater fusion of the target (the arenaceous limestone was perfectly adapted to the making of slag), but this vapor would have condensed instantly and most of the rock fragments and silica, instead of being almost snow white, as in the case of the silica, and wonderfully free from iron, would necessarily be abundantly stained by oxides of iron and nickel, both inside and outside of the crater. There is no escaping this conclusion. Think for a moment what an enormous amount of nickel iron vapor would have been produced by the volatilization of a mass of iron of sufficient size to have made this great crater.

A fact of interest in this connection is that where the drill finds the meteoric material representing fusion of the projectile to be most plentiful in the depths of the crater, 600 and odd feet below the visible floor (between 1100 and 1200 feet below the original plain level), there is immediately underneath a bed of very white and very fine silica or rock flour, which, so far as we know, contains no meteoric material. Nor has any ever been found below it. This is certainly strongly opposed to the theory that there has been much oxidation of meteoric iron (shale ball iron or any other kind) in the depths of the crater, at least in its central portion. From this point down the drill encountered in all of the 23 holes sunk below this level more and more compact sandstone, until it passed into the absolutely unaltered lower portions of the white or gray sandstone and into the unaltered Red Beds stratum. In all 28 holes were drilled in the central portion of the crater and not less than 14 encountered this undoubted meteoric material at between 450 and 680 feet, the greatest depth at which it has been found. This was in hole No. 20. In a large majority of the holes it was found very sparsely distributed, in a few of them more or less abundantly, but never, except in the hole above mentioned, forming more than a very small percentage of the fragmentary material brought up by the drill.

CONCLUSIONS.

To recapitulate, some of the principal arguments against the steam explosion theory are (No. 1.) No rocks of igneous origin in or around the crater. (No. 2.) No evidence whatever of solfataric activity. (No. 3.) The finding of unaltered sandstone in place in the bottom of the crater in its proper stratigraphical position. (No. 4.)

Proved simultaneity in time between the formation of the crater and the deposition of the meteoric material found on the surrounding plain, and especially among the ejected rock fragments. (No. 5.) The formation of Variety A of the metamorphosed sandstone in various degrees of metamorphism, with its slaty structure showing great lateral pressure, or pressure radiating from the advancing projectile; also the formation of Variety B of the metamorphosed sandstone; and as part of these facts evidence of just such fusion of the sandstone as would have taken place under the influence of a sudden and very great, but not long continued, rise of temperature, which could not have taken place, it is safely assumed, if there had been such a great single steam explosion as has been advanced to account for this crater. (No. 6.) The fact that the ejected rock fragments were deposited, generally speaking, in the reverse order in which they occur stratigraphically. (No. 7.) The formation of, and especially the distribution of, vast quantities of silica or rock flour on the outer slopes of the rim of the crater and in the depths of the crater itself. (No. 8.) The roundness of the crater, especially when studied in connection with the remarkable symmetry exhibited inside and outside; that is to say, by the dip of the strata, by the two fields of big boulders (angular limestone fragments) which were thrown out to the east and west, by the fact that a much greater amount of ejected material was thrown to the south than elsewhere, by the fact that this material is more comminuted than elsewhere; all of which facts, when considered together, are suggestive of impact and would be impossible under the steam explosion theory. (No. 9.) The vertical bodily uplifting of the strata, forming a portion of the southern wall for one-half mile in length, with the turning backward of the same strata on either side, in a way which not only, as I think, precludes the possibility of the effect having been produced by a steam explosion, but which suggests that it was produced by something having been driven underneath like a wedge. (No. 10.) The fact that the crater is situated in almost the exact center of an area on which more iron meteorites have been found than on all of the rest of the surface of the earth, added to the fact, as stated above, that it is proved that these iron meteorites fell at the same time that the crater was made. (No. 11.) The finding of undoubted meteoric material not only deeply embedded in the talus at the base of the limestone cliffs and underneath the lacustrine deposits, but also, which is conclusive, five and six hundred feet below the floor of the crater in association with the two varieties of the metamorphosed sandstone and with the other fragmentary material which fills the lower portion of the crater.

These are the principal arguments which occur to me at present, but there are many others which, as I think, render the steam explosion theory or any other theory based upon manifestation of volcanic activity absolutely untenable. We are therefore forced back to the theory of impact, against which in all of the diligent exploration, which has been extended over a period of six years, we have not found a single fact great or small.

The only argument worth considering against the meteoric hypothesis is that there are no systematic variations of the magnetic declination, or of the magnetic dip, in or around the crater. From such experiments as we have been able to make it is believed that there might be many thousands of shale ball or other iron meteorites in the bottom of the crater, the combined magnetic field of which would not effect the dip needle at a distance of 500 or 600 feet. (In this connection note the experiment described under the final heading, "What has become of the projectile?"). The shale ball iron and also iron oxide, as I understand, both show intrinsic magnetization; from which it is argued that the irregularly distributed masses in the bottom of the crater would neutralize each other's fields. Besides, the probability is that the magnetic lines of force of the mass where it probably lies would not deviate much from the earth's lines.

Since the facts are as I have stated them to be it would seem to me that it is idle to further discuss the origin of the crater. It is proved from this overwhelming array of facts that some extra terrestrial body—supposedly a giant iron meteorite composed of both kinds of iron which I have described, or as now seems much more probable, a dense swarm or cluster of iron meteorites composed of shale balls and perhaps also of ordinary Canyon Diablo siderites—entered the crater. The discussion, therefore, should henceforth be narrowed down to what was the nature of this mighty projectile and what has become of it, which is by far the most interesting visitor or group of visitors from outer space of which we have any record. So far we are utterly unable to account for such a mass of nickel iron as could have made this great hole in the rocky surface of the earth, a mass which, as has been very roughly estimated, probably weighed in excess of a million tons. It would seem that it must have been several hundred feet in diameter; for conservatism let us say three hundred feet. A very few thousand tons is all that we are able so far to account for on any reasonable hypothesis, both inside and outside of the crater, and most of this, as we shall see, can probably be excluded from the calculation. This is not enough. Where is the other ninety-nine per cent. plus?

WHAT HAS BECOME OF THE PROJECTILE?

The following facts and conclusions are given at the risk of repetition, so that the argument may be easily followed:

Since we can dismiss as unworthy of discussion, if not impossible, the theory that the whole mass of the projectile after striking the earth rebounded into space, or rebounded so high that when it again fell upon the earth it sank, for example, beneath the waters of the Pacific Ocean (for it is nowhere on the treeless rocky plain which surrounds the crater for many miles), it seems to me that the discussion is narrowed down to

(A) Was the projectile broken into many small pieces and thrown out of the crater after having penetrated, as has been proved, between 1100 and 1200 feet of rock?

(B) Has it disappeared in the crater through oxidation or from any other cause?

(C) Is it still somewhere and in some form in the depths of the crater?

We shall take up first the consideration of A, which is, in effect, are all the pieces of nickel iron or nickel iron oxide, shale ball or otherwise, which we find distributed around the crater to an extreme distance of approximately five and one-half miles from it, fragments of the mass which made the crater? It seems to me now that this must be answered in the negative, for we know or have strong reason to believe

1. That all of the nickel iron shale which we find distributed about the crater to the extreme distance mentioned is due to the terrestrial oxidation of shale balls.

2. That the original shape of the great majority, if not of all, of these shale balls was roughly globular, rounded, pear, almond or egg shape, often, as among the specimens now converted into hard dense iron shale, very distinctly pointed at one end.

3. That they are therefore not fragments of anything, but that most of them, if not all, were separate individuals when they fell. This we know not only from finding more than a hundred shale balls at considerable distances one from the other in the upper portion of the silica and rock fragments on the outer slopes of the crater rim, but also from the frequently observed grouping of many slightly curved pieces of iron shale of characteristic shape far out on the plain and removed from any other iron shale by hundreds of yards, which is indicative of the fact that a shale ball fell and disintegrated at this spot.

4. That the iron centers of these shale balls upon section show in all cases the Widmanstatten figures, and also that the Canyon Diablo siderites, great and small, also always show somewhat different Widmanstatten figures when cut and etched.

5. That they could not show these figures upon section if these pieces of meteoric iron had ever been heated beyond 800 degrees Centigrade. If they were fragments hurled out of the crater, many to great distances, at the time of the impact because of the splitting up of the projectile, it seems certain that not only would their shape be angular and otherwise indicative of the fact, but it is also reasonably certain that many of such fragments would have been white hot when they left the crater. It has been suggested that they may have been drops of liquid molten iron. This is clearly impossible for a number of reasons. For example, such drops could not have held together for considerable distances. In this connection it should be remembered that the remains of some of the shale balls have been found approximately five and one-half miles distant from the crater, much further than any of the ejected rock fragments. Also that some of the very small shale balls, now converted into hard, dense iron shale, have been found several miles from the crater. Therefore, as has been pointed out, it is practically certain that these were not ejected from the crater. The distance, in all probability, is too great. The fact that the large spurts or jets of white sandstone fragments are confined, practically speaking, to the northeast one-third of the crater rim, and the further fact that most of the shale balls which we have so far found embedded in the silica and rock fragments, have been found, so to speak, between these spurts, strongly suggest, as I am willing to admit, that some of the shale balls were thrown out of the crater at the time when the jets or spurts of white sandstone were squeezed out of it. (See Appendix.) It should also be remembered that it is certain that the shale balls do not owe their

present globular shape to weathering *in situ* in the silica or in the soil on the outside plain. Any one who has dug them out of the almost snow white silica and observed the very small amount of concentric staining by which they are surrounded, does not need to be further convinced of this fact. The oxidation of the iron having proceeded equally fast from the outside inwardly, the present shape of the iron center is also conclusive proof that the original shape of the complete meteorite was not very dissimilar. From all of these facts and arguments it is highly probable, if not proved, that most of the so-called shale ball meteorites so far found fell out of the sky independently of the main mass or cluster, and as separate individuals struck the earth at or within a few feet of the places where we now find them or their remains, and therefore had nothing whatever to do with the formation of the crater.

6. That a large majority of the ordinary Canyon Diablo siderites are, in all probability, merely residuals from the decomposition of the shale balls. (N. B.—It will be noted that I say the large majority, for I cannot yet bring myself to believe that all of the Canyon Diablo siderites were once parts of shale balls.)

7. Even supposing that the amount of nickel iron or nickel iron oxide which has been found concentrically distributed on the plain round about the crater (not to exceed 10 tons, which is an outside estimate) represents only about one-half of one per cent. of the amount or iron which was so distributed immediately after the impact, and supposing that it was all part of the projectile which made the crater, we would have something like two thousand tons as the total weight of the projectile. This is on the supposition, in my opinion clearly erroneous, that all of the projectile was hurled out after the impact except that now represented by the finely divided nickel and iron oxide which we have found in the depths of the crater. Even when this is added there would be represented a mass which is absurdly small when the great size of the crater (three-quarters of a mile in diameter) and the enormous amount of energy which has been expended is remembered. In short, even if we double or treble the weight of all the meteoric iron which we can reasonably assume to have existed a moment after the impact, either outside or inside of the crater, from all the masses and particles of iron or of iron oxide *which we have found*, it is not conceivable, in view of the facts presented, that a meteorite or cluster of meteorites of such relatively small weight could have done the work.

By exclusion this brings us to the consideration of B, that is to say, has the meteoric material of which the projectile was formed oxidized in the bottom of the crater since the fall, and to all intents and purposes disappeared, having been carried off by percolating waters, or has it practically disappeared through any other agency? This also must be answered in the negative, since

1. All of the oxidized meteoric material which we have so far found in the depths of the crater by means of the drill—in the aggregate representing at the most, in my opinion, only a few hundred tons of nickel iron—is in an exceedingly fine state of subdivision, and is known to have been plastered on, as if it had been thrown against, Variety B, and is often found in connection with Variety A of the metamorphosed sandstone, as well as in the silica. Many of these

particles of meteoric iron oxide are so small as to be seen with difficulty by the unassisted eye. Some of the larger of these particles are shown to contain what appear to be metallic cores, or it may be schreibersite, when rubbed in an agate mortar. (The oxide or iron shale forming part of shale balls found on the outside of the crater frequently show thin bright streaks or small masses of what I have been informed is schreibersite.) This does not indicate complete oxidation even of such minute particles. In this connection it is not improper to point out that if the mass struck hard enough to split up into these minute particles, it would have split up in this way, in all probability, at the instant it struck, and long before it penetrated some 1100 to 1200 feet of solid rock. It is certain that the bits of metal represented by these particles, which are now either in the form of nickel iron oxide or nickel iron silicate, and which vary from mustard seed to pin heads in size, though occasionally somewhat larger, could not in themselves do much in the way of penetrating rock. (It is of course recognized that their brittleness and the grinding action of the drill when it detached them from the metamorphosed sandstone, to which in some cases they were doubtless adhering, have contributed to their apparent smallness in size.) It is perfectly safe to assume that the small mass of nickel iron, which would be represented by the aggregate weight of all of these minute particles of nickel iron oxide, could not have made such a crater, even if it had been moving at the highest speed meteorites are known to have in space and irrespective of the retardation, whatever it may have been, of the earth's atmosphere. The smaller the mass the greater the retardation. And in this connection it must not be forgotten that if the mass struck at such very high speed it could not, in my opinion, have penetrated to the proved depth of over 1100 feet, because the energy would have been largely expended in the deformation of the projectile. If it had been traveling at such speed we would have had, besides a very shallow crater, abundant evidences of fusion of the rocks and volatilization of the projectile. Conversely, the fact that the projectile was not volatized and the fact that we know that it penetrated over 1100 feet through solid rock, furnish, as it seems to me, quite strong proof that the mass, when it struck and began to penetrate the horizontal strata, was not moving at a very high speed, considering the speed at which bodies in space are known to travel; also that the weight of the mass was very great.*

2d. We do not find enough evidence of heat or of staining to justify us in the belief that all of the great metallic projectile, whatever its form, went at any time into this state of subdivision.

