Waste Isolation Pilot Plant

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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

REGIONAL GEOLOGY AND CENOZOIC HISTORY OF PECOS REGION, SOUTHEASTERN NEW MEXICO

By

George O. Bachman

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ABSTRACT

This report summarizes the Cenozoic history of the Pecos drainage in the Delaware basin, southeastern New Mexico, and incorporates an outline of the dissolution and karst development in Permian evaporites in the region.

Evaporites include anhydrite, gypsum, halite and related minerals. They are included in the Castile, Salado and Rustler Formations of Late Permian (Ochoan) age. These formations have been transgressed by strata of the Dockum Group of Late Triassic age and unnamed formations of Early Cretaceous age.

Complex karst features include collapse sinks, karst mounds (new term), karst domes (new term) and caves. Karst mounds are erosional remnants of regional breccia. Karst domes are structural features which have formed on a very irregular dissolution surface. They are analogous to towers, kegelkarst or mogotes in tropical regions except that karst domes are almost buried by their own dissolution residue.

Breccia chimneys are collapse sinks which have formed over the Capitan aquifer system. They appear to be the result of unsaturated water rising under a strong hydraulic head through fractures and dissolving upward into the evaporite sequence.

Breccia chimneys, karst mounds and karst domes studied during this work were formed during middle Pleistocene time.

Dissolution has been an active process in the Delaware Basin at least since Triassic time and it is impractical to attempt to calculate a rate of dissolution for the basin. Earlier estimates of the rate of dissolution are considered to be conservative. Subsurface evidence does not suggest that deep dissolution is presently an active process in the Castile Formation beneath the thick beds of Salado salt.

Pleistocene glaciation in the northern and central United States was probably accompanied by "pluvial" periods in southeastern New Mexico. Pluvials are characterized by less extreme temperatures, less evaporation and more effective moisture than at present.

