THE ORIGIN OF KILBOURNE HOLE, NEW MEXICO.

PARRY REICHE.

ABSTRACT. Observations at Kilbourne Hole show that its rim is not chiefly composed of explosion debris, as heretofore reported, but is an erosion remnant of fluviatile sands, beneath which earlier-formed accumulations of ejecta are buried. Tilted blocks of the sands which form the rim occur also on the floor of the Hole and indicate its subsidence origin. A similar origin of other depressions in the same district is thought likely. Data bearing on the cause of the subsidence are discussed.

KILBOURNE HOLE is a depression about two miles long by a mile and a quarter wide. Its floor is 250 to 300 feet below the general level of the surrounding country, and on three sides it is bordered by a rim which rises ten to 150 feet above that level. It was described and explained,[1] over thirty years ago, as a volcanic explosion crater. That explanation, which has been reiterated several times in the literature,[2] is herein challenged.

Kilbourne Hole is the larger and more informative of two depressions known as the Afton Craters. It is about 25 miles south-southwest of Las Cruces, New Mexico. The surrounding district is a flattish erosion surface, the 'La Mesa' plain, which lies about 350 feet above the level of the Rio Grande River. This surface is mantled, here and there, by Recent basaltic flows, of which one center of eruption lies a few miles north of Kilbourne. The plain is cut on Tertiary and Pleistocene(?) river sediments within the upper 50 feet of which there are occasional interbedded basalt flows. The sediments are ill consolidated and of unknown thickness. With the very minor exceptions noted on page 217, they are undisturbed.

In Fig. 2 are shown the Afton Craters and a third large depression, Phillip's Hole, which is not crateriform, but which, presumably is closely related in origin to Kilbourne and Hunt's.

[1] Lee, Willis T.: Afton Craters of Southern New Mexico. Bull. Geol. Soc. Amer. Vol. 18, pp. 211-220, 1907.

[2] Darton, N. H.: Explosion Craters. Scientific Monthly. Vol. 3, p. 425, 1916.

Idem. Red Beds, etc., U. S. Geol. Surv. Bull. 794, p. 65, 1928.

Idem. The Southern Pacific Route. U. S. Geol. Surv. Bull. 845, p. 134, 1933.

Dunham, K. C.: Geology of the Organ Mts. N. Mex. Sch. Mines. Bull. 11, pp. 182-183, 1935.

Phillip's Hole is intermediate in size, depth and shape to the Afton Craters and a large number of shallower depressions which dot the Noria Quadrangle. These range in depth up to thirty feet, and some are several miles in extent. They exhibit no regularity of outline or pattern. They have doubtless been greatly modified by wind erosion; some of them may have been formed by that process.

At Kilbourne Hole wind erosion can have had at most a very minor modifying effect. The inner walls are steep, exposing a cliffed basalt flow which separates lower beds, probably of Ter-

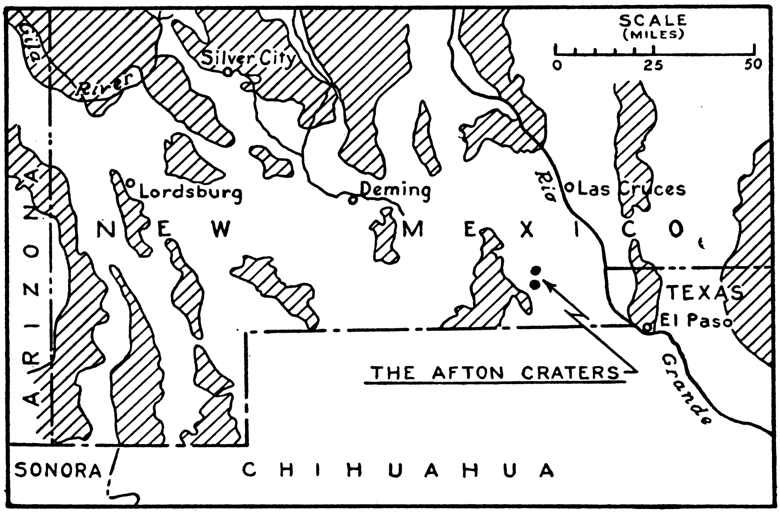

Fig. 1 Index map showing position of Afton Craters, New Mexico. Rugged tracts shaded.

tiary age, from upper sands which are possibly Pleistocene.[3] The basalt is about 15 feet thick in the northwest wall and thins to extinction to the south, where, for short stretches, it is absent. It rests upon a heavy caliche zone of wide extent which may well represent a disconformity between upper Tertiary and Pleistocene deposition.