3d. The evidence also is all against its having gone into a state of vapor at the moment of impact. In this connection it is only necessary to again point out that the absence of staining on a grand scale, in the depths of the crater and outside, is practically conclusive proof that the projectile did not either go into the form of vapor or of metallic mist upon impact, for a small amount of such metallic vapor or mist, so to speak, would have caused an immense amount

---

**In this connection, however, and in connection with the third argument below, see the recent interesting remark of Professor H. N. Russell, which is given in the Appendix at the end of this paper.*

of staining of the rock fragments and silica. If this negative proof is not sufficient the absence of evidences of fusion of the rocks on a grand scale coupled with it, would seem to be conclusive that the projectile was not vaporized and did not go into the form of metallic mist. It is argued with force, on the other hand, that something very solid and incompressible penetrated deeply into the white or gray sandstone, hundreds of feet below the original level of the plain where it struck. It is necessary only to remember in this connection the peculiar slaty cleavage so frequently shown by Variety A of the metamorphosed sandstone. How can this be explained otherwise?

4th. The body of unstained and almost snow white silica immediately underneath the horizon where we find most of the finely divided but undoubted meteoric material, precludes the possibility of any large mass of iron having oxidized in this horizon, at least where we have explored it. The amount of iron and nickel oxide which has been found in the central area of the crater prospected by the drill has been, after all, as pointed out, only in the aggregate probably less than a thousand tons; certainly not enough, especially when reduced back to a metallic condition, to account for more than an exceedingly small fraction of such a mass as was required to make the crater, even assuming high speed. This much might easily have been thrown off as sparks (some of it, as has been proved, being vaporized) from a very large projectile or a large, compact cluster of shale balls and other meteorites while penetrating some twelve hundred feet of rock.

By further exclusion we are now brought to the consideration of C, that is, is the mass which made the crater still in it at some undiscovered place and in some form? In my opinion, this question must be answered affirmatively.

The only argument which now seems to be worthy of serious consideration against this conclusion is that the magnetic dip needle has not shown, in two carefully made surveys within the crater and immediately outside of it, any variation from the usual dip in this region; that is to say, anywhere within a ten or twenty-mile radius of the crater. As against this theory we know that a box half full of shale balls and ordinary Canyon Diablo siderites weighing in all nearly 200 pounds, was brought directly under the dip needle in an excellent instrument, in fact, between the legs of the tripod on which the instrument was mounted and within three feet of the instrument itself, and yet no movement of the needle was noticed. It would seem justifiable, therefore, to conclude that a vast number of similar masses of meteoric iron may be hidden in the depths of the crater, five to seven hundred feet below the surface, without the needle in the instrument showing any variation of dip because of their presence.

We are thus compelled to conclude that the mass which made the crater, and which, as has been suggested above, may have been the metallic head of a small comet, lies in the bottom of it somewhere; for if it was a compact cluster of iron meteorites which made the crater—there is certainly a great deal of evidence in favor of this theory and none against it—it would seem from the evidence most unlikely that any considerable portion was expelled after the cluster had penetrated some 1100 to 1200 feet of limestone and sandstone strata. When the metallic mass is found, it would seem probable that it will be found to have partially oxidized, much after the manner of the buried shale balls, in which event it would still possess great commercial value. As yet we do not know where it is in the large area covered by the crater, but I personally think it probable that, in the form of a vast number of shale balls and perhaps Canyon Diablo siderites lying more or less closely together, most of it will be found far over in the southern or southeastern portion of the crater, where no prospecting by the drill has been done, and that some of it, if not the larger part of it, will be found underneath the perpendicular cliffs which form the southern wall.

APPENDIX.

Since the above paper was read Professor H. N. Russell has made a suggestion to the author which interests him greatly, and on the theory, which now seems so plausible, that the mass which made the crater was composed of many thousands of shale balls and ordinary Canyon Diablo iron meteorites, explains quite satisfactorily many of the facts which he has endeavored to describe. Briefly it is this. The meteoric mass, in passing through the atmosphere, would necessarily push before it a great mass of compressed and highly heated air. There would be no time for this air to escape sidewise to any great extent. A mass of the great size (perhaps several hundred feet in diameter) necessary to account for all the phenomena observed, moving at 15 to 30 miles per second—which is the sort of velocity to be expected—would cut out a "wad" of air going through the atmosphere like a charge of shot going through a board in front of the muzzle of a shotgun. The total mass of this entrained air might be as great as that of the original meteorites. In this way the blow at the earth's surface would be to a certain degree cushioned, which would help to account for the absence of notable evidences of volatilization of the iron. The mass of hot air would be fairly driven into the sandstone and limestone strata by the first impact, and would then escape upward around the advancing projectile and be very efficient in removing the pulverized and shattered rock, and so in digging the crater.

This cushion of air, as it seems to me, would not only explain why the shale ball and ordinary Canyon Diablo iron meteorites were not deformed or broken by the impact, but, on the theory that the cluster held together, shedding, perhaps, a number of meteorites as it passed through the atmosphere, might explain the distribution of part of the small proportion of the mass, or the remnants thereof, which has been found outside of the crater and immediately surrounding it. That is to say, when the cushion of compressed air struck, the rock immediately in front of it was ground to impalpable powder. The entrained air then began to escape with great force around the sides of the mass and carried backward with it not only all the first made pulverized rock, but, during the later stages of the process, stripped off some of the meteorites from the outer portions of the cluster, and distributed them through the ejected material. I still think it probable, however, that many, if not most, of the meteorites found in the uppermost layers of the debris, and all of those found on the open plain, fell directly from the sky, as stragglers following the main mass.

The less violent escape later of some remaining portion of this compressed air imprisoned in front of the projectile, as it advanced through the white or gray sandstone, hundreds of feet below the surface of the plain, may also account for the remarkable spurts or jets of white or gray sandstone fragments on the northeast one-third of the rim, and for the relatively large number of shale balls found embedded in the upper portion of the silica on its outer slopes between these spurts of sandstone. The highly heated mass of compressed air may also be largely responsible for the formation and distribution of Variety A and Variety B of the metamorphosed sandstone and of the bluish opalescent quartz.

If this additional theory is correct—it will be noticed that it is not opposed to any of the principal theories advanced in the above paper to account for the creation of the crater and the attendant phenomena, —then it, practically speaking, proves several things. First, that the crater was made by a great cluster of iron meteorites, weighing in all likelihood not less than a million tons, for the cluster must have had very considerable superficial area or opposing surface. Second, that if the shale ball and other iron meteorites stripped off the cluster while it was penetrating the strata and carried backward out of the crater, especially those which were thrown out last, were saved from being volatilized by the cushion of compressed air, practically all the rest of the cluster which remained in the crater was likewise saved from such a fate. Third, that we have a very fair sample of the composition and general characteristics of the individuals composing the cluster in those torn off from its outer portions. Fourth, that probably upwards of ninety per cent. of the mass lies in the bottom of the crater or beneath the cliffs which form its walls. The mass of compressed air having escaped from in front of the projectile, it is conceivable that there would have been an opportunity for the individual meteorites, composing that portion of the cluster which remained in the crater, to separate to a limited extent in the space dug by the compressed air ahead of the cluster while the flying rock fragments were still in the air and before some of them settled back into the crater and filled its lower portion.

Note.—There are three collections of specimens which include everything from Meteor Crater to which reference has been made in this paper; one at the Guyot Laboratory of Princeton University, Princeton, N. J.; one at the U. S. National Museum, Washington, D. C., and one at the Crater itself in Coconino County, Arizona. If it is possible, these specimens should be studied by those who are interested in the subject. Such a study cannot fail to be of assistance in enabling them to understand the arguments set forth in this paper. But it is of far more importance that they should visit the Crater itself, for not until one does so can he appreciate fully all that this and other papers on the subject have attempted to describe.

A number of the photographs which illustrate this paper have been taken by Prof. Gilbert Van Ingen, of the Geological Department of Princeton University. His work in this connection is gratefully acknowledged.

BIBLIOGRAPHY.

The following references to papers on Meteor Crater are given in the order of the dates of their publication:

A. E. Foote, in Amer. Jour. of Sci., vol. 42, p. 413, 1891; also in Proc. Am. Assoc. Adv. Sci., vol. 40, pp. 279-283, 1892.

G. K. Gilbert, 13th Ann. Rept. U. S. Geological Survey, part 1, p. 98, 1892; 14th Ann. Rept., part 1, p. 187, 1893; Geological Society of Washington, Presidential Address, March, 1896; Science (new series), vol. 3, pp. 1-13, 1896.

O. A. Derby, Constituents of the Canyon Diablo Meteorite, Amer. Jour. of Sci., Vol. 49, February, 1895, pp. 101-110.

Brezina, Cohen and Huntington have also written on the Canyon Diablo irons.

Chamberlin and Salisbury's Geology (1904), vol. 1, p. 569.

D. M. Barringer and B. C. Tilghman, First mention of the discovery that the crater is an impact crater and not a crater produced by a steam explosion. President's statement, Proceedings of Acad. Nat. Sci., Philadelphia, December 5, 1905.

D. M. Barringer, Coon Mountain and its Crater. Proc. Acad. Nat. Sci., Philadelphia, December, 1905, pp. 861-886. (Issued March 1, 1906.)

B. C. Tilghman, Coon Butte, Arizona. Ibid., pp. 887-914.

J. W. Mallet, Amer. Jour. of Sci., vol. 21, May, 1906, pp. 347-355.

J. C. Branner presented the papers of Messrs. Barringer and Tilghman before Section E, Amer. Assn. Adv. Sci., at the Ithaca meeting, June 29, 1906, with the results of his own study of the phenomena, which favored the view of meteoric origin of the crater. Science, vol. 24, September 21, 1906, pp. 370-371.

H. L. Fairchild, at Tenth Session of the International Geological Congress, in Mexico, September 14, 1906, presented the new facts favoring the impact origin of the crater, and exhibited the various materials. The record will be found in Compte Rendu, X Session, Congress Geol. Inter., Mexico, 1906, p. 147.

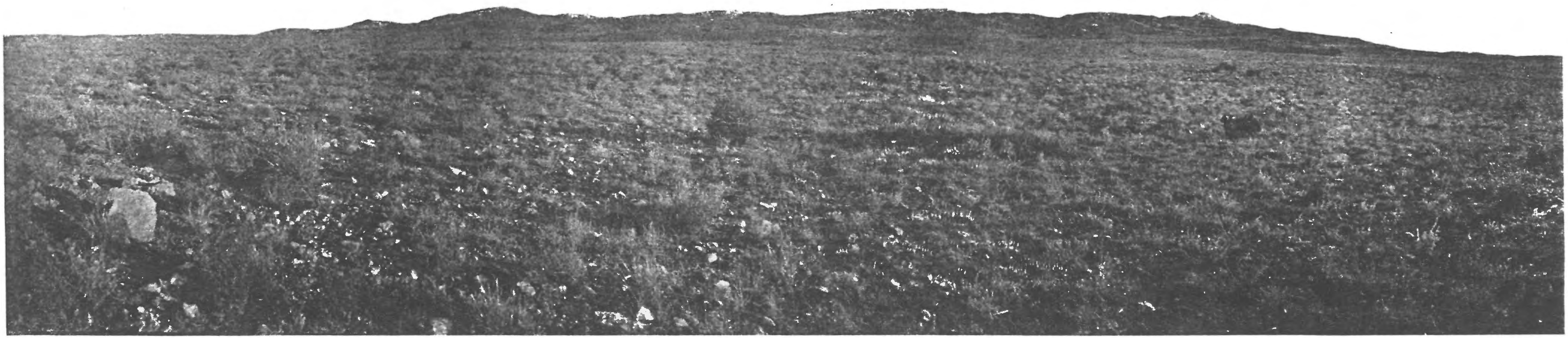
O. C. Farrington, Analysis of siderite oxides or "iron shale" and discussion of its origin and relation to the typical Canyon Diablo irons in Amer. Jour. of Sci., vol. 22, October, 1906, pp. 303-309.