TABLES

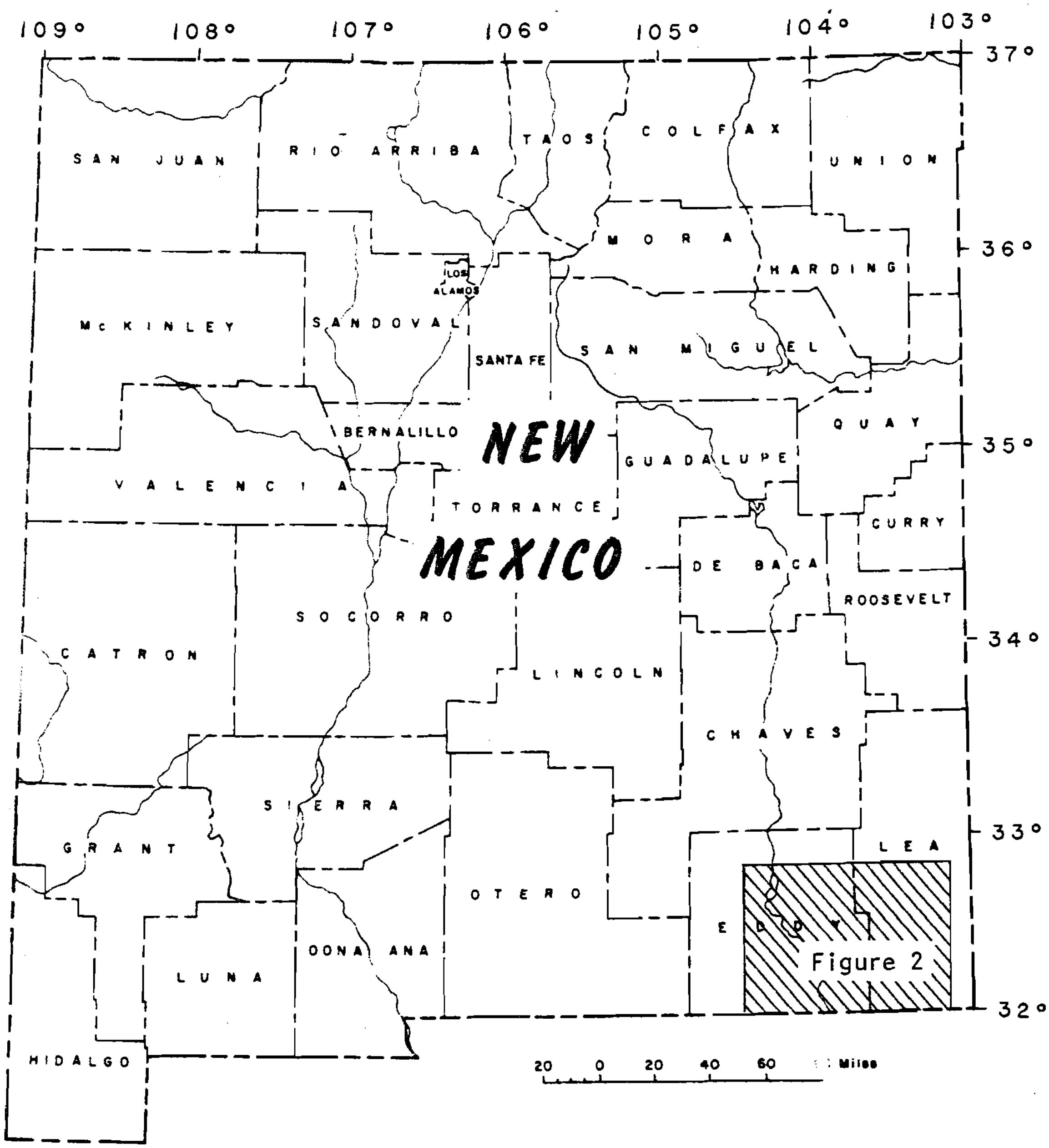

Figure 1. Index map of New Mexico showing study area (fig. 2).

INTRODUCTION

This report is part of a continuing study of the Los Medanos area, eastern Eddy County, New Mexico, to determine the feasibility of storing nuclear waste in underground beds of salt (fig. 1). A site has been proposed in this area for the construction of a Waste Isolation Pilot Plant (WIPP) by underground mining methods. The site and surrounding area is being studied geologically and hydrologically by field examination and exploratory drilling.

This report summarizes the geologic history of the region during the Cenozoic Era which is the time that has elapsed since the withdrawal of Cretaceous seas about 65 million years ago. Although this time interval is emphasized, it is impossible to isolate Cenozoic events completely from other aspects of the regional geology. For this reason the history of the region since the deposition of salt beds during Permian time, about 280 million years ago, is also outlined briefly. More complete discussions of the Permian stratigraphy have been presented elsewhere (Vine, 1963; Hayes, 1964; Gard, 1968; Jones, 1973).

This study has included detailed mapping of specific features in the vicinity of the WIPP site as well as reconnaissance mapping of the Pecos River drainage system in the general area of the site. Deposits and features pertinent to an interpretation of past erosion, dissolution, and climatic history have been examined to determine if there are continuing geologic processes which may pose a threat to the storage of nuclear waste at the site.

PHYSICAL GEOGRAPHY

Southeastern New Mexico is in the southern part of the Pecos River section of the Great Plains physiographic province. It is largely within the northern part of the Chihuahuan Desert life zone. The dominant plant assemblage is mesquite (*Prosopis*) and creosote bush (*Larrea*). Annual precipitation averages about 280 mm (11 in.) and evaporation averages about 2500 mm (98 in.) at Lake Avalon near Carlsbad. Drainage is mostly intermittent; the Pecos River is the only perennial stream in the region.

Field work consisted of detailed mapping of the eastern part of Nash Draw and other features in the vicinity of the WIPP site. This work was plotted on aerial photographs at a scale of 1:24,000. Reconnaissance mapping at various scales was undertaken along the Pecos River drainage system and is here compiled at a scale of 1:125,000 (fig. 2, in pocket). This map includes the area from lat 32°45' southward to the New Mexico-Texas State line. Detailed maps of some karst features were prepared at scales ranging from 1:1,200 to 1:6,000.

