H. H. Hobbs III

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Contents

JULY 1970

NATIONAL SPELEOLOGICAL SOCIETY

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The Application of the Method of Least Squares to the Closing of Multiply-Connected Loops in Cave or Geological Surveys

By V. A. Schmidt * and J. H. Schelleng **

ABSTRACT

The method of least squares is applied to cave and geological surveys to obtain an algorithm that allows multiply-connected loops to be closed in a reasonable and analytical manner. In addition, constraints may be applied to any part of the survey. The method is well-suited to use with computer programs for the reduction of survey data.

INTRODUCTION

Cave and geological surveys are generally carried out with relatively imprecise instruments and under conditions of time and circumstance that make high accuracy difficult to achieve. An indication of this accuracy is obtained whenever the line or passage being surveyed doubles back on itself to form a loop. The extent to which the survey line, when plotted, closes on itself is a measure of the accuracy of the survey. It is common practice in cave surveys to use hand-held or tripod mounted Brunton compasses and steel or cloth tapes under less than ideal conditions of instrument location and reading comfort. As a result, closure errors of greater than 10 feet in loops only a thousand feet long are common, and closure errors of less than a foot in loops of almost any length are extremely rare.

The problem of closing these loops has long been a troublesome one, especially when multiple loops are involved. The mapper can take one of several tacks. He can simply plot his sightings as they are, and if the closure errors are reasonably small, he can ignore them and construct the map around the uncorrected sightings. If the closure error in the loop begins to approach the dimensions of a cave passage, this procedure must be abandoned. If only one loop is present, the closure error can readily be distributed throughout the loop to effect a closure. If, however, multiply-connected loops are present, the situation becomes more difficult to judge by eye, and the necessary distribution of errors throughout the survey can become extremely tedious if attempted by hand.

With the advent of computer processing of cave survey data, it became clear that some analytical method of closing arbitrarily complicated surveys was needed if the power and elegance of these machines was to be utilized fully. This paper describes an analytical method which is a straightforward application of one of the most powerful statistical tools available to the data gatherer—the method of least squares.

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Theory

The method of least squares may be applied to any situation in which a larger number of measurements are made than are minimally necessary in order to uniquely determine the quantities being measured. As an illustration, let us assume that a number of measurements are made on some unknown quantity represented by r. The fundamental tenet of the method of least squares states (Young, 1962) that if the measurement errors are random and follow a Gaussian distribution, then the quantity r has a *most probable value* which we may call R and which is determined in such a way as to minimize the sum of the squares of the deviations of each measured value r_i from the most probable value R. If M independent measurements are made yielding measured values for r of $r_1, r_2, \ldots, r_i, \ldots, r_M$ with corresponding weights $w_1, w_2, \ldots, w_i, \ldots, w_M$, then R may be determined by minimizing the expression

$$\sum_{i=1}^{M} w_i d_i^2 = \sum_{i=1}^{M} w_i (r_i - R)^2 \qquad (1)$$

The application of this method to cave surveys is made by regarding the skeleton survey as a network of three-dimensional vectors, each vector representing a "sight" from one survey station to another. In general each vector represents three measurements: a distance, an azimuthal angle, and a vertical angle. In addition, the head and tail of each vector must be labelled with station names or numbers so that the network of vectors may be properly strung together to form the complete survey.

From this, we can see that the method of least squares may not be applied to a survey that contains no loops since only enough measurements have been made to uniquely determine the location of each survey station. (Once a base station has been established or defined, each sight locates one more station. If the traverse line never closes on itself, then each station has been given a location only once.) If, however, one or more loops are formed in the survey and the loops do not close perfectly, each station within the loops has been assigned more

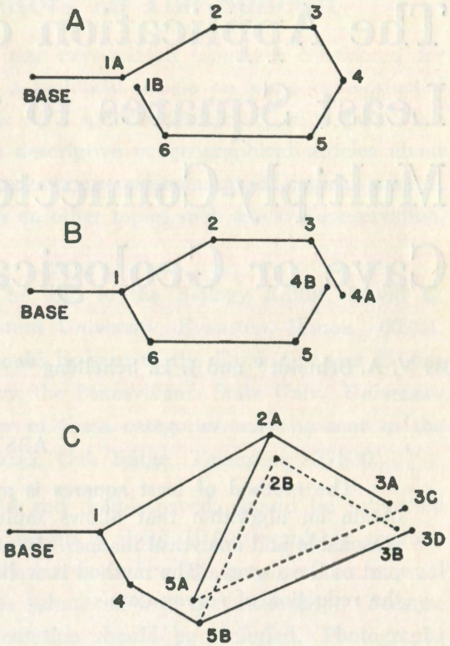


Figure 1. (a) and (b) demonstrate that the presence of a loop produces an ambiguity in the measured location of any station that may be reached from the base station via that loop. In (c), the addition of a second loop produces as many as four independent measured locations for station 3.

than one measured location. This is shown in Figs. 1a and 1b, where a survey of a simple measured loop has been plotted in two different ways in order to show that any station in the loop has been given two different measured locations as a result of measurement errors and the presence of the loop. Fig. 1c shows that adding an additional loop gives some stations within the loops *four* different and independent measured locations, since there are now four different ways of reaching these stations along measured paths without retracing. Each time another loop is added to any path connecting some station to the base station, that station's multiplicity is increased. Hence, in the presence of loops, at least some of the station locations are going to be overdetermined and the method of least squares may be applied.

The actual measurements that are involved in a survey are the sight-vectors that connect the stations. Let us call a measured sight vector connecting stations i and j, r_{ij}. We may denote the most probable value of this vector by R_{ij}, which should obey the vector relation

$$s_i + R_{ij} = s_j \qquad (2)$$

where s_i and s_j are vectors giving the most probable locations for the stations i and j. The set of relations of the form of equation (2) for all sights (all measured pairs of i and j) defines the desired survey, with all loops properly closed. The measured and most probable vectors differ by the *deviation*

$$d_{ij} = r_{ij} - R_{ij} \ , \qquad (3)$$

which is simply the probable error in each measurement. If w_{ij} is the weight assigned to each measured sight vector r_{ij}, we may combine equations (1), (2), and (3) to get

$$\sum w_{ij} d_{ij}^2 = \sum_{ij \text{ pairs}} w_{ij} (s_i - s_j + r_{ij})^2 \qquad (4)$$

as the relation that must be minimized with respect to the station locations. This is accomplished in the usual way by successively taking the partial derivatives of equation (4) with respect to each station vector s_i and setting each derivative equal to zero. This results in N linear equations with N unknowns, where N is the number of stations. We now need only construct the N by N + 1 matrix representing these linear equations, as in the example given at the end of the paper, to put the problem in a standard form readily used by a computer library subroutine for solving linear simultaneous equations.