G. P. Merrill, On a peculiar form of metamorphism in silicious sandstone. Proc. U. S. Nat. Museum, vol. XXXII, pp. 547-550; June 15, 1907.

G. P. Merrill and Wirt Tassin, Contributions to the study of the Canyon Diablo meteorites, Smithsonian Miscl. Collections (Quarterly Issue), vol. 50, part 2, pp. 203-215; pls. 8-21, September 12, 1907.

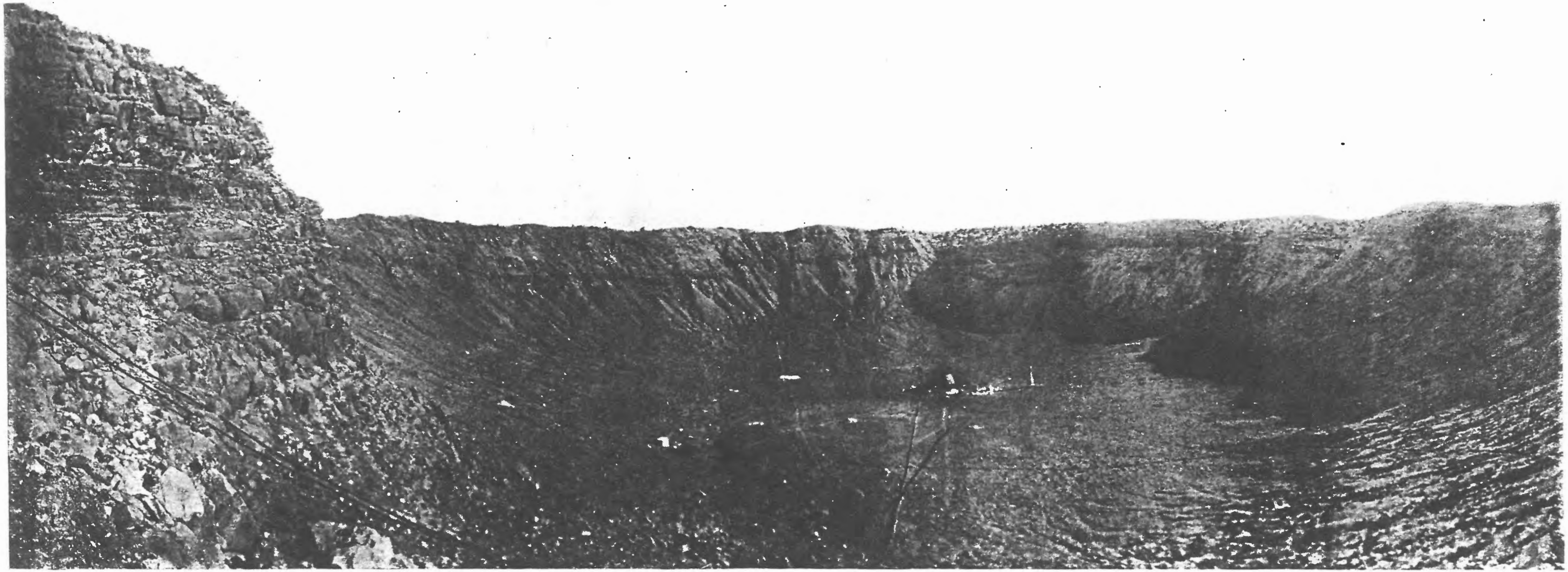
H. L. Fairchild, Origin of Meteor Crater (Coon Butte), Arizona Bulletin of the Geol. Soc. of Amer., vol. 18, pp. 493-504, pls. 54-56, December, 1907.

G. P. Merrill, The Meteor Crater of Canyon Diablo, Arizona; its history, origin, and associated meteoric irons, Smithsonian Miscl. Collections (Quarterly Issue), vol. 50, part 4, pp. 461-498; pls. 61-75, January 27, 1908.



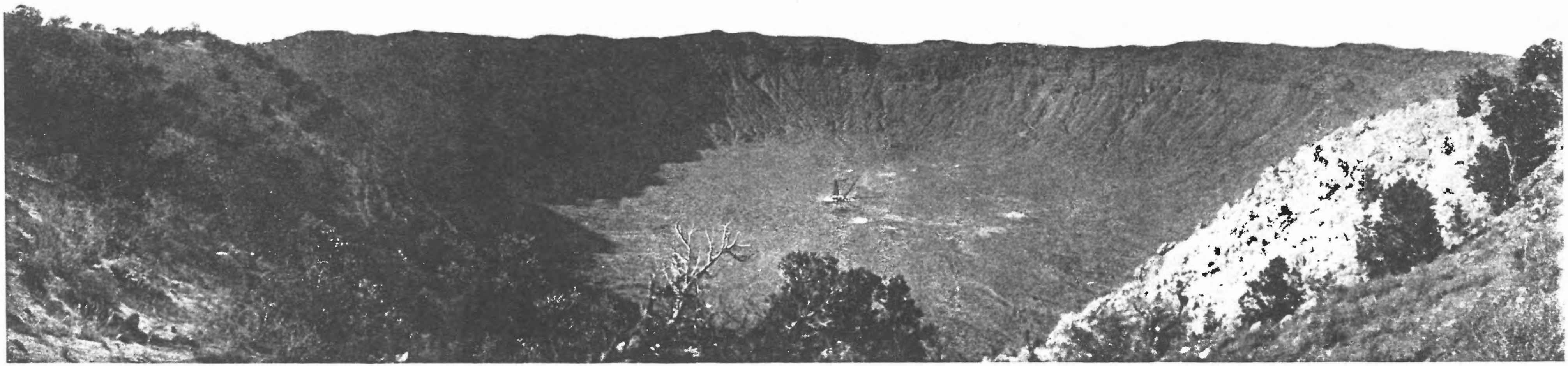
VIEW OF CRATER FROM W. N. W. AT DISTANCE OF SEVERAL MILES.
AT A DISTANCE THE VIEW FROM EVERY DIRECTION IS ALMOST THE SAME.

PLATE I



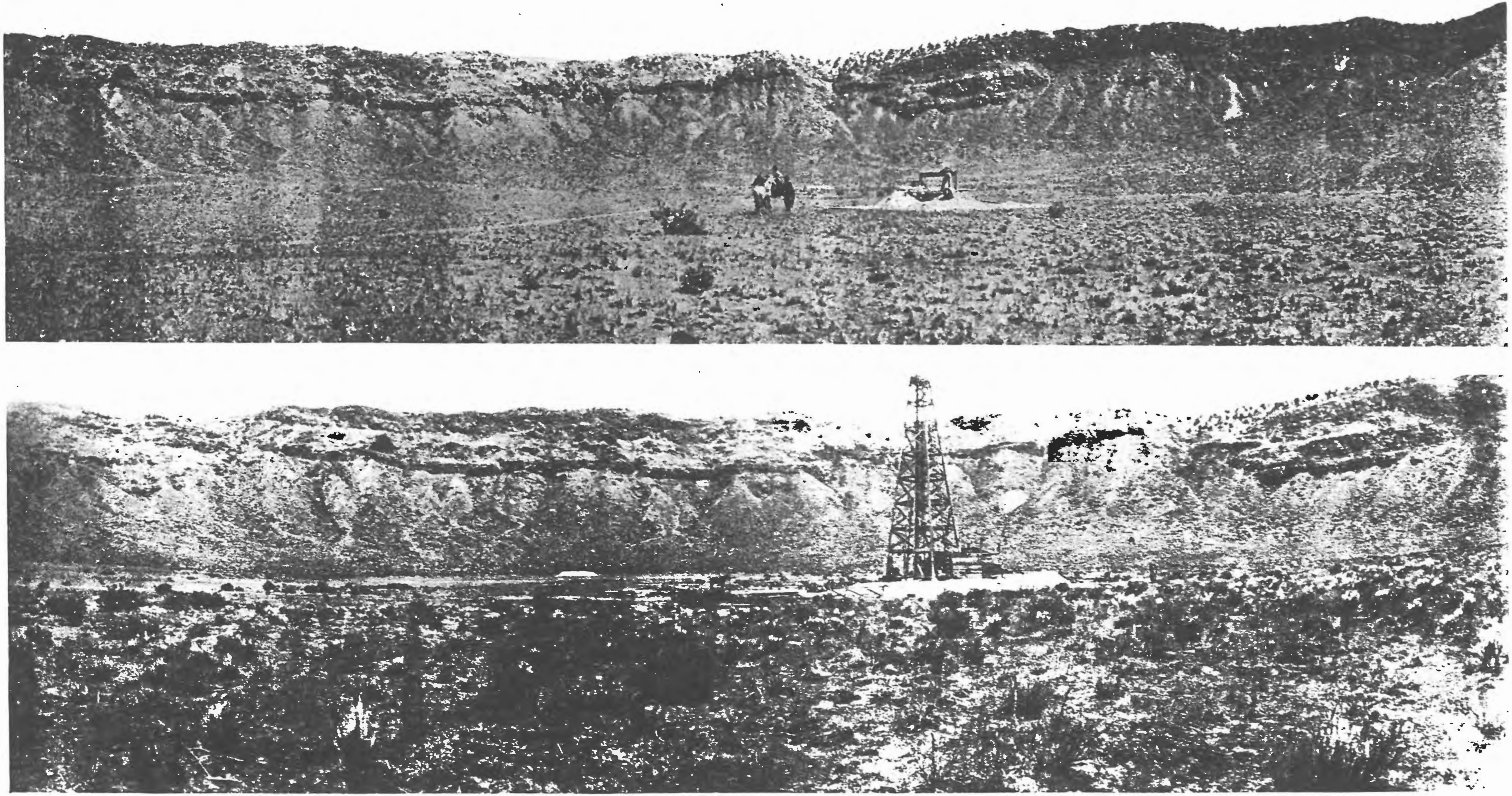
INTERIOR VIEW OF CRATER LOOKING S. S. E.

PLATE II

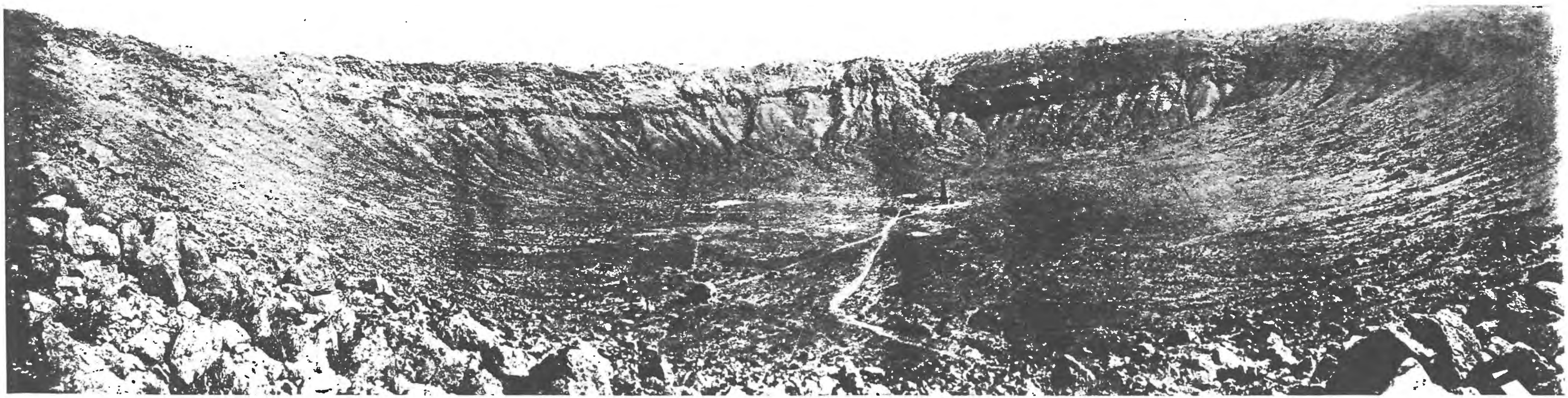


INTERIOR VIEW OF CRATER LOOKING N. N. W.

PLATE III



VIEWS TAKEN WITHIN THE CRATER SHOWING THE INTERIOR CENTRAL PLAIN.

