Waste Isolation Pilot Plant

Compliance Certification Application

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 Open-File Report 82-968

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

EVALUATION OF BRECCIA PIPES IN SOUTHEASTERN NEW MEXICO AND THEIR RELATION TO THE WASTE ISOLATION PILOT PLANT (WIPP) SITE, with a section on DRILL-STEM TESTS

Open-File Report 82-968

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By

R. P. Snyder and L. M. Gard, Jr.

with a section on DRILL-STEM TESTS, WIPP 31, by J. W. Mercer

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INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) site is located about 40 km (25 mi) east of Carlsbad, N. Mex. (fig. 1). The site geography has been described in detail by Powers and others (1978) and U.S. Department of Energy (1980, 1981). Site selection was based principally on the existence of a thick section of Permian evaporites, mainly halite. The purpose of establishing this site is to demonstrate whether or not an evaporite environment is acceptable for the disposal of trans-uranic waste generated by the Nation's defense programs.

The primary concern regarding safe disposal of nuclear waste is to isolate the waste from the biosphere until it is no longer a danger to mankind. One of the most probable methods of accidental release of radiation from nuclear waste isolated in a geologic medium is leaching and transport of the waste by moving ground water. It is therefore of primary importance to identify any potential channelways that might allow water to enter a repository site located in bedded salt of the Salado Formation of southeastern New Mexico. The presence of the thick Permian (225 m.y.) rocks attests to the fact that major dissolution of the halite by unsaturated ground water has not occurred at the WIPP site.

Focus of Current Study

This report describes several dissolution features in the Delaware Basin and elsewhere that have been referred to as breccia pipes. Breccia pipes (also called breccia chimneys) as they occur in evaporites are vertical cylindrical pipes or chimneys that may or may not involve more than one geologic formation. The chimneys are filled with downward-displaced brecciated rock. In this context, the rock is brecciated by having collapsed into a void at depth that was probably created by ground-water solution and removal of deep-lying evaporite or carbonate rocks in an underlying aquifer system (Anderson and Kirkland, 1980; Bachman, 1980). Such features have been described in evaporite deposits in many areas of the world.

The current study was done for the U.S. Department of Energy (DOE) in response to a suggestion that because breccia pipes are thought to be the result of deep dissolution, they may represent channelways for future ingress of ground water, and that they should be considered in risk assessment programs for the evaluation of proposed waste repositories in bedded evaporite rocks. To this end, features referred to as breccia pipes in southeastern New Mexico have been assessed in relation to the integrity of the WIPP site. Reports by Anderson (1978), Bachman (1980), and Vine (1960) described dissolution and karst features in the Pecos region of southeastern New Mexico

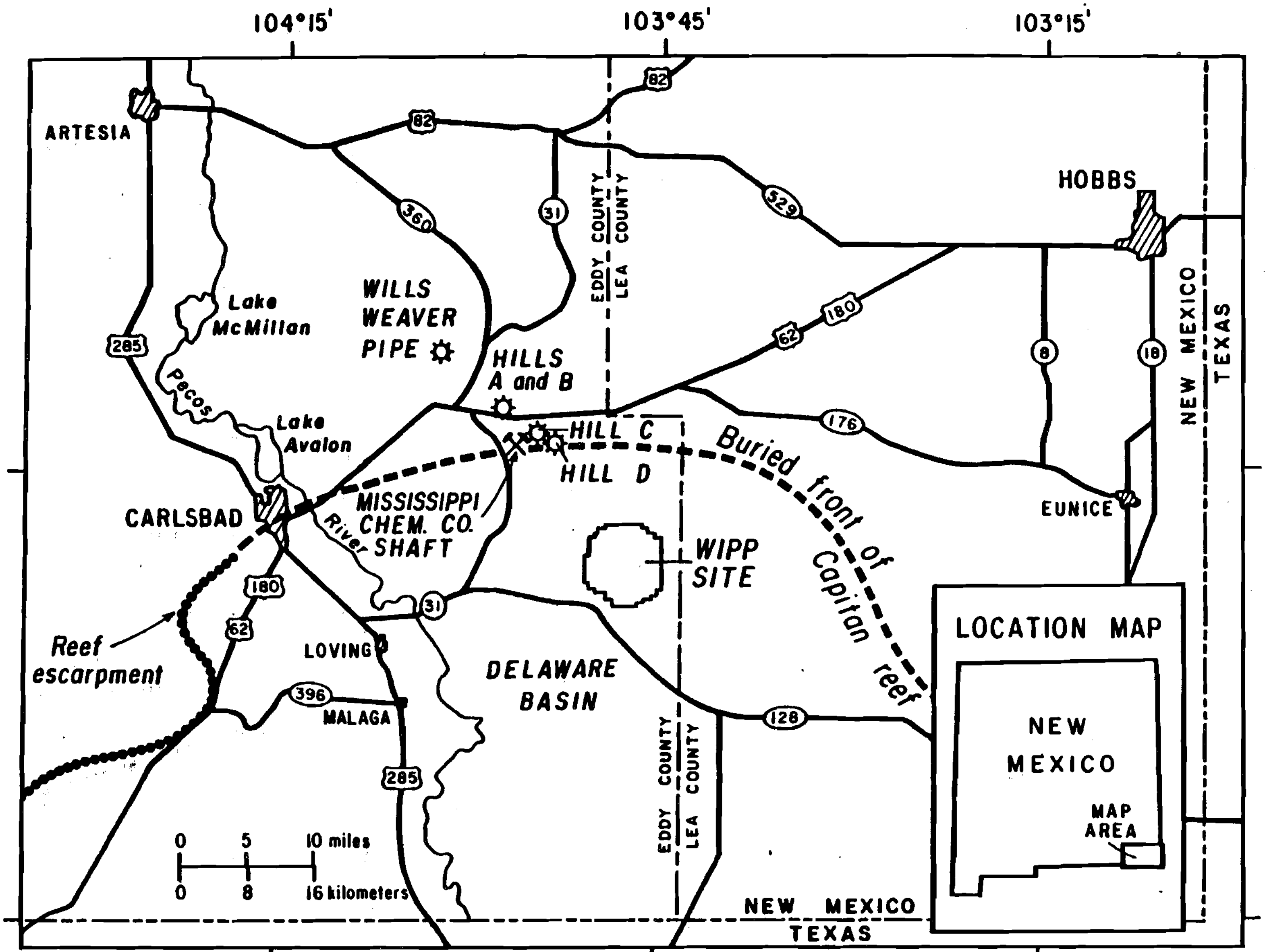

Figure 1.--The WIPP site, showing locations of Wills Weaver pipe, Hills A, B, C, and D.

and discussed the origin and history of breccia pipes. The present report is intended to supplement these studies and provide detail that was not available to them at the time their reports were written.

Using the data from exploratory work, answers may be found to the following questions concerning breccia pipes:

1. Do breccia pipes penetrate through the evaporite section?
2. What is the physical description of a pipe?
3. How are they formed?
4. How deep do they go?
5. When are they formed, and are they forming at present?
6. Are they permeable?
7. Where are they formed, can they form at the WIPP site?
8. Do they represent a threat to the WIPP site?

Acknowledgments

We thank James Walls, vice-president and general manager of Mississippi Chemical Corp., Eddy County, N. Mex., for his generous assistance and cooperation and for allowing us access to the mine. Discussions with C. L. Jones (USGS, retired) and Dennis W. Powers of Sandia National Laboratories (SNL) helped to clarify initial ideas into explainable processes.

STRATIGRAPHIC SETTING OF THE WIPP SITE

The WIPP site is at the northern end of the Delaware Basin of New Mexico and Texas, a sedimentary basin of Permian age which is surrounded by the Capitan Reef. The geology of the area has been described in detail by Jones (1973), Powers and others (1978), and Bachman (1980) and is only summarized here.

The stratigraphic sequence and time divisions of the rocks of southeastern New Mexico pertinent to this discussion are shown in table 1.

Permian Rocks

Permian rocks in the Delaware Basin are all of marine origin and they are divided into four provincial series, which are in ascending order: Wolfcampian, Leonardian, Guadalupian, and Ochoan. Only rocks of the Guadalupian and Ochoan Series are pertinent to this report.

Capitan Limestone and Backreef Equivalents, Tansill and Yates Formations

The Capitan Limestone and its backreef equivalents, the Tansill and Yates Formations, comprise the Guadalupian Series rocks. The Capitan is the reef limestone that surrounds the Delaware Basin. The limestone is generally porous and permeable (Bachman, 1980). Submarine canyons cut through the reef and were later filled with fine-grained carbonate-cemented sand (Hiss, 1975). These deposits are much less permeable than the reef limestone and they tend to retard the migration of ground water (Hiss, 1975).

Table 1.--Major stratigraphic and time divisions, southeastern New Mexico

(Time divisions from Berggren, 1972, and Bachman, 1980.)

ERA	SYSTEM	SERIES[1]	FORMATION	AGE ESTIMATE
Cenozoic	Quaternary	Holocene	Windblown sand	
		Pleistocene	Mescalero caliche Gatuna Formation	ca. 500,000 years ca. 600,000+ years
	Tertiary	Pliocene	Ogallala Formation	-5 million years-------
		Miocene		26 million years-------
		Oligocene Eocene Paleocene	Absent southeastern New Mexico	65 million years-------
Mesozoic	Cretaceous	Upper (Late) Lower (Early)	Absent SE N. Mex. Detritus preserved	136 million years-------
	Jurassic		Absent SE N. Mex.	190-195 million years---
	Triassic	Upper (Late) Lower	Dockum Group Absent SE N. Mex.	225 million years
Paleozoic	Permian	Ochoan	Dewey Lake Red Beds Rustler Formation Salado Formation Castile Formation	280 million years-------
		Guadalupian	Capitan[2] Limestone { Tansill Formation / Yates Formation	

[1]Terms in parentheses are Epochs.

[2]Rocks older than the Capitan Limestone are not described in this report.

The backreef correlatives of the Capitan, the Tansill and Yates Formations, are present in the areas of Hills A, B, and C, and the Wills-Weaver pipe, but are not present at the WIPP site. These formations consist mainly of bedded limestone ánd interbedded sandstones over the reef in the report area.

Castile Formation

The Castile Formation consists of several thick halite and anhydrite members (Anderson, 1972). In the basin, the Castile conformably overlies the Bell Canyon Formation and is, in turn, overlain by the Salado Formation. The Castile is about 412 m (1350 ft) thick at the WIPP site.

Salado Formation

The Salado Formation consists of halite units interstratified with thinner beds of anhydrite, polyhalite, beds of glauberite, and potash minerals. The halite beds contain varying amounts of silt and clay and are considerably "dirtier" than the halite beds of the Castile. Many of the anhydrite and polyhalite beds are persistent throughout the basin. These have been numbered (Jones and others, 1960) and are used as marker beds for correlation purposes. The basal unit of the Salado, where it overlies the Capitan Limestone, is the Fletcher Anhydrite of Lang (1942). Locally, the thickness of the Salado varies as the result of dissolution at the top of the formation. At the WIPP site the Salado is 603 m (1976 ft) thick.

Rustler Formation

Where no dissolution has occurred at the top of the Salado it is overlain conformably by the Permian Rustler Formation which is also part of the Ochoan evaporite sequence. The Rustler is divided into five members which are, in ascending order, the lower unnamed member, Culebra Dolomite, Tamarisk, Magenta Dolomite, and Forty-niner Members.

The lower unnamed member is composed primarily of siltstone. The Tamarisk and Forty-niner Members are similar to each other and where unaffected by dissolution, are composed of anhydrite and minor siltstone beds. Halite is present in all three members except where it has been removed by dissolution. This dissolution is progressing from west to east across the WIPP area. These three members vary in thickness depending on the amount of halite removed by dissolution. Where dissolution has occurred, a reddish-brown silty residue remains. This dissolution has created most of the karst features described by Bachman (1980).

The Culebra Dolomite and Magenta Dolomite Members are distinctive marker beds in the Rustler Formation. The Culebra, about 8 m (27 ft) thick, is a yellowish-gray, thin-bedded, finely crystalline dolomite. Many layers contain distinctive vugs about 2-10 mm (0.08-0.39 in.) in diameter which sometimes contain selenite crystals. The Culebra is the most significant aquifer in the basin area. The Magenta is composed of alternating thinly laminated reddish-brown dolomite and gray anhydrite layers. The laminae display distinctive undulatory bedding. The Magenta is about 7.6 m (25 ft) thick in the area and is also an aquifer, although to a lesser extent than the Culebra.

The average Rustler in the vicinity of the WIPP site is about 82 m (270 ft) and ranges from 11 to 146 m (35-480 ft) in thickness, depending upon the amount of dissolution that has occurred.

Dewey Lake Red Beds

The Dewey Lake Red Beds, conformably overlying the Rustler Formation, consist of soft, thin even beds of poorly indurated reddish-brown to reddish-orange siltstone and fine-grained sandstone which display numerous greenish-gray reduction spots 1-10 mm (0.04-0.39 in.) in diameter. Small-scale cross laminations and ripple marks are common. Lenses of cross-laminated fine-grained sandstone become more common near the top of the formation indicating that a change from marine to fluvial deposition was occurring near the end of Ochoan time. Evaporite deposits are not present in the Dewey Lake but secondary selenite fills concordant and discordant fractures. Selenite also fills partings along bedding planes. These openings were probably caused by sagging of the Dewey Lake over areas where dissolution had removed halite from the underlying Rustler Formation. The formation was eroded in pre-Triassic time and varies in thickness from zero to the west to 172 m (560 ft) to the east of the WIPP site.

Triassic Rocks

Rocks of Triassic age lie unconformably on and overlap the Dewey Lake Red Beds. Bachman (1980, p. 26) referred the Triassic rocks in this area to the Dockum Group and that usage will be followed in this report.

These rocks consist mainly of well-indurated fluvial sandstone, conglomeratic sandstone, and siltstone, most of which have been removed by erosion in southeastern New Mexico, and are irregularly distributed and preserved in the WIPP area. Although to the east in Lea County the Dockum Group is as much as 460 m (1500 ft) thick, it pinches out along a roughly north-south line that passes through the center of the WIPP site. These rocks are important to this report as they are found in breccia pipes elsewhere in the area.

Jurassic and Cretaceous Rocks

The area is believed to have been above sea level throughout Jurassic time and no rocks of that age are present. In Cretaceous time the area was covered by a shallow sea, but rocks of Cretaceous age are only found in collapse debris in areas of dissolution southwest of Carlsbad, N. Mex.--none being preserved in the WIPP area.

Cenozoic rocks

Cenozoic rocks in the WIPP area include the Ogallala Formation of Miocene and Pliocene age, and the Pleistocene Gatuna Formation and Mescalero caliche. Sheets and dunes of Holocene windblown sand are scattered across the area.

Ogallala Formation

The Ogallala Formation in southeastern New Mexico consists mainly of windblown sand on which the well-known "Caliche caprock" of the High Plains has formed. The Ogallala is not present at the WIPP site and was either never deposited or more likely has been removed by erosion. The closest outcrop of Ogallala is at "The Divide" 11 km (7 mi) east of the WIPP site.

Gatuna Formation

The Gatuna Formation of middle Pleistocene age or older (Bachman, 1980, p. 38) unconformably overlies the Permian and Triassic rocks in the area except where absent owing to erosion or nondeposition.

The Gatuna, mainly of fluvial origin, consists of unconsolidated beds ranging from silt to gravel. Much of the Gatuna is locally derived, especially from reworking of Triassic conglomerates and caliche of the Ogallala caprock.

Mescalero Caliche

The Mescalero caliche (an informal name) caps many of the older rocks of the area. According to Bachman (1980, p. 42) it appears to have accumulated as the C horizon of an ancient soil after deposition of the Gatuna Formation. Bachman reports that dates derived by the uranium series disequilibrium technique show that the Mescalero formed between 510,000 and 410,000 years ago.

PREVIOUS WORK ON BRECCIA PIPES IN SOUTHEASTERN NEW MEXICO

Numerous surficial features in and near the Delaware Basin have been described as being related to dissolution of the evaporites of the Ochoan Series. Vine (1960) described four domelike features as possible pipe structures. Later work done under the direction of personnel of the SNL and the USGS during studies for the WIPP site showed that two and probably three of the four domal structures are indeed breccia pipes.

Additional surficial features have been mentioned as possible pipe structures. Reports by Reddy (1961), Vine (1963), and Anderson (1978) mention several domal structures in the basin. Vine (1963, p. B40-B41) cites 11 of these to the west of the WIPP site. Many of these domal structures were found by Bachman (1980) to be no more than caliche-capped hills carved prior to Mescalero time. The hill in the SE 1/4 sec. 24, T. 23 S., R. 29 E. was mapped in detail by Bachman (1980, fig. 20) and described as an example of ancient solution and fill structure. Another structure cited by Vine (1963) in secs. 33-34, T. 22 S., R. 29 E. was mapped by Bachman (1980, fig. 18) and drilled (WIPP 32) as part of the studies for the WIPP site (Snyder and McIntyre, 1980). No indication of dissolution in the Salado below the Vaca Triste Sandstone Member (Adams, 1944) was found. The structure is related to shallow dissolution in the Rustler and Salado Formations and not to deep dissolution. A nearby drill hole, WIPP 29 (Snyder and McIntyre, 1979), drilled to gain information for hydrologic studies in Nash Draw also showed no dissolution below the Vaca Triste.

A hill in the NW 1/4 sec. 11, T. 21 S., R. 29 E. about 1.6 km (1 mi) west of the Mississippi Chemical Corp. (MCC) main shaft was mapped by Bachman (1980) and found to have beds of the Dewey Lake Red Beds dipping as much as 19°. According to Bachman, "the Dewey Lake Red Beds which are gently folded but not brecciated," are covered with caliche. "The folds are presumed to be the result of dissolution and hydration of evaporites in the underlying Rustler Formation."

Another example of domal structure called Tower Hill, located in secs. 1, 2, 11, 12, T. 21 S., R. 29 E., has been partially penetrated by mining out horizontal rooms for use in storing blasting powder used in the MCC mine. C. L. Jones (oral commun., 1980) has stated that the bedding is nearly horizontal and undisturbed around the walls of these rooms.

Reddy (1961) studied several domelike, quasi-circular features southeast of Malaga at Queen Lake. The features are generally surrounded by hogback ridges dipping outward from the central portions of the domes. These hogbacks are nearly always the Culebra Dolomite Member of the Rustler Formation. The central portions of these domes consist of brecciated Salado and lower Rustler Formation rocks. Reddy (1961) attributed the doming to upward movement of the Salado or Castile halites, the movement being caused by differential loading of the overburden during late Pliocene or early Pleistocene time. Additional stress applied during the late Cenozoic uplifts of the Guadalupe and Delaware Mountains could have aided in accelerating the upward movement of the halite and causing the Rustler Formation to be intruded by the lower formations (Reddy, 1961, p. 71).

Bachman (1980, p. 74, fig. 15) interprets the formational history of these domes somewhat differently. He defines the features as "karst domes." Much of the area near Malaga Bend (Queen Lake locale) is underlain by chaotic breccia of the Rustler Formation. The domes have a central insoluble residue of Salado partially overlain by a brecciated cover of Rustler. The less soluble dolomites are draped around the sides of the domes. According to Bachman, the formation of these domes is related to dissolution of the soluble portions of the units and tectonism or salt flowage is not a factor.

Lang (1947) explained Cretaceous debris found lying on the Castile near the Black River valley about 40 km (25 mi) southwest of Carlsbad as the result of collapse into a solution channel formed in the Salado Formation. This debris was washed into the channel and preserved. Subsequent erosion of the surrounding Permian (Ochoan) beds eventually left the debris scattered on the surface on the Castile Formation. There are no remnants of Ochoan rocks other than the Castile in the immediate area which implied to Lang that simple erosion of the intervening Ochoan beds was not the answer.

Bachman (1980) believes that the Cretaceous rocks were deposited on tilted and beveled rocks of the lower Rustler, Salado and Castile Formations, and the fossil debris is the remnant of that heavily eroded Cretaceous section. The debris may be the material from a shallow collapse sink which formed during Cenozoic time (Bachman, 1980, p. 84). Anderson (1981) questions this interpretation citing other Cretaceous deposits nearby that rest in younger-than-Castile depressions at stratigraphic horizons equal to the lower Salado. He also states that a "truncation surface sufficient to allow pre-Cretaceous dissolution to reach into the Castile" would dip about 19 meters per kilometer (100 feet per mile) and because this is the present regional dip, there is no allowance for post-Cretaceous uplift.

GEOPHYSICAL STUDIES

Numerous geophysical studies have been carried out on and around the WIPP site specifically to gain subsurface information concerning the site. Some of these surveys were designed to search for possible breccia pipes. Among these were magnetic and gravity surveys by Ferruccio Gera (1974) of Oak Ridge National Laboratory (ORNL) in conjunction with R. Hopkins of the Tennessee Valley Authority (TVA), and gravity and electrical resistivity surveys by Mining Geophysical Surveys (West and Wieduwilt, 1976) interpreted by Elliot Geophysical Company (Elliot, 1976a,b; 1977).

The resistivity surveys interpreted by Elliot (1976a,b) were run over eight suspected or known pipes. Table 2 lists the names or areas involved and the locations. Resistivity profiles across selected sites are shown in figs. 2, 3, 4. and 5. Complete profiles and technical data for all eight locations are given by Elliot (1976a). The resistivity data across Hill A shows a definite anomaly. The central part of the breccia pipe has a low resistivity that is bounded by high resistivity peaks as the survey line crosses the circular ring fault. Interpretations of the resistivity profiles along with additional data discussed later in this report have led us to the conclusion that the following are breccia pipes: (1) Wills-Weaver, (2) Hill C, (3) Hill A, and (4) Hill B. The remaining four sites are not interpreted as pipes.

Gravity surveys by Mining Geophysical Surveys (West and Wieduwilt, 1976) were run across the Wills-Weaver site, and Hills A, B, C, and D. The data were interpreted by Elliot Geophysical Company (Elliot, 1976b). Reasoning behind the belief that gravity surveys across breccia pipes would show anomalous readings is as follows:

If the brecciated material in the pipe was not well consolidated, the additional porosity as compared to the porosity of the surrounding rocks would cause the instruments to record a gravity low across the pipe, and if the material is denser than or better cemented than the surrounding rock, a gravity high would be recorded.

Figures 6, 7, and 8 show the gravity and topographic profiles across the Wills-Weaver area, and Hill C and Hill A, respectively. Figures 6 and 8 show a definite gravity low at the Wills-Weaver and Hill A sites, but there is no such low at the Hill C site (fig. 7). Elliot (1976b, v. 1, p. 22) states that gravity data do not give a consistent gravity response across known breccia pipes; and that gravity surveys are not a definitive method for locating these breccia pipes.

Seismic-reflection data (Hern and others, 1978) were obtained across the Wills-Weaver and Hills A-B locations. Generally uninterpretable reflections came from the center of these features.

Table 2.--Designation, location, and remarks, eight locations covered by electrical resistivity surveys

Breccia pipe designation or locale identification	Location Sec.,	T. S.,	R. E.	Remarks
Wills Weaver	12,	20,	29	Small hill, center of hill 400 ft northwest of GW-1 drill hole that penetrated 821 ft (250 m) of breccia from the surface.
Hill C	5,	21,	30	Hill, drill hole W-16 penetrated 1300 ft (396 m) of breccia and downdropped Rustler Formation, MCC mine drift intersected breccia pipe directly under hill.
Hill A	35,	20,	30	Breached hill, drill hole W-31 penetrated 1,981 ft (604 m) of brecciated rock and downdropped Santa Rosa Sandstone, Dewey Lake Red Beds, Rustler and Salado Formations and Fletcher Anhydrite(?).
Hill B	1-2,	21,	29	Hill adjacent to Hill A, breached on southwest side exposing brecciated rock.
Hill D	5,	21,	30	Hill southeast of Hill C, no rock exposed under caliche cap, no indication of dipping beds in underground workings that pass close to where pipe would be.
Unnamed hill	11,	21,	29	Hill about 1 mi west of MCC main shaft, mapped by Bachman (1980) and found to have no breccia exposed, did have folded bedding.
Sec. 9 sink	9,	22,	31	Surface sink in southeast corner of sec. 9, northern part of WIPP site, drill hole W-14 located here to obtain data to explain gravity anomaly. Normal stratigraphic section as deep as 1000 ft.
Sec. 14 sinkhole	14,	23,	30	Sink hole southwest of WIPP site, line run over wrong part of section, missed sinkhole, data inconclusive.