I worked previously in this region as part of a team engaged in a broad reconnaissance study which considered several potential sites for waste disposal. Results of that reconnaissance were published in a series of reports (Bachman and Johnson, 1973; Bachman, 1973a, 1973b, 1974, 1976). The present work incorporates a reevaluation of the earlier studies.

R. E. Kelley assisted in much of the mapping in Nash Draw. S. L. Drellack, J. L. Gonzales, and A. F. McIntyre, Jr., assisted in detailed mapping and in measuring stratigraphic sections. This study was done in cooperation with Sandia National Laboratories, Division of Waste Management, on behalf of the United States Department of Energy.

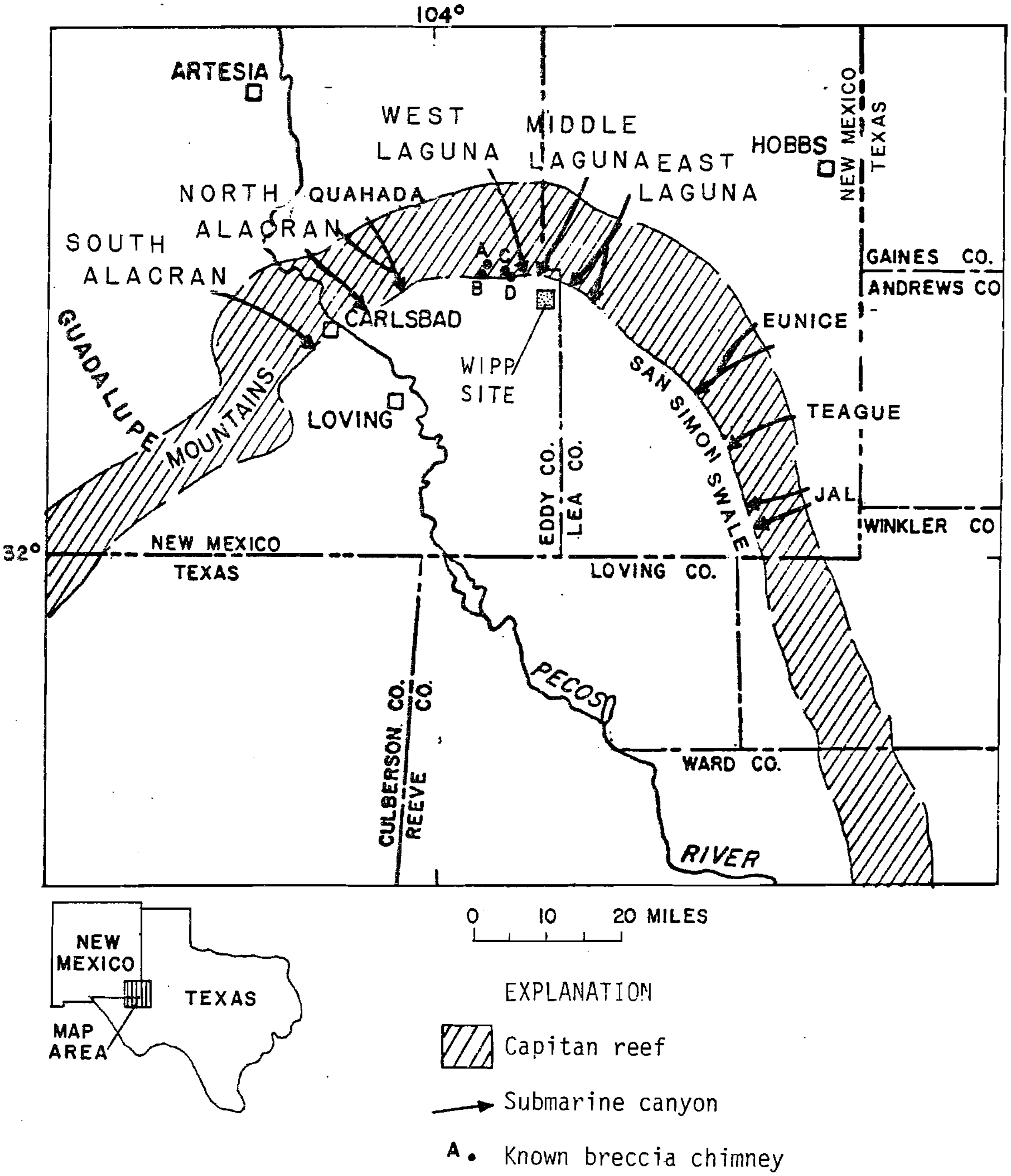

Figure 3 .--Index map showing location of submarine canyon deposits in Capitan reef. (Generalized from Hiss, 1975, fig. 11)