Except where the basalt is lacking, the sediments below its horizon are mantled by a heavy talus. A few large slid blocks of the basalt occur at or near the base. One of the latter, near

[3] Dunham, K. C.: op. cit., pp. 175-176.

the north end of the Hole, is the cap of a Toreva-block[4] 500 feet long, dipping 58 degrees towards the cliff.

The caliche-capped sediments below the basalt horizon are exposed to a depth of about 65 feet in the southeastern reentrant of the Hole. They include reddish and buff, bedded, clean, sorted sands and silts, with very minor red clays. There is a second thin caliche about 30 feet below the top. No volcanic grains or fragments are megascopically visible in any of these materials. In a general way they strongly resemble the fluviatile Santa Fe formation (Miocene-Pliocene) of central and northern New Mexico.

Above the basalt flow the sediments rising to the rim of the Hole are gray, rather than reddish in hue, and are thin bedded and strongly cross-laminated at low angles.[5] They are evidently fluviatile, and are characterized by abundant basaltic lapillae. The probability that the fossil reported by Lee (see p. 225) was authigenous to, or reworked from, these beds has led to their map designation as "Pleistocene(?)." The outer slopes and in places the crest of the rim are mantled by active blow sand.

In the original description of Kilbourne Hole it was implied that its rim was formed of a volcanic explosion breccia,[6] and it was this implication which lead to the conclusion of explosion origin. In point of fact, there is abundant explosion debris forming the remnants of several masses of ejecta which rest upon the basalt flow, and were buried by the upper cindery sands. In no place do the ejecta rise to, or form, the rim-crest.

A vent below one of the breccia accumulations is exposed in section in the north wall of the Hole. At this place the continuity of the basalt and of the lower sands is broken for a distance of about 530 feet. The basalt preserves its normal thickness quite to the break, but is slumped slightly downward toward it for about 50 feet on either side. The vent is filled with explosion debris, which is well exposed in sharp gulches (Plate I, Fig. 2). The material consists of a whitish, dusty, sand matrix, with abundant scattered angular fragments, chiefly basaltic, of granule and pebble dimension. Through this occur, sporadically, angular blocks of basalt up to several

[4] Reiche, P.: The Toreva-block, a distinctive landslide type. Journ. Geol., Vol. XLV, pp. 538-548, 1937.

[5] This fact was noted by Darton in 1933, (loc. cit.) who, however, showed them in cross-section as "ejected material."

[6] Lee: op. cit., pp. 218-219.

feet in diameter, as well as boulder and cobble sized fragments of the following, approximately in order of decreasing abundance:

- basalt.
- medium-to coarse-grained olivine-augite segregations of dimensions up to ten inches, with partial or complete skins of basalt.
- dark grey marine limestones with poorly preserved fossils.
- felsite of several sorts.
- buff sandstone.
- greenish soft micaceous siltstone.
- whitish, intensely fractured, garnetiferous gneiss, locally with imbibed bubbly basaltic glass films along the planes of schistosity.
- black glassy augite[7] in choncoidally fractured masses up to two inch dimension, occasionally with marginal basalt films.

It is noteworthy that, of the above listed, only the felsite, the glassy augite and the basaltic fragments are angular; the limestone, sandstone and siltstone fragments invariably appear water-worn. The basalt with slight doubt originated by explosive fragmentation of the flow seen in the walls of the crater; the felsite fragments presumably came up from a buried flow, or possibly a very slightly worn gravel. The earthy matrix, comprising most of the debris, resembles, and is probably due to comminution of sands and silts, like those seen in the walls of the present Hole, below the basalt. In a few places there are trains of small fragments traceable for two or three feet. With such rare exceptions the debris is massive; it is also unsorted and uncemented.

The accumulations of ejecta lying on the basalt are in every way similar to the vent material which has been described. They are poorly exposed, since their present upper surface is a blocky rubble due to removal of the finer fractions from a considerable thickness of material by deflation and wash.

For nearly a mile north of the middle of the eastern rim of the Hole, and again locally in its northern reentrant the ejecta rise to within 25-30 feet of the crest of the rim. A lesser mound of the same material occurs in the rim west-northwest

[7] No index oils being locally available to the writer, at the time, this material was kindly identified by Prof. Howel Williams, who reports: $\beta = 1.704 \pm .002$; $Z \wedge c = 45°$; $2V = 60°$; $\rho > v$, and a purplish tint in thick grains suggesting some TiO_2.