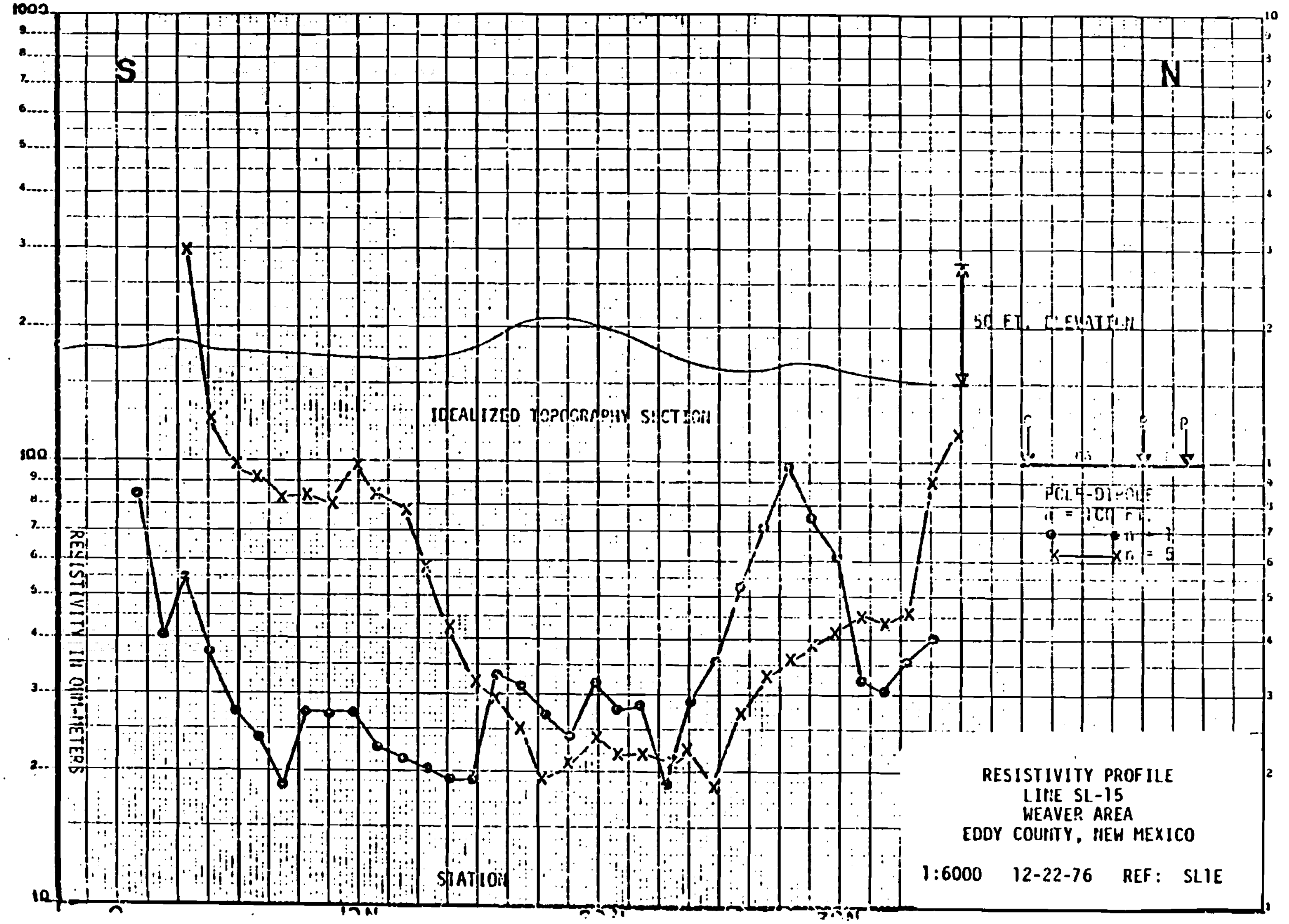

Figure 2.--Resistivity profile line SL-15, Wills-Weaver area, Eddy County, N. Mex. (from Elliot, 1976a).

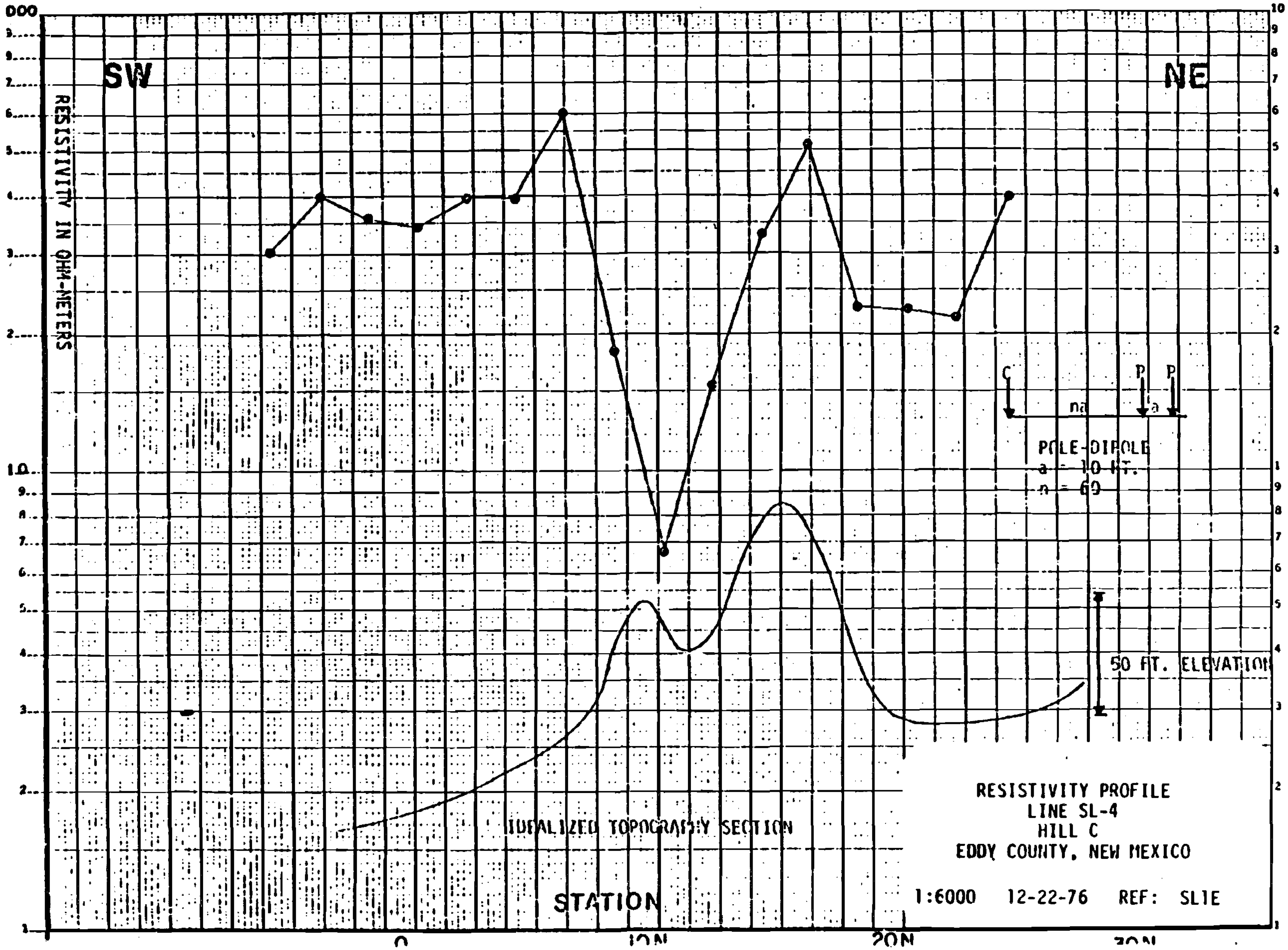

Figure 3.--Resistivity profile line SL-4, Hill C, Eddy County, N. Mex. (from Elliot, 1976a).

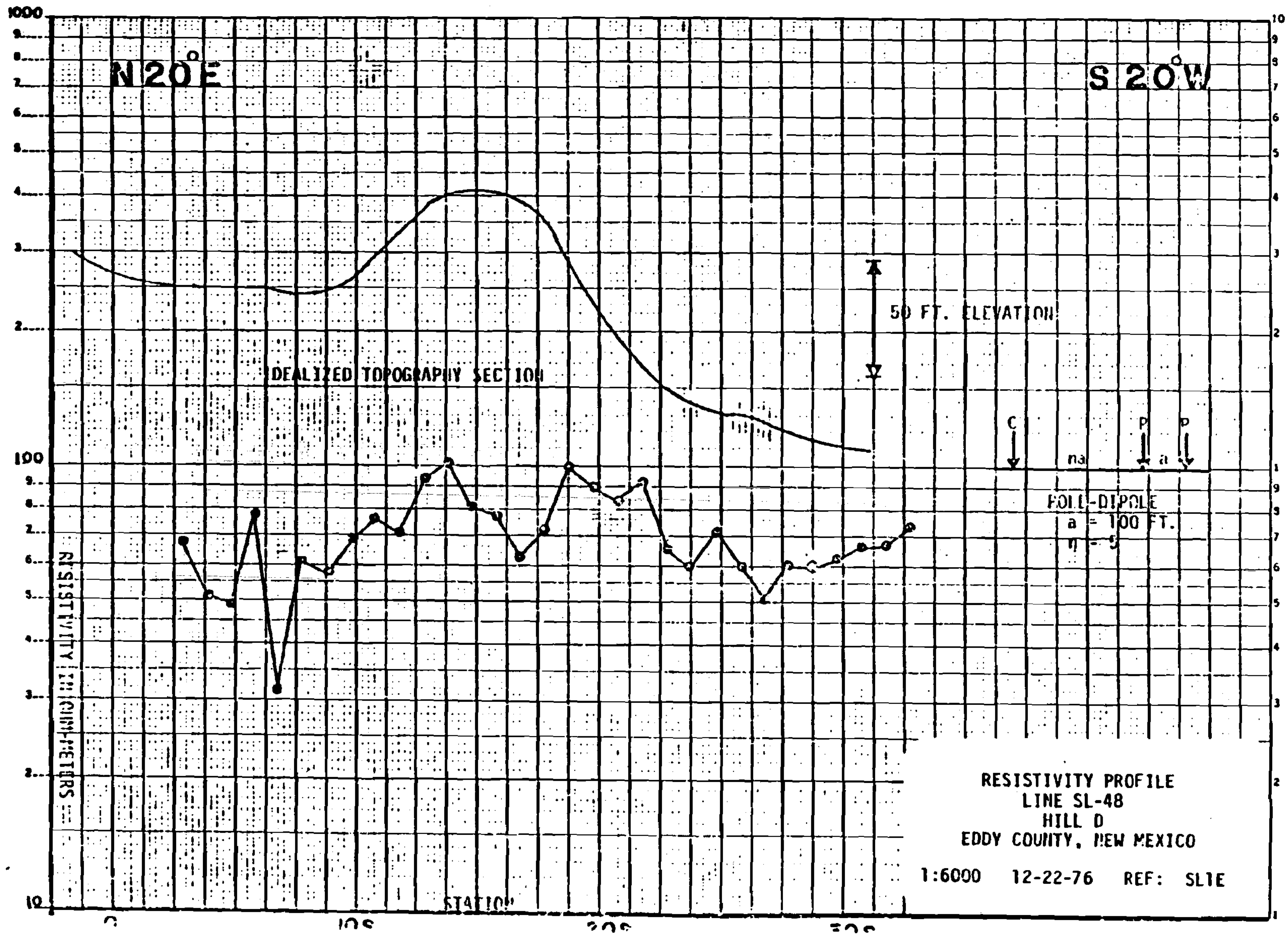

Figure 4.--Resistivity profile line SL-48, Hill D, Eddy County, N. Mex. (from Elliot, 1976a).

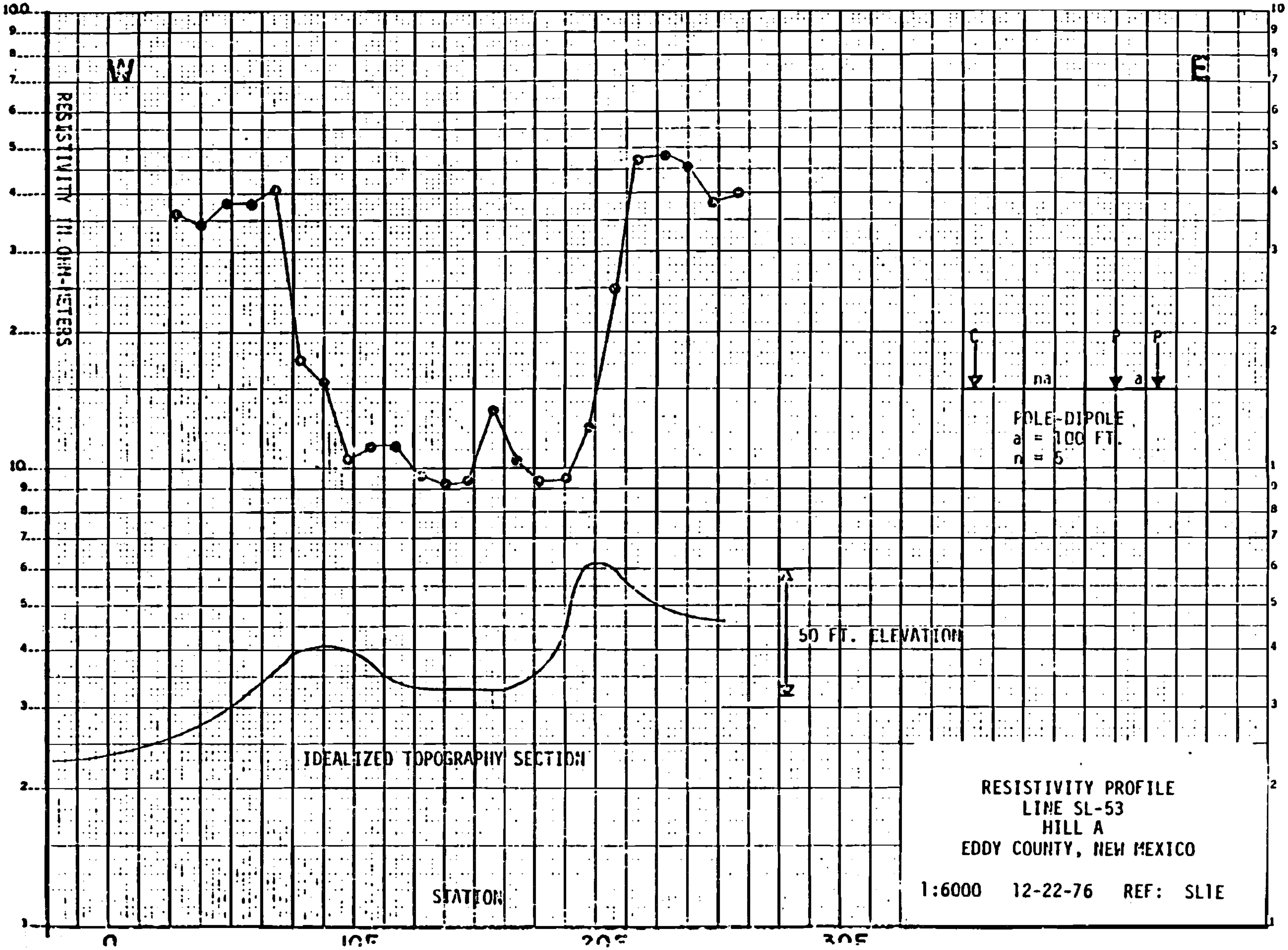

Figure 5.--Resistivity profile line SL-53, Hill A, Eddy County, N. Mex. (from Elliot, 1976a).

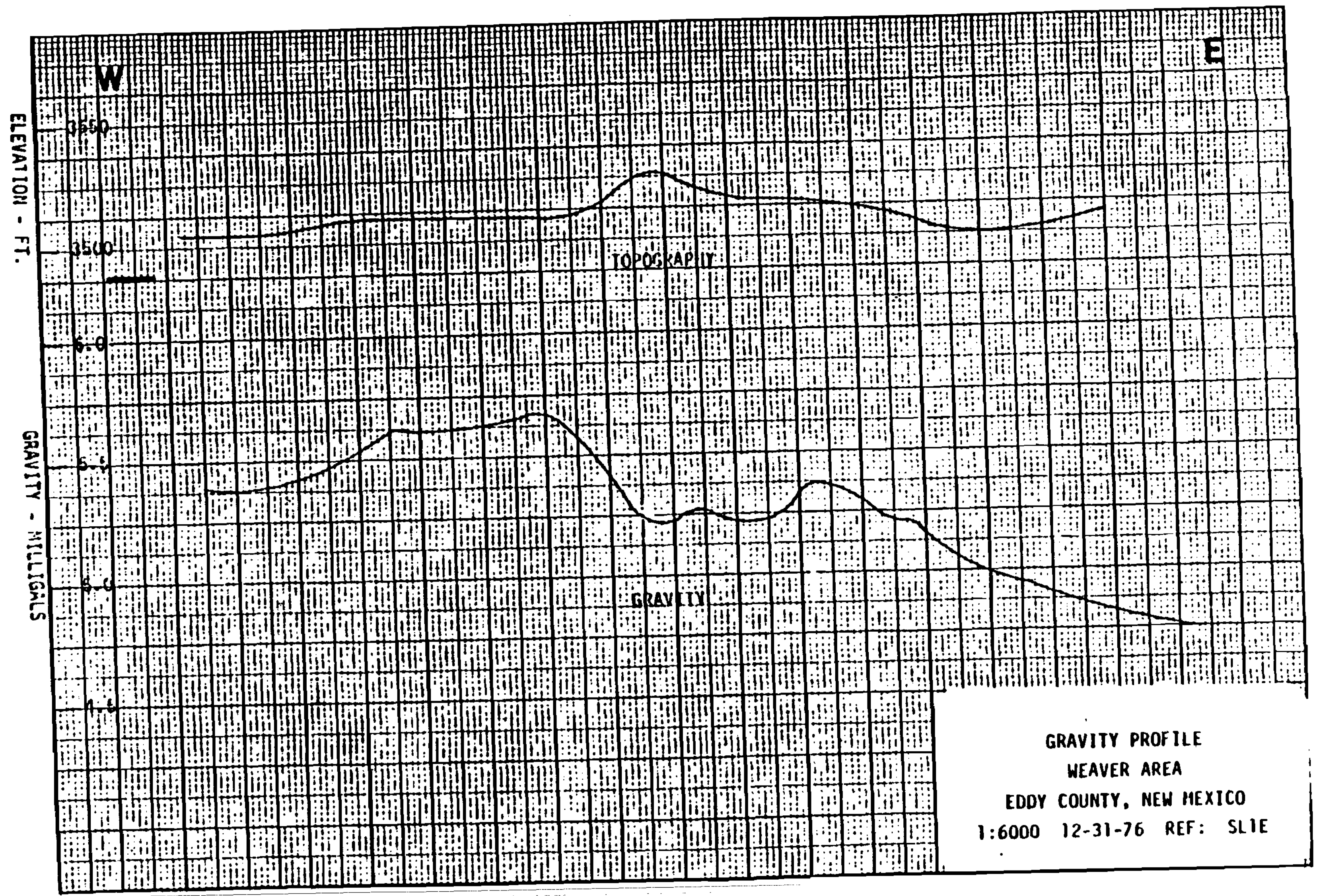

Figure 6.--Gravity profile Wills-Weaver area, Eddy County, N. Mex. (from Elliot, 1976b, v. 1).

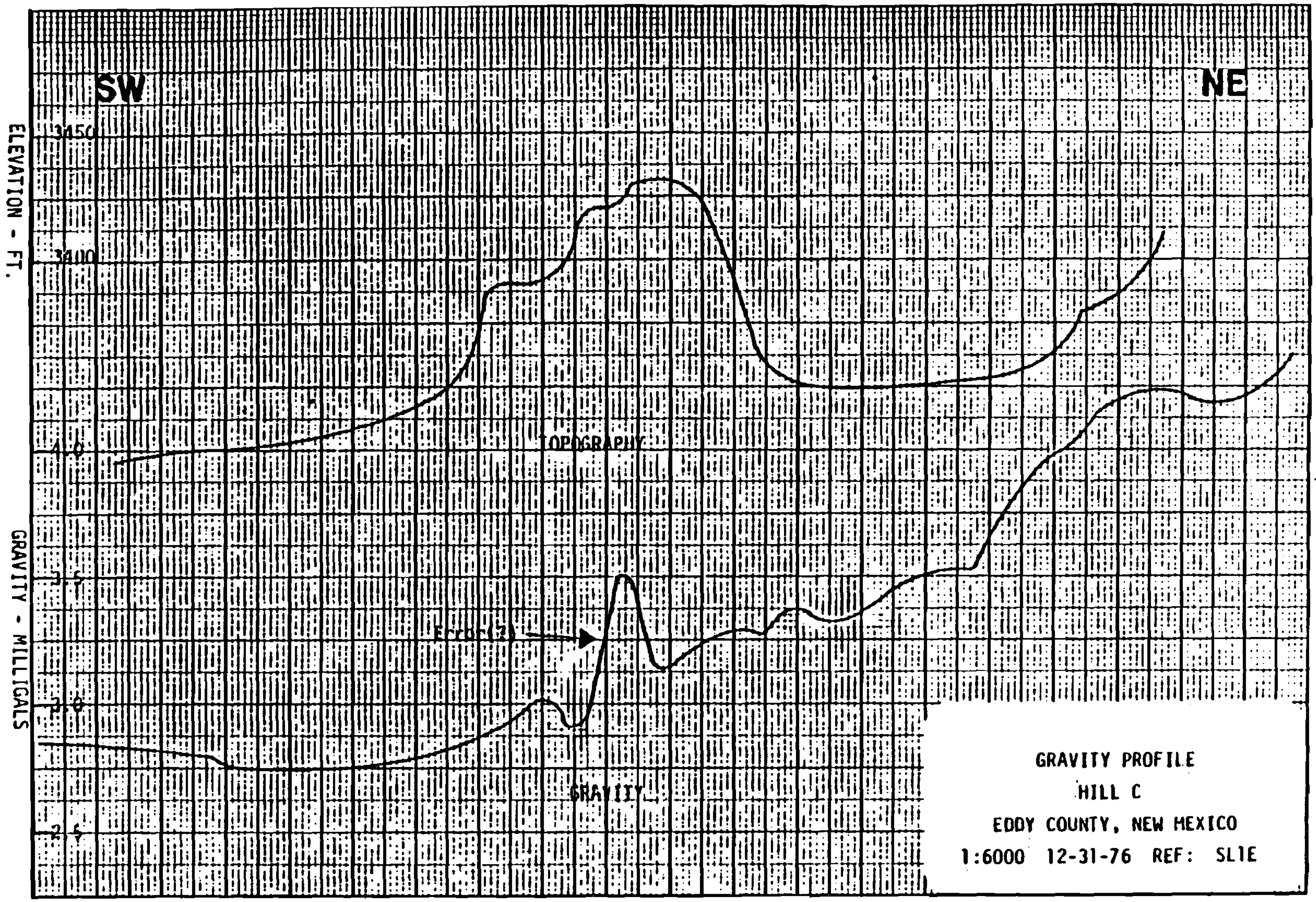

Figure 7.--Gravity profile Hill C, Eddy County, N. Mex. (from Elliot, 1976b, v. 1).