The WIPP site is located within the Delaware basin on a rolling surface, capped by caliche and partially stabilized sand dunes about 40 km (25 mi) east of Carlsbad, Eddy County, New Mex. (fig. 4). The proposed shaft to the underground beds of salt, which are about 640 m (2,100 ft) below the surface, is in the same place as the drill hole designated ERDA-9. Proposed land withdrawal boundaries which form a buffer zone surrounding the site as well as selected test holes drilled for geologic information are indicated on figure 4.

The site is about 8 to 9.5 km west of a low ridge, called The Divide, which separates the Pecos drainage to the west from San Simon Swale to the east. The latter is an intermittent drainage system in which runoff flows into local closed basins.

Nash Draw is a closed drainage basin west of the WIPP site. It trends northeasterly and is about 24 km (15 mi) long and 5 to 13 km (3-8 mi) wide. Maximum relief is about 122 m (400 ft) but topographic closure of the basin is little more than 3 m (10 ft). Salt Lake (Laguna Grande de la Sal) is a playa in the southwestern part of Nash Draw. Livingston Ridge marks the eastern rim of Nash Draw and is the western edge of the rolling geomorphic surface which continues eastward across the WIPP site.

The Delaware basin is an ancient sedimentary feature in southeastern New Mexico and western Texas whose perimeter is marked by the Capitan reef (fig. 3). Although these features were formed in Permian seas more than 280 million years ago, they have continued to influence the geologic history of the region to the present. The Capitan reef is a massive limestone, known as the Capitan Limestone, exposed along the front of the Guadalupe Mountains which today mark the western margin of the Delaware basin.

The Pecos River flows southeastward into the Delaware basin about 17 km (11 mi) northwest of Carlsbad. At lat 32°00', a broad unnamed geomorphic surface separates the Pecos River Valley from San Simon Swale. The surface is in part an ancient karst plain whose irregularities have since been filled by alluviation and other constructional processes. It is broadly correlative with the Mescalero surface which lies east of the Pecos between Roswell and Carlsbad.

Much of the region eastward from the Guadalupe Mountains as far as San Simon Swale is underlain by highly soluble rocks of Permian age such as gypsum and halite. At places where these rocks have been partially dissolved the surface is pitted by karst topography. Individual karst features in the modern landscape include collapse sinks, domes, caves, and intricate solution passages.