We will now derive an algorithm to construct the appropriate matrix from the survey data. Each term in equation (4) will contribute to only two partial derivatives: those with respect to s_i and s_j. The contributions from each term will be $2\,w_{ij}(s_i - s_j + r_{ij})$ to the derivatives with respect to s_i and $-2\,w_{ij}(s_i - s_j + r_{ij})$ to the derivative with respect to s_j. The factor of 2 is present in every contributed term and may be eliminated immediately. Bear in mind that the derivative with respect to s_i is represented by row i of the matrix and the coefficient of s_i in each derivative is represented by column i. Column N + 1 contains the negative of the constant terms that are not coefficients of an s vector. The negative sign arises because these constant terms are standardly placed to the right of the equals sign, as in the example. Hence each term of equation (4) contributes to row i (representing the partial derivative with respect to s_i) $+w_{ij}$ to column i, $-w_{ij}$ to column j, and $-w_{ij}r_{ij}$ to column N + 1. To row j it contributes $-w_{ij}$ to column i, $+w_{ij}$ to column j, and $+w_{ij}r_{ij}$ to column N + 1. This procedure is repeated for each term in equation (4) to complete our construction of the matrix representing the N simultaneous equations. Note that since we are dealing with vectors, we have actually constructed three matrices, one for each cartesian coordinate.

We may restate the algorithm we have devised in a more directly applicable way. Let us assume we have M sights locating N stations in the survey. We first convert the measured sight vectors to cartesian coordinates. Then we construct three empty matrices (one for each of x, y, and z coordinates) with N rows and N + 1 columns. Next a weighting factor w_{ij} (see below) is assigned to each measured sight r_{ij}, where the sight was made from station i to station j. For each sight we do the following:

1. Add $+w_{ij}$ to (i, i) and (j, j)
2. Add $-w_{ij}$ to (i, j) and (j, i)
3. Add $w_{ij}x_{ij}$ to (i, N + 1)
4. Add $-w_{ij}x_{ij}$ to (i, N + 1)

Carrying out the same procedure for the y and z matrices using y_{ij} and z_{ij} instead of x_{ij} completes the construction of the three matrices. The solution of the simultaneous equations that they represent yields the most probable locations for the N stations, which is the desired result.

Constraints

At least one constraint, the establishment of a base station, must be applied before a unique solution to the above is possible. In the simultaneous equations, this is accomplished simply by replacing the s vector for the constrained station by its assigned value and eliminating the partial derivative with respect to that station location vector, since it is no longer a variable. In the matrix formulation the following algorithm does the same thing.

To constrain station i to the value $s_i = C$:

1. Multiply column i by the constant C and subtract it from column N + 1.
2. Eliminate row i and column i from the matrix, reducing its order by one.

A dividend of this method is that the above algorithm may be applied successively to accommodate more than one constraint. Hence if a cave has more than one entrance and these entrances have been accurately located on a topo map or by a good transit survey, the underground survey may be constrained to conform to the known entrance locations.

Weighting

The simplest method of weighting assigns to each sight a weight that is inversely proportional to its absolute length, the tape distance ($|r_{ij}|$), giving

$$w_{ij} = \frac{1}{|r_{ij}|} \quad . \qquad (5)$$

This method of weighting has been used with considerable success by the authors in a number of surveys. However, since the same weight is applied independently to each cartesian coordinate, this weighting scheme takes no account of the fact that the actual measurements are taken in spherical coordinates and that these measurements are not made with equal precision. In general, the tape measurement in a Brunton and tape survey does not contribute nearly as much error to a sight as the two angular measurements. It is not possible to take these considerations strictly into account so long as the least squares method is applied independently in each of the three Cartesian coordinates. Attempts to modify the weighting to take some account of what is going on in the other two dimensions (for example, by assigning a weight to each sight in the x dimension matrix that is inversely proportional to the projection of that sight on the yz plane, and similarly for the y and z matrices) have not proved to be worthwhile because there is still no way of coordinating the sense of the corrections made in each dimension.

Some Practical Considerations

At first sight the method outlined here might not seem practical for large surveys since each station adds to the number of simultaneous equations that must be solved. Most large computers have library subroutines that can deal efficiently with only 50 or 100 simultaneous equations, which would represent a rather small survey of an equal number of stations. However, two devices may be employed to increase the capacity of the method many times: (1) "Strings" of sights linking constrained stations, dead ends, and/or junctions of three or more sights can be constructed prior to least squares treatment and used in place of individual sights, eliminating all stations contained within strings. (2) Strings leading to unconstrained dead ends do not participate in the analysis and may be eliminated, to be reintroduced in the final plot of the map.

In this way the number of "stations" (and hence the number of simultaneous equations) can be reduced to the number of loop junctions plus the number of constrained stations. In all but the most complex maze surveys, this number should rarely exceed 50.

Using this approach, the analysis yields the most probable locations for the junction stations. The location of the intermediate stations on each string may be made by proportionally shifting each sight in a string according to its weight to fit the established junctions and constraints. Particular care must be exercised in assigning weights to strings, as our previous considerations apply only to individual sights. For strings of sights, equation (5) must become

$$w_{string} = \frac{1}{\Sigma |r_{ij}|} \quad , \qquad (6)$$

where the sum is taken over all the sights in that string.

One of the authors (V.A.S.) has written computer programs that utilize the methods outlined here. They have proven to be practical and highly efficient, as evidenced in Figs. 2 and 3, which are reproduced directly from Cal Comp plots drawn by the program itself. Bear Cave, Pa., shown in Fig. 2, is a survey of 2590 feet with 105 sights and 8 loop closures. The corrected survey was produced by an IBM 7090 computer in 14.8 seconds of execution time, exclusive of plotting time. The program will accept up to 1000 sights in up to 50 strings. The efficiency of this least squares method is due to its use of an analytical rather than an iterative approach, allowing the analysis to be made in a single pass.