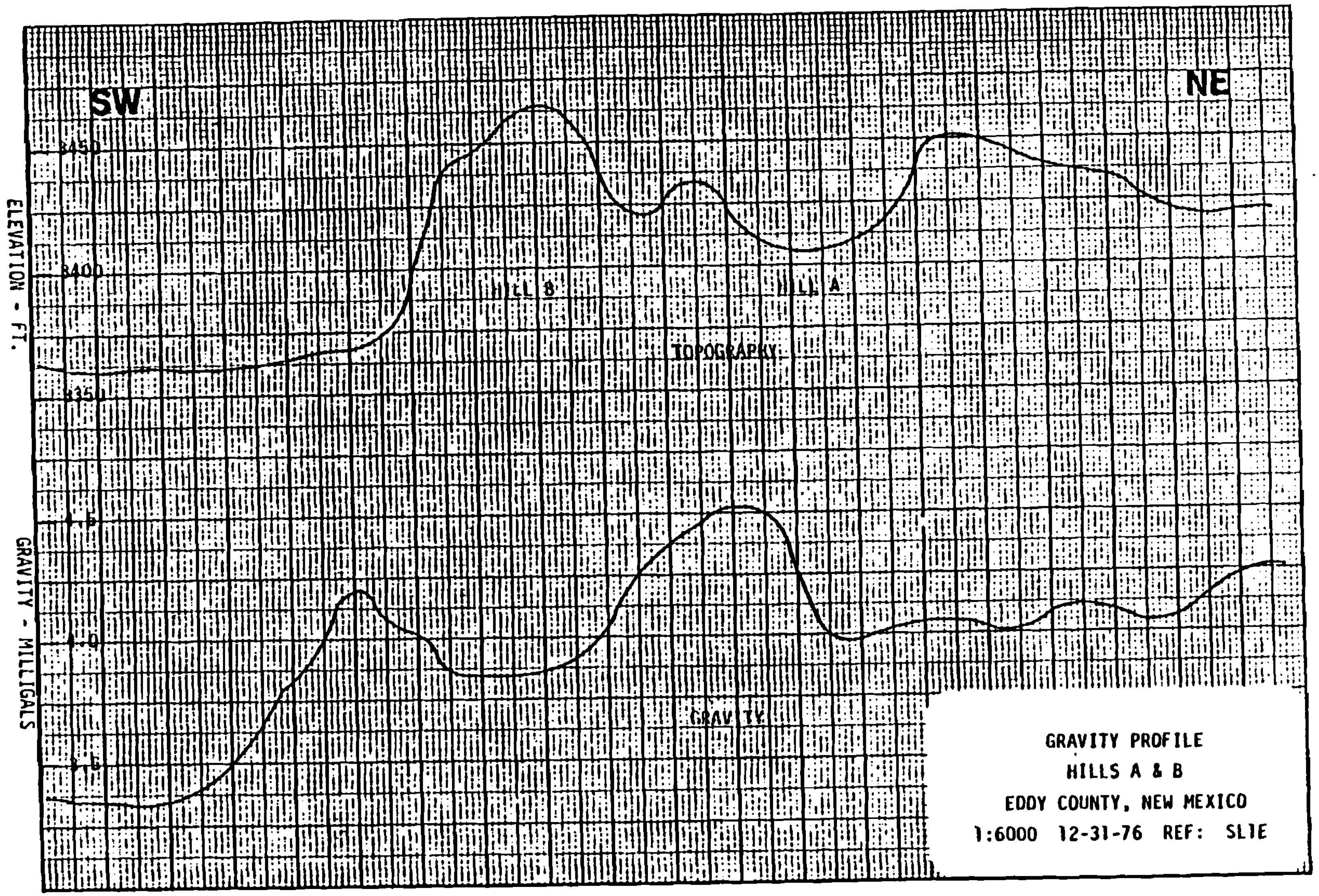

Figure 8.--Gravity profile Hills A and B, Eddy County, N. Mex. (from Elliot, 1976b).

CORE HOLES AND UNDERGROUND MAPPING AT HILLS A AND C

Hill A

Hill A lies in the SW 1/4 sec. 35, T. 20 S., R. 30 E., about 30 km (18.5 mi) east-northeast of Carlsbad (fig. 1) and is the location of drill hole WIPP 31. It has been described in detail by Vine (1960, p. 1905) and by Bachman (1980, p. 62). The hill has a low-circular shape with relief of about 15 m (50 ft) and is about 370 m (1200 ft) in diameter. It is crossed by a spur of the Atchison, Topeka, and Santa Fe Railroad. The central part of the hill has been eroded as a shallow basin that drains to the west. The outer slopes of the hill are formed by Permian Dewey Lake Red Beds overlain by Triassic rocks and capped by Mescalero caliche which dips quaquaversally about 15° (figs. 9 and 10).

Within the basin and within a ring fault about 245 m (800 ft) in diameter lie brecciated angular rock fragments of the Triassic Dockum Group that both Vine and Bachman agree appear to have come from rock stratigraphically higher than that presently exposed outside the ring fault.

To explain the beds at the surface dipping away from the breccia pipe as shown on plate 1 (in pocket) and figure 10, a discussion of the dissolution front is needed. The name dissolution front can be applied to two different stratigraphic horizons, the Rustler Formation and the top of the Salado Formation. Work at the WIPP site and the surrounding area has shown that halite from both of these formations is being removed by near-surface dissolution. This dissolution is progressing from west to east across the Delaware Basin (fig. 9). It appears that the dissolution front is roughly wedge shaped, trending north-south, with the leading edge toward the east. This leading edge starts in the Forty-niner Member of Rustler and, as the wedge thickens, progresses downward and westward into the lower two halite-bearing members of the Rustler and into the upper part of the Salado Formation. The overall appearance of this wedge of dissolution is a "stair step" arrangement dropping stratigraphically down from east to west. The leading edge in the Rustler at the WIPP site is in the southeast quarter of the site and the leading edge in the Salado is in the western side of the site.

This dissolution pattern is also present over the Capitan Limestone in the vicinity of Hill A. The geophysical logs of the two oil and gas exploratory holes (Big Eddy 17 and 78) show no probable halite in the Rustler and definite removal of halite from the top of the Salado.

Field mapping has shown the Mescalero caliche draping the outward-dipping surface of Hill A did not form on the present-dipping surface, thus, the area around and across the pipe must have been fairly level during deposition of the caliche. Only after the formation of this caliche did the removal of halite from the area surrounding the pipe cause the area to subside, which did not affect the relatively impermeable rock in the pipe. This lowering of the surrounding area has resulted in the outward dipping of the surface at Hill A. Bachman (1980, p. 42) states that the Mescalero began to form about 510,000 years ago and that the upper crust formed about 410,000 years ago. This would date the movement of the dissolution front through the area as less than about 400,000 years ago.

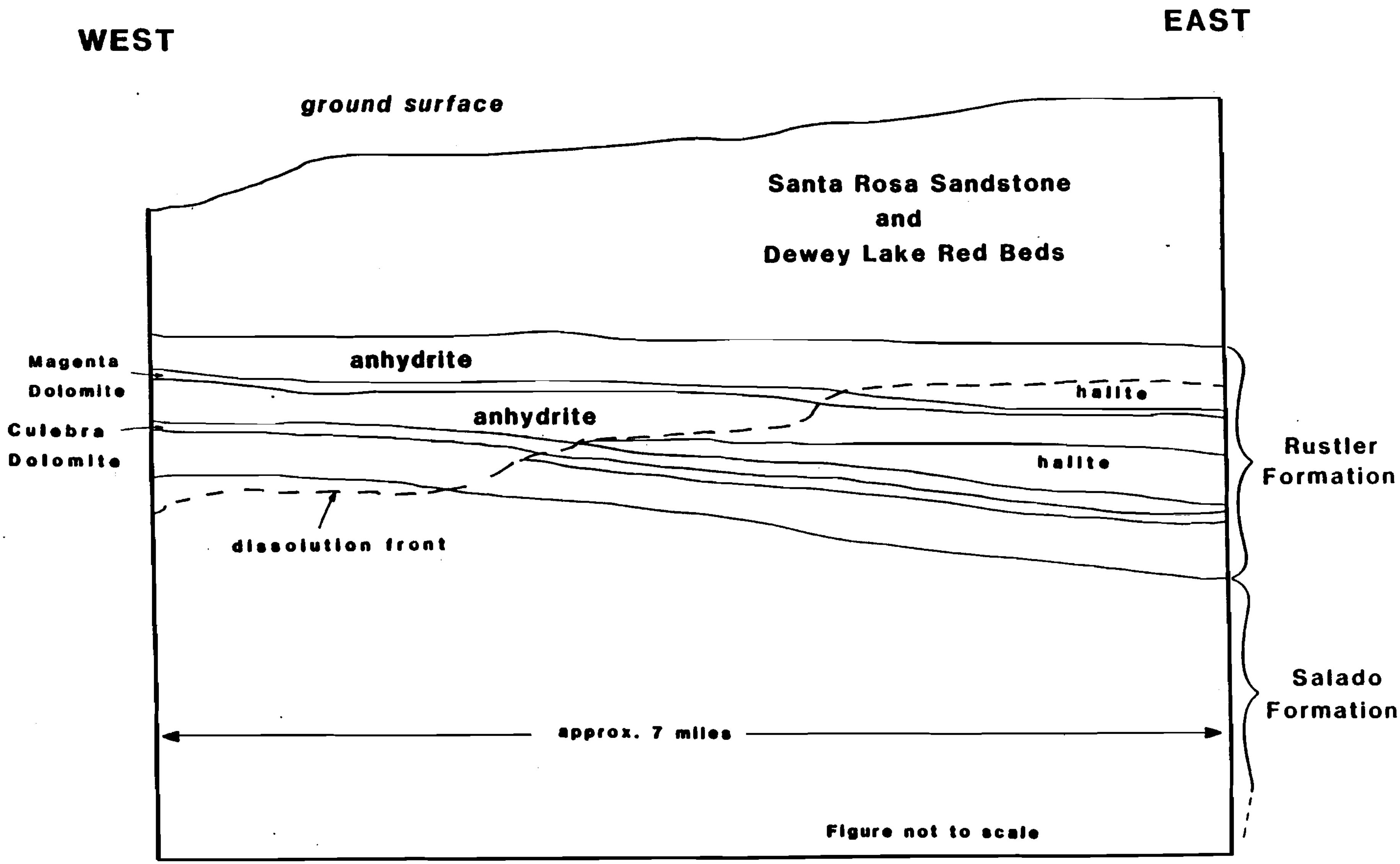

Figure 9.--Diagrammatic sketch west to east across WIPP site showing downward progression of dissolution front. Front is migrating from west to east, removing successively lower halite beds.

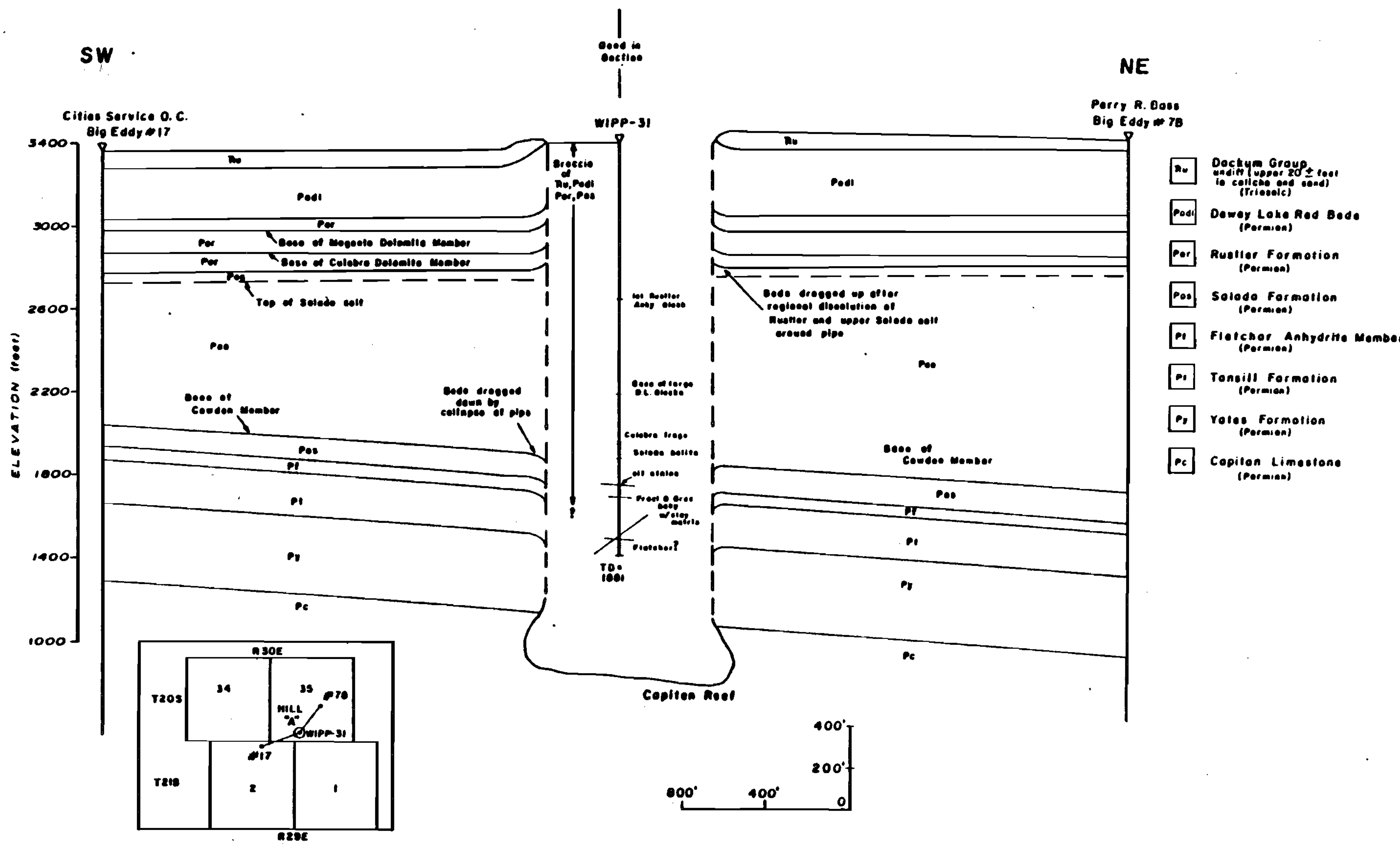

Figure 10.--Southwest to northeast cross section through Hill A.

Drill hole WIPP 31, Hill A

Drill hole WIPP·31 was sited inside the ring fault zone mapped by Vine (1960) and Bachman (1980). The hole was drilled in two stages. The first 247 m (810 ft) were drilled during September and October 1978, and the hole was later (July-August 1980) deepened to 604 m (1981 ft). Only a few feet of core were taken in the upper 247 m (810 ft) of the hole. One core, from 229 to 230 m (750-756 ft), was anhydrite of the Rustler Formation, the first indication of this formation and somewhere between 8 and 94 m (25-310 ft) below its normal stratigraphic position. Table 3 describes in general the lithology of cuttings and core from WIPP 31.

It should be pointed out that although a specific rock, identifiable as the Rustler Formation, was first found at a specific depth, it does not imply that the stratigraphy is normal from that depth downward (fig. 11). In fact, rocks of the Dewey Lake Red Beds were found as deep as 503 m (1650 ft), which is about 366 m (1200 ft) below the base of the unit in the surrounding area. Fragments of the Magenta (fig. 12) and Culebra Dolomite Members (fig. 13) of the Rustler Formation were found 274-366 m (900-1200 ft) below their normal positions.

One part of the Salado Formation halite (about 12 m or 40 ft; true thickness) was the only thick recognizable part of that formation cored, but many of the anhydrite fragments and much of the reddish-brown clay probably are Salado rocks. The anhydrite, starting at a depth of 580 m (1903 ft) and continuing to a total depth of 604 m (1981 ft) is tentatively assigned to the Fletcher Anhydrite, or the base of the Salado Formation. It is the only known anhydrite in this area that is thick enough to account for the amount cored. The 50° dip noted on the laminations would give the cored interval of 24 m (78 ft) a true thickness about 15 m (50 ft). It is estimated that about 3-9 m (10-30 ft) of the Fletcher remains below total depth of WIPP 31.

Because the Tansill and Yates do not contain water-soluble evaporites, they are probably not the cause of the collapse of the overlying rocks. Below these formations is the Capitan Limestone, a somewhat soluble rock known to contain large caverns (Carlsbad Caverns). The most reasonable explanation for collapse of the rocks cored in WIPP 31 is that a large cavern formed in the Capitan, and the overlying rocks, as young as the Triassic Dockum Group, collapsed into the void. The Fletcher Anhydrite probably acted as a supporting beam over the collapse for some time, but as the cavity in the Capitan grew wider, the width exceeded the ability of the Fletcher to serve as a support, and collapse occurred. Another possible method to consider is that the cavity was filled with water to the base of the Fletcher, and declining water levels removed the bouyant support on the Fletcher. This would cause an apparent increase in weight of ±50 percent of the Fletcher that would increase the stress and exceed the rock strength. The Fletcher is considered as the support beam rather than one of the units in the Tansill or Yates because of its lack of bedding and its intergrown crystalline structure. The Tansill and Yates are thin bedded granular rocks.

Most of the halite of the Salado Formation, and all of the halite in the Rustler Formation are missing in the core from WIPP 31. There is no Castile Formation present over the Capitan. In an oil and gas exploration hole (Cities Service Oil and Gas, Big Eddy unit 17) about 0.8 km (1/2 mi) southwest

Table 3.--Lithologic description of cuttings for WIPP 31

[Color designation from Rock-Color Chart (Goddard and others, 1948). Depths not correlated with geophysical logs. To convert feet to meters multiply feet by 0.3048; depths are from ground level]

Description	Thickness depth (feet)	interval (feet)
Cuttings		
No returns--	0 - 37	37.0
Mud and siltstone, dark-reddish-brown (10R 3/4) through dark-yellow-brown (10YR 3/4), some greenish-gray (5GY 3/4) siltstone; trace biotite and limestone; calcareous; as much as 10 percent sandstone in part----	37 - 65	28.0
No returns--	65 - 190	125.0
Mud, siltstone, and sandstone, as in 37- to 65-ft interval--	190 - 230	40.0
No returns--	230 - 459	229.0
Core 1		
Rubble of siltstone, sandstone, and mudstone, moderate-reddish-brown (10R 4/6), dark-reddish-brown (10R 3/4) and grayish-red (10R 4/2), numerous greenish-gray (5GY 6/1) reduction spots 1/2-2 mm in diameter; rubble fragments as large as 15 cm--------------------------	459 - 465.3	6.3
No core--	465.3- 467.0	1.7
Cuttings		
Mudstone, siltstone, and sandstone same as unit at 37-65 ft; occasional fragments of chert, selenite, and micaceous siltstone and sandstone-----------------	467 - 519	52.0
Core 2		
Mudstone, siltstone, and sandstone, dark-reddish-brown (10R 3/4) to grayish-red (10R 4/2) and moderate reddish-brown (10R 4/6); siltstone contains selenite veins and greenish-gray (5GY 6/1) alteration spots and biotite and pyrite; fragments as large as 22 cm--------	519 -526.3	7.3
No core--	526.3- 529	2.7
Cuttings		
Siltstone, sandstone, and mudstone, moderate reddish-brown (10R 4/6), grayish-red (10R 4/2) and light-gray (N7-N6); calcitic, biotitic, minor selenite------------	529 - 579	50.0
Core 3		
Mudstone, siltstone, and sandstone, moderate-reddish-brown (10R 4/6), dark-reddish-brown (10R 3/4), and grayish-red (10R 4/2); greenish-gray (5GY 6/1) reduction spots in siltstone, selenite veins cut siltstone and mud matrix; scattered chert pebbles; possible carbonaceous plant material at 584 ft---------	579 - 589	10.0
Cuttings		
Siltstone, mudstone, and gumbo clay, moderate-reddish-brown (10R 4/6), dark-reddish-brown (10R 3/4) and light-gray (N7); minor chert pebbles------------------	589 - 695	106.0

Table 3.--Lithologic description of cuttings and core for WIPP 31--Continued

Description	Thickness depth (feet)	interval (feet)
Cut 4		
Siltstone, mudstone, and minor sandstone, moderate-reddish-brown (10R 4/6) and dark-reddish-brown (10R 3/4); greenish-gray (5GY 6/1) reduction spots; siltstone contains bedding planes dipping from 32° to 40°--------	695.5- 703.4	7.9
No core--	703.4- 705.0	1.6
Cuttings		
Siltstone and mudstone, same as unit at 589-695 ft-------	705.0- 750.0	45.0
Anhydrite, white (N9)----------------------------------	750.0- 751.0	1.0
Core 5		
Anhydrite, grayish-green (5G 5/2) and dusky yellowish-green (10GY 3/2), gypsiferous; mottled; very finely crystalline; laminated; irregular argillaceous laminae at 753.8 ft; dip of laminae ranges from 32° to 40°-----	751.0- 756.6	5.6
Siltstone, dark-reddish-brown (10R 3/4) and grayish-red (10R 4/2); gypsiferous anhydrite bands at 757.0 and 757.4 ft); siltstone faintly bedded------------------	756.6- 758.9	2.3
No core--	758.9- 759.7	.8
Core 6		
Mudstone breccia; grayish-red (10R 4/2) through dark-reddish-brown (10R 3/4) and medium-dark-gray (N4), fragments less than 3 cm; slightly calcareous matrix---	759.7- 767.5	7.8
Sandstone, dark-reddish-brown (10R 3/4) and grayish-red (10R 4/2), very fine grained, hard, friable, minor calcite cement, MnO_2 stain on bedding surfaces, gypsum filled fracture-------------------------------	767.5- 771.0	3.5
Cuttings		
Siltstone, mudstone, sandstone and gypsum, reddish-brown (10R 3/4), grayish-red (10R 4/2) and dark-reddish-brown (10R 3/4) siltstone, mudstone same with some medium dark gray (N4), sandstone same color as siltstone, gypsum, white (N9); minor chert pebbles and selenite---	771.0- 800.0	29.0
Core 7		
Breccia of mudstone and siltstone, moderate-reddish-brown (10R 4/6), dark-reddish-brown (10R 3/4), grayish-red (10R 4/2), greenish-gray (5GY 6/1); slightly calcareous; mud matrix; portions colored dark-yellowish-orange (10YR 6/6)----------------------	800.0- 809.8	9.8
No core--	809.8- 810.0	.2
No returns---	810.0- 819.0	9.0
Core		
Mudstone-siltstone breccia, moderate-reddish-brown (10R 4/6) to dark-reddish-brown (10R 3/4); mudstone fragments up to 20 cm; siltstone contains greenish-gray (5GY 6/1) reduction spots, lower 4 ft is one block, siltstone in rest of unit, fragments as much as cm, most less than 4 cm--------------------	819.0-1022	203.0

Table 3.--Lithologic description of cuttings and core for WIPP 31--Continued

Description	Thickness depth (feet)	interval (feet)
Anhydrite, olive-gray (5Y 4/1), finely crystalline, interlayered with moderate-reddish-brown (10R 4/6) siltstone containing alteration spots------------------	1022.0-1032.4	10.4
Siltstone, moderate-reddish-brown (10R 4/6) and dark-reddish-brown (10R 3/4), numerous reduction spots and veins of selenite; unit mostly shattered fragments of single block of rock----------------------------------	1032.4-1051.7	19.3
Anhydrite, light-olive-gray (5Y 6/1) to dark-yellowish-brown (10YR 4/2), laminated in upper 2 ft; very finely crystalline and medium-gray (N5) in lower 0.8 ft--	1051.7-1054.4	2.7
Siltstone, dark-reddish-brown (10R 3/4) and moderate-reddish-brown (10R 4/6); numerous greenish-gray (5GY 6/1) reduction spots; many lengths of core are from individual blocks; gray (N6) clay filling fractures near base of unit, some sandstone layers-----	1054.4-1147.4	93.0
Anhydrite, medium- to medium-dark-gray (N5-4); finely crystalline, large fragments of anhydrite--------------	1147.4-1149.8	2.4
Siltstone same as unit at 1054.4-1147.4 ft, anhydrite fragment at 1167.9-1168.2 ft; some mudstone intervals; most of unit appears to be large broken block with dips of bedding as much as 55°-------	1149.8-1210.8	61.0
Anhydrite, medium- to medium-dark-gray (N5-4), finely crystalline, many large blocks interspersed with small (<10 cm) blocks of anhydrite and siltstone; 1.5-ft-thick gravel layer at 1224.6-1226.1, gravel is rounded siltstone; dolomite fragments at 1249, 1250, 1254, 1263, 1267.5, 1276, 1280-1285 ft; dark-gray (N3) siltstone at 1251-1253.3 ft overlying reddish-brown (10YR 4/6) dissolution residue-------------------------	1210.8-1292.0	81.2
Siltstone breccia, moderate- to dark-reddish-brown (10R 4/6-10R 3/4); minor fragments of anhydrite as large as 45 cm (1.5 ft); minor mudstone and sandstone fragments; rounding of edges of fragments common------------------	1291.0-1436.6	145.6
Anhydrite, medium-light-gray (N6) to medium-dark-gray (N4), very finely crystalline; brecciated zone filled with clay from 438.3-438.4 m (1437.9 to 1438.4 ft)-----	1436.6-1442.5	5.9
Mudstone, siltstone, sandstone, and anhydrite breccia; moderate-reddish-brown (10R 4/6), dark-reddish-brown (10R 3/4) siltstone, mudstone, and sandstone, medium-gray (N5) anhydrite; fragments of light-gray (N7) to light-olive-gray (5Y 6/1) dolomite scattered through core; halite filled vug 4X7 cm at 1447.9 ft) medium-bluish-gray (5B 5/1) clay at base---------------	1442.5-1457.6	15.1