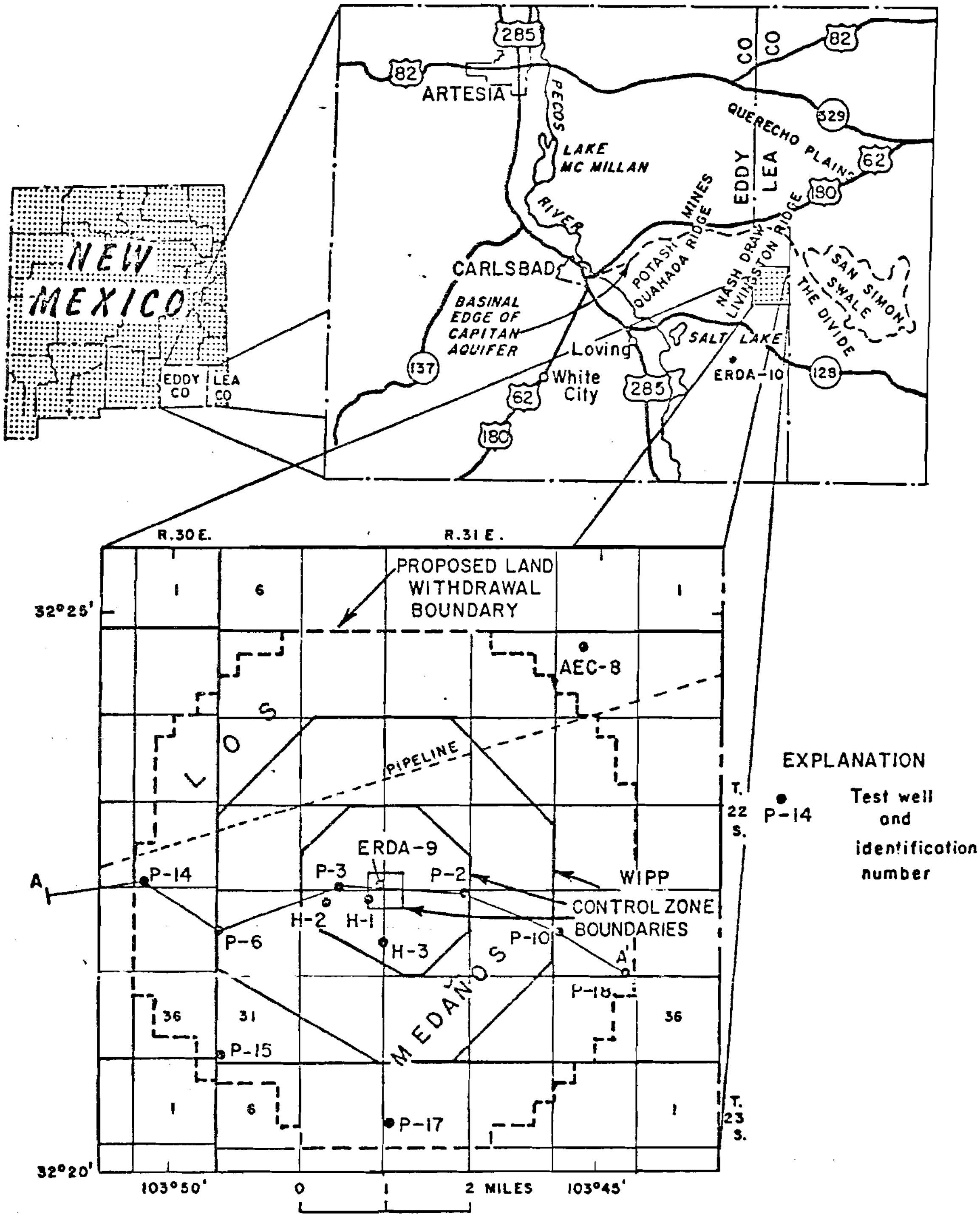

Figure 4.--Location map of the WIPP study area showing hydrologic and selected geologic test holes at Los Medanos.

STRATIGRAPHY

Major geologic events can be isolated from one another only by understanding the stratigraphic sequence. This sequence is discontinuous with gaps in deposition that represent intervals of nondeposition or erosion. These gaps may represent times when the region was uplifted tectonically above sea level. At such times erosion was active and soluble rocks were undergoing dissolution by ground water. These gaps in depositional history are of major importance in the consideration of the post-depositional history of soluble rocks in the region. Consequently, the gaps are discussed here in the context of the stratigraphic sequence. The regional stratigraphic sequence is summarized in table 1.

Permian Rocks

Rocks of Permian age in the Delaware basin are divided into four series, in ascending order, the Wolfcampian, Leonardian, Guadalupian, and Ochoan. Wolfcampian rocks record the transgression of seas across older Paleozoic and Precambrian terrain. Following this transgression there was a relatively continuous marine, or epicontinental, environment throughout the remainder of Permian time. Sand, clay, carbonates, sulfates and chlorides were deposited in this environment. Most soluble rocks in the Delaware Basin, including thick deposits of bedded salt, were deposited during Ochoan time.

Table 1.--Major stratigraphic and time divisions, southeastern New Mexico (Time divisions from Berggren, 1972, in part.)