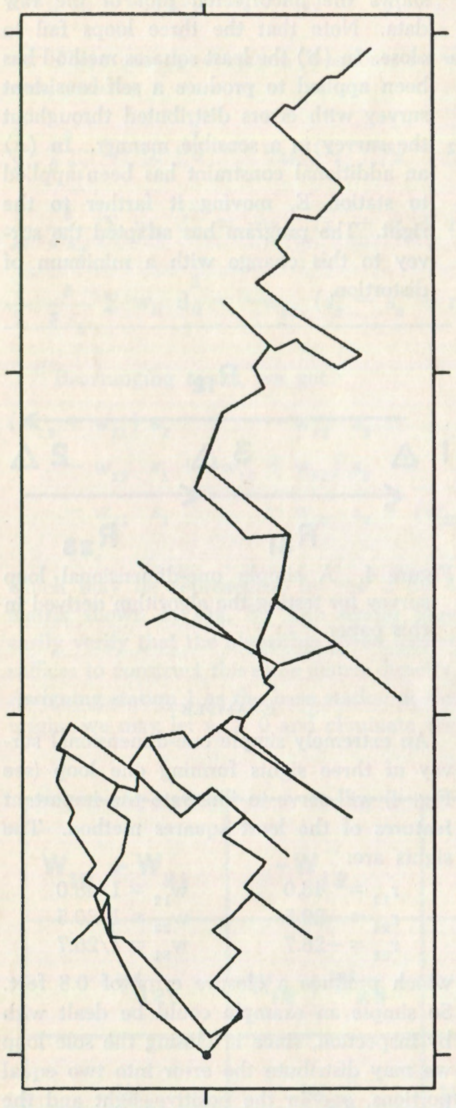
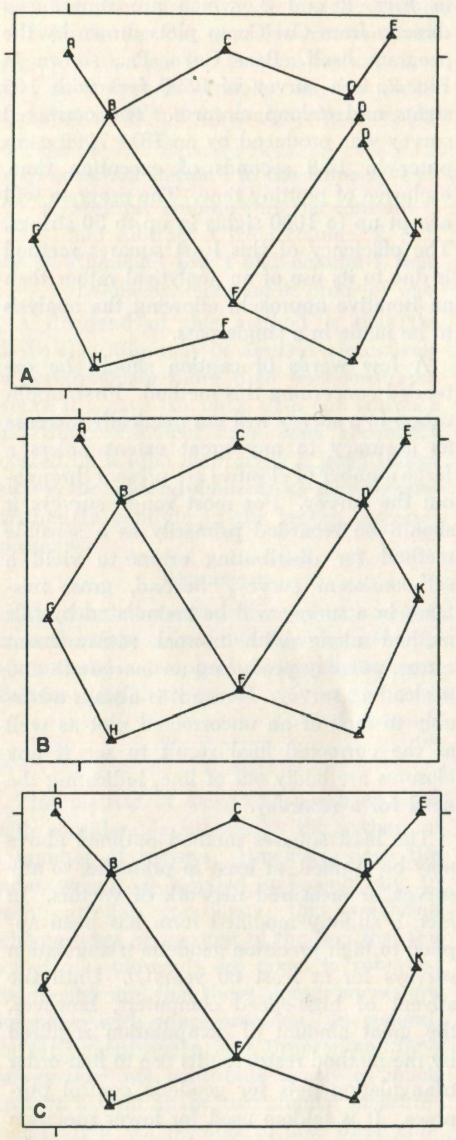


Figure 2. Bear Cave, Pennsylvania. This is the fully corrected output of a computer program utilizing the least squares method described in this paper. The tick marks along the border denote intervals of 200 feet. The diagram was drawn by a Cal Comp x-y plotter attached directly to the computer.

A few words of caution should be extended concerning this method. First, application to a survey will not magically increase its accuracy to any great extent unless a large number of closures are present throughout the survey. For most rough surveys it should be regarded primarily as a sensible method for distributing errors to yield a self-consistent survey. Second, gross mistakes in a survey will be assimilated by this method along with normal measurement errors, possibly producing an inaccurate and misleading survey. Hence it is always advisable to look at an uncorrected plot as well as the corrected final result to see if any closures are badly out of line, indicating the need for a resurvey.

The least squares method outlined above may be applied, at least in principle, to any survey or measured network of vectors. In fact, a slightly modified form has been applied to high precision geodetic triangulation surveys for at least 60 years(1). Until the advent of high-speed computers, however, the great amount of computation required by the method restricted its use to first-order triangulation nets for geodetic control purposes. It is seldom used for lower precision surveys, since even in these surveys, the normal closure errors are kept so small as to be infinitesimal on the scale used for the plot. It is precisely because the closure errors in cave or geological surveys appear

(1) For a detailed discussion of the application of the method of least squares to high-precision surveys, see Durgin and Sutcliffe (1927) and Adams (1915).



quite substantial at commonly used scales (50′/inch or 100′/inch) that the use of the method becomes worthwhile for these applications.

Figure 3 (to left). Pretzel Cave demonstrates the action of the least square method. (a) shows the uncorrected plot of the raw data. Note that the three loops fail to close. In (b) the least squares method has been applied to produce a self-consistent survey with errors distributed throughout the survey in a sensible manner. In (c) an additional constraint has been applied to station E, moving it farther to the right. The program has adapted the survey to this change with a minimum of distortion.

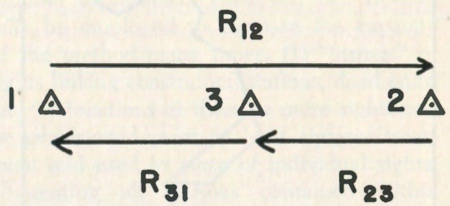


Figure 4. A simple one-dimensional loop survey for testing the algorithm derived in this paper.

Example

An extremely simple one-dimensional survey of three sights forming one loop (see Fig. 4) will serve to illustrate the important features of the least squares method. The sights are:

$$r_{12} = 48.0 \qquad w_{12} = 1/48.0$$
$$r_{23} = -20.5 \qquad w_{23} = 1/20.5$$
$$r_{31} = -26.7 \qquad w_{31} = 1/26.7$$

which produce a closure error of 0.8 feet. So simple an example could be dealt with by inspection, since in closing the sole loop we may distribute the error into two equal portions, one in the positive sight and the other in the two negative sights, yielding an adjusted position for station 2 at 47.6 feet. Nonetheless, we will apply the full least squares method for illustrative purposes.