Table 3.--Lithologic description of cuttings and core for WIPP 31--Continued

Description	Thickness depth (feet)	Thickness interval (feet)
Halite, light-gray (N7), medium-gray (N5), pale-reddish-brown (10R 5/4) moderate-reddish-orange (10R 6/6), finely to coarsely crystalline; light-gray portions appear to be recrystallized; pale-reddish-brown portions are argillaceous, and moderate-reddish-orange portions are polyhalitic; dips measured along polyhalitic streaks range from 50° to 60°--------	1457.6-1518.7	61.1
Siltstone and anhydrite breccia; siltstone, moderate-reddish-brown (10R 4/6) and dark-reddish-brown (10R 3/4), many fragments contain greenish-gray (5GY 6/1) alteration spots; angular anhydrite fragments range from olive gray to very light gray (5Y 4/1 to N5); fragments of pitted dolomite at 1549.5-1551.2, 1559, 1578, 1586.7, 1614 to 1624 ft; laminated light-brownish-gray (5YR 6/1) dolomite fragment at 1627.2 ft; oil stains at 1629 and 1648 ft; glauberite crystals at 1628.9-1629.3 ft; halite filled fractures and vugs in lower 30 ft-------------------------------	1518.7-1651.6	132.9
Anhydrite, medium-gray (N5), speckled with dusky-yellowish-brown (10YR 2/2) specks, very finely crystalline; scattered halite crystals throughout unit---	1651.6-1658.2	6.6
Anhydrite and siltstone breccia, matrix of mud; angular anhydrite fragments medium-dark-gray (N4) ranging to 50 cm; siltstone, moderate-reddish-brown (10R 4/6) to dark-reddish-brown (10R 3/4); dark-reddish-brown (10R 4/3) mud matrix about 30 percent of unit----------	1658.2-1702.6	44.4
Mud, anhydrite, and siltstone breccia; medium-light-gray (N6) to light-bluish-gray (5B 7/1) mud is about 60 percent of unit, anhydrite and siltstone fragments as in unit above; pitted dolomite fragments at 1703 ft; scattered glauberite crystals and halite filled fractures--------------------------------------	1702.6-1762.8	60.2
Mud and anhydrite breccia; mud matrix grayish-red (5R 4/2) and some medium-gray (N5); anhydrite as in unit at 1658.2-1702.6 ft------------------------------	1762.8-1782.8	20.0
Anhydrite and mud breccia; anhydrite as in unit at 1658.2-1702.6 ft; mud matrix, light bluish-gray (5B 7/1)--	1782.8-1802.6	19.8
Anhydrite, medium-gray (N5) to medium-dark-gray (N4), very finely crystalline; rock is brecciated and fractures are filled with medium-bluish-gray (5B 5/1) clay; some intervals contain subrounded laminated and subrounded dense anhydrite fragments as large as 4 cm in a mud matrix--------------------------------------	1802.6-1903.0	100.4

Table 3.--Lithologic description of cuttings and core for WIPP 31--Continued

Description	Thickness depth (feet)	Thickness interval (feet)
Anhydrite, medium-gray (N5) and light-olive-gray (5Y 6/1) laminated in part with brownish-gray (5YR 4/1) and grayish-black (N2) anhydrite, unit dips about 50° and appears to be one large block------	1903.0-1981.0	78.0
Total depth-----------------------------------	1981.0	

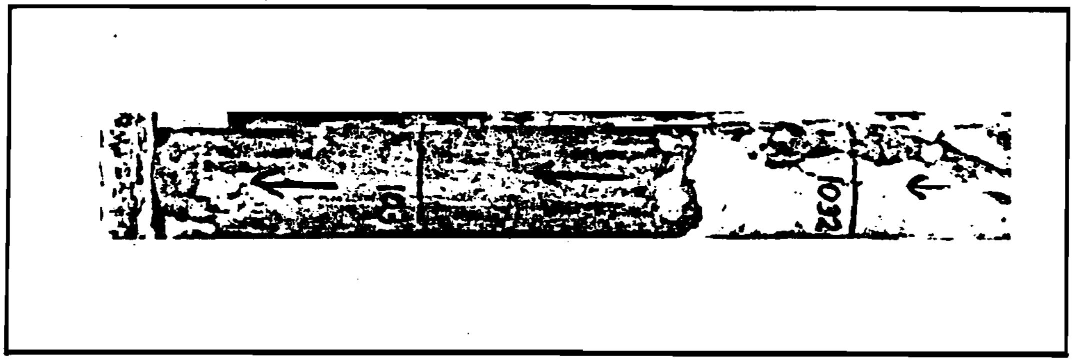

Figure 11.--Core from WIPP 31 showing block of younger Dewey Lake Red Beds underlying older fragments of Rustler Formation. The small light-gray spots in lower part of core are reduction spots. Arrows point downhole.

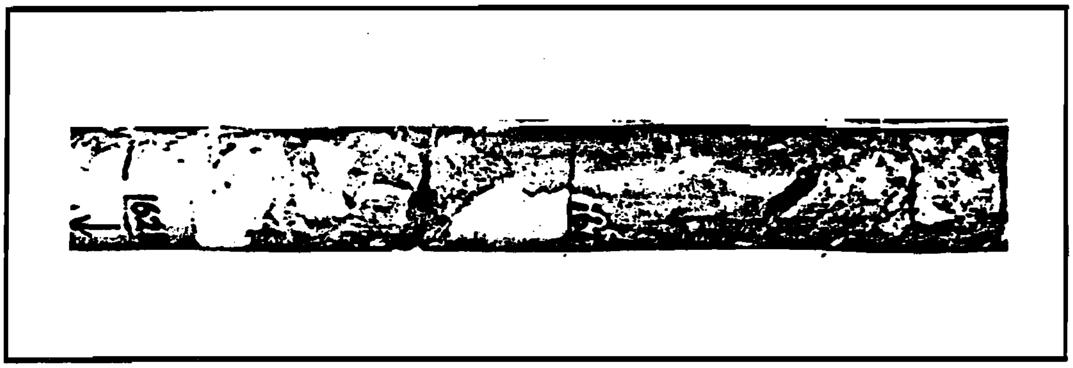

Figure 12.--Fragments of siltstone and anhydrite with a fragment of the Magenta Dolomite below 1627-footage mark in WIPP 31. Arrows point downhole.

Figure 13.--Breccia from WIPP 31 containing anhydrite and siltstone fragments. A fragment of the Culebra Dolomite has the depth number 1448 written on it. Arrows point downhole.

of drill hole WIPP 31, there is a total thickness of at least 358 m (1175 ft) of halite in the Salado. In a second hole (Perry R. Bass, Big Eddy unit 78) about 0.8 km (1/2 mi) northeast of WIPP 31, there is over 305 m (1000 ft) of halite preserved in the Salado Formation. The missing halite (>305 m or >1000 ft) of the Salado in WIPP 31 must have been dissolved after collapse of the material in the pipe.

At some time, minor amounts of oil migrated from the Yates Formation upward into the Salado. Traces of oil found in the brecciated rock in WIPP 31 have been identified (Palacas and others, 1982) as being similar to oil from drill holes nearby that are producing from the Yates Formation. The oil stains were found in breccia (497 m or 1629 ft) consisting of siltstone, anhydrite, and dolomite fragments and a matrix of mud, recrystallized halite and glauberite crystals (rocks of the Dewey Lake, Rustler, and Salado Formations).

Results of hydrologic tests in WIPP 31 run by USGS personnel are reported in a following section. Continuous monitoring of the drilling fluid performed by Morco Geological Services to determine the presence and amounts of nitrogen, carbon dioxide, hydrogen sulfide, and hydrocarbons demonstrated that none of these gases was present in detectable amounts.

Briefly, the order of the formation of the breccia pipe at Hill A is interpreted as follows:

1. Deposition of rocks as young as Triassic Dockum Group.
2. Cavity formation in the Capitan Limestone by circulating ground water.
3. Collapse of the Yates and Tansill Formations into cavity.
4. Support by the Fletcher Anhydrite kept further upward collapse from occurring for some time.
5. Eventual collapse of the Fletcher and downdropping of Salado and younger units. This stage probably consisted of some massive and some fragmental downdropping.
6. Continual dissolution of Salado and Rustler halites in the pipe, possibly from downward moving water. Mud and small rock fragments in the pipe continually being carried or dropped downward during this stage.
7. Formation of Mescalero caliche across nearly horizontal surface.
8. Dissolution front removes all Rustler halite and some upper halite from the Salado from around the pipe causing near-surface beds to dip away from pipe.

Hill C

Hill C is another dome-shaped surface feature 3 km (2.5 mi) southeast of Hill A. It rises about 30 m (100 ft) above the surrounding terrain, is roughly circular in plan, and is about 350 m (1150 ft) across. It has been breached on the west side in a manner similar to Hill A but to a lesser extent. The surface, where not eroded, is formed by draped Mescalero caliche which partially engulfs the Gatuna Formation and brecciated rock of Triassic age. The Mescalero caliche is offset slightly in several places and is displaced downward toward the center of the hill, apparently in response to minor readjustments of the breccia mass (fig. 14). Unlike Hill A, only a very small area of Dewey Lake Red Beds is exposed in the gully that drains the western part of the hill. The rock exposed in the center of the hill is brecciated Triassic Dockum Group fluvial sandstones and siltstones.

Samples for palynomorph analyses were collected from the brecciated Dockum Group rocks and were studied by Robert M. Kosanke of the USGS. Kosanke reported (oral commun., 1981) on the findings as follows: The samples yielded few palynomorphs and they were poorly preserved. Palynomorphs are usually not found in red or oxidized rocks and the presence of calcareous matter does not normally help with the preservation. The samples did, however, yield a few poorly preserved palynomorphs. Kosanke states (written commun., 1981) "The most abundant of these would be the remains of the alga Botryococcus cf. B. braunii. Botryococcus is known to occur from early Paleozoic time to the present day where it is a member of the freshwater plankton, is widely distributed throughout the lakes of the United States, but is rarely abundant. Botryococcus is abundant and the primary constituent of boghead or algal coals known to occur in Alaska, Australia, France, Scotland, South Africa, and mainland United States. It is not so much an indicator of age as it is an indicator of freshwater environment. A single pollen grain, probably related to the Compositae was found together with two tricolpate pollen grains, and several winged pollen grains assignable to Pinus. In addition, several spores referable to the fungi were observed. This is not an assemblage--there is not enough evidence to evaluate with any degree of confidence. If what was found is valid and not modern contamination, the presence of the Compositae would suggest Oligocene or younger."

The rocks, as mentioned above, have been dated by field mapping as Triassic; thus indicating the likelihood of contamination of the samples precluding the use of palynomorphs, in this case, to date the exposed rocks in the central surficial part of Hill C.

The breccia pipe at Hill C provided an unparalleled opportunity to study a pipe in three dimensions. Prior to our investigation, this was the only breccia pipe that was known to contain brecciated rock at depth. During mining operations in 1975, in the 7th ore zone (see Jones and others, 1960, for stratigraphic location of ore zones) in the MCC potash mine one of the mine entries encountered the edge of this pipe. Not only were the rocks adjacent to the pipe exposed 366 m (1200 ft) below the surface, but also some of the breccia in the pipe itself could be studied.

The objectives of investigating Hill C were to explore and define the horizontal dimensions of the breccia pipe at mine level, and study the effects of the collapse on the adjacent rock in the MCC potash mine. Additionally, it was planned to match the underground pipe boundary with its surface expression and to identify the stratigraphic origin of the displaced rock fragments in the pipe at mine level. Additional objectives were to determine the permeability and porosity of the pipe and, if possible, the origins and of mineral phases associated with dissolution.

It was planned to drill horizontal core holes across the brecci[illegible] from the mine level to examine the breccia, determine the pipe dim[illegible] collect samples that might be useful for age determination. Befo[illegible]

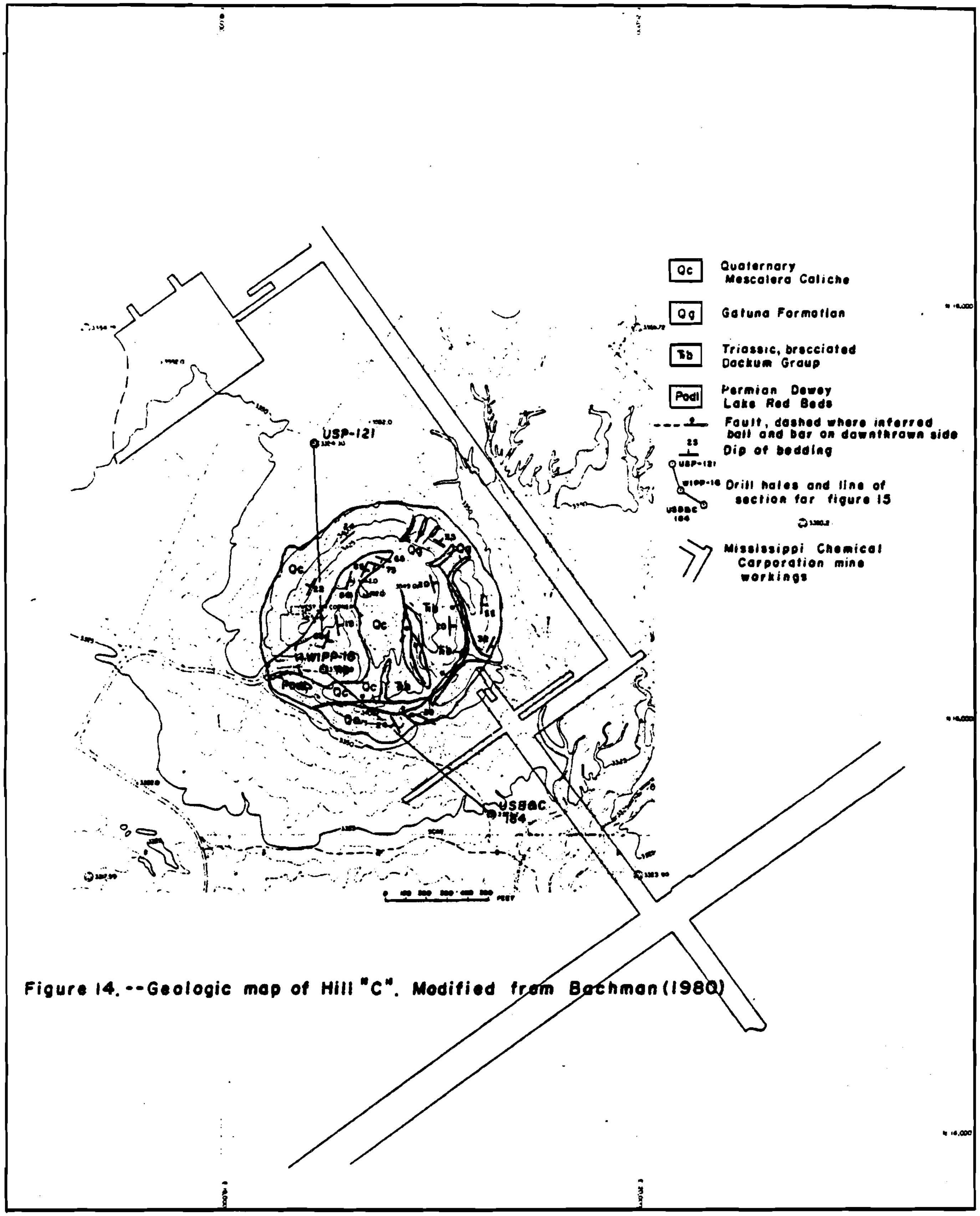

Figure 14.--Geologic map of Hill "C". Modified from Bachman (1980)

holes were to be drilled, it was thought advisable for safety reasons to drill a vertical hole from the surface to ascertain whether the breccia contained fluids or gases that might endanger the mine if intercepted by horizontal holes. Borehole WIPP 16 was designed for this purpose and was located on Hill C (NW1/4 SW1/4 sec. 5, T. 21 S., R. 30 E.). The hole was cored from 37.5 m (123 ft) to a total depth of 396 m (1300 ft), about 27 m (88 ft) below the mining horizon. A summary of the stratigraphy for rocks recovered from WIPP 16 is given in table 4, and an abbreviated lithologic log is given in table 5.

Exploratory drill holes for potash are located in the immediate vicinity of the breccia pipe (fig. 14), and two of these are combined with borehole WIPP 16 to construct a cross section across the pipe and into the surrounding rock (fig. 15).

WIPP 16 penetrated brecciated rock of the Triassic Dockum Group, and the Permian Dewey Lake Red Beds and part of the Rustler Formation. Although the Rustler has been downdropped and shattered, the beds, unlike the overlying rocks, were in recognizable stratigraphic order. The contact of the Rustler and the overlying Dewey Lake has been downdropped about 189 m (620 ft) (fig. 15), as has the Culebra Dolomite Member of the Rustler. Halite below the Culebra was cored in WIPP 16, and this differs markedly from drill hole WIPP 31 at Hill A where no halite and no recognizable stratigraphic sequence of rock was found to represent the Rustler.

The explanation for the nearly intact Rustler, minus halite in the Forty-niner and Tamarisk Members, in WIPP 16 is a problem. At Hill A (WIPP 31), the sequence of deposition, collapse of material in pipe, erosion, deposition of caliche, and dissolution of halites in the Rustler and upper Salado seems reasonable. To preserve Rustler halite in the pipe at WIPP 16, and arrange a plausible sequence of events for the formation of the pipe at Hill C, calls for stages of dissolution of the Rustler and upper Salado halites that suggest an unreasonable timing for the dissolution of these halites. It is probable that the formation of the pipes at Hills A and C occurred at widely spaced times.

The dipping beds shown abutting the pipe in figure 15 are explained by the following evidence. The surface dips of the undifferentiated Triassic rocks are mappable at the surface. The inward dipping rocks of MB 121 are mapped in the potash mine drift (fig. 23). Dips of beds between these two horizons and below MB 121 are hypothetical, but a reversal between the surface and MB 121 is true, and somewhere above the base of the dissolution of halite in the Salado (MB 109) is a reasonable place to put it.

Oil smears were found on core from WIPP 16, just as they were in WIPP 31. In WIPP 16 the rocks containing these smears were anhydrite, halite, and dolomite of the Rustler Formation. (Analysis of this oil was reported by Palacas and others, 1982.)

Hydrologic testing of WIPP 16 was not done because of the instability of the hole walls. A neutron log run by USGS personnel, Albuquerque, N. Mex., did not indicate the presence of water. Morco Geological Services continuously logged drilling fluids to detect CO_2, hydrocarbons, nitrogen, and

Table 4.--Stratigraphic column of borehole WIPP 16

Stratigraphic unit	Thickness Meters	Thickness Feet
Chaotic breccia of Triassic rocks and Dewey Lake Red Beds	0-349	0-1145+
Rustler Formation----------------------------------	349-396	1145-1300+
Forty-niner Member, anhydrite, sandstone and siltstone.----------------------------	396-361	1145-1186
Magenta Dolomite Member---------------------	361-365	1186-1199
Tamarisk Member, anhydrite, sandstone and siltstone.----------------------------	365-382	1199-1252
Culebra Dolomite Member---------------------	382-389	1252-1276
Lower unnamed member, halite, anhydrite, siltstone----------------------------------	389-396	1276-1300
Total depth-----------------------	396	1300

Table 5.--Abridged lithologic log of borehole WIPP 16

[Color designation from Rock-Color Chart (Goddard and others, 1948). Cuttings 40-120 ft, core 123-1300 ft; depths from driller, not matched to geophysical logs; to convert multiply footage by 0.0348; depths are from ground level]

Description	Thickness depth (feet)	Thickness interval (feet)
No cuttings logged--	0 - 40	40.0
Sandstone, siltstone, and clay; sandstone is grayish red (10R 4/2), very fine to fine grained and ranges from 10 to 60 percent of sample; siltstone is moderate reddish brown (10R 4/6) and light olive gray (5Y 6/1) with traces of greenish-gray (5GY 6/1) reduction spots, 40 percent of sample; clay is medium light gray (N6), 0-30 percent of sample; some (10 percent) moderate-reddish-brown (10R 4/6) to dark-reddish-brown (10R 3/4) mudstone in lower (25 ft)------	40.0- 120.0	80.0
No returns--	120.0- 123.0	3.0
Siltstone breccia, moderate-reddish-brown (10R 4/6) and dark-reddish-brown (10R 3/4); scattered blebs and patches of greenish-gray (5GY 6/1) alteration zones; core consists of unbroken blocks as large as 0.3 m (1 ft) as well as angular and rounded fragments of recemented siltstone; alteration spots do not cross fragment boundaries; dips, where bedding apparent, are as steep as 71°, but there is no regular pattern; some mud matrix between siltstone in places; core loss from 125.4-126.4, 130.0-132.1, 135.7-136.7, 151.0-153.3, 153.6-154.0, 163.7-164.0, 169.2-170.2, 172.1-176.0, 180.6-181.0, 185.3-186.0, and 189.0-191.0 ft-----------	123.0- 191.7	68.7
Sandstone, grayish-red (10R 4/2), moderate- and dark-reddish-brown (10R 4/6-10R 3/4), fine grained; fractures rehealed with calcite and selenite; dips of crossbedding range from 50°-80°, no core from 59.7 to 59.7 m (195.8-196.0 ft)------------------------	191.7- 201.4	9.7
Siltstone and mudstone breccia, moderate-reddish-brown (10R 4/6) siltstone; dark-reddish-brown (10R 3/4) mudstone; fragments are subangular to subrounded and range in size from 0.5 to 4 cm (1/2-1 1/2 in.)---------	201.4- 203.0	1.6
Sandstone, siltstone, and breccia consisting of sandstone, siltstone, and mudstone, moderate-reddish-brown (10R 4/6), and dark-reddish-brown (10R 3/4); some greenish-gray (5GY 6/1) zones and spots; dips of crossbedding in sandstone range from 50° to 75°; fractures in sandstone and siltstone rehealed with calcite and selenite; much of breccia has a matrix of mud; no core recovery at 220.6-221.0, 224.0-226.0, 244.9-247.0, 247.8-251.0, 260.4-261.0, and 265.6-265.8 ft--	203.0- 265.8	62.8

Table 5--.--Abridged lithologic log of drill hole W-16--Continued

Description	Thickness depth (feet)	interval (feet)
Mudstone, dark-reddish-brown (10R 3/4); breccia of mudstone and sandstone and siltstone; some greenish-gray (5GY 6/1) mud filling between fragments; most fragments range from 3 to 5 cm (1-2 in.)---------------	265.8- 272.5	6.7
Sandstone, moderate-reddish-brown (10R 6/4), very fine grained, fractures filled with mud; few scattered greenish-gray (5GY 6/1) reduction spots----------------	272.5- 280.0	7.5
Mudstone, dark-reddish-brown (10R 3/4) brecciated and interspersed with subrounded sandstone and siltstone fragments ranging from 2 to 10 cm (1-4 in.); minor greenish-gray (5GY 6/1) alteration spots and zones throughout unit; minor core loss at 295.9-296.0 and 305.9-306.0 ft---	280.0- 329.8	49.8
Sandstone, siltstone, and mudstone breccia same as unit at 61.9-81.0 m (203.0-265.8 ft); calcite and mudstone filled fractures throughout unit; fragments range from 2 to 17 cm (1-7 in.), matrix of mud; no core from 458.8-459.0, 489.0-491.0, 494.5-496.0, 498.8-501.0, and 504.8-506.0 ft---	329.8-563.0	233.2
Mudstone breccia, dark-reddish-brown (10R 3/4), scattered subrounded to angular fragments of siltstone and sandstone ranging from 1 to 10 cm (1/2-4 in.); scattered greenish-gray (5GY 6/1) reduction spots; no core from 17.7 to 177.1 m (580.8 to 581.0 ft)----------	563.0- 594.6	31.6
Sandstone, siltstone, and mudstone breccia same as unit at 329.8-563.0 ft; calcite healed fractures in sandstone fragments; mud matrix around fragments that range in size from 0.5 to 17 cm (1/2-7 in.), dips of crossbedded sandstone about 55° where measured; core loss at 610.3-610.8, 619.7-621.0, 624.0-626.0, 628.9-631.0, 634.0-636.0, 637.6-641.0, 641.7-646.0, 648.4-651.0, and 654.4-656.0 ft------------------------	594.6- 657.3	62.7