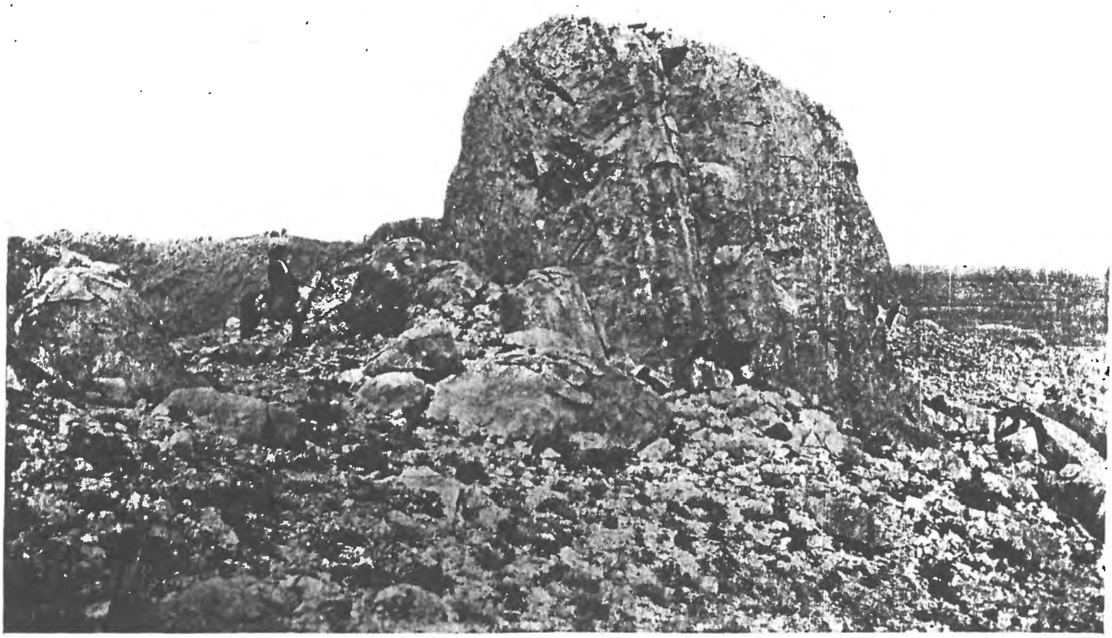


GENERAL VIEWS OF CRATER.
THREE QUARTERS OF A MILE FROM RIM TO RIM.

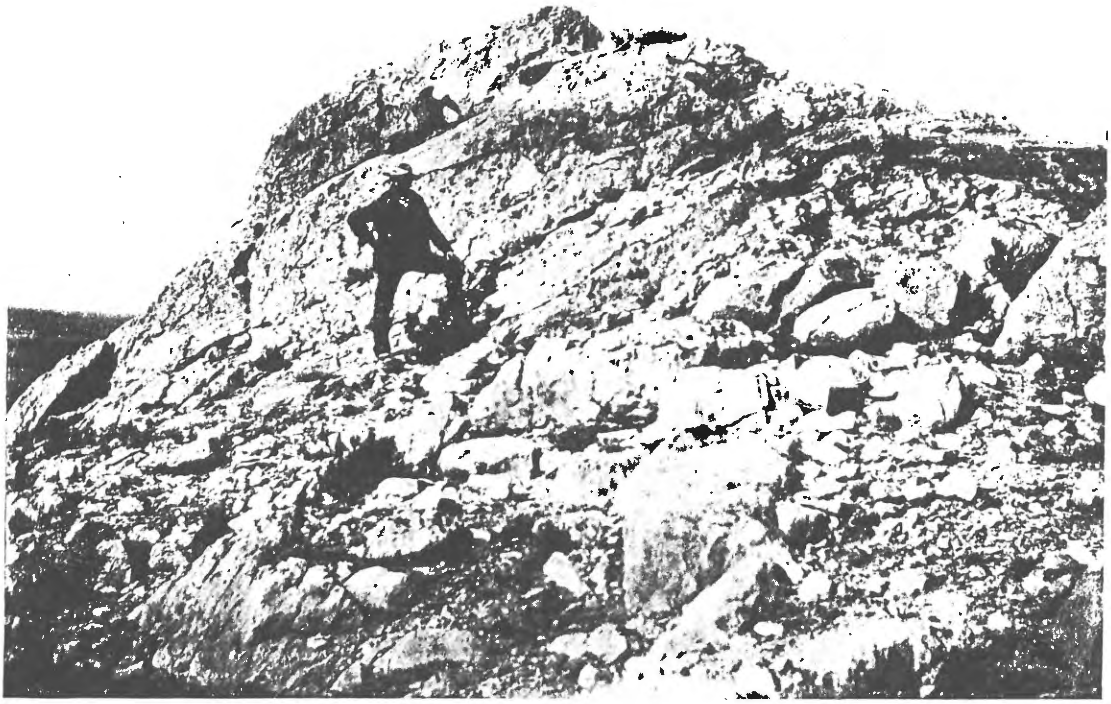
PLATE V

WHALE ROCK—IN WESTERN FIELD OF BIG BOULDERS.

ONE OF THE FURTHEST-THROWN LARGE FRAGMENTS OF LIMESTONE.

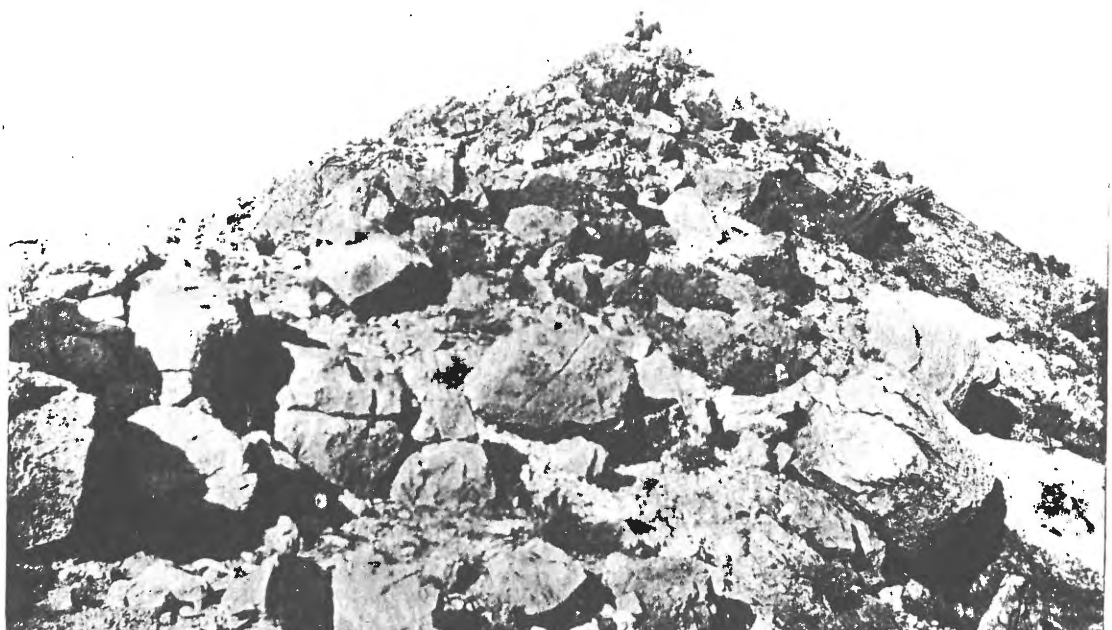


MONUMENT ROCK—NEAR RIM IN EASTERN FIELD OF BIG BOULDERS.



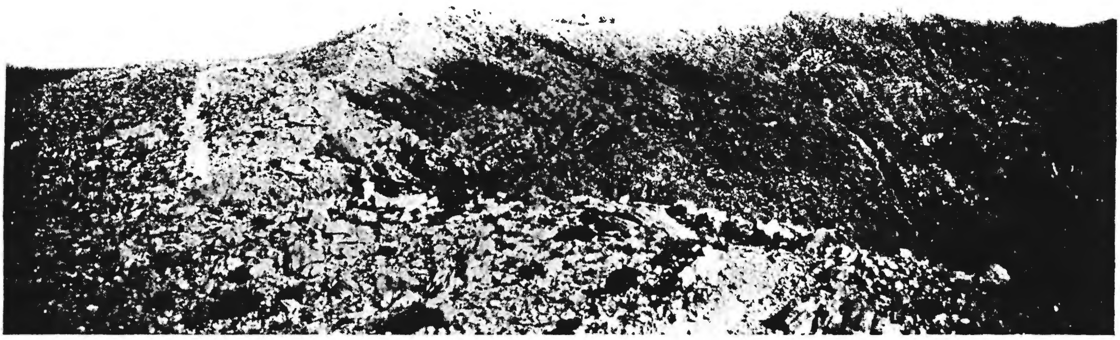
ONE OF THE VERY LARGE HALF-BURIED FRAGMENTS OF LIMESTONE ON WESTERN SLOPE.

CHARACTERISTIC VIEW OF CRATER RIM SHOWING PLAIN IN THE DISTANCE.



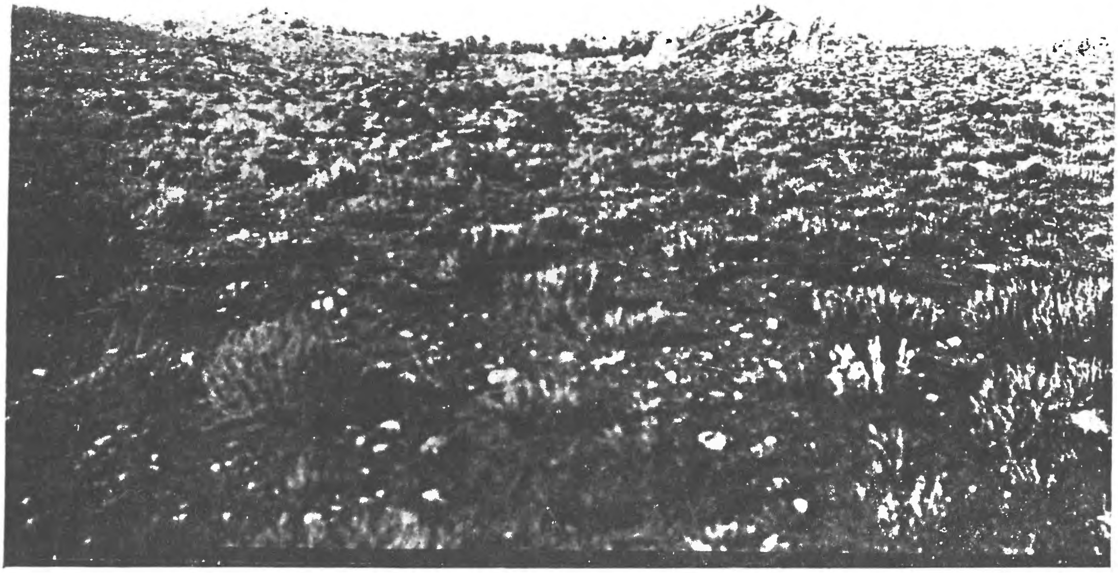
BARRINGER POINT--HIGHEST POINT ON CRATER RIM.

CHARACTERISTIC VIEW OF RIM—SHOWING TILTED STRATA.



ANOTHER VIEW OF THE RIM WITH PLAIN IN THE DISTANCE.

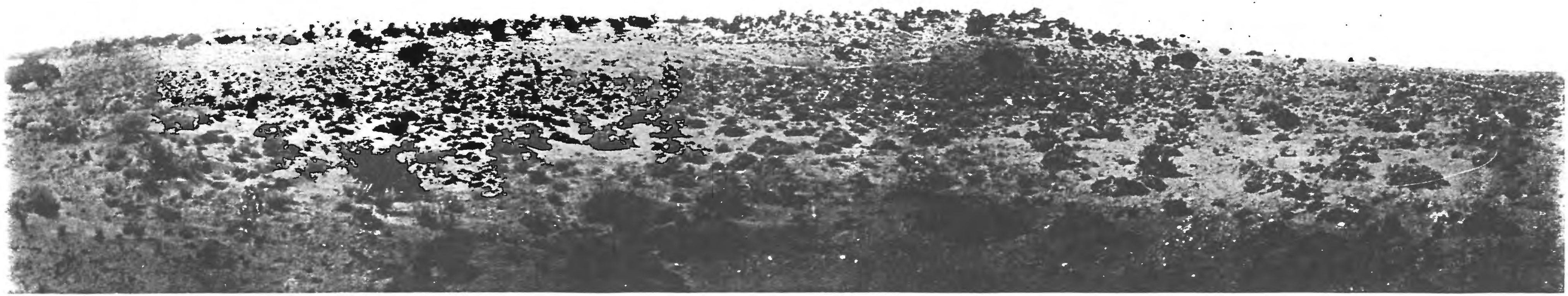
ANOTHER VIEW OF THE RIM -SHOWING OUTCROP OF SLIGHTLY TILTED UPPER RED SANDSTONE AND OF THE LIMESTONE UNDERNEATH.