Equation (4) becomes for this example

$$\sum w_{ij} d_{ij}^2 = w_{12}(s_1 - s_2 + r_{12})^2 + w_{23}(s_2 - s_3 + r_{23})^2 + w_{31}(s_3 - s_1 + r_{31})^2 \quad . \qquad (7)$$

There are three station locations, so we take the partial derivative with respect to each, yielding

$$\frac{1}{2}\frac{\delta}{\delta s_1}\sum w_{ij} d_{ij}^2 = w_{12}(s_1 - s_2 + r_{12}) - w_{31}(s_3 - s_1 + r_{31}) = 0$$
$$\frac{1}{2}\frac{\delta}{\delta s_2}\sum w_{ij} d_{ij}^2 = -w_{12}(s_1 - s_2 + r_{12}) + w_{23}(s_2 - s_3 + r_{23}) = 0 \qquad (8)$$
$$\frac{1}{2}\frac{\delta}{\delta s_3}\sum w_{ij} d_{ij}^2 = -w_{23}(s_2 - s_3 + r_{23}) + w_{31}(s_3 - s_1 + r_{31}) = 0 \; .$$

Rearranging terms, we get

$$(w_{12} + w_{31})\, s_1 - w_{12}\, s_2 - w_{31}\, s_3 = -w_{12}\, r_{12} + w_{31}\, r_{31}$$
$$-w_{12}\, s_1 + (w_{12} + w_{23})\, s_2 - w_{23}\, s_3 = w_{12}\, r_{12} - w_{23}\, r_{23} \qquad (9)$$
$$-w_{31}\, s_1 - w_{23}\, s_2 + (w_{23} + w_{31})\, s_3 = w_{23}\, r_{23} - w_{31}\, r_{31}$$

which may be represented by the 3 by 4 matrix shown in Fig. 5. The reader may easily verify that the algorithm given earlier suffices to construct this same matrix directly. Assigning station 1 as the base station at the origin, we may let $s_1 = 0$ and eliminate the first of equations (9). This is equivalent to eliminating the first row and the first column in the matrix. The remaining two simultaneous equations are readily solved to yield $s_2 = 47.6$ and $s_3 = 26.9$, in accord with our earlier estimate.

$W_{12} + W_{31}$	$-W_{12}$	$-W_{31}$	$-W_{12} R_{12} + W_{31} R_{31}$
$-W_{12}$	$W_{12} + W_{23}$	$-W_{23}$	$+W_{12} R_{12} - W_{23} R_{23}$
$-W_{31}$	$-W_{23}$	$W_{23} + W_{31}$	$+W_{23} R_{23} - W_{31} R_{31}$

Figure 5. The matrix denoting the simultaneous equations to be solved for the survey given in Fig. 4.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to the Computer Centers of Carnegie-Mellon University and the University of Pittsburgh, who provided computer time and services that were invaluable in the development of this project. We are also indebted to Prof. J. M. Nutt of the Civil Engineering Department of the University of Pittsburgh for reviewing the manuscript. He also led us to the original applications of least squares to surveying methods outlined in the references cited in the footnote.

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Badland Caves of Wyoming

By Eric N. Clausen *

ABSTRACT

Badland caves in four representative areas of Wyoming are described in detail. In each area visited, subsurface drainage was found to be significant. Subsurface pipes opened into large chambers, some as large as 80 ft by 30 ft by 20 ft. Caves were found behind talus slopes, dripstone adobe walls, and under what appeared to be normal hillslopes. The various types of caves apparently have different origins, though most seem to be developed along bedrock-debris contacts. The roofs of most of the caves seemed to be supported by the adobe crust which forms on the surface of most badland clays. Claystone under the crust disaggregates and is washed away by subsurface drainage, leaving the chambers.

INTRODUCTION

Badland pseudokarst features have been noted from time to time, however they have usually been considered oddities. Mears (1963) described a group of sinks, disappearing streams, hanging valleys, and natural bridges found in the badlands of the Chinle Formation of the Petrified Forest in Arizona. Sinks were attributed to the disaggregation of swelling clay minerals (montmorillonite and illite) rather than solution which affects limestones in true karst areas.

Mears proposed two origins for the natural bridges. Some bridges were believed to "result from slump and flowage of valley walls that were undercut by sharp small meanders during thundershowers . . .". Other bridges composed of bedrock claystone develop from abandoned valley segments resulting from subterranean diversion of streams into sinks. These bridges represent the last erosional remnants of either a lateral hanging valley mouth or, like some true karst bridges, of stretches along a valley bottom terminating in a rock step or dry falls. In either case, the upper reaches of the valleys have been eroded to a profile conforming with the local base level of the master drainage. The deep penetration of water to form the conduits was attributed to fractures found in the badland claystones.

Brown (1962, p. 221) attributes piping to displacement of soil particles by subsurface rather than surface drainage. He considers sparse vegetation an aid to piping. Fletcher and Carroll (1948, p. 546) cite three types of piping: 1) the classical tunnel where subsurface flow is along an impermeable soil layer, 2) soil washing along cracks, and 3) leaching or settling of fine surface material into deeper, more permeable subsoil. Downes (1946, p. 259) describes three stages in the development of a piped area. First, severe sheet erosion results in loss of vegetation and surface cracks. Second, the general lack of vegetation during sheet erosion produces an erosion pavement; tunnels appear as the drainage goes underground. Finally the tunnels collapse.

Parker (1964) has described a large pipe or cave over 700 ft in length, developed in the John Day Formation of Oregon. This pipe is believed to be increasing in size by the disaggregation of the claystone bedrock.

THE MADDEN AREA

Description of area. The area described below is a fourth order drainage basin (contour crenulations on the 1:24,000 Madden topographic sheet are considered first order channels) located about 4 mi. southwest of

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the Madden station on the Chicago, Burlington, and Quincy Railroad and about 3 mi. north of U. S. highway 20-26 in the NE¼, NE¼ Sec. 15, T. 37 N., R. 90 W. Access is from the Humble Oil Frenchie Draw Unit #2.

The north scarp in the Madden area is approximately 2½ mi. long and about 350 ft high. The scarp is on the north face of an inselberg carved in the Wind River Formation with a width of approximately 1 mi. The south-facing scarp of the inselberg is only about 100 ft in height, with what appears to be a southward-sloping pediment surface at its foot leading to Poison Creek and Merrian Meadows 3 mi. to the south. All faces of the inselberg form badlands, however those on the north are most pronounced. Caves or pipes, described below, are abundant on the north, but rare on the other faces where relief is less.

Except for alluvial deposits, the entire region is underlain by the nearly horizontal beds of the Early Eocene Wind River Formation which here is several thousand feet thick (Thompson and White, 1952, p. 8). The upper 150 ft in the sampling unit contain the typical red-banded mudstones of the Wind River Formation, while the lower 200 ft of the scarp are cut in light gray to greenish gray tuffaceous mudstones interbedded with discontinuous siltstone and yellow-orange sandstone lenses.