Table 5--.--Abridged lithologic log of drill hole W-16--Continued

Description	Thickness depth (feet)	interval (feet)
Siltstone and mudstone breccia, dark-reddish-brown (10R 3/4) and moderate-reddish-brown (10R 4/6), much of unit consists of fairly undisturbed rock, except for its steep dip. Scattered subrounded fragments of moderate-reddish-brown (10R 4/6) sandstone and greenish-gray (5GY 6/1) mudstone and clay fillings between fragments; dips of 30°-65° on bedding planes; scattered fractures rehealed with gypsum and selenite; core loss at 659.0-661.0, 685.9-686.0, 703.6-706.0, 706.6-709.5, 719.4-720.7, 730.9-731.0, 734.7-735.3, 747.0-747.5, 755.0-755.5, 762.7-767.9, 774.6-776.0, 777.1-781.0, 783.6-786.0, 790.3-791.0, 791.8-796.0, 797.7-798.2, 805.4-805.6, 810.2-810.6, 833.6-833.8, 850.8-851.0, 853.4-857.0, 938.9-939.0, 945.6-946.0, 960.8-961.0, 977.8-978.0, 1070.6-1071.0, 1078.5-1079.0, 1084.7-1086.0, 1123.6-1124.2, 1138.0-1139.5, and 1144.0-1145.3 ft	657.3-1145.3	48.80
Anhydrite, medium-gray (N5) and olive-gray (5Y 4/1) laminated in part with brownish-gray (5YR 4/1) and moderate-brown (5YR 4/4), partly brecciated, fractures filled with clay; dolomitic band 3 cm (1 in. thick) at 355.7 m (1167.0 ft); laminae dip from 20° to 36°; oil bleeding from brecciated zone at 352.3-353.0 m (1156.0-1158.2 ft)	1145.3-1168.9	23.6
Mudstone, moderate-reddish-brown (10R 4/6), containing siltstone fragments and reduction spots	1168.9-1172.0	3.1
No core	1172.0-1175.0	3.0
Anhydrite, olive-gray (5Y 4/1) and medium-bluish-gray (5B 5/1), argillaceous filling in hairline fractures	1175.0-1177.7	2.7
No core	1177.7-1178.0	.3
Anhydrite, brownish-gray (5YR 4/1), light-bluish-gray (5B 7/1), light-greenish-gray (5GY 6/1) and grayish-yellow (5B 8/4), very finely crystalline, dips 38°-40°; fractures filled with clay	1178.0-1186.3	8.3
Anhydrite, dolomitic, greenish-gray (5Y 6/1) and light-brownish-gray (5YR 6/1)	1186.3-1186.6	.3
No core	1186.6-1186.9	.3
Anhydrite, dolomitic, same as unit at 1186.3-1186.6 ft, brecciated and recemented; laminae dip 36°	1186.9-1192.6	5.7
Dolomite, greenish-gray (5GY 6/1), light-olive-gray (5Y 6/1), and light-brownish-gray (5YR 6/1) wavy olive-black (5Y 2/1) laminae, gypsum along some laminae; brecciated and rehealed in part	1192.6-1198.6	6.0

Table 5--.--Abridged lithologic log of drill hole W-16--Continued

Description	Thickness depth (feet)	interval (feet)
Anhydrite, same as unit at 1145.3-1168.9 ft, brecciated in part and containing subangular to subrounded dolomite dolomite fragments, breccia very well cemented; laminae in unbroken parts dip 50°	1198.6-1220.4	21.8
Anhydrite, light-olive-gray (5Y 6/1) mottled with brownish-gray (5YR 4/1), very finely crystalline, 2-cm-long dolomite fragment at 1224.3 ft; minor fractures filled with mud	1220.4-1227.0	6.6
Anhydrite and brecciated anhydrite and dolomitic anhydrite; medium-gray (5B 5/1) and dark-greenish-gray (5GY 4/1), dolomitic parts laminated with light-olive-gray (5Y 6/1); fragments are subangular to subrounded mud filling between fragments; some fractures mud filled	1227.0-1237.0	10.0
Mudstone, medium-bluish-gray (5B 5/1) grading to moderate- and dark-reddish-brown (10R 4/6-10R 3/4), pliable, contains fragments of siltstone and gypsum less than 2 mm; lower foot mostly anhydrite/gypsum	1237.0-1243.4	6.4
Anhydrite, medium-light-gray (N6), faintly laminated and mottled dark-yellowish-brown (10YR 4/2); few bituminous laminae with oil bleeding from them	1243.4-1249.4	6.0
Dolomite, light-olive-gray (5Y 6/1-5Y 5/2), very finely crystalline	1249.4-1250.1	.7
Anhydrite, same as unit at 1243.4-1249.4; halite crystals filling vugs along bedding	1250.1-1251.5	1.4
Dolomite, medium-light-gray (N6) to light-bluish-gray (5B 7/1); very finely crystalline; anhydritic in part, lower part grades to grayish-yellow (5Y 8/1) and (5Y 7/2); numerous vugs; halite filled fractures in lower part of unit	1251.5-1276.1	24.6
Mudstone and clay, brownish-gray (5YR 4/1), medium-gray (N5), and moderate-reddish-brown (10R 4/6); contacts with upper and lower units dip 32° and 35°, respectively	1276.1-1278.4	2.3
Halite, moderate-reddish-brown (10R 4/6), finely to medium crystalline, very argillaceous; numerous anhydrite stringers scatered throughout; oil bleeding from halite at 1281.5-1282.0 ft	1278.4-1286.9	8.5
Clay, grayish-red (10R 4/2) and olive-gray (5Y 4/1); rounded anhydrite fragments in lower part	1286.9-1287.3	.4
Anhydrite, very light gray (N8) to light gray (N7), very finely crystalline; numerous halite filled fractures; faint laminae dip 40°-45°	1287.3-1293.5	6.2
Halite, moderate-reddish-orange (10R 6/6), finely crystalline; anhydrite stringers scattered throughout	1293.5-1294.0	.5

Table 5--.--Abridged lithologic log of drill hole W-16--Continued

Description	Thickness depth (feet)	interval (feet)
Anhydrite, same as unit at 1287.3-1293.5 ft, halite bands parallel to anhydrite laminae diping 40°-45°------------	1294.0-1297.7	3.7
Mudstone, anhydritic, dark-reddish-brown (10Y 3/4), gypsiferous and halitic----------------------------------	1297.7-1300.0	2.3
Total depth------------------------------------	1300.0	

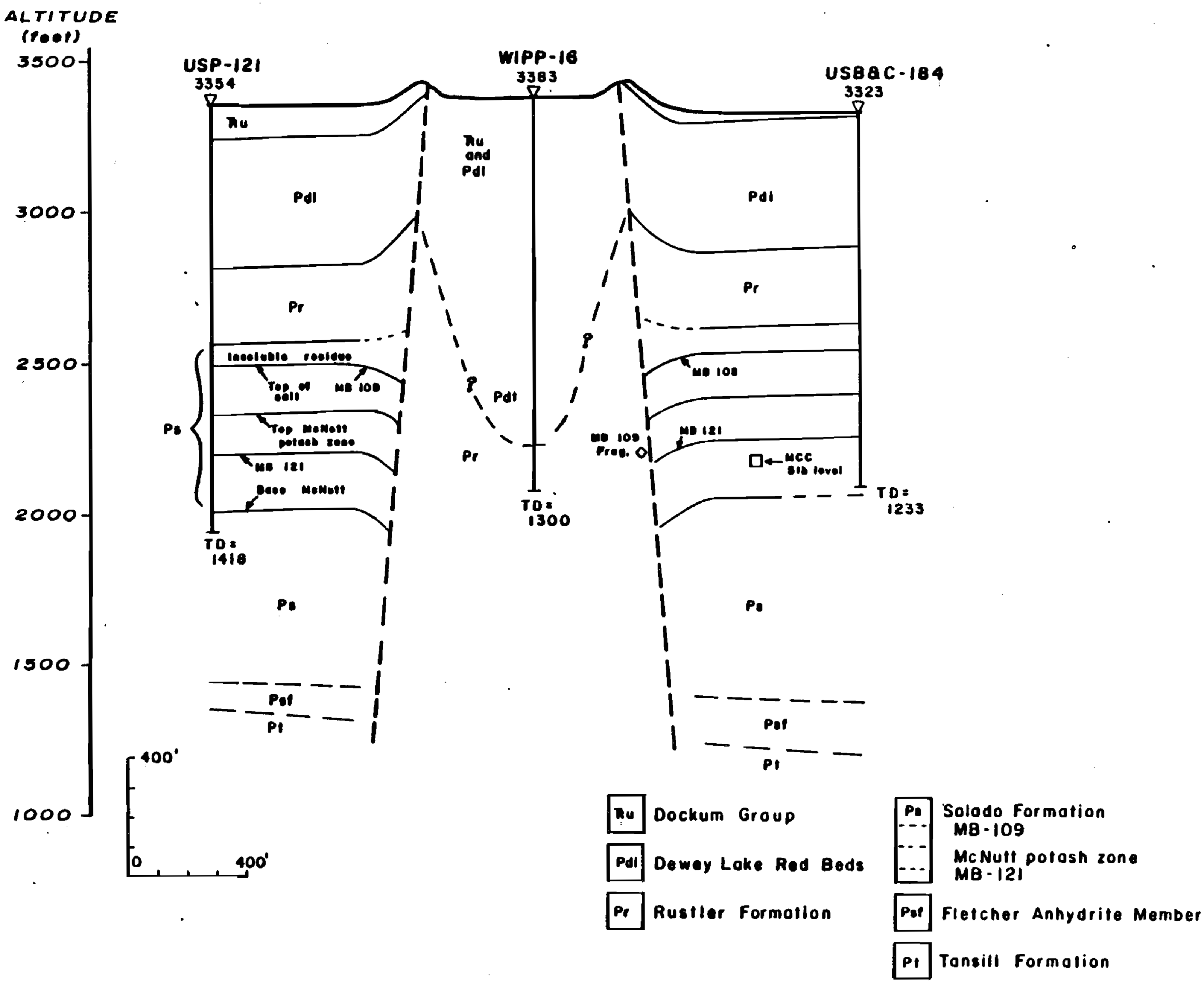

Figure 15.--Cross section through Hill C breccia pipe.

hydrogen sulfide. Between depths of 362 and 367 m (1188 and 1204 ft), hydrogen sulfide was detected; the readings indicated as much as 6 parts per million between 365 and 366 m (1198 and 1200 ft). No other gases were detected in the drill hole.

In WIPP 16, all of the breccia above the Rustler Formation is composed of Triassic Dockum Group and Permian Dewey Lake Red Beds. Some idea of the minimum thickness of these units at the time of collapse of the material into the pipe can be estimated. The present thickness of these two units in the pipe is about 350 m (1150 ft). These units without collapse are about 145 m (475 ft) thick in nearby drill holes. Using an approximate bulking factor of 1.25, averaged from those of Houser (1970) for alluvium and zeolitized bedded tuff at the Nevada Test Site, the expected thickness of the brecciated rock in the pipe would be about 181 m (595 ft). This is about half (181 versus 350 m; 595 versus 1150 ft) of what is present. Apparently there was another ±145 m (±475 ft) of Dockum Group rock overlying the present Dockum Group. Following this line of reasoning, the collapse may have occurred at a time when a more complete sequence was present. The core from WIPP 16 contained no voids, but rather a great deal of fine sediments, mostly clay and silt-size material. This filling would have been obtained from disintegrated fragments of collapse material, and this would lower the bulking factor to something less than 1.25 and thereby require an even thicker section of rock than the extra ±145 m (±475 ft) at the time of collapse.

This estimation technique cannot be used in WIPP 31 because the loss of halite in the Salado and Rustler Formations adds too many variables to the calculations. Unfortunately, there is no way of estimating the erosional rate of the Dockum Group rock, but it must have taken hundreds of thousands of years to remove most of the rock. The Dockum Group is about 220 m (720 ft) thick 26 km (16 mi) to the east of Hill C, and thicknesses of over 457 m (1500 ft) are found farther east.

During this stage of the collapse, a depression probably formed at the surface allowing surrounding Triassic surface material to be washed into the depression. This material, especially the smaller fragments of sandstone and siltstone, was carried downward to form the matrix of the brecciated material now found in the pipe.

Underground Exploration

In doing development work to open another area of the 7th ore zone in the MCC potash property for mining, entries were driven to the northwest from the main haulage entry (fig. 14). In the MCC mine, the 7th ore zone dips gently northeast. As the new entries were advanced northwestward and approached the breccia pipe, the ore zone began to dip down at a steeper angle than the mining machine could follow, so the machine mined progressively higher and higher beds (figs. 16 and 17) until the edge of the pipe was reached (fig. 18). Mining exposed about 19 m (63 ft) of stratigraphic section above the 7th ore zone in a horizontal distance of 44 m (145 ft) (fig. 8). Mining was advanced about 5.5 m (18 ft) into the breccia pipe and a horizontal exploratory hole was drilled 10.7 m (35 ft) into the pipe and still encountered breccia. The hard polyhalite marker beds above the 7th ore zone

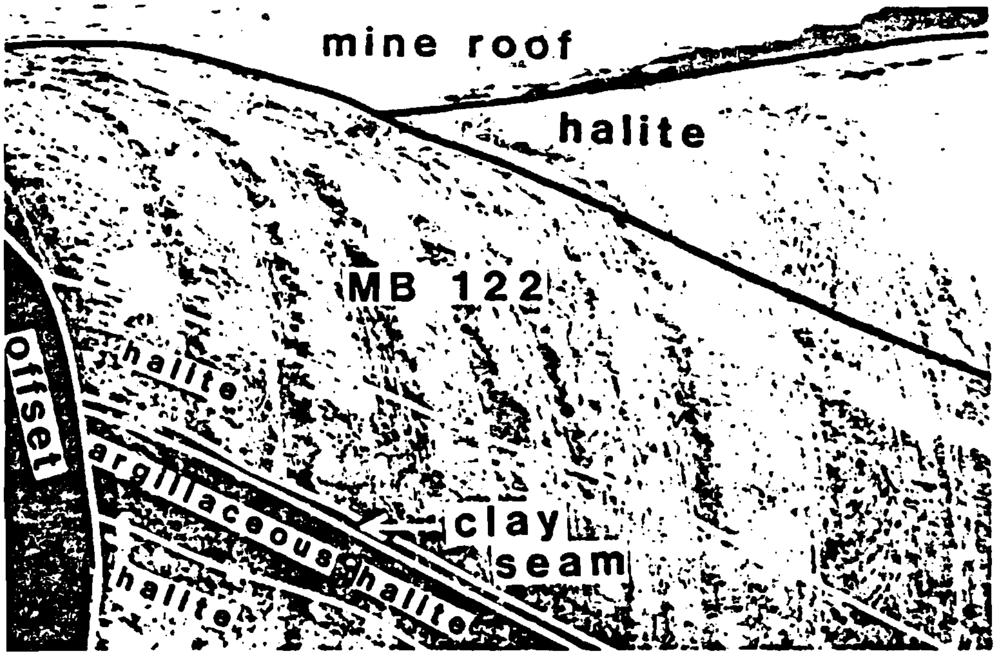

Figure 16.--Left rib of 16-L drift, breccia pipe to right of photo. Back of drift shows at top of picture. The light bands dipping about 23° to the right are the anhydrites of MB 122. The dark band at the lower right (NW) is a very argillaceous halite capped by a 0.3-m- (1-ft-) thick clay seam. Dark left edge of picture is an offset room 23 m (75 ft) from pipe edge. Arcuate striations on all pictures are caused by mining equipment.

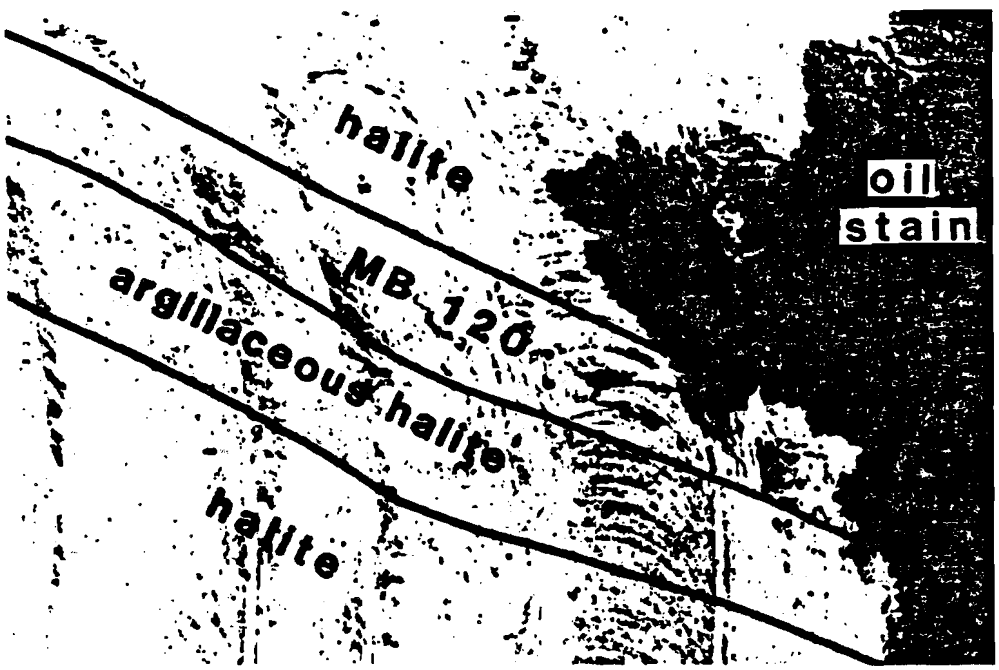

Figure 17.--Left rib of 16-L drift as in figure 16. Base of MB 120 is slightly below the center of photo, top of MB 120 is near upper left corner. Dark portion of picture to right is oil stain. Pipe about 5 m (16 ft) to right.

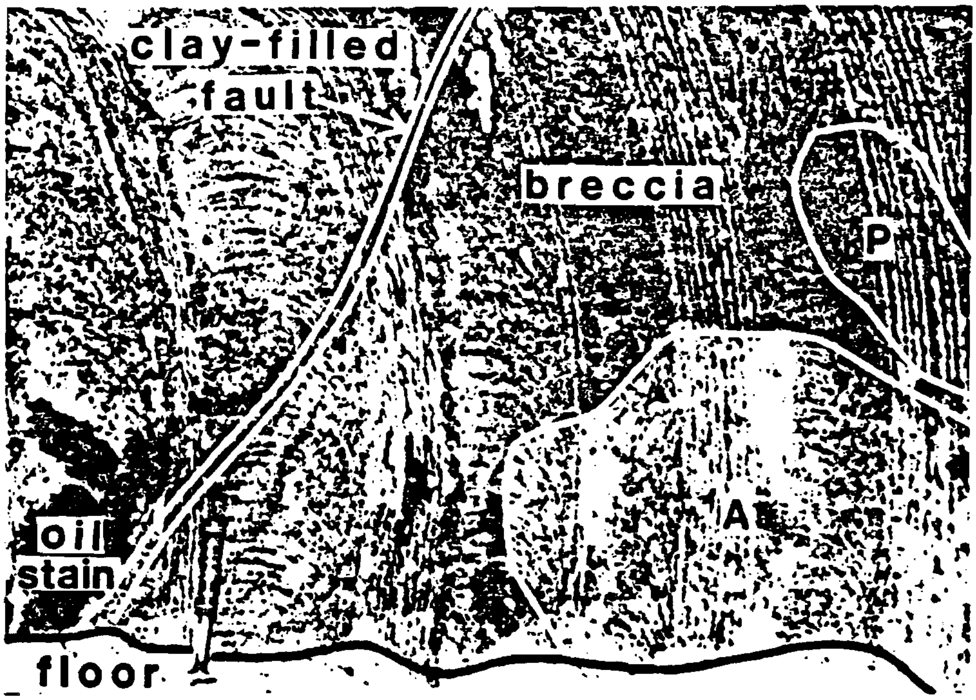

Figure 18.--Left rib 16-L drift. Pick leaning on breccia pipe material. Boundary of inplace halite and breccia of pipe is line that starts at base of oil stain in lower left corner, passes just above hammer handle and reaches top of photo near center. The line is a clay-filled (not gouge) fault zone. The fragments of anhydrite, polyhalite, and halite to the right of the fault show as various shades of gray. P=polyhalite, A=anhydrite.

(Nos. 120, 121, and 122) and the blocks of anhydrite and polyhalite (figs. 19 and 20) in the breccia caused so much difficulty for the mining machinery that mining in that direction was discontinued.

Developmental mining was continued by driving the entry to the northeast for 183 m (600 ft) and then proceeding northwest again in order to bypass the breccia pipe. Here again the ore zone was found to dip more abruptly and steeply than the machine could follow. In this case the beds also dipped down toward the pipe, but the pipe now lay to the southwest of the newly mined entry. The ore zone disappeared beneath the floor for a distance of about 76 m (250 ft) and the drift exposed about 3 m (10 ft) of the stratigraphic section above the ore zone (fig. 21). To the northwest along the new entry, the ore zone rises to its normal altitude again and the regional dip resumes. This perturbation of the regional dip is also shown by the structure contours in figure 22. It is assumed that the dip of the beds in the bypass drift, which is very abrupt, is in response to collapse of material into the pipe which lies to the southwest of that entry. No faulting is seen in this entry or in a small diameter core hole that SNL drilled horizontally towards the pipe for 19.5 m (64 ft).

Permission was granted by the MCC for USGS personnel to do underground mapping and for SNL personnel to perform several experiments in the vicinity of the pipe in order to determine the shape and dimensions of the pipe. Two underground radar studies were done by personnel of SNL and by Dr. Robert R. Unterberger of Texas A&M (Unterberger, 1981). The purpose of these field studies was to attempt to outline a portion of the breccia pipe wall by recording return signals from the radar. The radar experiments were not successful in delineating the breccia-pipe boundary. Geologic mapping of the mine entries in the vicinity of the breccia pipe was done in February 1980 by preparing profiles of the ribs (walls) to show as much stratigraphic and structural detail as possible (fig. 23). The mapping was supplemented in several places by augering upward through the back (roof) to probe for certain marker beds. The auger and crew were furnished by the MCC.

Mapping showed that not only had the strata of the Salado Formation on the south side of the pipe been bent downward by the collapse but also the beds are displaced downward toward the pipe about 5 m (17 ft) by a nearly vertical peripheral fault 43 m (140 ft) from the pipe (fig. 24). This faulting and the downbowing of the beds suggest that the underlying chamber into which the rocks collapsed may have been larger in diameter than the present diameter of the pipe at the surface.

Oil seeps were encountered in the mine (fig. 23) near the breccia pipe in drifts 15-L and 16-L. Most of this oil was seeping from the fault 43 m (140 ft) from the pipe and moving along bedding planes, especially where polyhalite and anhydrite beds intersected the fault. Analysis of this oil and that from the horizontal drill holes is reported by Palacas and others (1982).

Horizontal Coring Underground

Using a portable drilling assembly designed and built by SNL personnel, three horizontal core holes were bored from mine level toward the breccia pipe (fig. 25). The plan was to intersect the pipe at the three localities. The

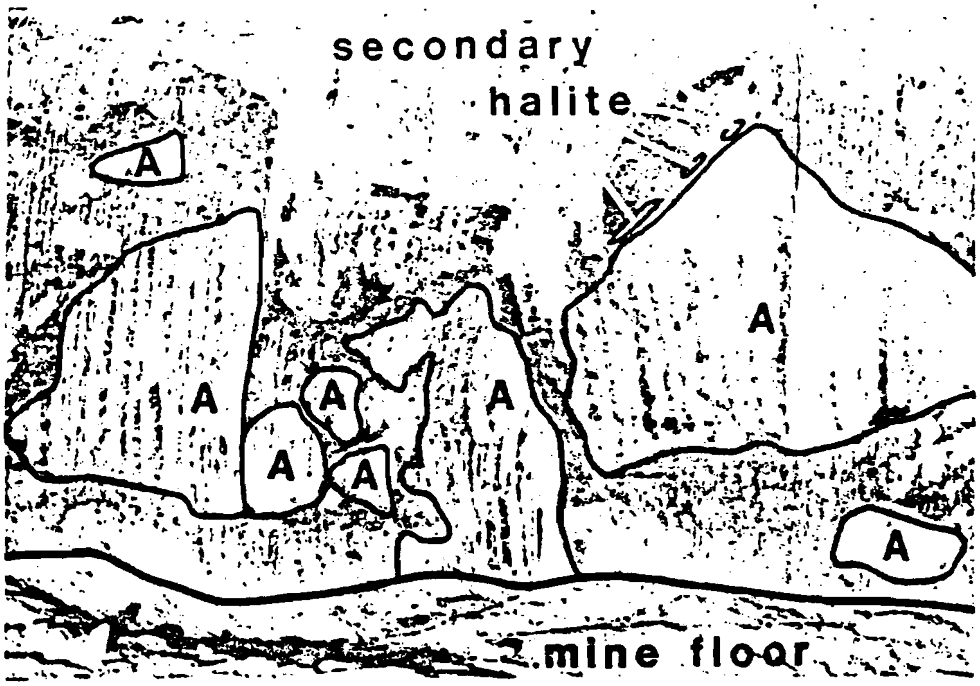

Figure 19.--Left side of exposed breccia pipe at end of 16-L drift showing numerous anhydrite blocks and matrix of clay and halite and anhydrite fragments. A=anhydrite.