ERA	SYSTEM	SERIES	FORMATION	AGE ESTIMATE
Cenozoic	Quarternary	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	
		Guadalupian Leonardian Wolfcampian	Capitan Limestone and Bell Canyon Fm. Present but not discussed in this report	280 million years-----

Guadalupian Series

Rocks of the upper part-of the Guadalupian series are pertinent to this discussion because they record the early stages of development of the Delaware Basin in which the evaporites of the Ochoan Series were deposited. Guadalupian rocks are divided into formations whose characteristics reflect their environment of deposition (fig. 5).

The Capitan Limestone was deposited as a reef which enclosed much of the Delaware Basin (fig. 3). It is well exposed along the front of the Guadalupe Mountains where it forms steep cliffs and the walls of deep canyons. It consists of two members, a massive member and a breccia member (Hayes, 1964, p. 20). These members grade into one another and have been interpreted as the "reef" and "reef talus" facies, respectively, of Newell and others (1953, fig. 24). In addition to the extensive exposures of the Capitan Limestone in the Guadalupe Mountains, its distribution and facies relations are well known in the subsurface surrounding the Delaware Basin where drilling by the petroleum industry in the search for oil and gas has accumulated exhaustive data on this formation.

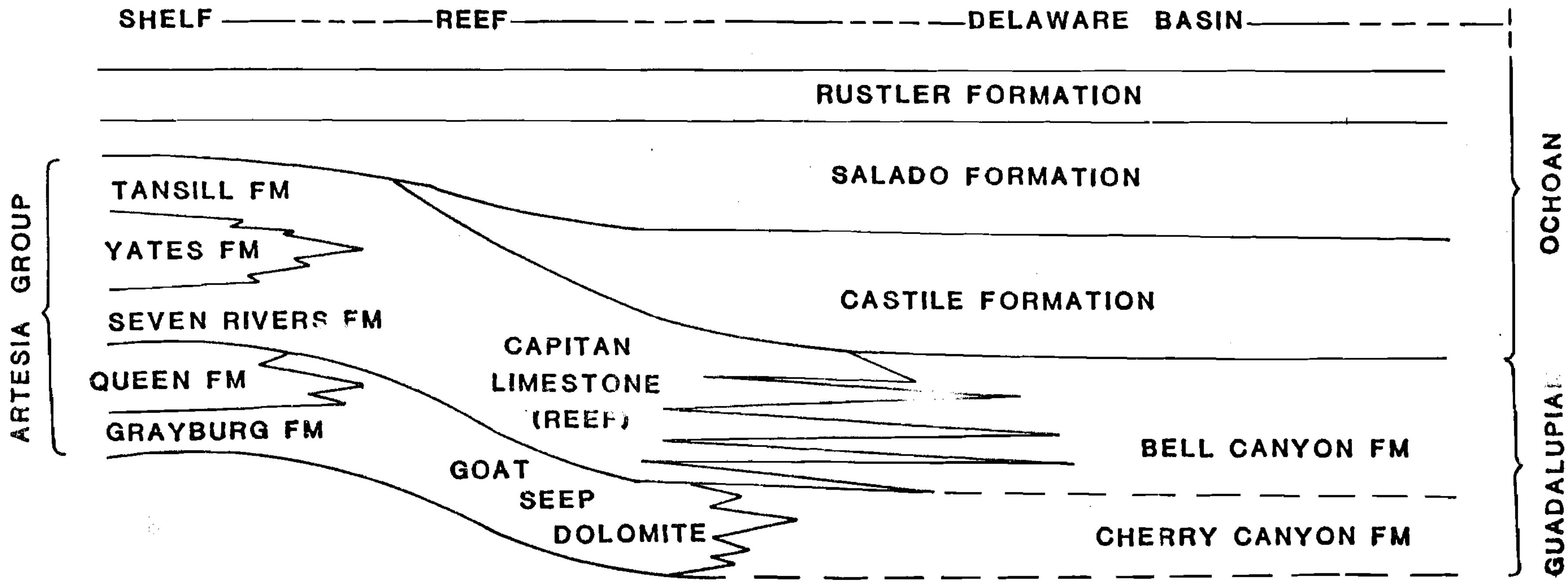

Figure 5.--Diagram showing stratigraphic relations of Guadalupian and Ochoan rocks northwestern part of Delaware Basin.