The badland surfaces generally have a mantle of debris ranging from a few inches to many feet in thickness covering the bedrock. The surface crust of this mantle is composed of a baked adobe which, when dry, often contains dessication cracks. Where the montmorillonite content is high, the surface has a bread crumb appearance. When wetted, the clays composing the mudstone swell, closing the cracks and forming an impermeable seal. Drying of these clays results in the hard adobe crust and the surface cracking.

Mass movements along the narrow valleys are common especially when the mudstones become saturated for some reason (e.g., repeated freeze-thaw conditions and melting of snow may greatly increase water penetration). Some scars along the valley walls indicate recent slides. In one area a recent slide was observed completely blocking the valley and causing a small pond to form. The best evidence of the frequency of the slides is found in the numerous debris piles appearing to block the narrow valleys.

The north face of the inselberg is cut by numerous "U" and "V" shaped valleys. The walls of these valleys can become vertical in slope with the sandstone ledges supporting the cliffs. Cliffs of 100 feet or more are common along many of the valleys. Rubey (1928) found numerous depressions or sinks associated with the "U" shaped valleys. He developed a hypothesis of gully formation by *ground sinking* (p. 421): "Some . . . process of washing out of material seems . . . the best explanation of the elliptical depressions and perhaps of the vertical scarps also. In loose, sandy soils with a low water table and in soils deeply cracked by repeated droughts, percolating water would carry with it the finer clay and silt particles and eventually develop small passageways. Miniature tunnels would form just below the temporary ground water level of the rainy season, and once started, the effects would be cumulative. As these small passageways grew, more vigorous subterranean erosion and transportation would be possible. Subsidence of the roofs over the tunnels would develop surface depressions which would concentrate rain water and intensify percolation and erosion. Loose wet soil would gradually move in from both sides to fill the tunnels and the ground would sink, perhaps as a flat gully floor. That is, the soil would creep toward the middle of the gullies to fill the tunnels, thus causing the sod at the margins of the moving mass to crack and the ground inside the marginal cracks might sink evenly. In turn, cracks formed by soil creep would localize percolation and thus start new tunneling."

Buckham and Cockfield (1950, p. 139) proposed that "the silts have a certain amount of permeability, apparently quite variable from place to place. Water, at times of spring melting and after infrequent storms, percolates into the silts and travels downward until it reaches a temporary water table, when it travels more nearly horizontally until it reaches a point on the gully wall or otherwise returns to the ground surface at a lower level. This forms a body of saturated silt; from the lower end of which water carrying silt emerges. Commonly a block of silt suddenly slides out, and a tunnel is formed running back into the silt body. It appears that a "free face" of some sort is necessary to initiate the process. Of course, once the underground passageway has formed, it itself provides a free face throughout its length.

"We have, then, the surface water tending to disappear underground and travel some distance below the land surface, at first dropping steeply and then traveling more nearly horizontally. At a free face, blocks of saturated silt drop out forming the beginning of underground channels which rapidly work their way inward from the point where the water discharges from the bank or steep gully face. Once a passageway is opened up, water flows through it as a stream, much more freely than when it was percolating through the silt. The silt, because of its extremely fine grained character, is readily carried in suspension by the stream. The stream greatly increases the rate of erosion and the underground channel is thus enlarged until the roof can no longer support the load and parts of it fall in. There are thus formed one or more funnel shaped depressions, which in turn serve to collect more water from the surrounding area and pass it into the underground system. As the process continues the rims between adjacent sinkholes collapse, thus forming a continuous gully."

The Madden area was the first of many of the sampling units to be visited in this study in which "ground sinking" or "pseudokarst" (Parker, et al., 1964, p. 393) was prevalent. Unlike the areas in which Rubey and Buckham and Cockfield worked, the "caves" in the Madden area were of sufficient size to permit easy human entrance and observation. Several of these caves are described below with reference to their origin and future development.

The caves. Most measurements in the caves are only approximations since parts of the caves were inaccessible or considered unsafe for entrance. Where possible distances were measured with a tape. Easy human entrance, though not necessarily safe, is possible to all the caves described below and also to many others not described in this report. Many similar, but smaller, pipes are found in the region, and entrance to these was usually impossible. In some cases these restricted pipes may open into large chambers similar to those described. Two major types of caves observed were the meander type and the gully type. They apparently differ more in form than in origin.

Meander type caves are formed along the sides of the "U" shaped valleys. The caves are found behind what appear to be steep talus cones at the foot of cliffs with vertical elevations of 50 to 100 ft (Figs. 1, 2, and 3).

The maximum dimensions of the largest observed cave of the meander type are 80 ft in length, 30 ft in width, and 20 ft in height. Of the 30-ft width some 20 ft is cut into bedrock (Fig. 2).

Undercutting in the bedrock indicates that the cave is migrating downstream behind the talus debris. Upstream, short abandoned passages at two higher levels indicate that the cave has existed for some time and has migrated downstream to its present position as badland dissection of the scarp proceeded.

At present there are four openings to this cave. These openings are the swallow hole, the downstream channel exit, and two windows or sinks in the talus roof. Each of these is large enough to permit human entrance. The two windows probably started as small holes adjacent to the bedrock-adobe contact and have been enlarged by repeated rainwash. A few small rills lead from the windows into the cave. Erosion along these rills will further widen the windows. Thus the cave apparently is near its maximal size, although it is not in danger of collapse. There is abundant evidence that the cave has been used for shelter by deer, antelope, bats, and various birds.