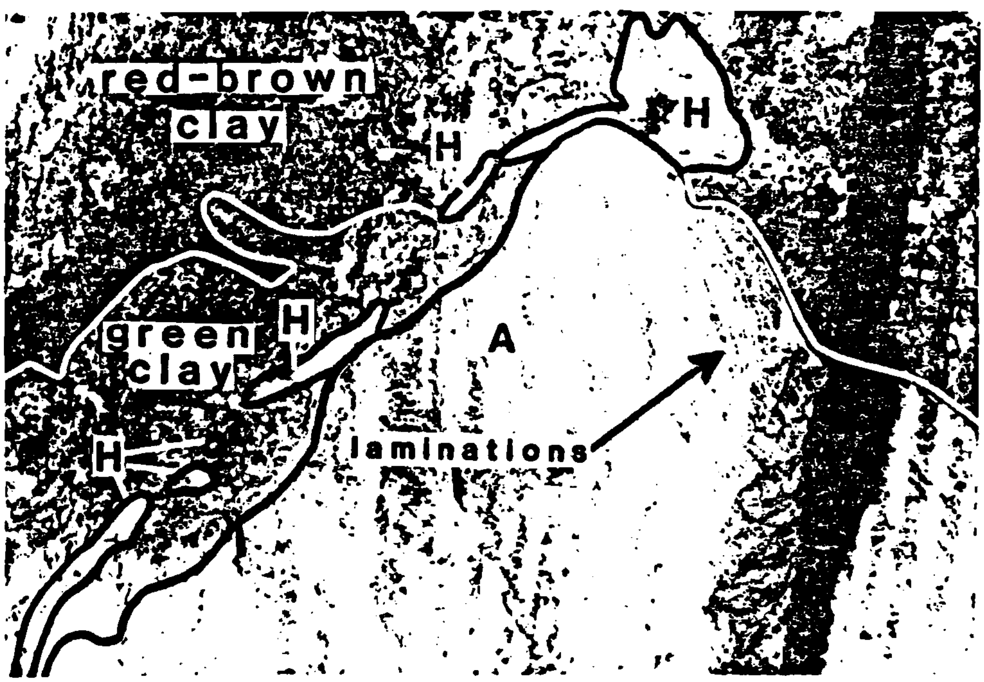

Figure 20.--Enlargement of upper right portion of figure 19. Light streaks along left side of anhydrite block are secondary halite seam cutting through greenish clay. Above greenish clay in upper left is reddish-brown clay. Laminations apparent on upper right side of anhydrite. Dark streak on right is shadow. A=anhydrite, H=halite.

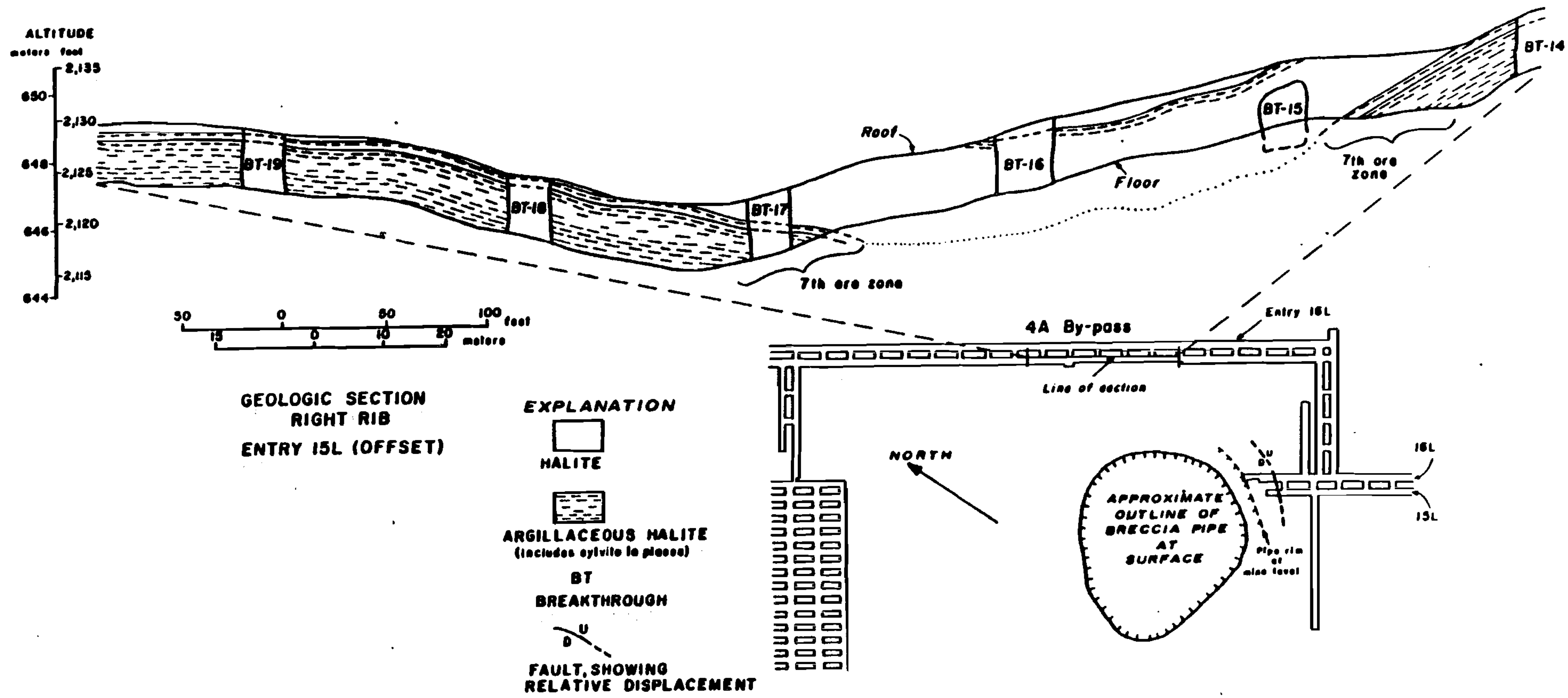

Figure 21.--Structural depression of salt beds by subsidence near northeast flank of Hill C breccia pipe, panel 4A, 5th level, MCC mine.

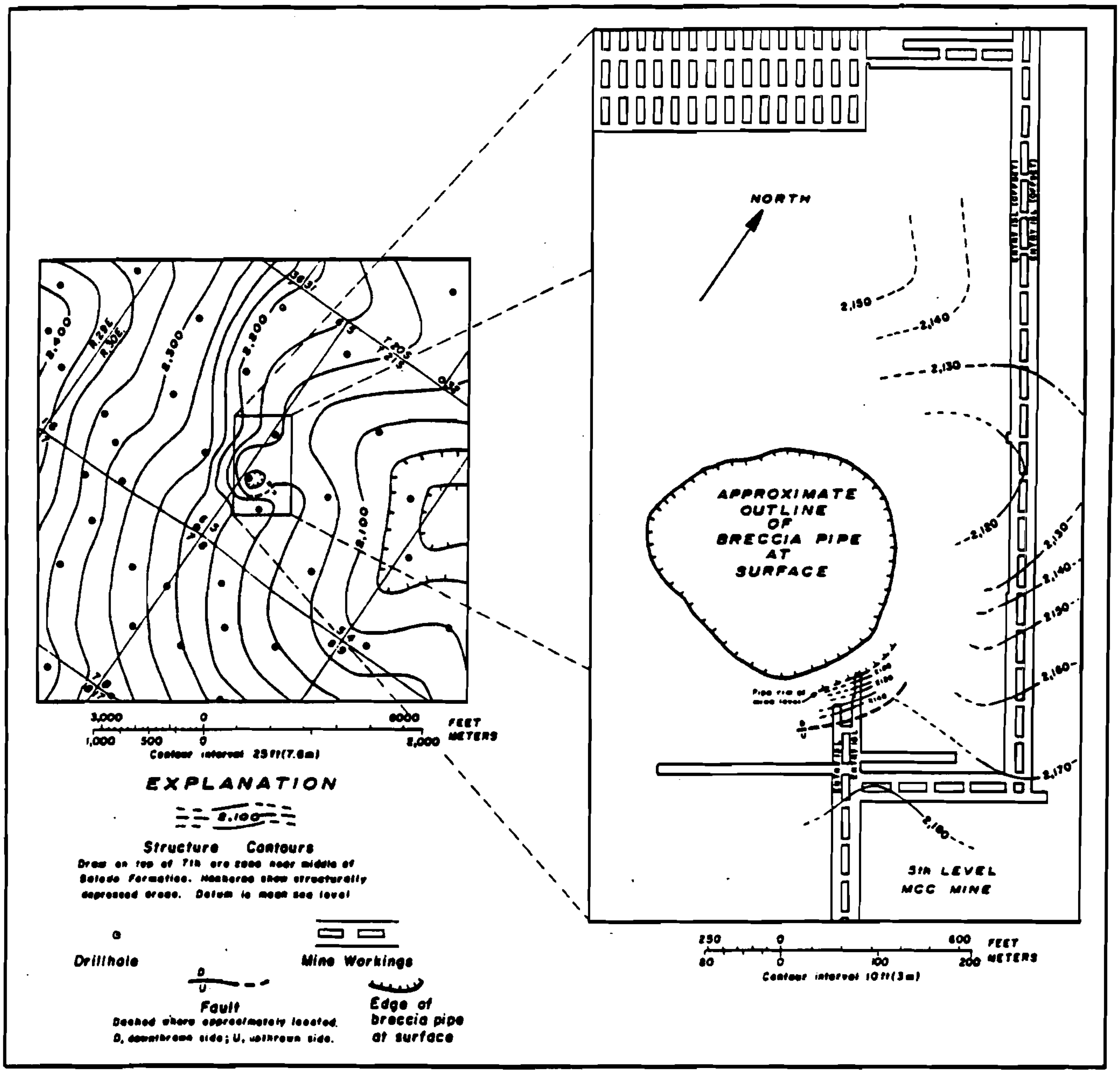

Figure 22.--Structure of salt beds (top of 7th ore zone) in vicinity of Hill C breccia pipe.

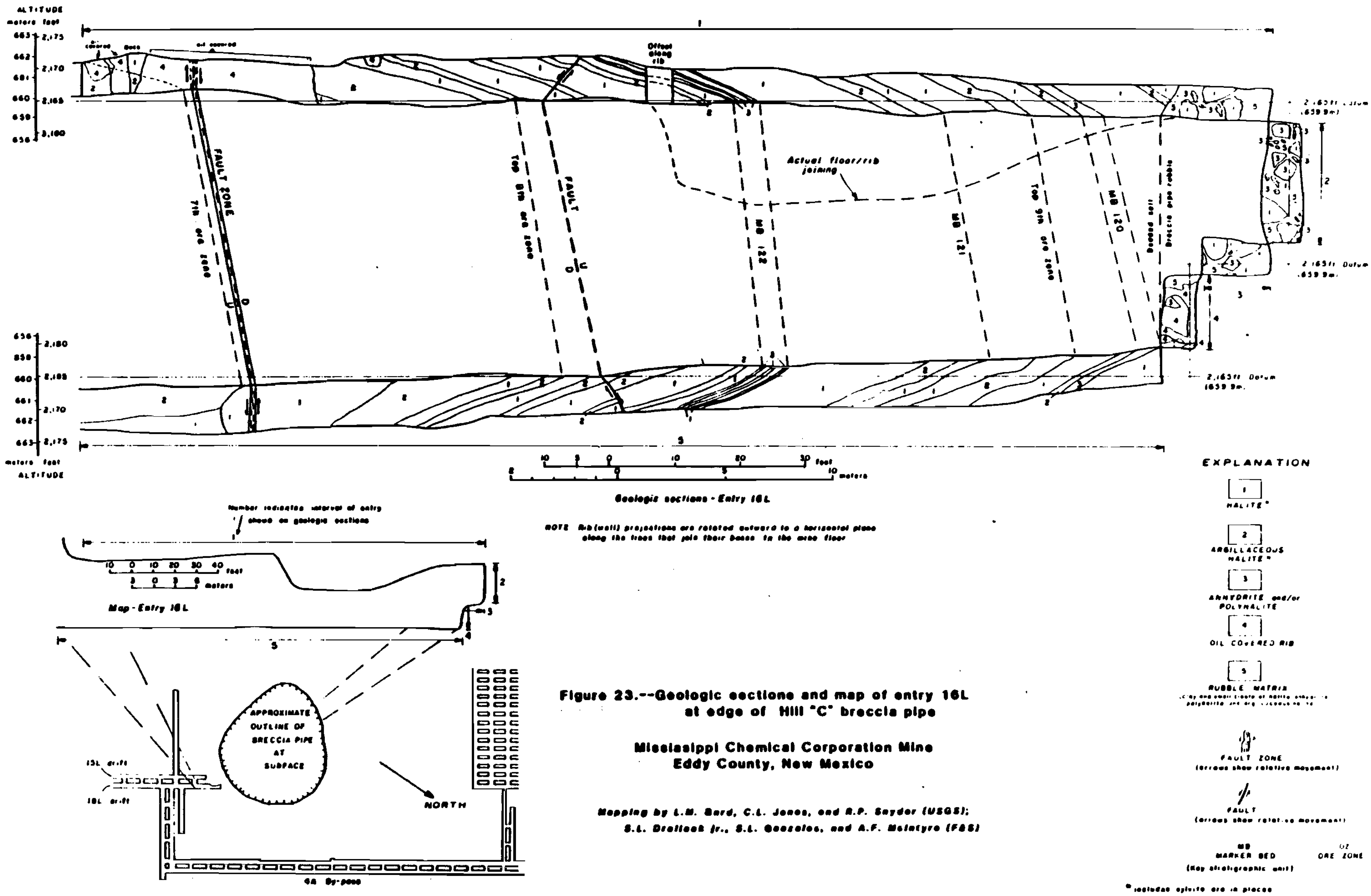

Figure 23.--Geologic sections and map of entry 16L at edge of Hill "C" breccia pipe

Mississippi Chemical Corporation Mine
Eddy County, New Mexico

Mapping by L.M. Bard, C.L. Jones, and R.P. Snyder (USGS); S.L. Drellack Jr., S.L. Gonzales, and A.F. McIntyre (F&S)

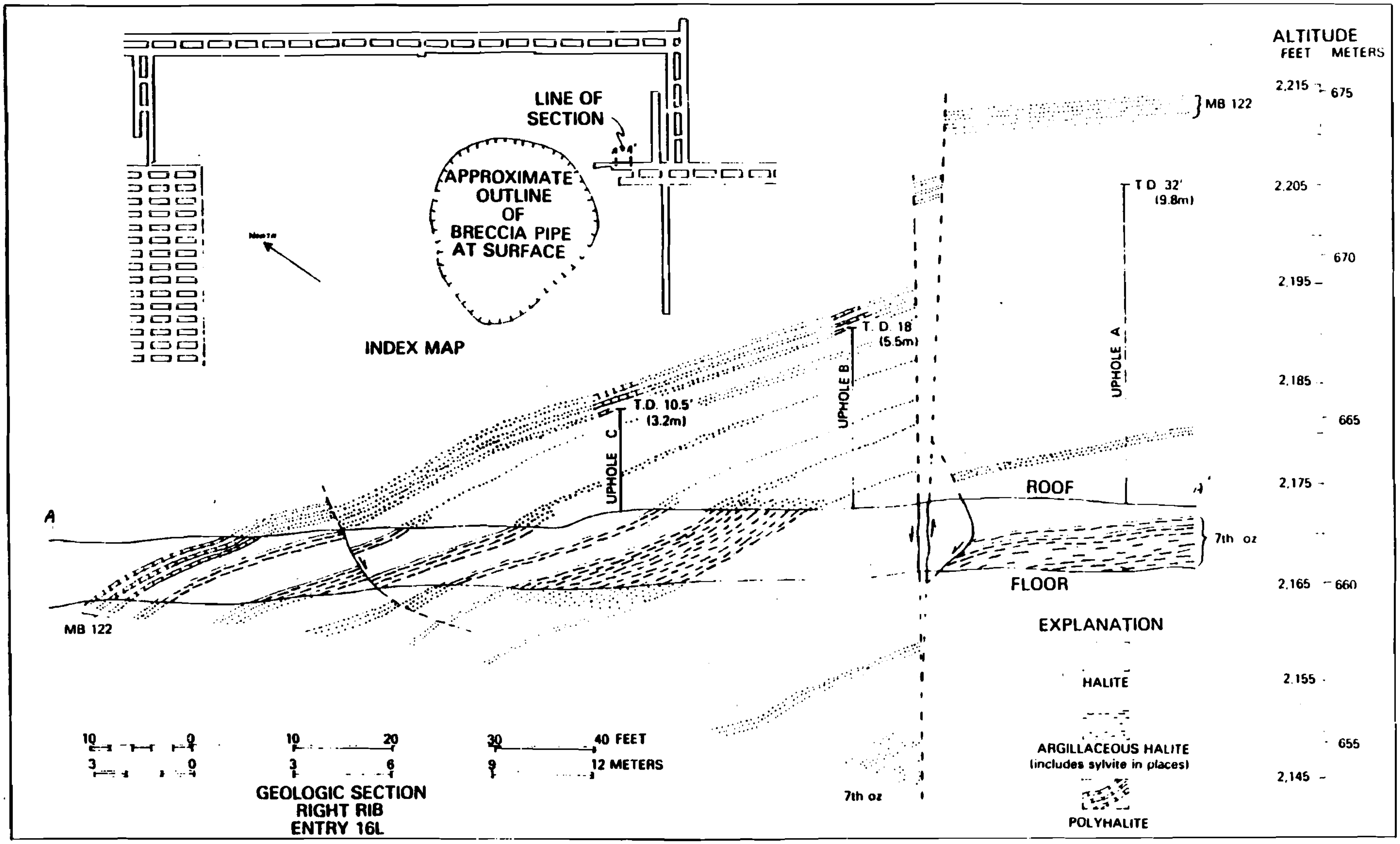

Figure 24.--Displacement of salt beds by faults near southeast flank of Hill C breccia pipe in mine workings, Panel 4A, 5th level, MCC mine.

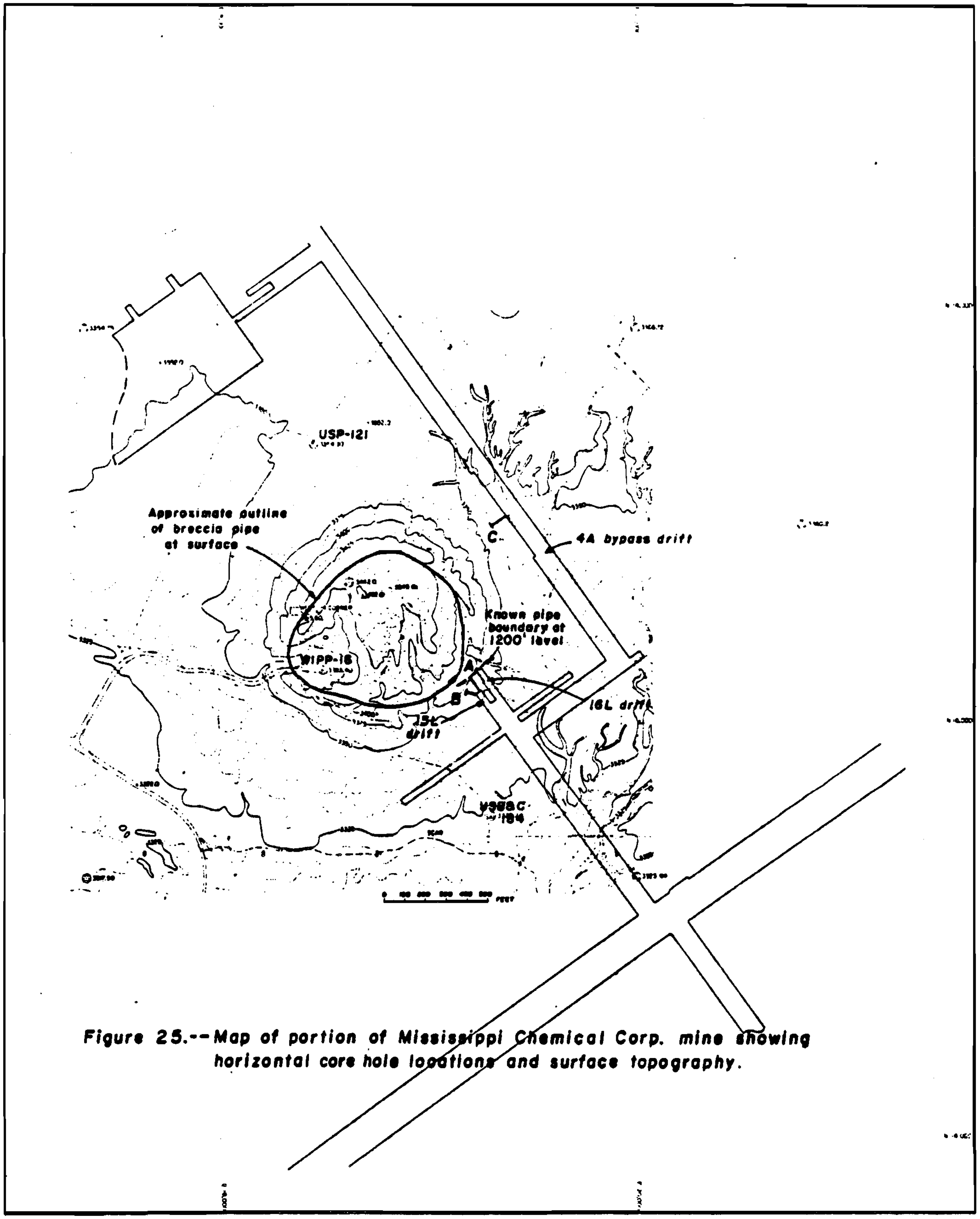

Figure 25.--Map of portion of Mississippi Chemical Corp. mine showing horizontal core hole locations and surface topography.

holes were cored in alphabetical order (A, B, C); the core was 2.5 cm (1 in.) in diameter. Hole A penetrated the pipe boundary. Figure 26 shows about 1.8 m (6 ft) of core at the "bottom" of drill hole A. The discing of the core was caused by torque and direct pressure on the bit face and the discs varied from about 3 mm to 10 cm (1/8 to 4 in.) in length. Argillaceous halite and anhydrite layers made up the longest lengths.

In the next to the bottom row of core in figure 26, just in from the left side is the clay seam contact 24.7 m (80.9 ft) between the normal stratigraphy and the breccia pipe. In the bottom row of core, the shades of gray are fragments of halite and anhydrite in a brown clay matrix. The black disc in the second row left is an oil-stained halite. Figure 27 is a geologic cross section of the hole.

Hole B (fig. 25) was cored to a length of 18.3 m (60.1 ft). The core in the first four rows in figure 28 was shattered during drilling, less pressure was applied to the bit during coring of the rock in the last two rows. Oil stained the lower 0.4 m (1.4 ft). The oil caused a lack of circulation of the air cooling the bit and hindered removal of the cuttings below 17 m (56 ft) and the bottom 1.2 m (4.1 ft) of core was lost. The pipe boundary was not reached. Oil from this hole was described in Palacas and others, 1982. Figure 29 is a geologic cross section of the hole.

Hole C (fig. 25) was drilled slightly up from horizontal to a length of 19.6 m (64.15 ft). No recognizable lithologic units were penetrated. Clay was penetrated in the last 0.6 m (2 ft) of the hole and the bit and pipe were jammed in place. A total of 14.6 m (48 ft) of drill pipe was recovered, leaving 7.3 m (24 ft) in the hole. It is not certain whether or not this clay represents the pipe boundary; the SNL drillers believe that the rock being cored just before the pipe became stuck was drilling like halite and not like the breccia material in drill hole A. The pipe boundary was predicted several tens of feet beyond the end of drilling. Figure 30 is the geologic cross section of hole C.

The question of whether or not the walls of the breccia pipe are vertical or the pipe is a cylindrical-shaped body cannot be fully answered with the available data. Superimposing the surface trace of the pipe with the one area underground shows that the underground boundary of the pipe is about 30 m (100 ft) further to the southeast than the corresponding part of the pipe at the surface. This could indicate that either the pipe does increase in diameter with depth or if it is a cylinder, then the cylinder is not in a vertical orientation.

In studies done by Piper and Stead (1965, p. 34), it was found that most collapse structures over underground nuclear tests are roughly cylindrical. In additional studies on the same subject, Houser (1970) used a cylindrical shape in his interpretations, although he states (p. 51) that while evidence points to the cylindrical shape in some cases, other cases indicate an inverted cone (opening downward).

Landes and Piper (1972) in studies of brine cavity subsidence in Michigan, state that surface features outside the collapse area do not extend

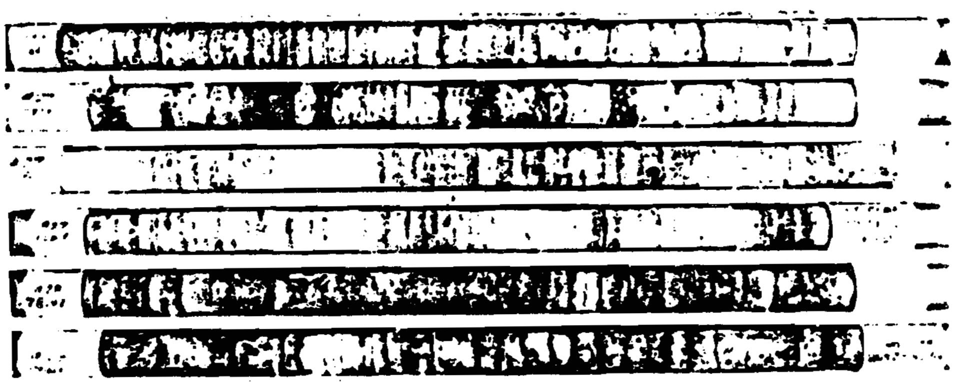

Figure 26.--Bottom core from drill hole A, MCC mine horizontal hole. Nearly all of the bottom two rows of core are breccia pipe material (core measures 1 in. in diameter).