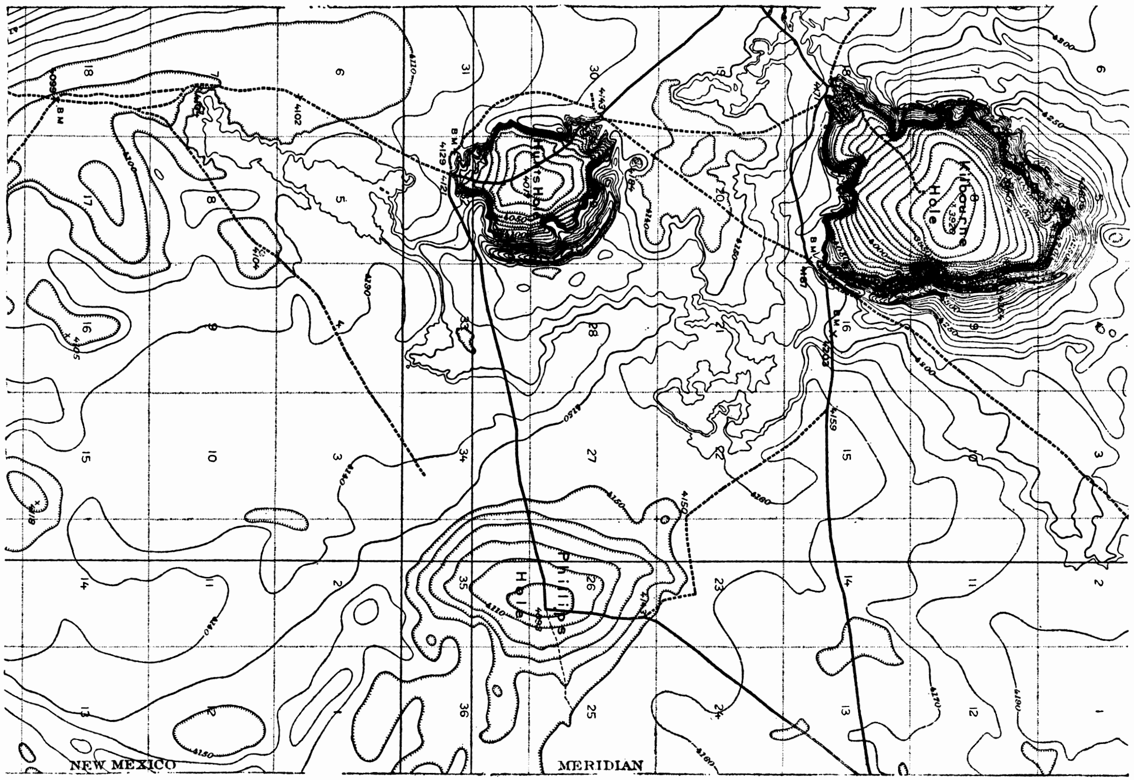

Fig. 2. Portion of the Noria Quadrangle of the U. S. Geological Survey. The grid interval is one mile. Contour interval ten feet.