The floor of this cave, like those of many others, shows silt benches roughly 2 ft above

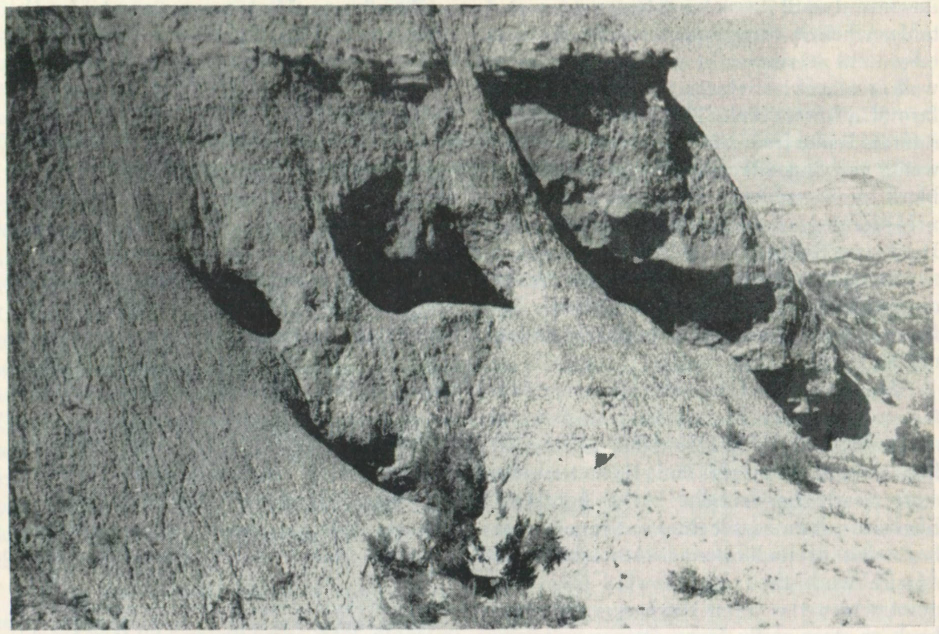

Figure 1. Talus debris with windows into a large meander type cave.

Figure 2. Upstream section of a large meander type cave showing the adobe-bedrock contact.

the present channel level. This evidence suggests backfilling and later trenching along the stream channels in this basin.

The upper part of the cave is cut in green-gray tuffaceous mudstones while the lower 6 ft is cut in siltstones. The siltstones support much of the bedrock overhang.

Enlargement of the cave chamber is probably the result of undercutting by the intermittent stream followed by collapse of the well fractured bedrock. Under the adobe roof, enlargement is probably the result of flaking off and collapse into the stream channel of unsupported pieces of debris not adequately cemented to the roof.

The adobe cone has probably been built up in thickness (up to 8 ft) by wash and slump debris from the mudstone on the cliff above. Windows may be the result of collapse of weakly cemented sections when underlying material is removed and/or the result of water penetration through the clay seals at the bedrock-adobe contacts turning the adobe locally into mud.

The cave may have begun as a meander cut into the steep valley wall (Fig. 3). Collapse of overhanging bedrock, at the center of the meander where undercutting was greatest, would not have blocked the stream channel, but would instead have permitted the establishment of a talus cone on which an adobe roof could have developed. Undercutting would then proceed as the adobe layer thickened, causing gradual downstream migration and enlargement of the chamber.

A gully type cave was formed in a relatively minor valley which has been filled by mudstone debris from the steep valley walls above. The adobe crust on the surface of the landslide material forms much of the roof of this cave. With the exception of one window which permits access, there are no openings for a distance of over 150 ft along the gully. The window opens to a chamber 80 ft by 25 ft by 15 ft. Passage beyond this chamber into other chambers may be possible both up and downstream.

The north wall and about half of the roof

Figure 3. Incipient meander type cave.

are cut into the mudstone bedrock, while the remainder of the cave is cut in adobe material. Rills leading into the cave from the window suggest that the opening is being enlarged. The relatively small size of the window would probably permit closing of the cave should the adobe roof be able to support the weight of a landslide when the overhang in the bedrock above the opening collapses.

Combinations of the meander type and gully type caves were also observed. One of these is located in a narrow, "V" shaped valley and presents the appearance of a natural tunnel through which one can easily walk along the graded stream channel floor. The straight line distance from portal to portal is only 40 ft, although the meandering stream channel is well over 80 ft long between portals. The maximum height is approximately 10 ft. The width at the portals is only about 5 ft although inside it increases to 15 ft.

Inside the cave, there is again evidence of backfilling and more recent trenching. The debris pillar contains stratified silt, sands, and fine conglomerates up to 5 ft above the present channel floor. Benches along the present channel with excellent mudcracks suggest recent trenching of 2½ ft. The present channel floor is cut in a sandstone layer.

General observations. In all some 22 large pipes were observed in the one basin studied. Many smaller caves to which entrance was not possible were also observed. Several of these smaller ones could potentially contain chambers as large or larger than the chambers observed in the large systems. There is no reason to believe that windows (which served as the only means of access to 12 of the caves entered) have penetrated to even a significant minority of the subsurface chambers in the basin. They have probably penetrated only the very largest chambers. Many other debris piles and talus cones exist which could easily be hollow.

In most of the caves, two or more levels of chambers were observed. In several, backfilling and later trenching along stream channels existed. Others showed only evidence of recent trenching. The various cave levels are thus thought to have resulted from minor climatic fluctuations causing periods of aggradation and periods of degradation. The recent trenching may have resulted from the exceptionally wet spring of 1967.

In most of the caves, the adobe walls and parts of the roof are found on the south and west walls, while bedrock is exposed on the north and east walls. This preferred orientation may result from a greater number of landslides and slumps on the south- and west-facing valley walls. These landslides would occur if there was increased water penetration on these slopes during winter freeze-thaw conditions.

The location of all the caves in this sampling unit along or near bedrock-debris contacts, and the fact that the windows are usually developed along these contacts indicates that the contacts are more susceptible to water penetration and piping than the bedrock or adobe mantle alone. The absence of any cave systems cut entirely in bedrock forces rejection of the hypothesis that piping is associated with fracturing in the claystones in this particular sampling unit. The existence of parts of cave systems cut only in debris indicates that under proper conditions caves can develop without any bedrock support.

The sandstone and siltstone floors of many of the caves may mean that a lower impermeable layer aids the development of these pipes. The multiple chamber levels, some cut only in debris, and several caves with mudstone floors provide notable exceptions.

Once the cave or pipe is formed, it will grow to a point where the walls and roof are unable to support themselves and windows begin to penetrate to the chambers. In time this process results in the collapse of the debris roofs, and the gully is reformed, often at a deeper level than before. This new gully is again filled with landslide debris, and new caves or pipes are formed.

Devils Kitchen

The Devils Kitchen sampling unit, located in the NW ¼, Sec. 8, T. 53 N., R. 92 W., includes badlands cut in the gray to black marine shales of the Cretaceous Frontier Formation. Thick bentonite layers in the shale, mined commercially less than 2 mi. away, extend through the sampling unit.

The upper slopes in the sampling unit are on sandy shales. Extensive benches follow bentonite layers while cliffs are cut in black shales. Relief in the basin does not exceed 200 ft. The basin opens to the south.

Beds dip southeast at about 5°, reflecting their position on the southeast flank of Sheep Mountain Anticline. Badlands in the region seem localized along scarps of hogbacks and mesas cut in the Frontier Formation.