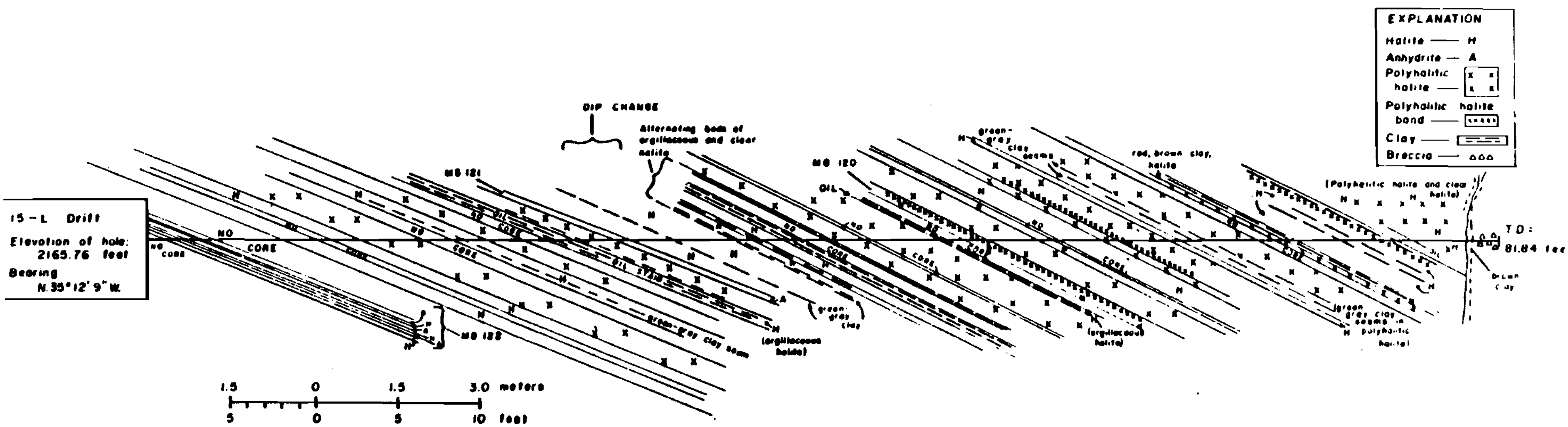

Figure 27. —— Cross-section, drill hole A, Mississippi Chemical Corp Mine breccia study

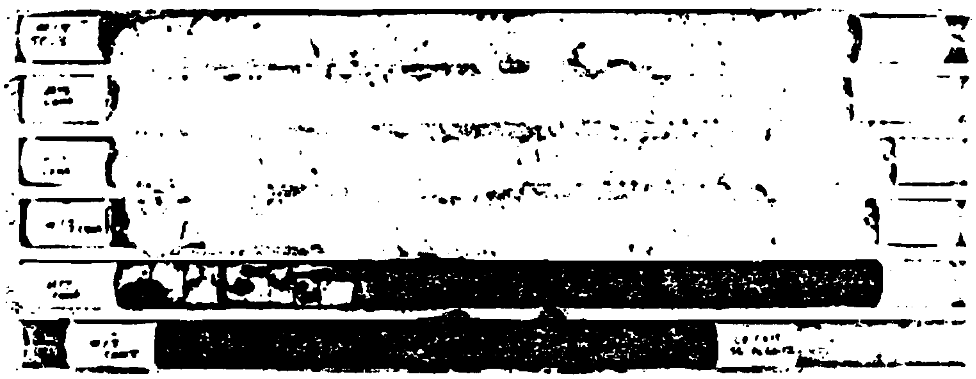

Figure 28.--Bottom hole core from drill hole B, MCC mine horizontal hole. The upper four rows are nearly pure halite crushed during coring, the lower two rows are oil-saturated argillaceous halite (core measures 1 in. in diameter).

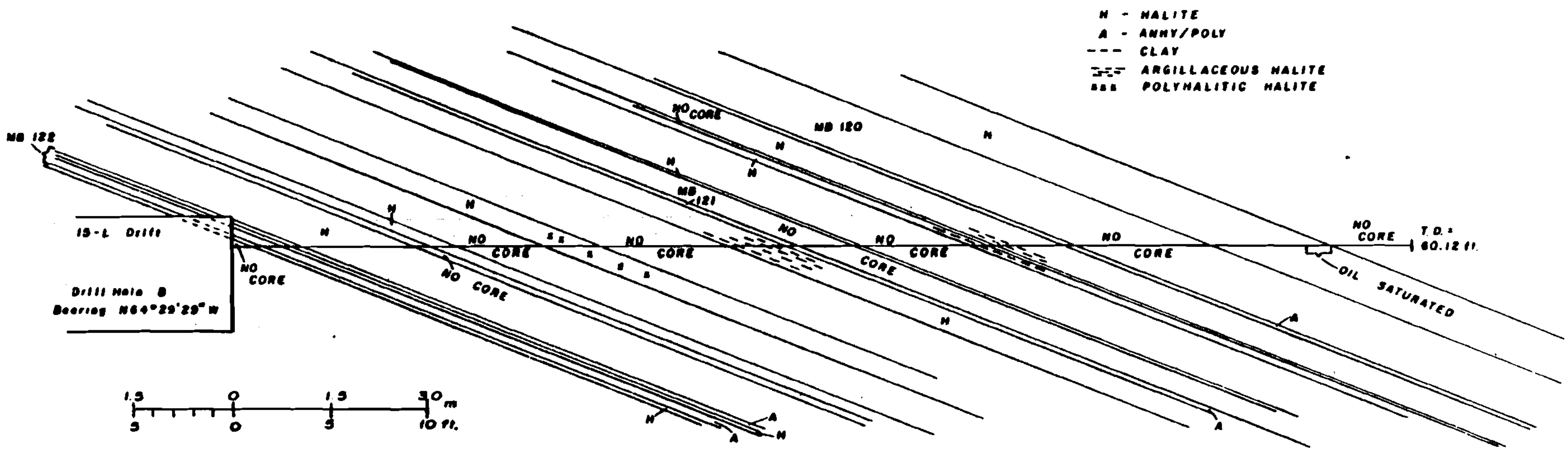

Fig. 29--Cross-section, drill hole B, showing lithology and structure

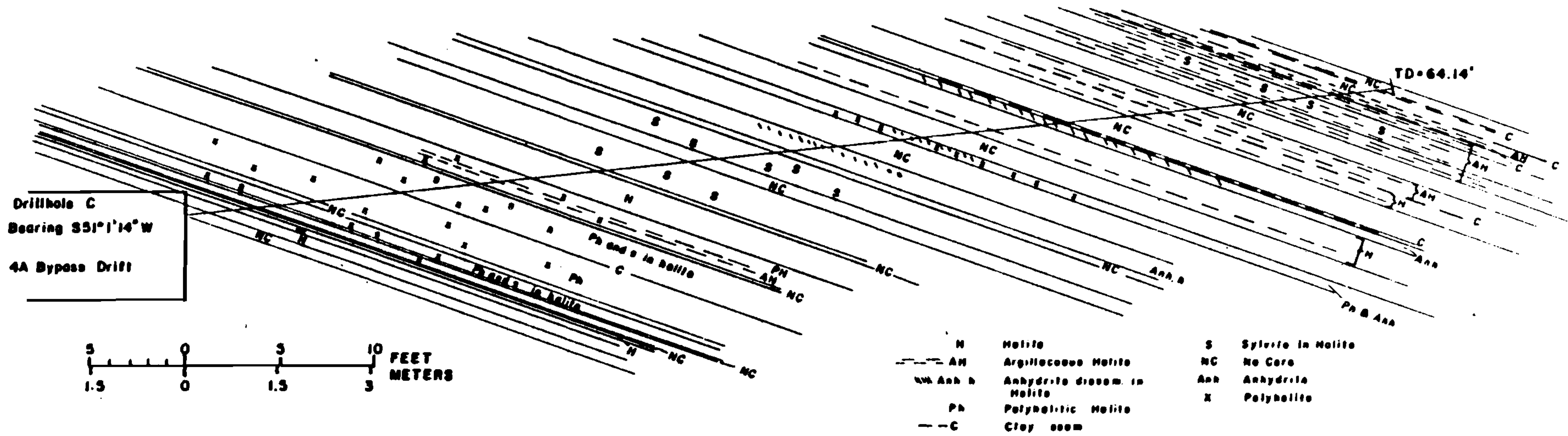

Figure 30.--Cross-section, drill hole C showing lithology and structure

outward farther than the underground solution cavity. This implies that the possible shape of the collapse structure is an inverted cone or a nearly vertical cylinder.

Eck and Redfield (1963) in their study on the Sanford Dam near Borger, Tex., report numerous filled chimneys having irregular vertical sides (p. 56). The upper portions of these chimneys have funnel shapes.

The general shapes of the breccia pipes at Hills A and C are believed to be near-vertical cylinders, possibly widening slightly with depth.

OTHER SUSPECTED PIPES IN DELAWARE BASIN

Wills-Weaver Pipe

In the earlier discussion of geophysical studies carried out in the basin for the WIPP site, the Wills-Weaver area was mentioned. A hole was drilled in sec. 12, T. 20 S., R. 29 E. and penetrated 250.2 m (821 ft) of brecciated rock. Interpretation of geophysical surveys, namely electrical resistivity (Elliot, 1976a) and gravity surveys (Elliot, 1976b), were run across the area and both gave anomalous readings across the suspected pipe. No other work has been done at this site. It is believed to be a breccia pipe. The hill over the pipe has not been breached by erosion and no near-surface structure can be seen.

Hill B

Hill B lies immediately south of Hill A (fig. 9) and rises 28 m (93 ft) above the surrounding terrain. It is round in plan, dome shaped and caliche capped. The hill is only slightly eroded on the west and south sides where some brecciated Triassic rocks (Bachman, 1980) are exposed, but no ring fault has been seen.

Electrical resistivity (Elliot, 1976a) and gravity (Elliot, 1976b) surveys give anomalous readings across the hill much like at Hill A. No drilling was done on Hill B, but the data of Bachman and Elliot strongly suggest that this hill marks the location of a breccia pipe.

WIPP 13 Area

An electrical resistivity survey (Elliot, 1977) across an area about 2.4 km (1 1/2 mi) north-northwest of the center of the WIPP site indicated a possible breccia pipe area. The resistivity signature across this area appeared much like those signatures across Hills A and C. In 1978, interpretation of a gravity survey across the area indicated a gravity low centered on the WIPP 13 site (L. J. Barrows, SNL, oral commun., 1981). There is no topographic expression, of either a hill or a depression; but because of the closeness of this area to the actual repository location, further exploration was needed. Drill hole WIPP 13 is located near the center of the resistivity anomaly. Core and cuttings, along with downhole geophysical logs indicate that no buried structural anomalies exist at the WIPP 13 location (Gonzales and Jones, 1979) to account for the resistivity anomaly. The probable cause for the anomaly is an increase of sandy, more porous material in the Dewey Lake Red Beds containing more water than is found in the surrounding area. WIPP 13 was later deepened from its original depth of 311.2 m (1021 ft) to about 1279.0 m (3868 ft) to study the structure in the Castile Formation.

WIPP 32 and WIPP 33

About 17.6 km (11 mi) west-southwest of the center of the WIPP site is a small topographic high which was described by Vine (1963) as an elongated domal structure. Rocks of the Rustler Formation are exposed at the surface. Drill hole WIPP 32 was located on this structure. Most of the soluble rocks of the Rustler, as well as the halites in the upper 34.7 m (114 ft) of the Salado Formation, have been removed by ground water. Below the Vaca Triste Sandstone Member in the Salado, a normal undissolved section was penetrated (Snyder and McIntyre, 1980). Bachman (1980) states that the brecciated Rustler and Salado rock in drill hole WIPP 32 is the result of blanket dissolution in the area, and the fact that the feature is not related to deep dissolution below the Salado precludes it from being a breccia pipe. The feature is called a karst mound by Bachman (1980, p. 78), and is primarily an erosional feature.

A small closed depression about 4.8 km (3 mi) northwest of the center of the WIPP site was found to contain an unusually thick amount of fill material (G. O. Bachman, oral commun., 1980). The sink might be the surface expression of a breccia pipe. WIPP 33 was drilled and cored in the depression to a depth of 256.0 m (840 ft). Below the thick fill (13.4 m or 44 ft), including artificial fill for drill pad, a normal stratigraphic section was found (Snyder and McIntyre, 1981). Dissolution residues in the Rustler Formation and the upper 0.3 m (1 ft) of the underlying Salado Formation were expected as the drill hole is located just east of Nash Draw and in the area where this dissolution has been found in other drill holes (Bachman, 1980). No breccia associated with pipe structures was found in WIPP 33.

PIPELIKE FEATURES IN OTHER AREAS

Pipelike structures have been studied and mapped in a number of places in the world. All of these structures are in areas that have evaporites in the subsurface.

South Dakota and Wyoming

In South Dakota and Wyoming, studies of the Minnelusa Formation by Bowles and Braddock (1963) show that the Minnelusa (Permian-Pennsylvanian), composed of limestones and gypsum has undergone dissolution and brecciation. The overlying rocks, as much as 305 m (1000 ft) thick, have been affected and blocks of the Minnelusa Formation have dropped as much as 45.7 m (150 ft). The unit underlying the Minnelusa is a sandstone that has undergone only minor boxwork weathering. Blocks of the overlying Opeche (Permian) and Spearfish (Permian-Triassic) siltstones are found incorporated in the breccia.

Solution that formed these pipes started in Tertiary time, proceeding downdip from surface exposures. Some pipes started development in Holocene time and are 73 m (240 ft) deep and 18 m (60 ft) in diameter. Analysis of water samples from springs and wells indicates that dissolution is continuing at the present time.

In a report by Brobst and Epstein (1963, p. 331), pipes "tens to hundreds of feet in diameter" and 61 m (200 ft) deep were mapped in the Fanny Peak quadrangle of Wyoming and South Dakota. The authors attribute the pipe formation to the solution of anhydrite and gypsum in the Minnelusa Formation. Fragments of overlying Permian rocks are incorporated in the breccia in the pipes. The formation of these pipes started after the Black Hills uplift (Late Cretaceous-Early Triassic), and the dissolution is continuing to the present.

In the Wyoming-South Dakota area, the anhydrite-gypsum layers of the Minnelusa and overlying Opeche and Spearfish Formations are the rocks involved in the dissolution. Halite also was and is being dissolved from the formations as indicated by analysis of well water in the area. Brobst and Epstein (1963, p. 336) attribute the near-vertical orientation of the pipes to their formation at intersections of joints. They also postulated that most of the pipes have their roots in the Minnelusa, although some may be rooted in the underlying Pahasapa. The breccia in the pipes has been well-cemented by $CaCO_3$, and the pipes stand out on cliff faces and as small hills above the surrounding terrain.

Michigan

Michigan also contains breccia pipes. Landes and others (1945) describe the occurrence and possible formative history of these pipes in the Mackinac Straits area. They attribute formation of the pipes to cavity forming in the evaporite-rich Pointe aux Chenes Formation (usage of the Michigan Geological Survey) of Silurian age. In the subsurface the formation is called the Salina. No brecciated rocks have been found in the underlying Niagara Formation, and Landes and others put the base of the pipes in the Pointe aux Chenes.

Several previous explanations for the forming of the breccias are given in the Landes report. He and the other authors favor a solution to-cavity to-collapse of overlying rocks theory. Whether or not the collapse was catastrophic and occurred as a single event is unknown. Landes believes that some of the process involved catastrophic collapse, because brecciated rocks of much younger age are found in the breccia mass. Downward displacements of from 183 to 457 m (600 to 1500 ft) are recognized in a quarry at Calcite, Mich. (Landes and others, 1945, p. 129). Landes and others (p. 134) described these breccias as a conglomeration of rock fragments of every degree in size with interstices between the larger fragments filled with smaller fragments which range downward from a few inches to dust size.

Where calcium carbonate was available in the water moving through the brecciated rocks, they are firmly cemented by calcite. Other pipes have little cement if their matrix contains shale which filled the interstices between the limestone blocks and impeded the flow of ground water.

The age of the brecciation has been estimated by Landes and others (1945, p. 136-137). The youngest rock found in the breccia masses is the Detroit River Formation of Devonian age. These rocks must have solidified prior to collapse or they would not form discrete blocks in the breccia. At a quarry in Calcite, Mich., the flat-bedded Dundee Limestone (Devonian) can be seen overlying the brecciated Detroit River Formation. Collapse and brecciation must have been completed before the Dundee was deposited. Collapse could have begun in the formations below the Detroit River Formation prior to the deposition or induration of this formation, but there is no evidence for this. The dissolution of rocks in the Pointe aux Chenes Formation appears to be limited to the outer boundary of the Michigan Basin where the formation is near the surface. There may be some continuing dissolution now, but the majority of the formation not dissolved now lies below the level at which major dissolution occurs.

Canada

Underground exploration in Saskatchewan, Canada, for potash resources has added greatly to the study of dissolution of evaporites. Much of the research has covered large-scale (megabrecciation) dissolution in the Prairie Evaporites (Devonian), but local collapse and brecciation have been documented (Gorrell and Alderman, 1962; DeMille and others, 1964; Christiansen, 1971).

Crater Lake in southeastern Saskatchewan is described by Christiansen (1971) as a breccia chimney or pipe. The structure consists of two concentric fault-bounded cylindrical collapses; the inner cylinder about 30 m (100 ft) in diameter and the outer cylinder about 213 m (700 ft) in diameter. The collapse of the inner cylinder occurred before late Pleistocene and the outer about 13,600 years ago. Total vertical collapse for the two cylinders is about 58-73 m (190-240 ft) (Christiansen, 1971, p. 1511-12).

Figure 31 is a diagram by Gorrell and Alderman (1962, p. 307) that can, with modification, explain the anomalous structure of the breccia pipe at Hill C in New Mexico (fig. 32), where beds in the subsurface dip toward the pipe and those at the surface dip away from the pipe. In comparing these two figures, the caliche in figure 32 could be substituted for the Jurassic in figure 31 to explain the outward dipping of the surficial rocks at Hills A and C.

Dissolution in the Venn area may be the result of the porous Winnipegosis reef acting as a channelway for freshwater to reach the overlying salt and cause local dissolution (Bishop, 1954, pl. 1 and fig. 4; Gorrell and Alderman, 1962, p. 311).

Germany

Numerous collapse structures in the Zechstein area of Germany have been described by Prinz (1973), Bernhard (1973), and Grimm and Lepper (1973), among others. The surface expressions of these structures are nearly always depressions. The collapsed rock at the surface, the Bundsandstein of Triassic age, overlies the halite of the Zechstein (Upper Permian). Grimm and Lepper (1973) cite examples of breccia-filled pipes in the Solling Arch in the Bundsandstein 750-950 m (2460-3117 ft) above the Zechstein salts. The diameter of these sinks ranges from 20 to 250 m (66-820 ft). There is no soluble material in the Bundsandstein, and the inference given by Grimm and Lepper is that the pipes go downward to the Zechstein.

Bernard (1973) describes an area 25 km (16 mi) northwest of Kassel, FRG having collapse sinks now filled with rocks of Keuper and Muschelkalk (Triassic) age. These sinks are in rocks of the Lower Muschelkalk (Middle Triassic) which overlie the Bundsandstein. He attributes the collapse to the

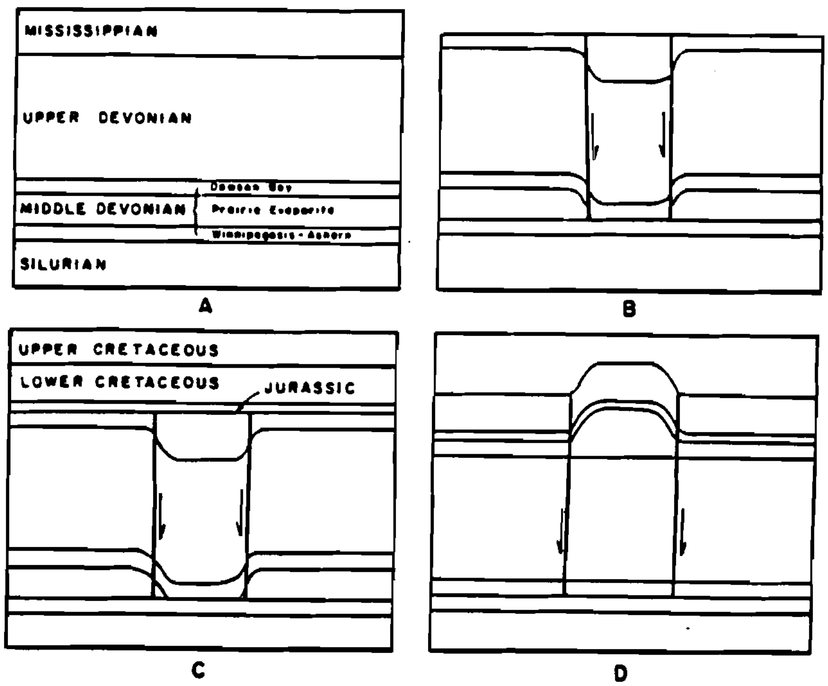

Figure 31.--Formation of anomalous Mississippian thicks and coincident structural highs in younger strata. (A) Post-Mississippian erosion; (B) Later stage during post-Mississippian peneplanation following removal of Prairie Evaporite salt section by solution; (C) Subsequent deposition of uniform thicknesses of Jurassic and Cretaceous beds on smooth Mississippian surface; (D) Final stage following solution of remaining Prairie Evaporite salt (modified from Gorrell and Alderman, 1962).

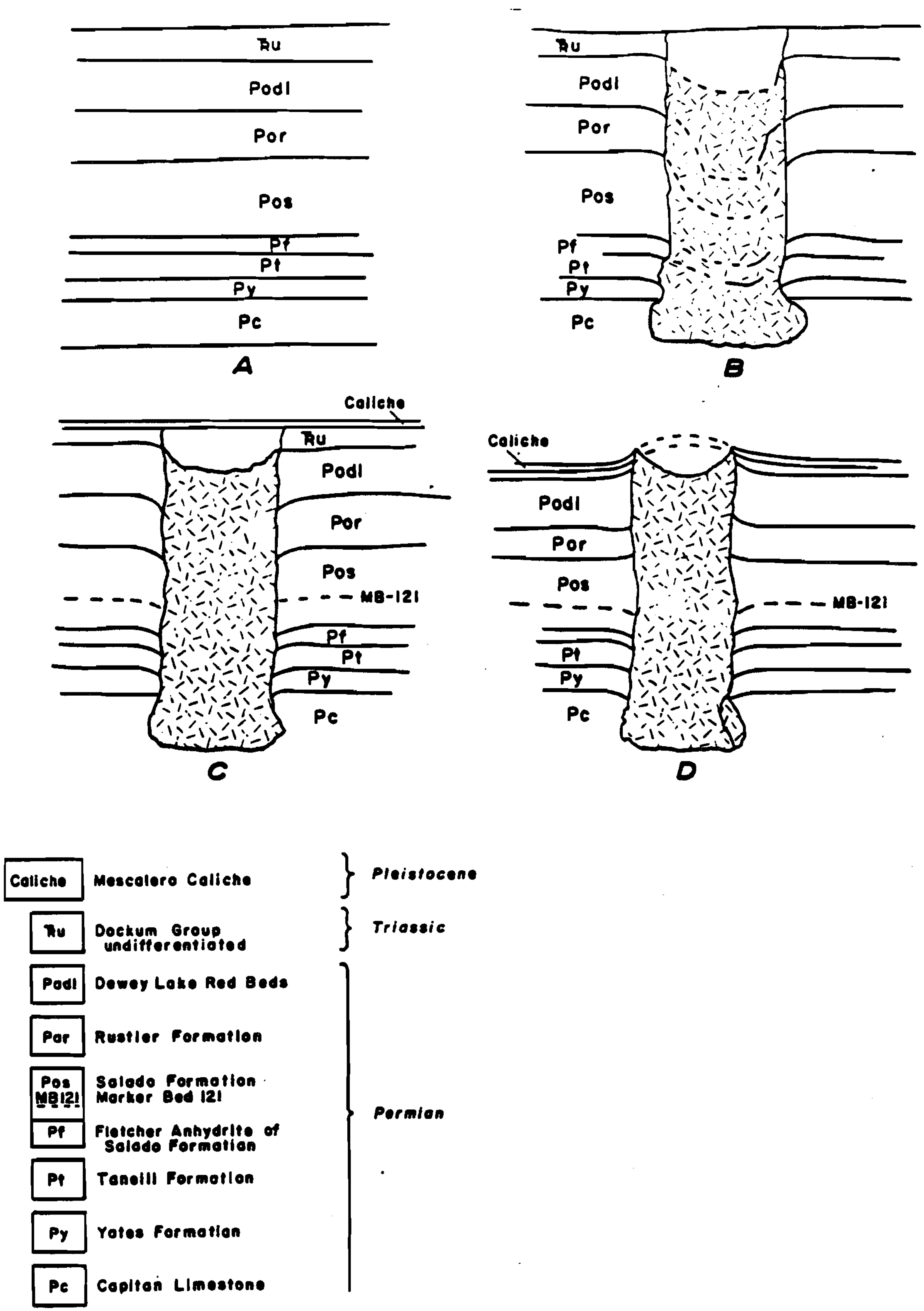

Figure 32.--Formation of breccia pipes in southeastern New Mexico illustrating how surficial beds dip outward and deeper beds dip inward toward pipe boundary. (A) Precollapse; (B) After cavity formed in Capitan Limestone, collapse of overlying beds dragged surrounding beds downward toward pipe; (C) Collapse complete, surface sink infilled by erosion of Dockum Group, caliche formed over surface; (D) Halite removed from Rustler Formation and upper Salado Formation by dissolution causing surficial rocks to dip outward.

dissolution of anhydrite and possible minor amounts of halite from the Röt facies of the Bundsandstein (possibly as much as 100 m or 328 ft of evaporite rocks). Bernard believes that the Zechstein at the locations of these pipes contains little halite; the edge of the Zechstein is in this area, and therefore could not be the root zone for the pipes. He does acknowledge the existence of Zechstein rooted sinks 25 km (16 mi) to the north of Kassel in the "Cloudburst" area of Tendelburg. Bernhard (1973) dates the formation of the pipes near Kassel as late Tertiary to early Quaternary on the basis of the sink-fill material containing Keuper rocks (Upper Triassic).