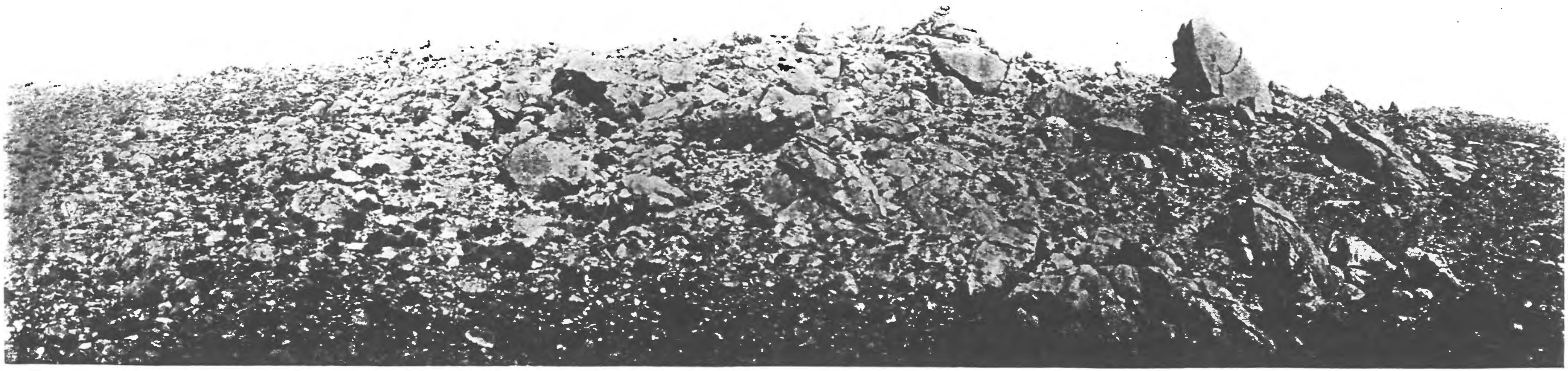


ONE OF THE FURTHEST THROWN LARGE FRAGMENTS OF LIMESTONE—SOUTHWEST SLOPE.

VIEW ON SOUTHERN RIM—CEDAR FOREST ON PLAIN AND SUNSET MOUNTAIN IN DISTANCE.

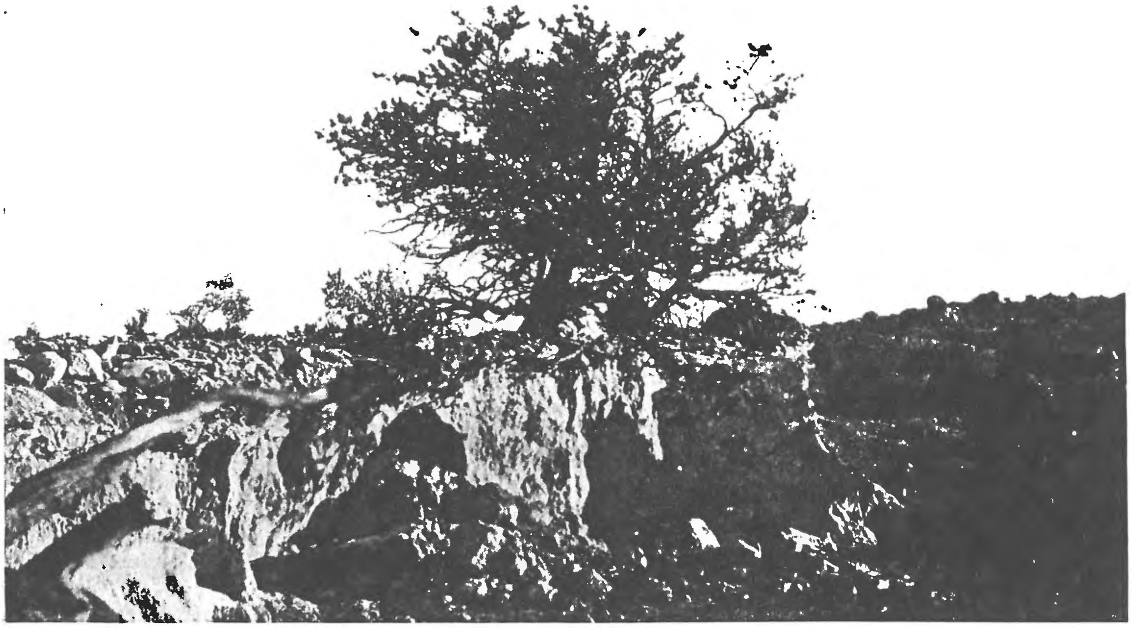
SOME OF THE LARGE FRAGMENTS OF LIMESTONE IN THE WESTERN FIELD OF BIG BOULDERS.



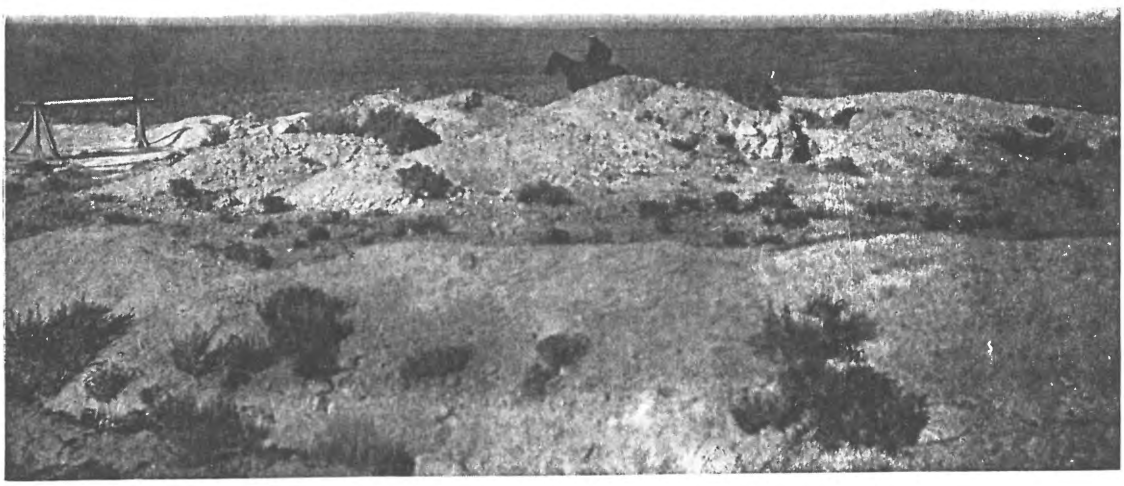


UPPER PHOTOGRAPH SHOWS SOUTHERN SLOPE OF RIM WHILE LOWER PHOTOGRAPH SHOWS WESTERN SLOPE AND PART OF FIELD OF BIG BOULDERS.

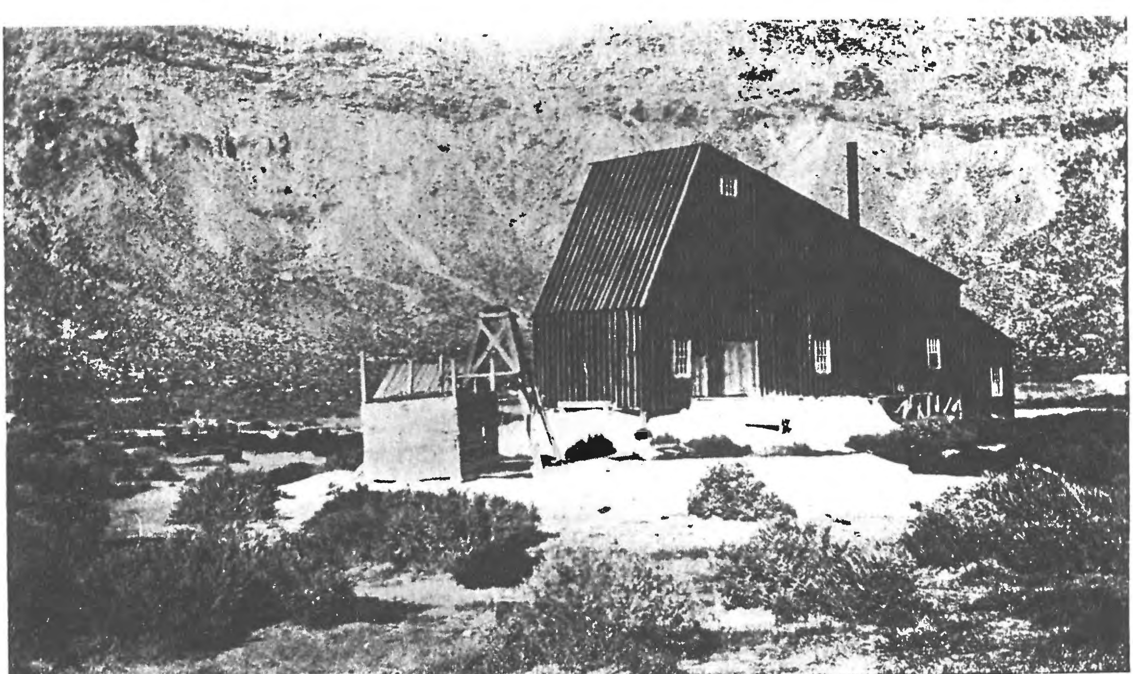
PLATE X



SILICA NATURALLY EXPOSED IN ARROYA ON SOUTHWEST SLOPE.

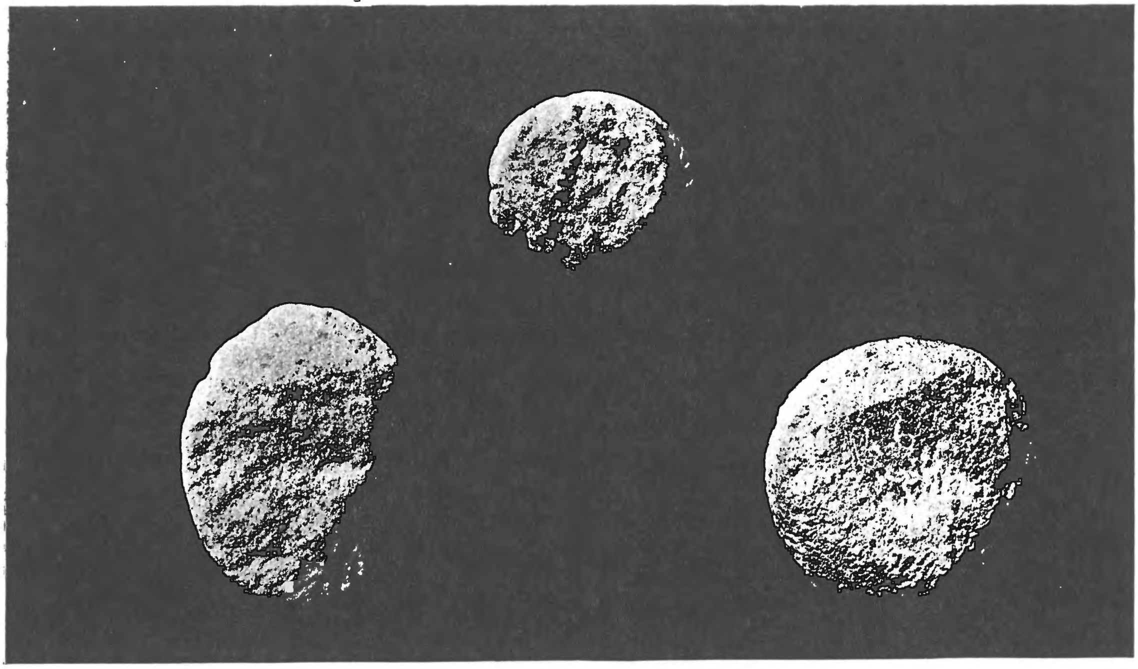


CUT No. 10, ON NORTHERN SLOPE, WHERE MANY SHALE BALLS WERE FOUND.