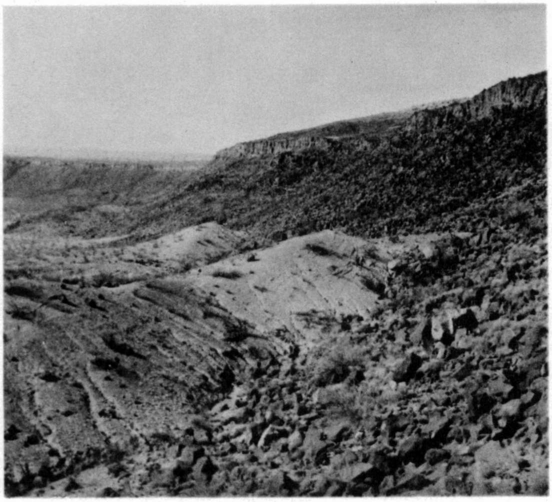

FIG. 1

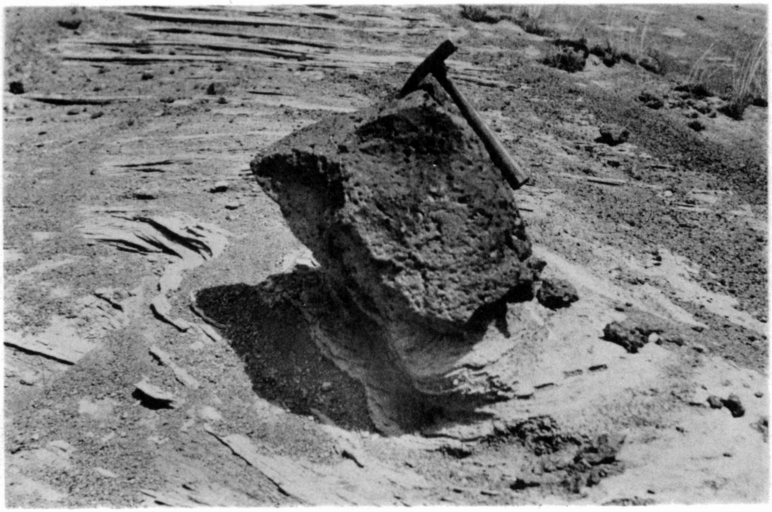

FIG. 2

FIG. 1. Looking northerly along base of east wall of Kilbourne Hole. Basalt cliff and talus, and a dissected inward-dipping block of the post-basalt fluviatile sands are shown.

FIG. 2. Block of basalt from earlier ejecta cone incorporated in the post-basalt sands.

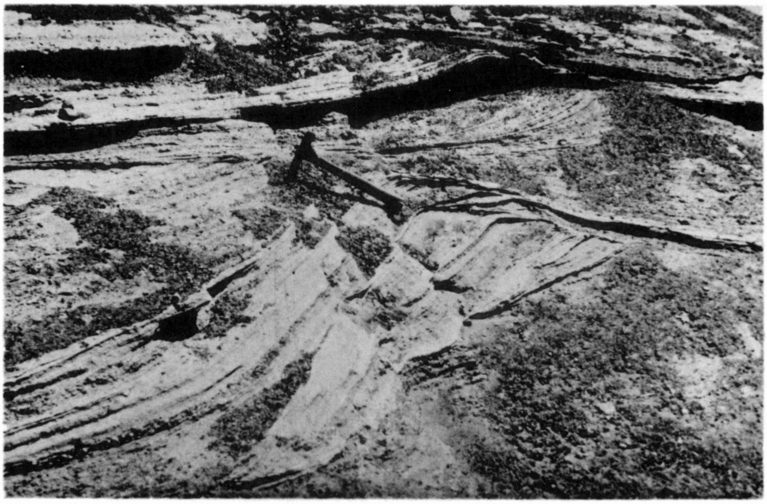

FIG. 1

FIG. 2

FIG. 1. Fluviatile sands in the rim of Kilbourne Hole.
FIG. 2. Ejecta filling vent in north wall of Kilbourne Hole.

of the windmill. The southern and southwestern segments of the crater margin are essentially without ejecta and the upper grey fluviatile sands rest directly on the basalt, or, where that is not present, on the caliche capping the lower sands. The thickness of ejecta decreases nearly to zero between the several maxima.

Fragments from the breccia were, naturally, incorporated in the fluviatile sands which built up around the ejecta accumulations and finally buried them. Such fragments are found only in the immediate vicinity of the buried masses, and in a few definite horizons. The conclusion seems inescapable that the explosions long antedated the present depressions.

As was noted in the papers which have been cited, the upper sands exhibit local folding and tilting, in marked contrast to the horizontality of underlying materials. The attitudes indicate 1): an eastern tilt of four to six degrees along the east rim of the crater and 2): an asymmetric north-northwest plunging anticlinal axis with four to eight degree flanking dips, in the northern rim. These structures are somehow related to underlying ejecta masses, to the upper surface of which they roughly conform. Differential compaction suggests itself, although obviously none of the conditions are favorable to that origin. Where the ejecta are very thin or absent, the upper sands rest horizontally and conformably on the underlying materials.

The floor of Kilbourne Hole is mantled by colluvial and alluvial fan materials, sloping inward towards a playa. The form and extent of the fans show that the southern margin of the crater, where the basalt is thin or absent, has been extended very considerably by erosion since its formation. A well drilled in the floor of the Hole, prior to 1907, is reported to have yielded hot sulphurous water from a depth of about 100 feet.[8] This well has since been abandoned.[9]

Between the base of the inner slopes and the floor of the crater in its northeastern and northern segments, and forming a detached ridge rising from the floor in the northwest, are masses of cindery post-basalt sands. These dip inward at

[8] Lee, W. T.: op. cit., p. 217.

[9] Dr. W. M. Tucker states (personal communication) that Mr. J. F. Kilbourne, the owner, informed him in 1930 that broken basalt was encountered in the bottom of two wells in Kilbourne Hole and that these wells were 180 and 173 feet deep, with water at 100° F. rising about 70 feet.

angles between 21 and 34 degrees. Approximately 90 feet of the upper sands are present in the isolated hill mentioned above. There can be no question of the identity of the material. Near the north reentrant of the crater floor, under a shallow veneer of alluvium, the dip (21°) flattens rather sharply to the horizontal as the base of the inner slope is approached. For this no explanation suggests itself. In the same neighborhood the tilted materials have been covered thickly by explosion debris, apparently a result of slumping from the nearby vent-filling.