CONCLUSIONS

Method(s) of Formation of Breccia Pipes and Age of Formation of Known Pipes in Basin Near the WIPP Site

The understanding of the method(s) of formation of breccia pipes in the Delaware Basin is critical to the placement of a repository for radioactive waste at the WIPP site. The principal question is: Can a pipe develop under the repository and cause a breach in the system that will allow access of fluids to the waste canisters? A secondary question is: Could a nearby developing pipe adversely affect the repository? Investigations at and near the WIPP site have helped to define what a breccia pipe is and how a pipe develops, but not what governs its location--see below. Another question is: Can dissolution of beds affect the integrity of the repository?

Examples of pipes in Michigan show that at some stage in the development of those pipes there was catastrophic collapse. In the Mackinac Straits region of Michigan, breccia fragments have been identified 183-229 m (600-750 ft) below their normal stratigraphic horizon (Landes and others, 1945, p. 129). Limestone beds above the cavities where halite had been dissolved could have formed support beams which held until increasing widths of the cavities caused failure of the beams, at which time the material above the existing cavities could collapse rapidly, causing a jumbling of material in the collapse chimney.

Rock in core from WIPP 16 and WIPP 31, drilled into known or expected breccia pipes north of the WIPP site in southeastern New Mexico, also shows a great deal of intermingling of various strata. Dolomite fragments have been found 335 m (1100 ft) below their normal stratigraphic position in WIPP 31. Siltstone fragments in WIPP 16 are found 183 m (600 ft) below their expected level.

Depending upon the type of rock above the solution cavities, the downward movement of the overlying rocks can be catastrophic as in the above cases, or slowly as in many salt mines (actually as salt flowage). If the movement is slow or in the catastrophic cases if the drop is not far, the falling rocks will fracture but not be mixed and jumbled with surrounding lithologies.

The only known breccia pipes in the Delaware Basin in the vicinity of the WIPP site are located 19-32 km (12-20 mi) northwest of the center of the site. Two pipes, and probably a third, have surface expressions which are nearly circular, rounded and breached hills 15-30 m (50-100 ft) in elevation. These are Hills A, B, and C of Bachman (1980) (domes A, B, and C of Vine, 1960). Relief of a fourth pipe, the Wills-Weaver, is not as high, 5 m (15 ft), and is not breached to allow parts of the inner near-surface rock to be seen. All of these locales are over the buried Capitan reef.

Numerous other small hills and sinks in the Delaware Basin have been investigated to see if they are surface expressions of breccia pipes. Geophysical work, electrical resistivity and gravity surveys, as well as surface geologic mapping, suggest that all but the above four mentioned locations are caused by other types of solution of evaporites. Bachman (1980) describes the features as karst domes (Malaga Bend area, southeast of Carlsbad), karst mounds (WIPP 29, WIPP 32 drill-hole areas) and solution and fill structures (hill about 4.8 km or 3 mi) east of southern end of Laguna Grande de la Sal. All of these features are formed by near-surface dissolution of evaporites and do not have a deep-rooted base below the upper part of the Salado Formation.

The method of formation of the breccia pipe at Hill A can be partially reconstructed from the core of drill hole WIPP 31 and the cross sections constructed through the pipe using subsurface data from oil and gas exploratory holes (fig. 10). Initially, a cavern must be formed in some unit at depth. The only rock still below the bottom of WIPP 31 (604 m or 1,981 ft) that contains a great deal of soluble rock is the Capitan Limestone. Ground water moving through the Capitan could cause extremely large caverns to form. Bretz (1949) attributes the formation of Carlsbad Caverns and numerous nearby caves to phreatic conditions. Jagnow (1979) believes that the caves were formed under vadose conditions and only exfoliation and speleothem development modified them to their present shapes. Both authors agree that the major portions of the caves formed during and after uplift and northeastward tilting of the Delaware Basin during late Pliocene time.

The ground-water history during the late Pliocene tilting is unknown. In the area of Hills A and C, ground water must have moved through the fractured Capitan, dissolving the limestone along fracture sets similar to solution phenomena along the uplifted portions of the reef on the western edge of the basin. This dissolution could have caused the formation of caverns in the Capitan Limestone into which overlying rocks could collapse.

Above the Capitan Limestone at Hill A are the Yates and Tansill Formations, consisting of interbedded sandstones, siltstones, and dolomites. The soluble carbonates in these formations are not thick enough to account for the cavity size necessary to cause the massive collapse of the rocks above them. Core from the bottom part of WIPP 31 consisted of anhydrite, broken and rehealed, not jumbled, and dipping about 50°. This rock is tentatively assigned to the Fletcher Anhydrite. It is the only known anhydrite bed thick enough to account for the approximately 15 m (50 ft) (true thickness) of anhydrite in the drill hole. Using the projected depth at which the Fletcher should have been encountered (fig. 10), a drop of about 76 m (250 ft) occurred. During the early formation of the Hill A pipe, the collapse may have been a slow process with the Tansill and Yates dropping into the cavity forming in the Capitan Limestone until the thick beam of the Fletcher was reached. This unit could act as a support beam holding up the overlying rocks until the cavity below reached sufficient horizontal spread that the beam failed. At this time, the Fletcher could have dropped the complete 76 m (250 ft) at one time, allowing some of the overlying halite and thin anhydrite and polyhalite beds of the Salado Formation to drop with it. Rocks of the overlying Rustler Formation, Dewey Lake Red Beds, and Dockum Group may have also dropped.

The cavity would be filled with unsaturated water and as the mass of rock dropped nearly instantaneously into the cavity, the water would be forced out. The easiest path would be upward into the void and fractured rocks created by the collapse. Much of the halite would be dissolved by this water and eventually the now saturated water would move downward and out through the existing paths in the reef.

It is doubtful if collapse to the surface occurred all at one time. The mixture of rock units, with some rocks dropping as much as 335 m (1100 ft) to be mixed with rocks from a lesser vertical drop, implies that there were several stages of collapse as the pipe stopped its way to the surface.

Boulders of Dockum Group conglomerate now present on the surface overlying the pipe are believed to come from a higher stratigraphic position (Bachman, 1980, p. 67). The presence of these younger rocks implies that the Dockum Group was thicker at the time of formation of the pipe than it is now.

After the collapse to the surface, the resulting depression served as a catchment basin, and as the collecting water percolated downward, it also dissolved halite, potash, and other soluble rocks. Nearly all of the Salado halite and all of the Rustler halite was removed by this process aiding additional collapse in the pipe. This process also transported clay, silt, and sand downward and these particles became the matrix of the brecciated rock in the pipe.

Complete removal of soluble rocks has not occurred in the pipe filling at Hill A. Evidence of this is found in the anhydrite and gypsum fragments and beds still present, and in the large block of Salado halite cored between depths of 444 and 464 m (1458 and 1522 ft). Additional evidence of the incomplete removal of solubles is found in fragments of the Dewey Lake Red Beds. Stringers of selenite (gypsum) are found cutting these fragments but not the breccia matrix. Selenite stringers are found in the Dewey Lake Red Beds where the unit has not been brecciated. These deposits are thought to be caused by downward percolating of calcium sulfate-enriched water filling bedding-plane partings and fractures caused by gentle subsidence of the rock as units below are slowly being dissolved. This process is occurring or has occurred in much of the Dewey Lake Red Beds on the western half of the WIPP site (Jones, 1978) to the south of Hill A.

Over some period of time, surface erosion removed the Dockum Group rocks and any depression over the sink was filled in by debris-carrying surface water. About 600,000 years ago the Gatuna Formation was deposited across a gently rolling terrain filling in lows in the topography. Above the Gatuna, the Mescalero caliche was deposited on a nearly flat surface (410,000-510,000 years ago, Bachman, 1980). The caliche was deposited over the pipe at Hill A. The present dip of the caliche beds away from the center of Hill A indicates removal of halite from around the pipe. Holes drilled nearby show that the Rustler halite and the upper part of the Salado halite have been removed. This removal is referred to as the dissolution front (see p. 18), a wedge-shaped subsurface solution process, proceeding from west to east across the area. The presence of the Mescalero caliche at Hill A indicates that the dissolution front passed through the area less than 500,000 years ago. This process of dissolution around the margins of the pipe accounts for the outward-dipping beds.

Hydrologic tests (see section on Drill-Stem Tests, WIPP 31, this report) show that the pipe material is not capable of transmitting ground water. The clay matrix surrounding the rock fragments acts as an impermeable barrier, and so there is probably no additional dissolution of evaporitic rocks in the pipe; at least in the upper 549 m (1800 ft) above the massive anhydrite found at the bottom of drill hole WIPP 31.

The breccia pipe at Hill C exhibits much the same history of formation as the one at Hill A. In addition to a drill hole into the pipe from the surface, there is the added feature of a mine drift that penetrates a few feet of the pipe on the southeast side about 366 m (1200 ft) underground (MCC drifts 15-L and 16-L and a drift that bypasses the pipe on the northeast side). Both of these areas underground show that the strata of the surrounding rocks dip in toward the pipe. These dip directions are just the opposite of the ones at the surface of both pipes where the dips are outward. The reversal of dip is attributed to the following: during initial collapse of the material in the pipe, the surrounding beds were dragged downward toward the pipe; subsequent dissolution of upper strata, namely the Rustler halites above the Culebra Dolomite Member, as the dissolution front moved from west to east across the area, lowered the upper few hundred feet of the surface surrounding the pipe, causing the near-surface beds to dip away from the pipe.

To a depth of about 350 m (1148 ft) in drill hole WIPP 16 at Hill C, breccia fragments of the Dewey Lake Red Beds and the Dockum Group make up the material in the pipe. The first anhydrite of the Rustler was cored at 350 m (1148 ft), and from this depth to total depth (396 m, 1300 ft) a nearly normal section of Rustler was cored. The beds were dipping about 35°, indicating some tilting of the beds after coming to rest. These Rustler rocks are fractured but not jumbled lithologically like the overlying Dewey Lake Red Beds and Dockum Group rocks. Both marker dolomite beds are present in the core. Below the lower dolomite (Culebra), the drill hole penetrated halite beds normally found in the Rustler. Halite beds between the dolomites and above the upper one (Magenta) are missing and only an insoluble residue is left. This indicates that the dissolution front had not reached the halites below the Culebra at the time of the collapse at Hill C. This differs from Hill A where no halites were found that could be identified as Rustler.

The total depth of WIPP 16 (396 m, 1300 ft) is about 24 m (80 ft) below the drift in the mine. Rocks of Rustler were cored in the bottom part of WIPP 16, but in the wall of the pipe in the mine are rocks of probable Salado. These rocks include large blocks of anhydrite that could have come from MB 103 or 109, normally about 98-122 m (320-400 ft) above their present level.

Below the bottom of drill hole WIPP 16, the estimated depth to the Fletcher Anhydrite is 223 m (700 ft) at Hill C. The presence of a moderately disturbed upper Rustler Formation in WIPP 16 seems to imply that there may not have been the rapid downward movement in this pipe, but more than 183 m (600 ft) of rock of various lithologies was let down slowly, only tilting about 35° at its final resting depth. Here the two pipes differ in the condition of the rock, Hill A containing brecciated and jumbled rock down to the Fletcher Anhydrite Member, Hill C containing these only to the top of the Rustler Formation.

The dissolution front, moving from west to east, had penetrated into the Salado Formation at Hill A, but only into the Rustler Formation at Hill C at the time of collapse of the pipe, presuming that the two pipes formed at nearly the same time.

The caliche overlying Hill C has been downdropped toward the center of the pipe in several places indicating that minor collapse occurred after the main collapse. This minor collapse can be dated as less than 410,000 years ago.

Minor amounts of oil-stained core from both WIPP 16 and WIPP 31, as well as oil seeps in the MCC drifts near Hill C, were analyzed to see if an answer could be found to account for the presence of the oil (Palacas and others, 1982). Gas chromatograph and geochemical analysis indicate that the three oils are related to the oil from wells to the north of the pipes taken from the Yates Formation. The Yates overlies the Capitan reef on the backside of the reef. It is possible that oil from this formation migrated toward the area of the breccia pipes and either entered the rocks before collapse occurred or it was forcefully emplaced during collapse, being pushed stratigraphically upward by hydrostatic pressure as the water in the underlying void was forced upward by the infalling rocks. In WIPP 31, the oil stains were in rocks of Dewey Lake Red Beds, and Rustler and Salado Formations consisting of siltstone, anhydrite, and dolomite fragments and a matrix of mud, recrystallized halite, and glauberite crystals. In WIPP 16, the oil stains were in the Rustler Formation in anhydrite above the Magenta Dolomite Member and in halite below the Culebra Dolomite Member. The oil seeping into the MCC mine appears to be coming from a nearly vertical fault about 43 m (140 ft) from the edge of the breccia pipe.

Possible Effect on WIPP Site

Numerous domes and sinks dot the landscape in the Delaware Basin. Some of these features can be shown to be remnants of near-surface dissolution or surface erosion; others are from dissolution and cavity formation in the Capitan Limestone. Known locations where deep dissolution occurs and forms structures called breccia pipes are limited to areas over the buried Capitan reef, no closer than 16 km (10 mi) to the WIPP site. The four known occurrences are Hills A, B, C, and the Wills-Weaver site.

Collapse of these structures, at least to the surface, occurred sometime before 400,000-500,000 years ago.

Locales on and around the WIPP site that were investigated for evidence of pipe formation, with none being found, include the sites of drill holes WIPP 13, WIPP 32, WIPP 33, and WIPP 34. Numerous surface features were mapped and found to be near-surface erosion and dissolution features.

No examples of breccia pipes that could lead to breaching of a repository at the WIPP site have been found to date and are not likely because the Capitan Limestone is not present beneath the site.

DRILL-STEM TESTS, WIPP 31

By J. W. Mercer

INTRODUCTION

During drilling and coring of WIPP 31 reentry, formation tests were conducted over selected intervals of the borehole to determine the possible presence of fluids (liquids or gases) and, if present, to obtain estimates of quantity, quality, and source. The formation tests were conducted using standard drill-stem test procedures as described in Dolan and others (1957), Bredehoeft (1965), Hackbarth (1978), and in "Supplement #1 to the field operations plan for WIPP 31 Re-Entry" as discussed in a letter from W. D. Weart. SNL, to D. Schueler, DOE, dated July 25, 1980.

The drill-stem test is a temporary well completion whereby the zone of interest in the borehole is isolated by the expansion of a rubber packing element or packer attached to the drill string. These packers isolate the test interval, relieving the mud column pressure and allowing the zone to produce formation fluid (if present) to the drill pipe. In addition to these packers, the drill-stem-testing tool consists of valves, pressure-recorders, and related equipment. During each individual drill-stem test, normal procedures call for multiple opening (flow-in) and closing (shut-in) of the tester valve with subsequent recording of the pressure changes. As discussed in Bredehoeft (1965), interpretation and analyses of drill-stem tests can yield information about the undisturbed formation pressure, a coefficient of permeability for the stratigraphic interval tested, and in some cases a sample of formation fluid.

ANALYSIS

During coring of WIPP 31, seven individual formation tests were attempted over various stratigraphic intervals in the borehole. Of these seven tests, only five were successfully completed, the first two failing because of malfunction of the testing tool. The procedure prior to each drill-stem test included running geophysical logs (gamma, density, and neutron) for lithologic control as well as a caliper to select packer seats. As drilling proceeded, the core was monitored for any fracturing or lithologic changes that might indicate a zone of fluid entry.

Field data obtained during testing are included in table 6 and various packer configurations for the tests are shown on figure 33. These tests (DST-3 and -4) indicate that the zone tested from 246 to 324 m (808 to 1064 ft, DST-3) and 246 to 376 m (808 to 1235 ft, DST-4) contained some fluid, however, production rates were so low that the only fluid recovered was diluted drilling mud. Calculated permeabilities were 0.57 and 0.90 millidarcies (mD), respectively. DST-5 from 371 to 426 m (1,216 to 1,396 ft) indicated very low permeability with a calculated value of 0.11 mD. The tests for DST-6 (456-514 m or 1,495-1,687 ft) and DST-7 (451-604 m or 1,480-1,981 ft) indicated the formation was extremely tight and did not yield enough fluid to make calculations for permeability.

Table 6.--Summary of drill-stem test results WIPP-31, Eddy County, N. Mex.

[To convert feet to meters, multiply by 0.3048. PSIG, pounds per square inch gage; BPD, barrels per day; mD, millidarcies; DST, drill-stem test; leaders (---), not calculated]

DST No.	Date tested	Interval tested	Total thickness (ft)	Type of Test	Hydrostatic pressure (PSIG) Initial	Hydrostatic pressure (PSIG) Final	Flow period (minutes)	Bottom hole flowing pressure (PSIG) Initial	Bottom hole flowing pressure (PSIG) Final	Shut-in period (minutes)	Shut-in pressure (PSIG) Final	Calculated flow rate (BPD)	Calculated static bottom hole pressure (PSIG)	Horner calculated permeability (mD)	Calculated potentiometric surface (feet above MSL)
1	Packer slipped in hole, cound not actuate DST tool.														
2	Hydraulic tool malfunctioned, could not set packers.														
3	8/13/80	[1]808-1064	256	Bottom hole Conventional	391	391	15 60 480	94 136 142	117 140 155	30 240 495	157 198 198	3.3	229	0.57	3173.8
	(Remarks: Opened with weak blow, increased to strong blow after 1 min., second flow with a strong blow, third flow with a strong blow decreased to weak blow after 4-9 min and remained through flow period.)														
4	8/20/80	[1]808-1235	427	Bottom hole Conventional	418	[2] ---	30 60 240	111 155 185	142 175 191	30 120 495	187 222 234	6.6	263	0.90	3247.7
	(Remarks: Opened with strong blow, decreased and died after 20 min, second flow with a fair blow that remained throughout flow, third flow opened with strong blow decreased and died after 200 min.)														
5	8/28/80	1216-1396	180	Bottom hole Conventional	676	669	45 110 330	56 57 58	57 59 65	90 220 660	110 83 63	.9	113	0.11	2441.7
	(Remarks: Opened with weak blow, increased then decreased and died after 12 min, second flow opened with a weak blow, died in 5 min, third flow opened with a weak blow died in 4 min.)														
6	9/10/80	1495-1687	192	Bottom hole Conventional	846	832	45 1101 330	68 80 70	76 84 74	102 220 660	100 92 102	---	125	----	2170.2
	(Remarks: Opened tool with weak blow died in 17 min, second flow with no blow, and third flow with no blow.)														
7	9/25/80	1480-1981	501	Single inflatable	836	[2] ---	43 110 330	77 81 81	75 81 75	94 220 1320	171 151 204	---	253	----	2490.0
	(Remarks: Opened tool with weak blow remained through flow period, second flow with a weak blow for 15 s then died, third flow with no blow.)														

[1]Packer was set at 750 ft but hole was cased to 808 ft.

[2]No data available.

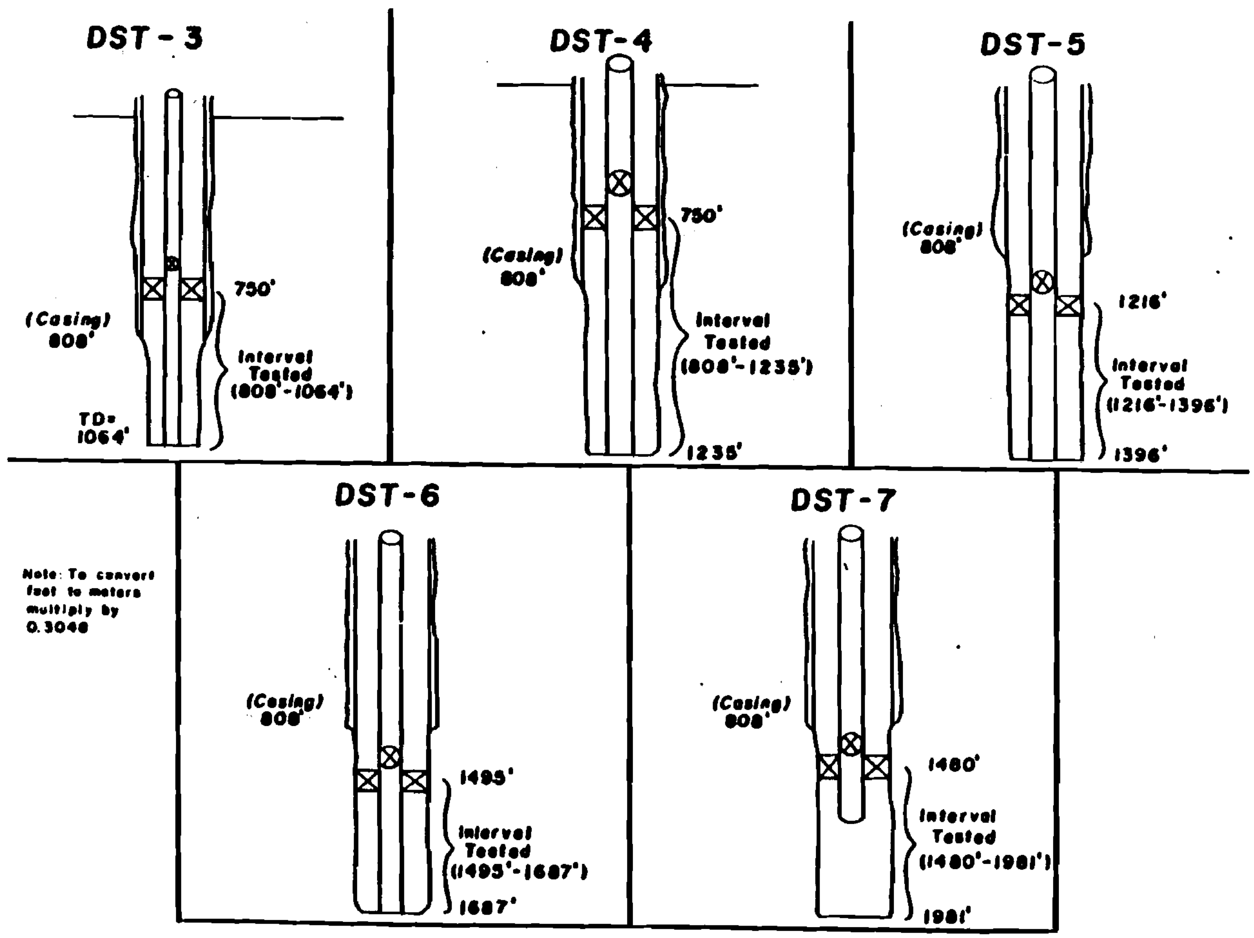

Figure 33.--Packer configuration for drill-stem tests of WIPP 31 test hole.

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