Slopes generally are rounded in appearance, although several vertical cliffs are cut in nearly unweathered shales along major drainage channels where downcutting is probably proceeding rapidly. Stream channels are well intrenched with sandy bottoms. The surrounding benches and slopes consist of a cindery gumbo, rich in bentonite.

The black shales are exceedingly well fractured. Digging into the hillside revealed certain zones of the shale where fractures have been filled with silt and sand forming natural passageways for ground water. Several slopes noticed in 1968 show where water has emerged on the surface, carrying silt and sand with it, with the silt and sand being deposited on the gumbo surface as the water soaked into the bentonitic clays.

Detailed studies of the sinks revealed that they are collapsed roofs of tunnels along which subterranean drainage flows. Cave systems were found under the benches. It soon became apparent that the benches contained a complex of tunnels and drainage channels which only came to light along major streams and scarps. Rabbits in the area appeared to use these tunnels for shelter and as means of traveling unseen across the wide expanses of the bentonite benches.

The caves or tunnels, unlike their counterparts at Madden, are not easily observed on the surface. Moreover the pipes seem to develop rapidly. An access road serving the mining operations and leading to the sampling unit had been extensively repaired between August 1967 and June 1968 (probably during the spring of 1968). Since the repairs there had been no traffic until I started to drive over it. The car suddenly sank through the roadway. Digging revealed that the car was hanging above a cave which had developed around a culvert installed at the time of the road repairs. The cave was over 4 ft in height and ranged up to 8 ft in width. The crust or roof through which the car had broken varied from 1½ to 3 ft in thickness.

Mason Draw Area

The easternmost of the three sampling units selected on the Mason Draw map is described below. The main scarp, adjacent to the Wind River, reaches some 600 ft above the river. A series of canyons emerge from this scarp. The sampling unit is one of these canyons and is located in the W ½, SE ¼ and NE ¼, Secs. 10 and 15 respectively, T. 41 N., R. 106 W.

The canyon floor is thickly vegetated with various grasses, shrubs, and trees. Numerous side canyons enter the main one. The valley sides are cut in variegated red, white, and lavender siltstones and sandstones of the Wind River Formation. At the top is a conglomeratic caprock forming grass-covered benches into which the badlands are cut.

Slopes are extremely steep. Many are vertical or nearly vertical. Valleys are for the most part "V" shaped and quite narrow. The steep slopes are found even in the alluvial debris adjacent to the main channel.

The canyon walls are cut by numerous vertical chimneys which are often over 100 ft in height and seem unrelated to major drainage channels above the badland cliffs. The chimneys probably result from water penetrating through a vetical crack which is repeatedly enlarged and rounded. Chimneys of this size were not observed in most other sampling units in this study. They are apparently found only in areas of pronounced relief.

Caves are abundant in the area. The largest observed in the sampling unit was also the largest found in the study and unique in its position. If one starts at the Wind River and proceeds upstream along the dry wash, he first passes through a fairly wide valley containing the braided badland stream. As

Figure 4. The Tunnel at Mason Draw, looking downstream. On the upstream side is a well-developed canyon system. The stream after entering the Tunnel passes almost 200 ft through the canyon wall and emerges some 50 ft above the floor of the main canyon as shown in Fig. 5.

Figure 5. The downstream end of the Tunnel at Mason Draw.

the badlands close in, a rich forest dominates the canyon floor. Eventually the canyon floor becomes too narrow for extensive vegetation, and a major fork in the canyon is reached. Following the left fork for about 150 ft brings one to a cliff over 200 ft high from which the stream channel emerges (Fig. 5) from a cave some 50 ft above the canyon floor. The cave entrance is about 10 ft high. Inside the cave, a ledge roughly 8 ft high can be climbed by means of an ancient ladder. Above this ledge is a chamber over 150 ft long and 50 ft wide. The claystone roof has collapsed in places leaving huge intact blocks of claystone on the chamber floor. Following the channel in the cave to the upstream entrance leads to another opening somewhat smaller than that on the downstream side (Fig. 4). Looking back one realizes that he has just passed through a wall about 200 ft thick and over 150 ft high (Fig. 6).

Careful analysis showed that the tunnel probably originated in much the same manner as tunnels in the Madden area. South of the tunnel is an abandoned channel (or at least a swale) cut into the wall and reaching down to only about 100 ft above the present canyon floor. The wind gap and the lack of bedrock on much of the south wall of the tunnel lead to the hypothesis that the channel has migrated from the old valley by cutting under the bedrock into the wall. Disturbing evidence is a large block of bedrock on the upstream side. This block appears to be out of place, although it is larger than any other out-of-place blocks found in debris piles in the area. If this block is indeed bedrock, an alternative hypothesis considering the fractures in the bedrock may be necessary. It is, however, difficult to imagine the extensive upstream valley as being carved since the formation of the tunnel.