Development of Kilbourne Hole.

From the data given, a number of stages in the evolution of the crater may be deciphered with varying degrees of certainty. A long period of aggradation in a broad valley or bolson was interrupted from time to time for intervals sufficient to permit caliche development. Subarid or arid climates are indicated.

The upper caliche is immediately overlain by a basalt flow, 15 feet or so thick at the north, an edge of which is cut by the south margin of the Hole.

Following the basalt flow, several large accumulations of ejecta were built at the site of the present Hole. The material thrown out is nearly all "accidental," with the possible exceptions of bomb-like masses of olivine-augite crystals, commonly with a skin of basalt, and of fragments of black glassy augite. The bulk of the material is of unconsolidated sand, resembling the pre-basalt sediments. With the exception of large basalt blocks torn from the flow exposed in the crater wall, most of the coarser fragments are water-worn and of considerable lithologic diversity. It seems probable that the explosions took place within the Tertiary beds. Locally the breccia piles rose at least 100 feet above the level of the basalt flow.

Following the explosions renewed valley aggradation was continued to a height of 125 feet or more above the basalt datum. Certainly, the debris accumulations were almost or quite buried. The fluviatile sands which form the greater part and the crest of the rim of the present Hole, are well bedded and cross-laminated throughout. They are conspicuously unlike the pre-basalt beds in their high content of basaltic cinders presumably derived from a source outside the district studied. As the breccia masses were buried, blocks and fragments from them were incorporated in the rising alluvium. Angular blocks of basalt may be observed as much as 100 feet away from their source, concentrated in a few definite horizons. Probably occasional intense storms are thus recorded. In a few places the fragments are present as residuals along the crest of the present rim. They must have been derived from beds above its elevation, and indicate an originally greater height of the ejecta accumulations, from which they were shed.

At some later time and for some cause not definitely ascertainable, the deeply alluviated flood plain, with its buried breccia masses was broken by a local subsidence of not less than 300 feet. This is shown by the antiquity of all explosion materials relative to the formation of the Hole and by the presence in the floor of the Hole of several inward-dipping blocks of the upper, post-explosion, cindery sands. Their dip is ascribable to drag during subsidence. The strong dip away from the cliffs, the unbroken condition and the length of the blocks (the largest is approximately three-eighths of a mile long) show that they are not landslides of later date than the formation of the Hole.

Presumably by virtue of a position on a low drainage divide, the lowering of the general surface outside the Hole by later erosion (pedimentation) has left the present narrow rim as a remnant. The rate of headward extension of a pediment must be drastically reduced as drainage divides are approached, so that narrow ridges, even in soft rock, must be relatively persistent land forms.

While the old flood plain outside of the Hole was being reduced to a narow rim, similar processes within the Hole were also active. Around the northern half of the Hole the basalt cliff of the inner slopes retarded erosion. Indeed, the northern half of the eastern wall has not retreated appreciably, as is shown by the position of the dragged upper sand block buttressing the foot of the slope. At the south, however, the basalt is thin to absent, and the form of the alluvial fans, which debouch from the southwestern and southeastern reentrants, suggests that the cliffs have receded a half mile or so in those directions.

Hunt's Hole.

The smaller crater south of Kilbourne offers fewer diagnostic data. Here are no vent ejecta, no inward-dipping blocks of the upper member. The rim, limited to the east and north sides of the Hole, owes nearly its entire height above the plain