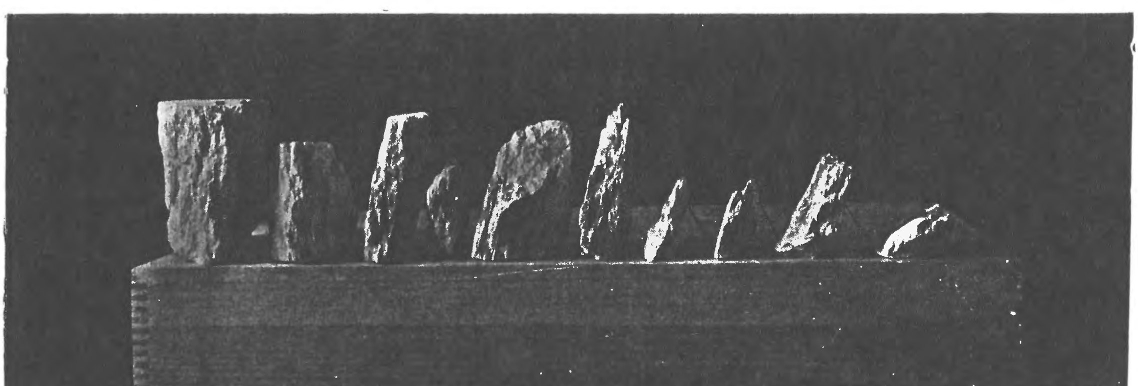
MAIN SHAFT IN CENTER OF CRATER—NOTE SILICA FROM SHAFT.

PLATE XI



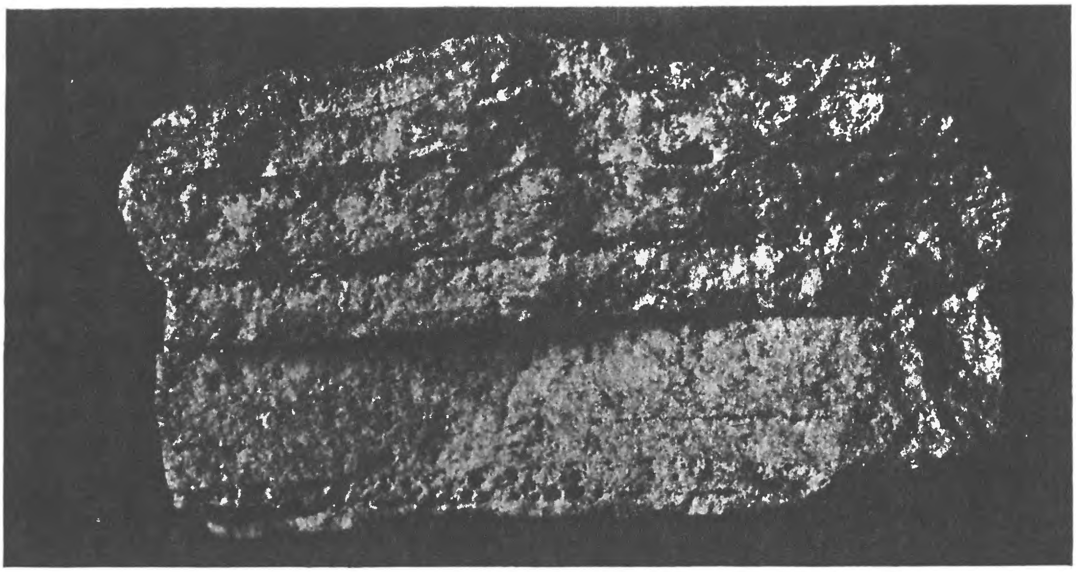
CORES FROM UNALTERED AND UNAFFECTED RED BEDS SANDSTONE STRATUM.

PIECE OF VARIETY "A" OF THE METAMORPHOSED WHITE OR GRAY SANDSTONE SHOWING ORIGINAL BEDDING PLANES.

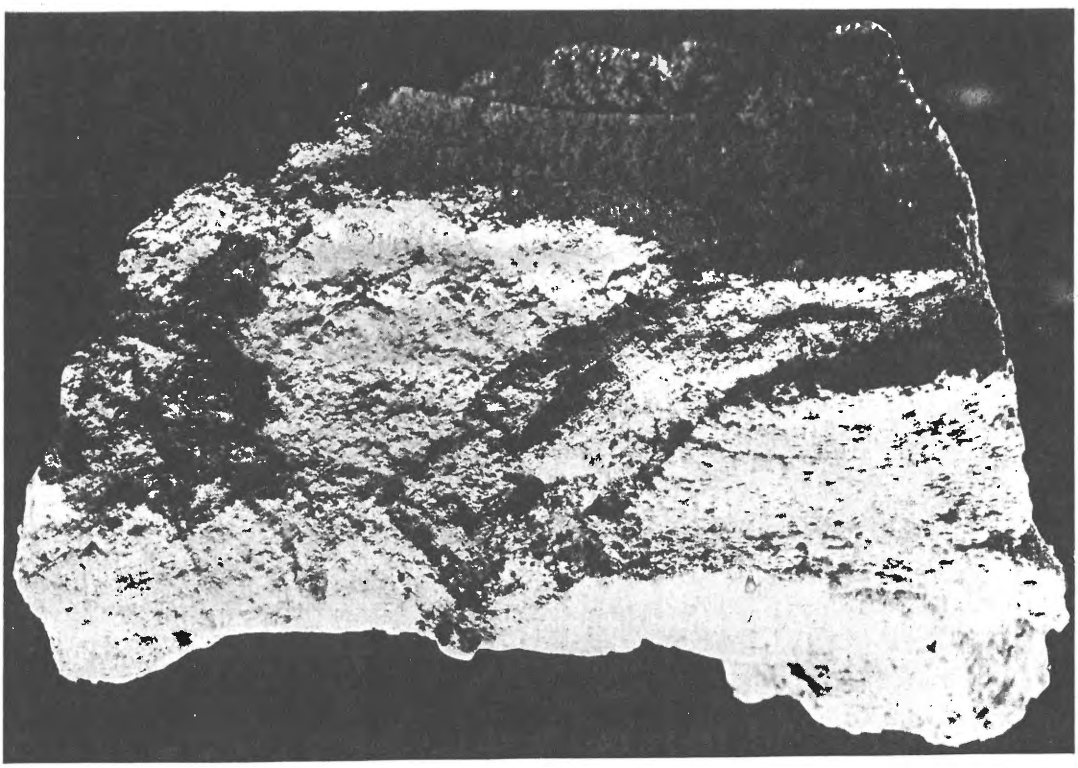


PIECES OF VARIETY "A" SO PLACED AS TO SHOW THE SLATY STRUCTURE NOT ONLY AT RIGHT ANGLES TO THE BEDDING PLANES BUT ALSO AT OTHER ANGLES WHEN COMPARED WITH THEM. THE BOTTOM OF EACH SPECIMEN REPRESENTS AN ORIGINAL BEDDING PLANE. (GREATLY REDUCED.)

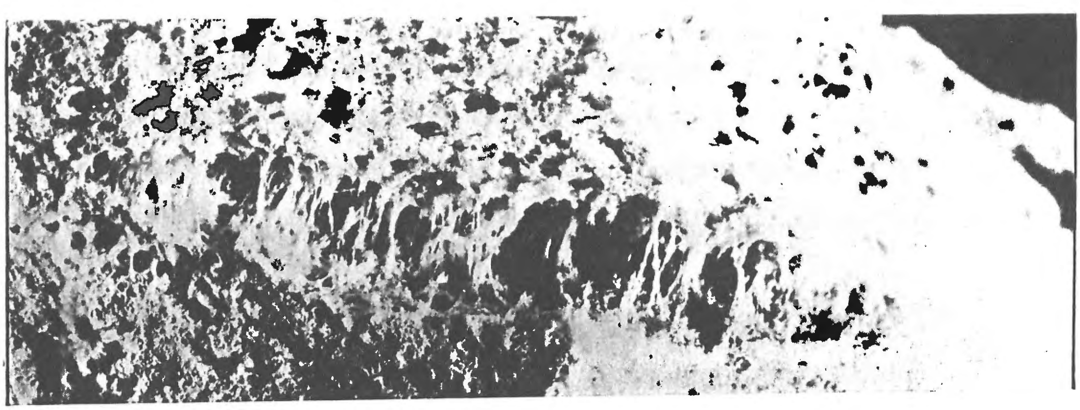
PLATE XII



PIECE OF VARIETY "B" OF THE METAMORPHOSED WHITE OR GRAY SANDSTONE SHOWING ORIGINAL BEDDING PLANES. (NATURAL SIZE.)

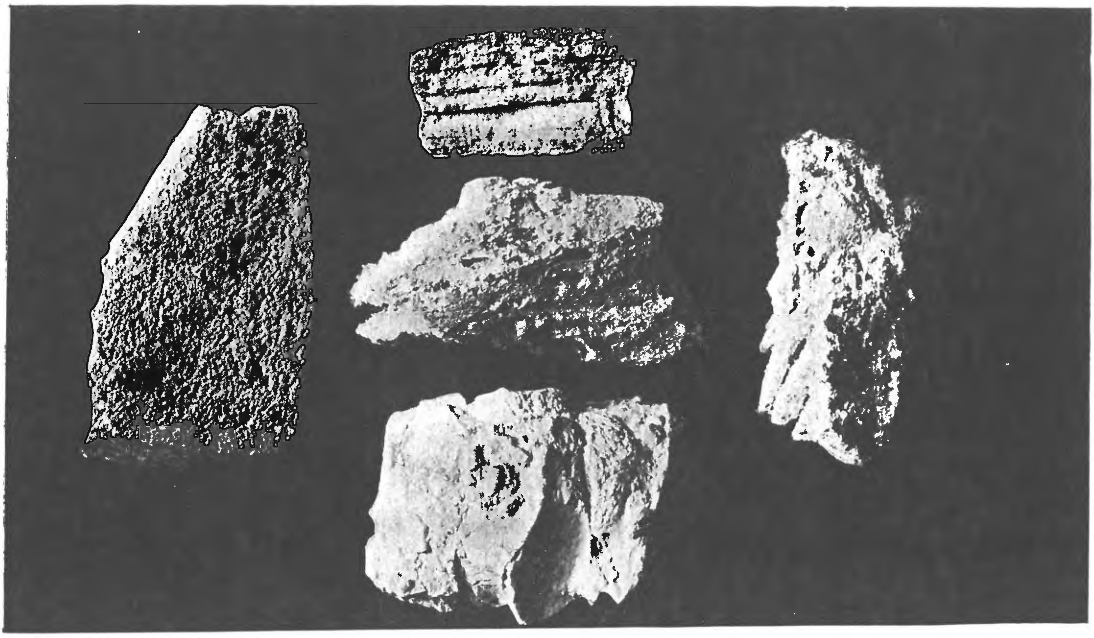


ANOTHER PIECE OF VARIETY "B," SHOWING DISTORTION OF ORIGINAL BEDDING PLANES. (GREATLY REDUCED.)



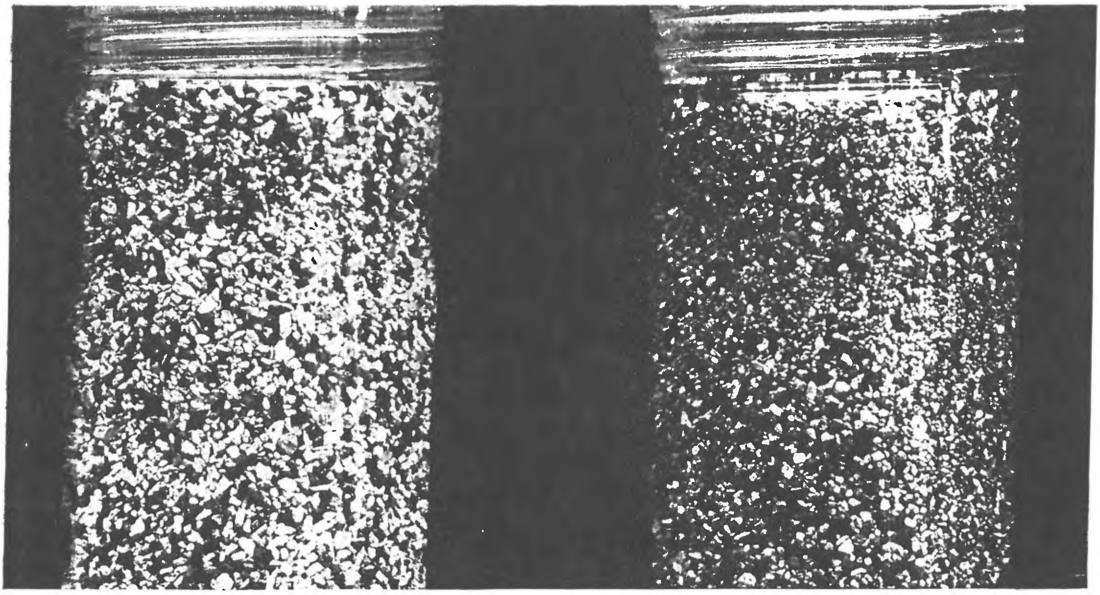
ANOTHER PIECE OF VARIETY "B," ENLARGED TWO DIAMETERS TO BETTER SHOW THE STRUCTURE AND THE FILAMENTS OF AMORPHOUS QUARTZ.