The Capitan is a porous and permeable light-gray, fine-grained limestone and in the subsurface is a major regional aquifer. Near the surface it is intricately jointed and large caves have been dissolved in the limestone. Both Carlsbad Caverns and New Cave in the Capitan Limestone and adjacent Tansill Formation are well-known examples. However, the reef in the subsurface is not consistently permeable. During the building of the Capitan reef in Permian time, submarine canyons, cut from the shelf area through the reef to the Delaware basin (fig. 3). These canyons are represented by stringers of fine-grained carbonate-cemented sand which are much less permeable than the adjacent reef limestone. These submarine canyon deposits retard the free migration of ground water (Hiss, 1975).

The Capitan grades laterally into the Bell Canyon Formation in the Delaware Basin (fig. 5). The Bell Canyon consists of interbedded limestone and sandstone. In the back reef, or shelf, area away from the basin, it grades laterally into interbedded dolomites, limestones, sandstones and evaporites of the Artesia Group. The Artesia includes, in ascending order, the Grayburg, Queen, Seven Rivers, Yates, and Tansill Formations.

Ochoan Series

Castile Formation

The Castile Formation is the basal unit of the Ochoan series. It was named by Richardson (1904, p. 43) for Castile Spring in Culberson County, Texas, about 33 km (20 mi) south of the New Mexico-Texas State line. For a time the Castile was called informally the "lower salt series" to distinguish it from an "upper salt series", later named the Salado Formation (Lang, 1935, p. 265-267). Still later an extensive bed of anhydrite which rests on the Capitan Limestone in places in the subsurface was defined as the base of the Salado Formation (Lang, 1939). This anhydrite was described in detail and named the Fletcher Anhydrite Member of the Salado Formation (Lang, 1942, p. 75-78). This definition restricted the Castile to the Delaware Basin.

However, Jones (1954, p. 109: 1973, p. 10) indicates that the upper part of the Castile includes a northward-thinning tongue of anhydrite which overlaps the Capitan and Tansill Formations outside the basin. Apparently this tongue includes the Fletcher which is transitional with the upper part of the Castile in the Delaware Basin. The Fletcher is readily separated from the Castile around the margin of the basin where it rests on the Capitan or Tansill but within the basin it merges with a sequence of thick anhydrite in the upper part of the Castile.

Massive beds of halite, anhydrite, and thick sequences of interlaminated anhydrite and limestone with minor amounts of dolomite and magnesite are distinctive rocks in the Castile Formation in the subsurface. In surface exposures the anhydrite has been hydrated to laminated or massive gypsum.

Anderson and others (1972) studied anhydrite-calcite couplets in the Castile Formation and concluded that they are the result of seasonal deposition and are correlative for distances as much as 113 km (70.2 mi) and "probably throughout most of the basin". They also indicated a time span of about 260,000 annual cycles for the deposition of the Castile Formation. Adams (1967) has questioned the concept that the anhydrite-calcite couplets represent all of Castile time on the basis that introduction of saline water to the Castile lagoonal basin may not have been at regular annual intervals. He postulated long intervals during which the lagoon was isolated from an influx of new saline water and annual couplets were not deposited.

Jones (1973, p. 8-9) indicated that the Castile is divisible into three informal members in the Los Medanos area. These include a lower member composed chiefly of anhydrite, a middle rock-salt member and an upper anhydrite member. However, southward from the vicinity of Malaga the Castile grades laterally into seven major members. These have been numbered in sequence, in ascending order, anhydrite I, halite I, anhydrite II, halite II, anhydrite III, halite III and anhydrite IV (Anderson and others, 1972, p. 74-82). These stratigraphic relations are shown diagrammatically on figure 6 (in pocket).