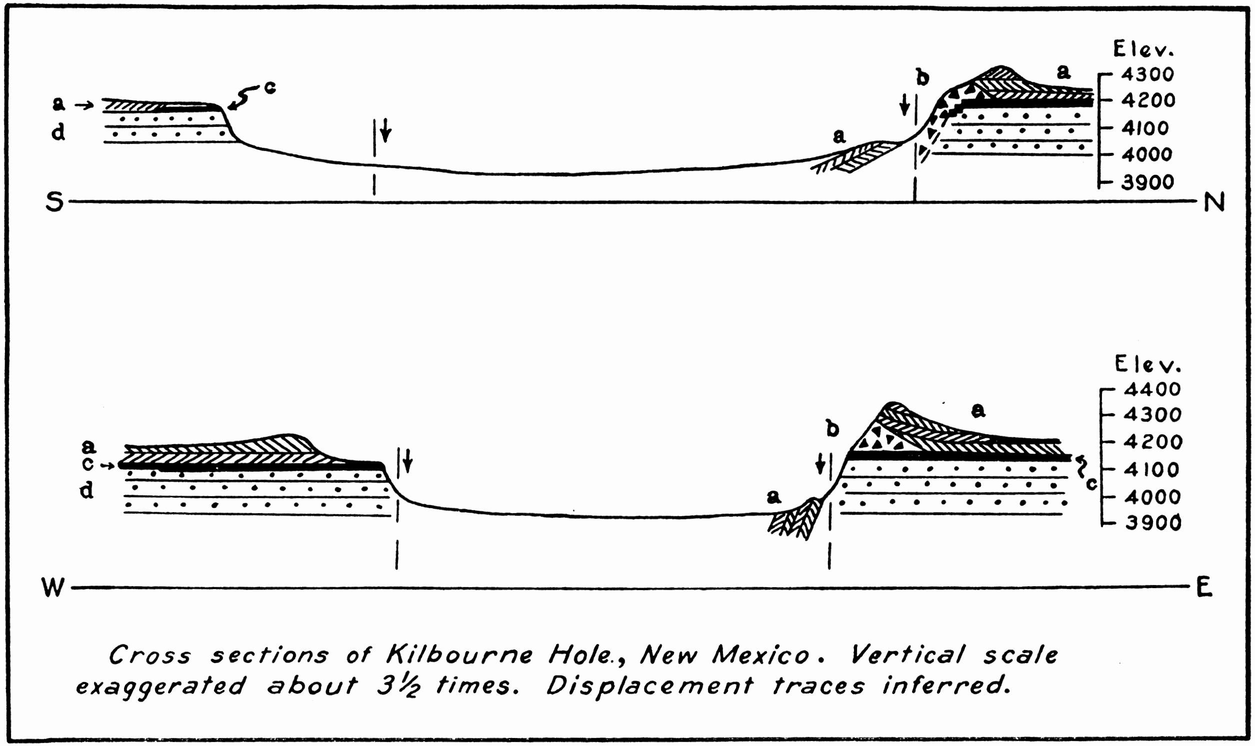

FIG. 3. Cross sections of Kilbourne Hole. Lines of sections are shown on Fig. 4, a, post-basalt fluviatile sands; b, ejecta; c, basalt flow; d, pre-basalt sands.

to recent blowsand accumulation. The basalt flow exposed in the crater walls was not a broad sheet, but a south-southeasterly directed linear flow about 1700 feet wide, so that the entire western half and a 2000 foot stretch of the eastern inner wall are beyond its limits. As in Kilbourne the flow rests upon a heavy caliche zone above pinkish and white non-cindery older alluvium, and is overlain by cindery, grey, cross-bedded sands.

A basalt-capped prong extends about 700 feet into the Hole from the northeast (see Fig. 2). Resting upon this there are five to eight feet of blocky debris resembling, but not as coarse as, the ejecta seen in Kilbourne. The fragments are of cobble and small boulder size, and include the lithologies noted at the larger Hole, except that no glassy augite or olivine-augite masses were noted.

South of the playa in Hunt's Hole a windmill is now in operation. The well is said to be about 150 feet deep. The water is cool and is not sulphurous.

Neither the very large Phillip's Hole, nor the many shallower depressions shown on the Noria and adjacent quadrangle are crateriform. The ill-consolidated sands in which they are entirely developed crop out poorly. The shapes and the dispositions are irregular.

Cause of Subsidence.

The data which have been given clearly establish the origin of the Holes as one of localized subsidence. While it appears that the cause of subsidence is not definitely ascertainable, the following items seem suggestive. The subsidence was greatest at the site of several much earlier-formed craters, which were, presumably, due to volcanic steam explosions. A well drilled in Kilbourne Hole is reliably reported to have yielded hot sulphurous water. The wells in Hunt's and Phillip's Holes, and others in the district, are not thus characterized. The plain, in which these features are located, is dotted with lesser depressions, ranging in depth to 30 feet, and of great diversity of size and outline.

Of the subground little is definitely known. The Plain is underlain by many hundreds of feet[10] of poorly consolidated fluviatile clastics of Tertiary and probably also Pleistocene

[10] The Lanark well, about eight miles east of Kilbourne had not passed out of these materials at 945 feet.

Lee, W. T.: U. S. Geol. Surv. Water Supply Paper 188, p. 17, 1907.