PLATE XIII



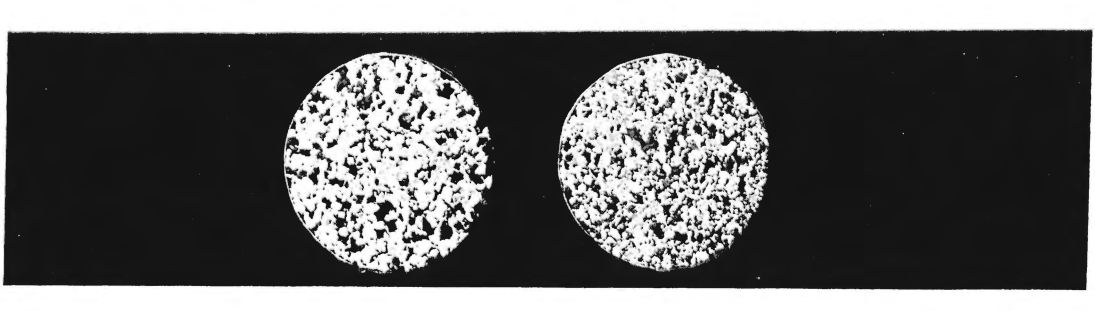
UPPER FOUR SPECIMENS ARE TYPICAL PIECES OF VARIETY "B."

Specimen on left abundantly stained and specked by nickel-iron oxide. The stain is supposed to represent the effect of flame and the dark-colored specks the effect of sparks or minute bits of burning metal. The lowest specimen is a fine example of the bluish, opalescent quartz surrounding variety "B," and representing complete fusion of the silica.



TYPICAL METEORIC MATERIAL FROM DEPTHS OF CRATER BROUGHT UP BY THE DRILL.

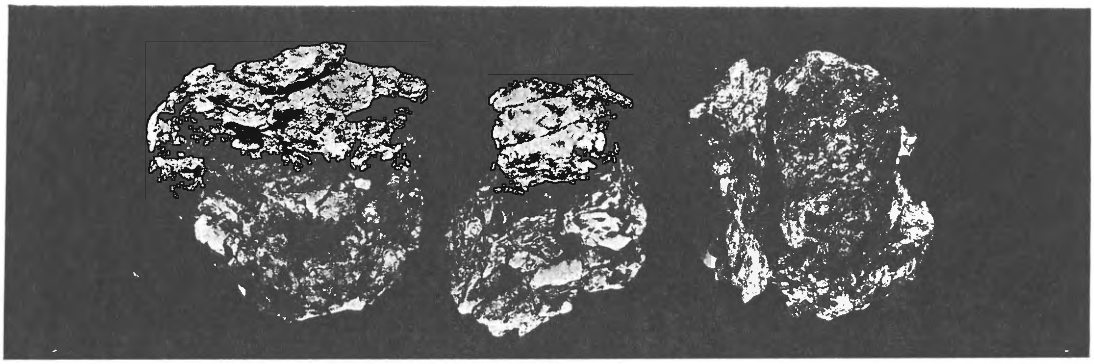
The black specks represent nickel-iron oxide and nickel-iron silicate; the white specks small fragments of variety "A" and variety "B." The trained eye with the aid of a glass will detect a few pieces of the bluish, opalescent quartz. Meteoric material more or less concentrated. Natural size.



SAME AS ABOVE.

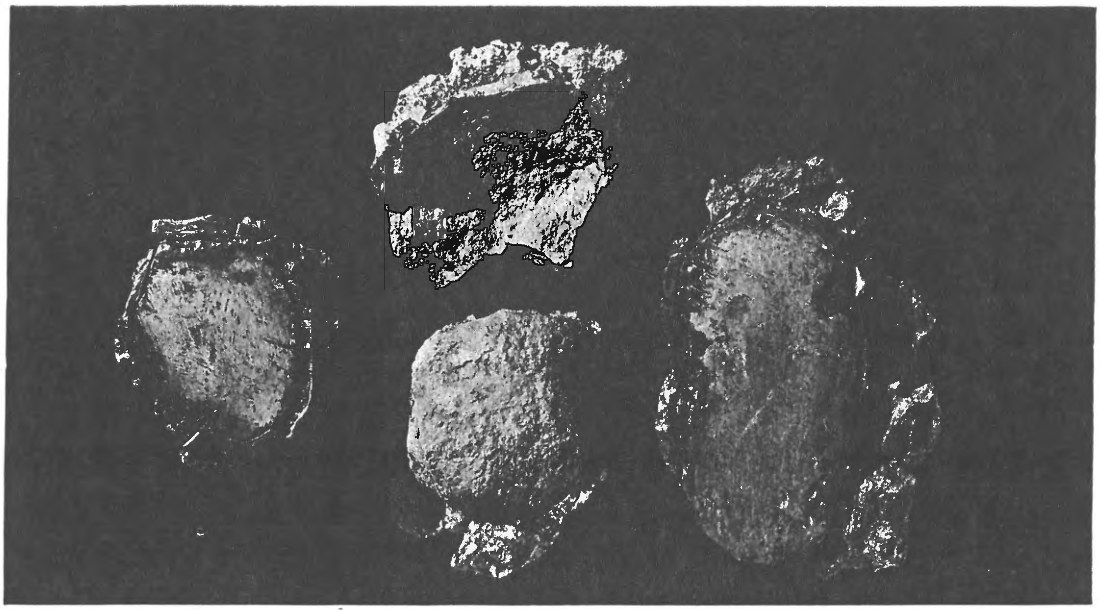
It must be understood that meteoric material has rarely been found in the depths of the crater as abundantly mixed with the surrounding material as shown in these photographs. Natural size.

PLATE XIV



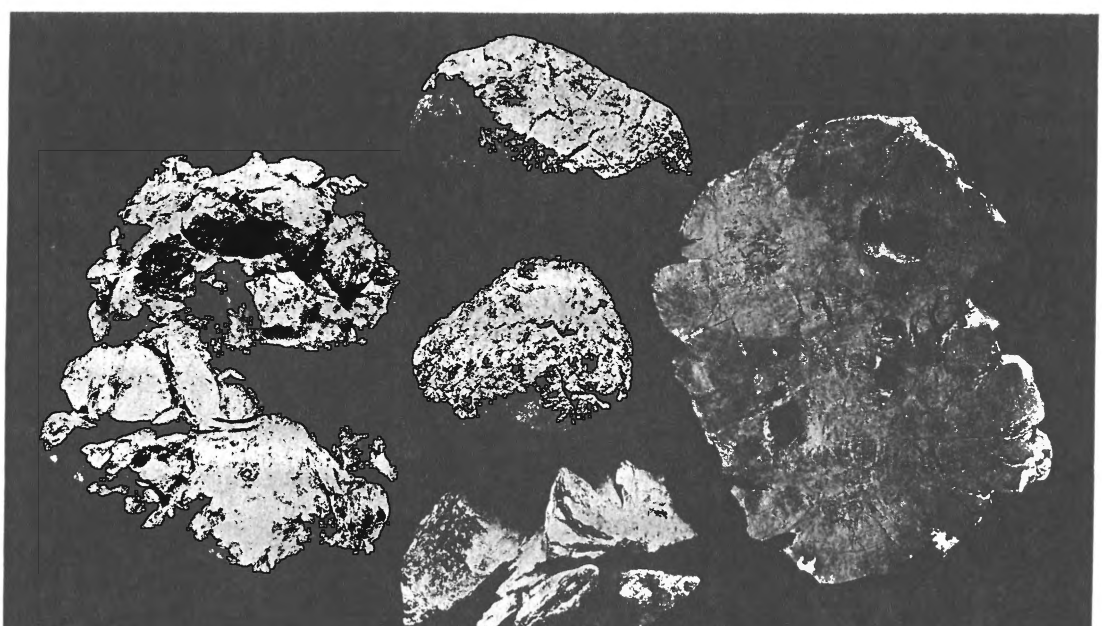
SHALE BALL METEORITES WITH NICKEL-IRON CENTERS AS THEY APPEAR WHEN DUG OUT OF THE SILICA.

One iron center (on the right) is disclosed, the others are still covered by a heavy coating of nickel-iron oxide, or so-called iron shale. Greatly reduced.



TYPICAL SHALE BALLS WITH NICKEL-IRON CENTERS.

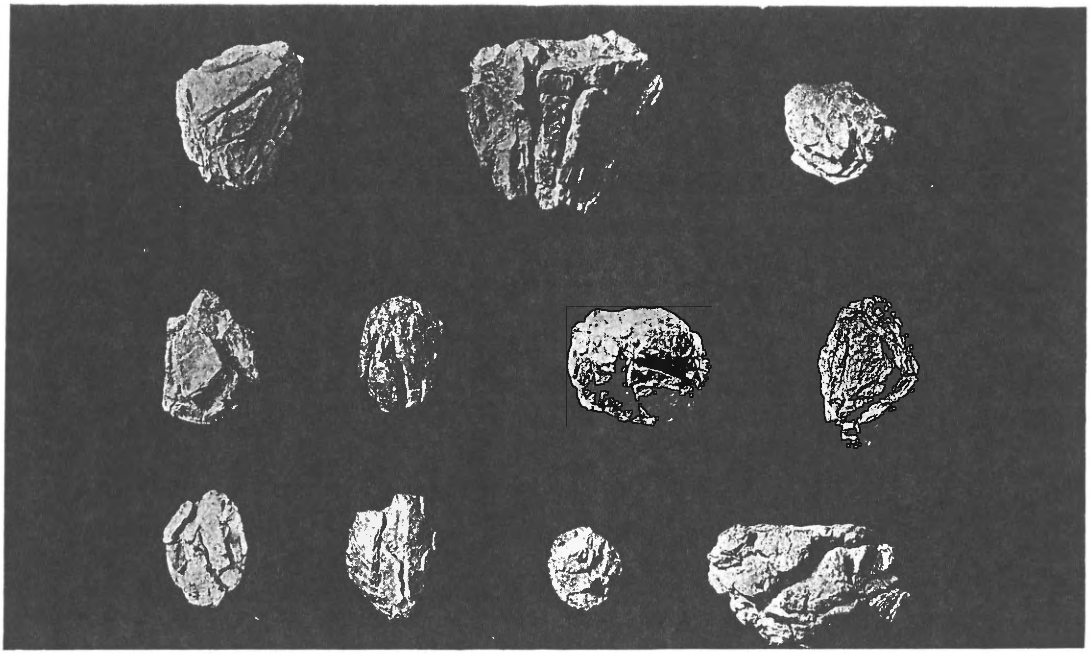
Note the Widmanstatten figures shown on the two specimens which have been sawed in two. Greatly reduced.



MORE OR LESS IRREGULAR MASSES OF NICKEL-IRON SHALE FOUND ON THE PLAIN AND REPRESENTING THE DECOMPOSITION OF SHALE BALL METEORITES.

Note what appear to be the remains of Widmanstatten figures in specimen on the right, which has been sawed in two. All photographs on this page have been greatly reduced.

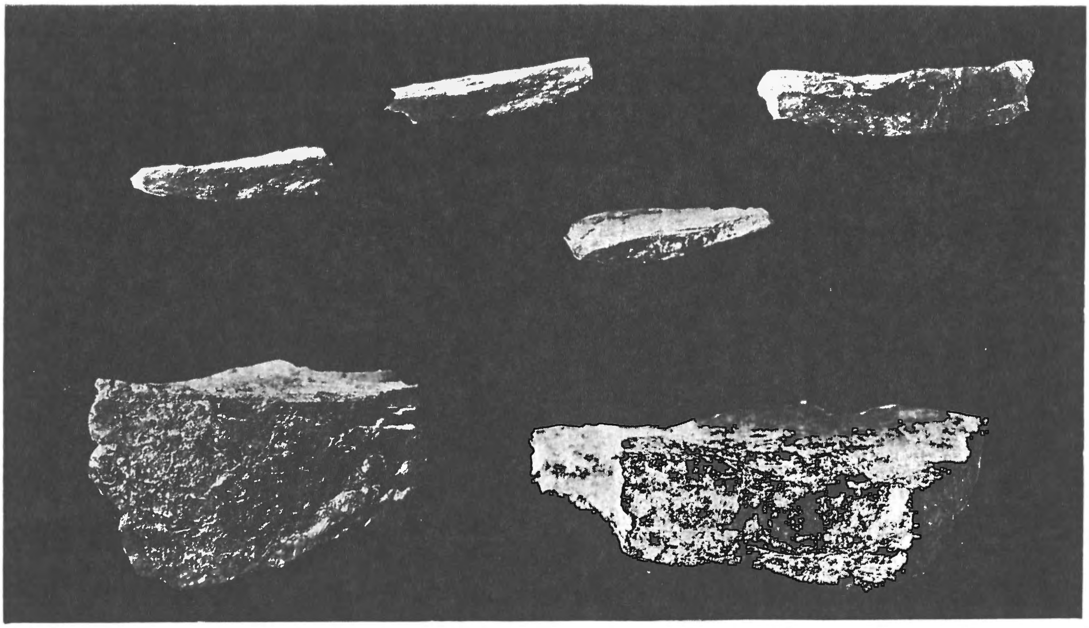
PLATE XV



TYPICAL EXAMPLES OF SMALL SHALE BALL METEORITES WHICH HAVE ESCAPED DISINTEGRATION, BUT WHICH ARE NOW ENTIRELY CONVERTED INTO HARD, DENSE NICKEL-IRON SHALE.