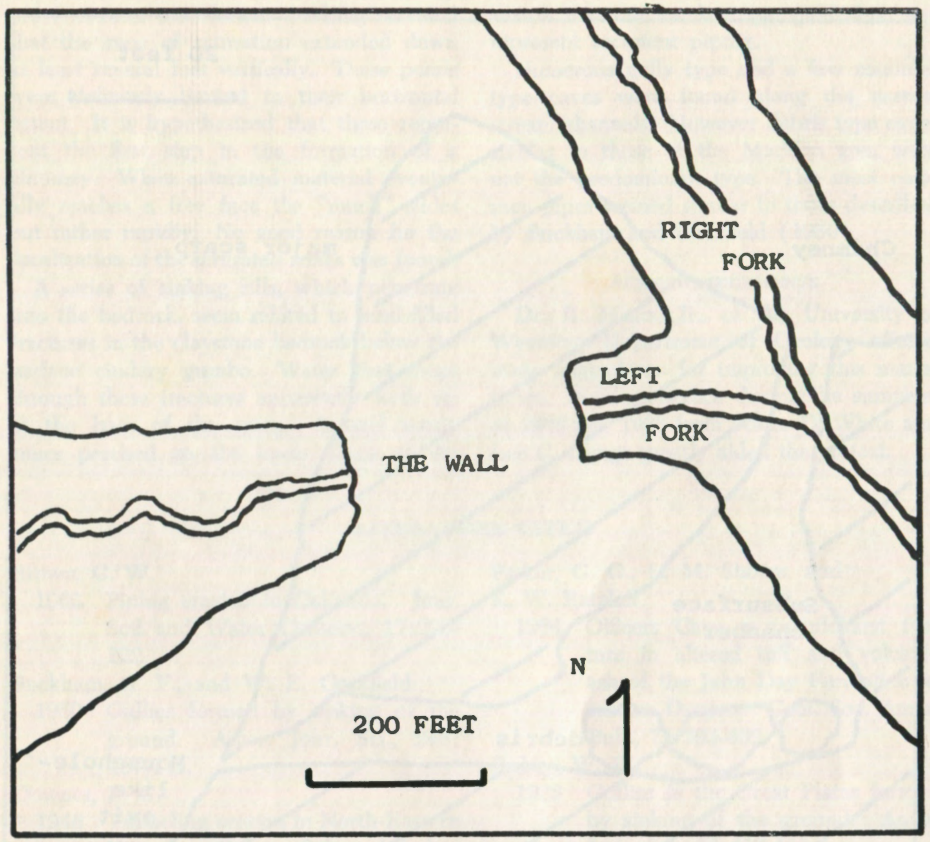

Figure 6. A map of the Wall. The left fork opens up into a large drainage network above the Tunnel.

A variety of other karst-like features were also noted. Numerous caves seemed to be located behind "dripstone" adobe walls of canyons. Numerous gully type caves were also found.

Several small springs in the canyons indicate that active ground water movement is shaping the karst-like features. These springs seemed to be related to sandy layers, although the path of subsurface flow was not determined.

The Dickie Springs

The Dickie Springs sampling unit consists of a unique set of badlands carved in the Eocene Wasatch Formation (Zeller, 1969, plate 1). The badland basin itself is cut into a steeply dipping fault or slump block. Dips range up to 60°. The detailed location for the sampling unit is NE¼, Sec. 28, T. 27 N., R. 101 W.

The sediments in this region are a series of red, tan, and lavender claystones interbedded with discontinuous sandstone and fine con-

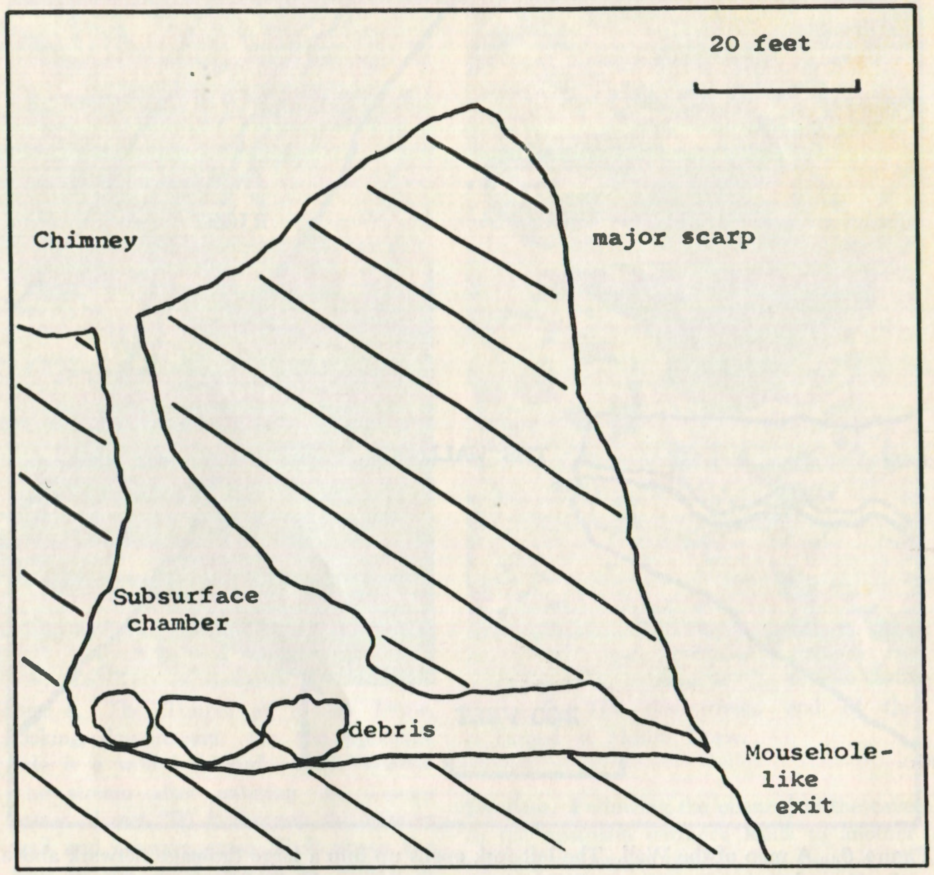

Figure 7. Cross section view of a chimney and its associated subsurface chamber. The dashed lines illustrate the attitude of the beds.

glomeratic layers. Several of the claystone layers weather to a cindery type of gumbo, while the remainder weather to the mud cake type. The presence of the cindery type gumbo probably indicates a high bentonite content, although no samples from this sampling unit were tested.

Piping is extremely well developed. Hollow buttes similar to those found in the Devils Kitchen sampling unit were found. Several small caves were noted behind the "gothic" dripstone walls. A series of chimneys cut across the various stratigraphic layers. The largest one dropped over 50 ft through claystone and sandstone layers. Its upper opening was about 5 ft in diameter. At the base it appeared to widen extensively into a large chamber. A scarp near the chimney contained a small "mouse" hole at about the same level as the floor of this chamber. Several hours of digging along the "mouse" hole confirmed that it did serve as the lower outlet for the chimney and the subsurface chamber (Fig. 7).

Adjacent to the chimney several standing pools of "water" (actually "muck") were wet at all times that the area was visited, both in the early and late summer of 1967 and the early summer of 1968. These pools may be concentrated by debris piles from previous mass movements. Probing revealed that the zone of saturation extended down at least several feet vertically. These ponds were definitely limited in their horizontal extent. It is hypothesized that these represent the first step in the formation of a chimney. When saturated material eventually reaches a free face the "muck" slides out rather rapidly. No good reason for the localization of the saturated zones was found.

A series of sinking rills, which penetrate into the bedrock, seem related to sand-filled fractures in the claystone bedrock below the surface cindery gumbo. Water that seeps through these fractures apparently wells up at the base of the scarp. Several sandy zones perched on the lower levels of the scarps seem to localize springs. This may represent incipient piping.

Numerous gully type and a few meander type caves were found along the narrow stream channels. However debris type caves similar to those of the Madden area were not the predominant type. The most common pipes seemed similar to those described by Buckham and Cockfield (1950).

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