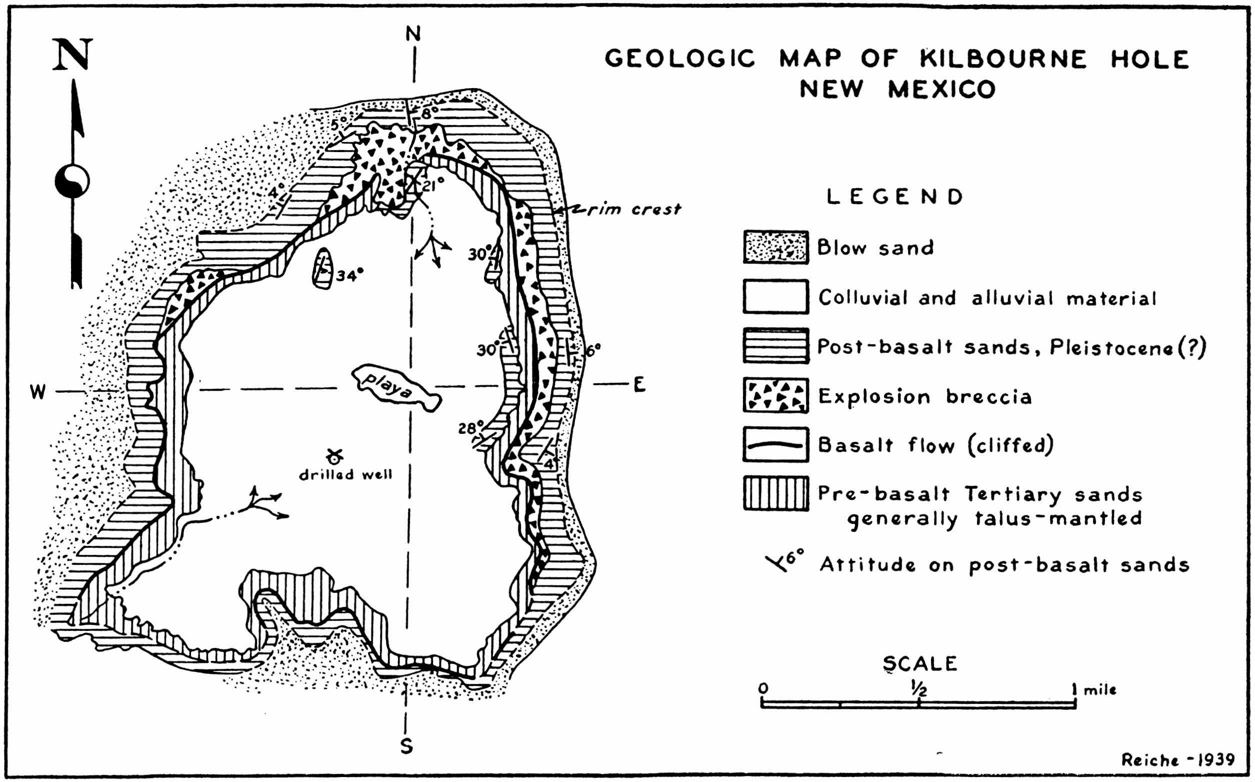

Fig. 4. Geologic map of Kilbourne Hole, New Mexico.

age. A water table about 350 feet below the surface of the Plain is known.

The Cerro de Muleros, 28 miles to the southeast, exposes lower Cretaceous marine limestones.[11] The structure is complex, possibly lacolithic.[12] Six or eight miles to the south-southwest of Kilbourne Hole the East Potrillo Mountains rise sharply from the plain. According to Dunham the limestones at their northern end, stated by Lee[13] to contain a Fredericksburg fauna, are not lithologically similar to the Cerro de Muleros Comanche limestones, and

> "it seems doubtful whether the whole range is . . . Cretaceous." . . .
>
> "The limestones in question correspond lithologically with the San Andres limestone of the Permian, or the Hueco limestone of the Pennsylvanian." . . . "The structure is anticlinal, the axis . . . lying near the crestline of the ridge."[14]

It seems at least possible that the fluviatile sediments of La Mesa are underlain in this district by a thick marine limestone sequence.

Any explanation offered for the Kilbourne subsidence should take into account, also, Hunt's and Phillip's Holes which almost certainly formed at about the same time and in the same way. It should also be capable of extension to such of the shallower depressions of the district as may prove due to processes other than deflation. Meteoritic impact is not suggested: there are neither meteorite fragments, silica glass, nor concentric structures in the country rocks. There remain to be considered only volcanic subsidence and collapse due to removal in solution of the subground.