The middle specimen in upper row represents the pointed end of a considerably larger meteorite than the rest. Such pointed specimens are not infrequently found. Considerably reduced.

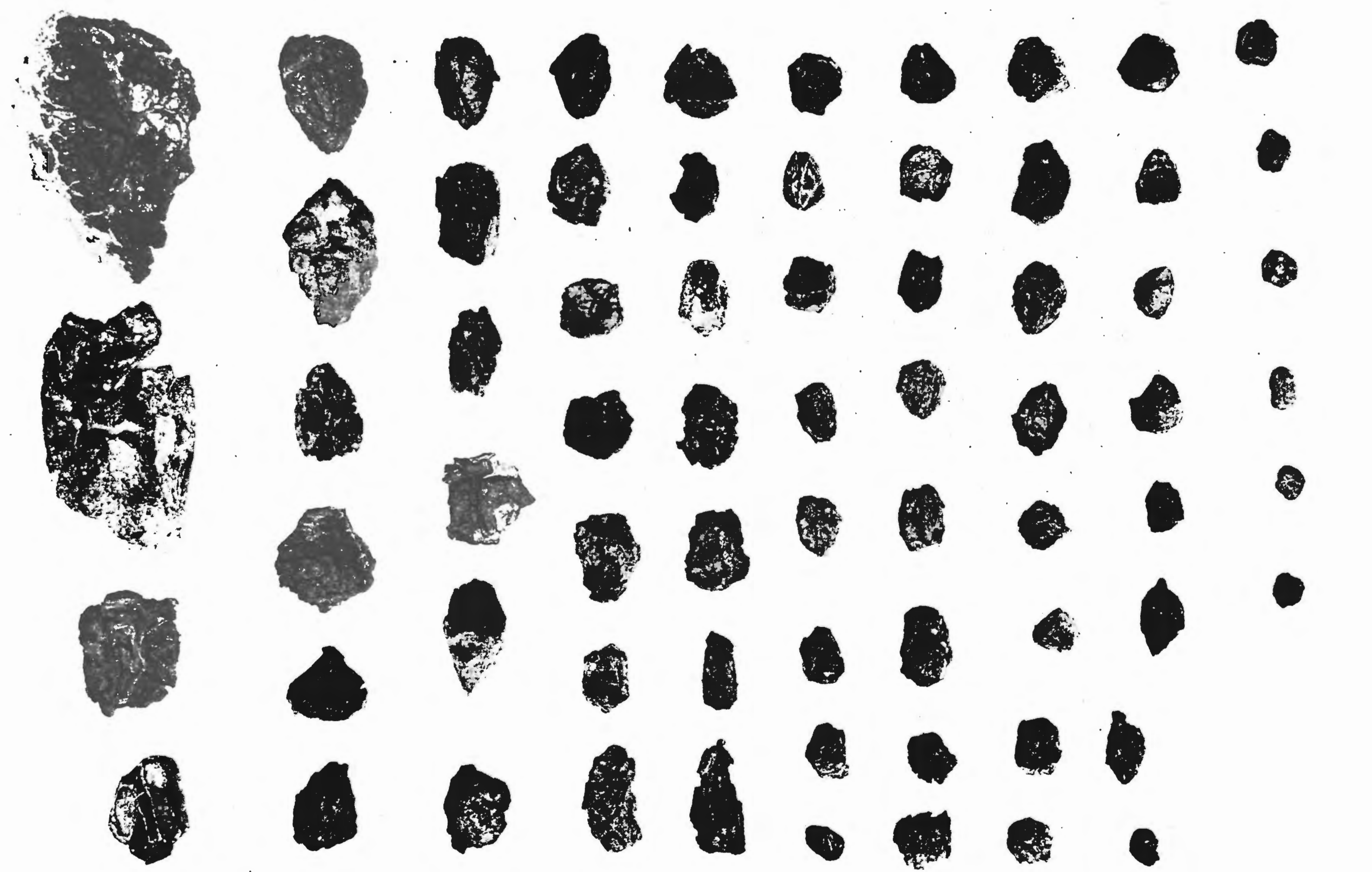
TYPICAL EXAMPLE OF A VERY SMALL OVAL SHALE BALL METEORITE NOW ENTIRELY CONVERTED INTO NICKEL-IRON SHALE. (NATURAL SIZE.)



TYPICAL PIECES OF HARD, DENSE NICKEL-IRON SHALE FOUND ON ALL SIDES OF THE CRATER IN GREAT NUMBERS.

Note the curvature indicating that they represent portions of shale ball meteorites which have disintegrated. Largest specimen in left-hand lower corner about 2½ inches thick. A few specimens have been found much thicker than this and some have been found as thin as a thin knife-blade.

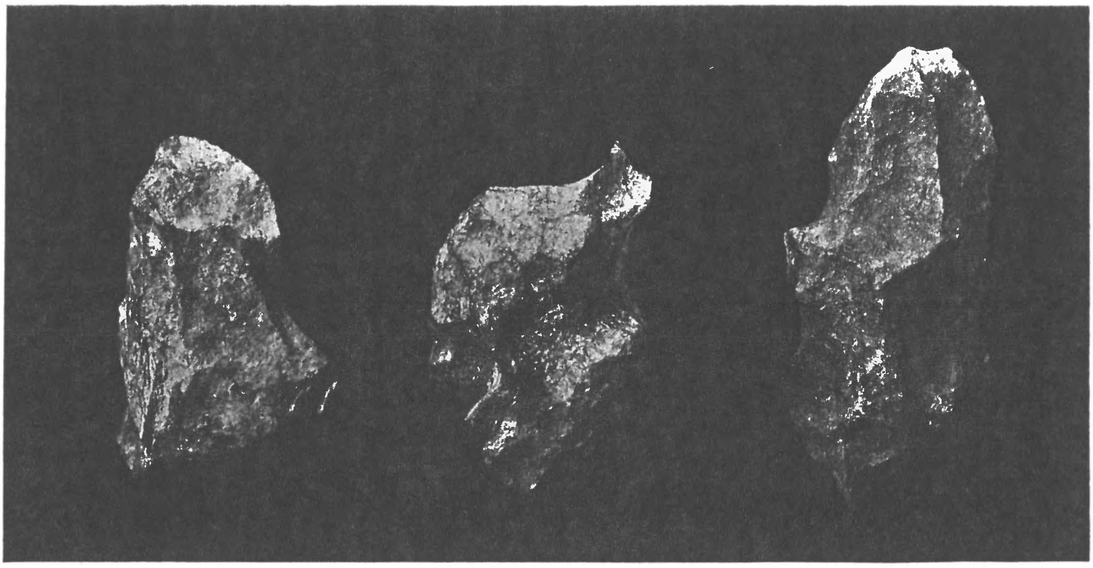
PLATE XVI



A NUMBER OF SMALL SHALE BALLS NOW THOROUGHLY OXIDIZED WHICH WERE FOUND ON THE OUTSIDE PLAIN.

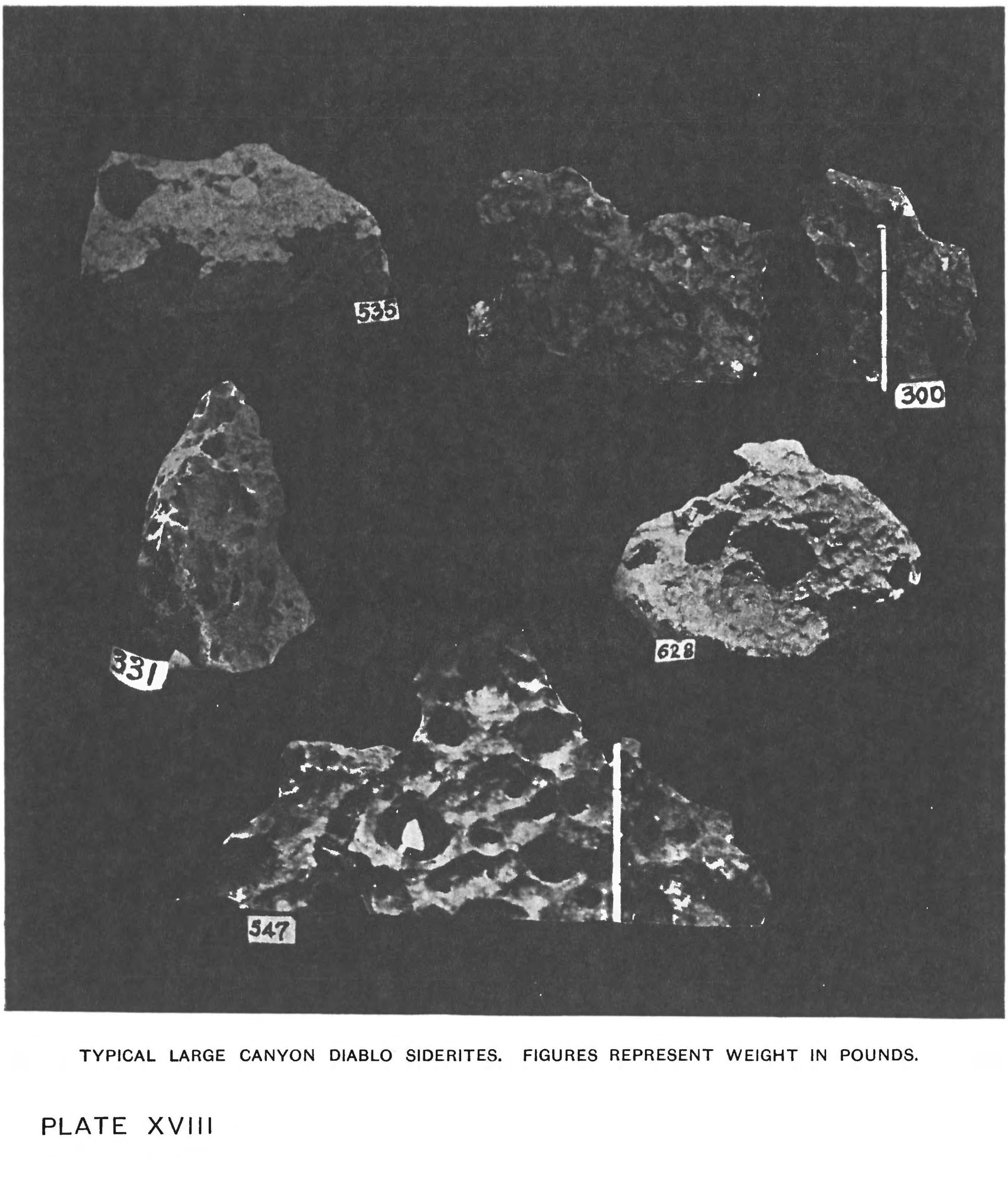
SOME OF THESE WERE FOUND SEVERAL MILES FROM THE CRATER. AS IS THE CASE WITH ALL SHALE BALLS, OXIDATION HAS PRODUCED ROUGH AND CRACKED SURFACES. (CONSIDERABLY REDUCED.)

PLATE XVII



TYPICAL PIECES OF ORDINARY SMALL CANYON DIABLO SIDERITES, SEVERAL POUNDS IN WEIGHT.

The specimen on the left shows a tendency to oxidize and originally was doubtless composed largely of shale ball iron. Note the piece of typical nickel-iron shale firmly adhering to the lower right-hand corner. From this and a few other specimens which have been found with a great deal of similar iron shale adhering to them it is inferred that many of the smaller ordinary Canyon Diablo siderites are residuals from the decomposition of larger masses of shale ball iron.



TYPICAL LARGE CANYON DIABLO SIDERITES. FIGURES REPRESENT WEIGHT IN POUNDS.

PLATE XVIII