The hypothesis of volcanic subsidence accords well with several of the critical data. The Holes are in a district of Quaternary volcanism; the largest Hole roughly coincides with earlier explosive volcanism, and a well in it has yielded hot sulphurous water. Finally, there can be no doubt of the adequacy of this process to form depressions of the size presented. Counter-indications are in no case conclusive:—nothing resembling ring-dikes was noted; the well waters of Hunt's and Phillip's Holes are neither hot nor sulphurous; the extension of

[11] Böse, E.: quoted by Dunham, op. cit., p. 168.
[12] Dunham: op. cit., p. 170.
[13] Quoted by Darton, N.H.U.S. Geol. Surv. Bull. 749, p. 39, 1928.
[14] op. cit., p. 245.

the hypothesis to these and possibly also to larger, shallow, elongate depressions still farther removed from the volcanic field might offer difficulties.

The possibility of a deeply buried limestone sequence, taken in conjunction with the data cited above suggest that limestone cavern development may have been active in this district. If so, it is probably still active, and the stage represented is the earlier of Davis' speculative two-cycle explanation of cavern development,[15] in which solution below the water table is the dominant activity.

The ability of ground water to dissolve great quantities of limestone at depths well below the water table is by no means established. Certain statements by Lee and by Davis offer support to such a contention.[16] Clearly, no cavern of the gross dimensions of the Kilbourne subsidence could develop, and a process of piecemeal and recurrent stoping and solution is essential to the hypothesis of collapse now under discussion.

The great thickness of overburden above the hypothetical cavernous limestone seems adverse to the collapse hypothesis. When it is recalled, however, that strong presumptive evidence was recently adduced for the formation of a sink through 800 feet of consolidated clastics, including a 125 foot sandstone caprock,[17] the first objection loses some of its force. Under La Mesa the clastic series is nearly unconsolidated; its thickness is probably not much greater than was the consolidated overburden of the case cited.

The association in space, of volcanic explosion with later subsidence, at Kilbourne, is too striking to be lightly dismissed. The following quotation from Davis[18] is of possible significance in this connection.

> "In regions that are invaded by volcanic magmas it is believed that warm juvenile water and carbon dioxide may ascend towards the earth's surface. This rising addition to descending ground water of meteoric origin would probably give it a great increase in solvent power while the mixture is still deep underground, . . ."

[15] Davis, Wm. M.: Origin of Limestone Caverns. Bull. Geol. Soc. Amer., Vol. 41, pp. 475-628, 1930.

[16] Lee, W. T.: Erosion by Solution and Fill. U. S. Geol. Surv. Bull. 760 C, 1925.

Davis, Wm. M.: op. cit., pp. 548-550.

[17] See Stockdale, Paris: Montlake, An amazing sinkhole, Journ. Geol., Vol. XLIV, pp. 515-522. 1926.

[18] op. cit. p. 487 (see also p. 621).

Davis' further reflection that the reduction of pressure on rising waters would bring about their saturation with CO_2, and cause them to act as depositing rather than dissolving agents, led him to discount their importance. Possibly in the Kilbourne case a sufficient depth, or such other factors as falling temperature and the protracted emission of juvenile waters counterbalanced these effects.[19] In addition, it is suggested that igneous intrusion may promote active, deep, ground water circulation, not merely by its juvenile emissions, but also by setting up effective temperature and pressure gradients.

No new data relative to the age of the 'craters' have come to light. Lee states[20] that part of the jaw of a Pleistocene horse was found 70 feet below the surface in the well at Kilbourne Hole and cites similar finds in neighboring districts. He thought it probable that the fossil had been reworked by slump and wash from the sands seen in the rim. The observations herein reported make it at least equally probable that it was in place, in upper cindery sands involved in the subsidence. For the latter an upper Pleistocene or very early Recent dating seems reasonable.

CONCLUSIONS.

In conclusion, Kilbourne Hole originated by local subsidence; its rim is an erosion remnant. Whether the subsidence resulted from volcanic processes or from removal in solution, at depth, of relatively soluble rocks cannot be definitely determined from the data in hand. In support of the hypothesis of volcanic subsidence, are the facts of past steam explosions and present hot sulphurous water at Kilbourne, and of basaltic extrusion in the neighborhood; and the inherent improbability of formation of caverns of the dimensions necessary. An alternate hypothesis involves subsidence by recurrent cavern enlargement and collapse, due to local removal in solution of the subground, some hundreds of feet below the water table under the influence of volcanic emanations. This alternate possibility has not been ruled out, although its highly speculative nature is patent.

Albuquerque, New Mexico.

[19] In this connection see also the chemical evidence collected by F. E. E. Germann: The occurrence of carbon dioxide. Science, Vol. 87, pp. 513-521, 1938.

[20] Lee, W. T.: Afton Craters: Bull. Geol. Soc. Amer., Vol. 18, pp. 214-215, 1907.