The Castile Formation is exposed over broad areas in south-central Eddy County and southward into Culberson County, Texas, but it is best preserved in the subsurface. It is about 546 m (1,775 ft) thick in the vicinity of the WIPP site. It ranges from zero to more than 640 m (0 - 2,100 ft) thick in the Delaware Basin (fig. 7).

During the present study the regional stratigraphic relations of the Castile Formation were examined to determine the depositional history and the time and extent that dissolution had occurred in the formation. The Castile was studied in the field in exposures along the western edge of the Delaware Basin in New Mexico and Texas and in the subsurface by means of numerous geophysical logs. Results of these studies are summarized in figures 6 and 7.

Although anhydrite and gypsum in the Castile are usually thinly laminated, massive beds of these rock types are present in the upper part of the formation. Along the western edge of the Delaware Basin southward from the latitude of Whites City surface exposures of the Castile include beds of massive gypsum (Hayes, 1957; 1964). In the subsurface laminated anhydrite in the Castile grades upward into massive, white anhydrite (Jones, 1954, p. 109; 1973, p. 9). The assignment of these massive beds to the Castile Formation rather than to the overlying Salado Formation is consistent with the regional stratigraphy. The Salado Formation is dominantly halite throughout the Delaware Basin.

Anderson and others (1972) suggested that halite deposition once extended to, or nearly to, the western margin of the Delaware Basin and that numerous beds of halite have since been dissolved from the Castile in that area. They describe "blanket solution breccia" which represents intervals of all major halite beds across the Delaware Basin (Anderson and others, 1972, p. 70, fig. 8).

Study of geophysical logs during the present work did not substantiate this hypothesis. Instead, interbedded halite and anhydrite in the Castile interfinger and are discontinuous. These evaporites were deposited in individual and subordinate depositional pans within the Castile depositional basin (fig. 6). Beds of halite thin and wedge out towards the western edge of the basin and it appears that thick beds of halite were never deposited near the margins of the Delaware Basin during Castile time.

Salado Formation

Lang (1935, p. 367) named the "Salado halite" as the "upper salt series" of the Castile Formation. The Salado includes many potassium-bearing minerals as well as halite and has since been ranked as a formation. The Salado Formation is represented at the surface only as a discontinuous outcrop belt of insoluble residuum. However, in the subsurface it consists of bedded halite, sylvite, and other chloride and sulphate salts.

Parts of the Salado Formation are mined for potash minerals in eastern Eddy and western Lea Counties, New Mexico, and the formation has been drilled at numerous places during exploration for these minerals. Consequently, the details of Salado stratigraphy are well known and have been summarized extensively in the literature (Jones, 1973, p. 10-21; 1978). Only those stratigraphic units pertinent to this discussion are outlined here.

The Salado Formation is divisible into three members: an unnamed lower member, the McNutt potash zone, and an unnamed upper member. Jones (1973, p. 13) has called attention to the cyclic nature of the sedimentary units within the Salado. A typical sequence begins with claystone at the base grading upward through anhydrite or polyhalite to halite which is in turn capped with claystone. Jones (1973) interprets these rock sequences to "represent a fundamental sedimentation unit or evaporite cyclothem". They are believed to record discrete intervals of evaporation of sea water and subsequent precipitation of sulfate and chloride salts.

Persistent interbeds of anhydrite or polyhalite have been designated numerically as "marker beds" (Jones and others, 1960). These marker beds are indispensible to the correlation of horizons within the Salado and are of particular value in determining the presence, or absence, of dissolution.

The Salado Formation ranges from a knife edge to about 738 m (2,400 ft) thick in the Delaware Basin. It is 603 m (1976 ft) thick at the WIPP site. Much of this variation in thickness is the result of dissolution of the soluble minerals. The time during which this dissolution occurred is discussed in another section of this report. Other variations in thickness are probably the result of salt flowage after deposition. Figure 8 (in pocket) is an isopach map showing the thickness of the Salado Formation in the central and northern parts of the Delaware Basin.

Rustler Formation

The Rustler Formation of Late Permian (Ochoan) age was named by Richardson (1904, p. 44) for exposure in the Rustler Hills, Culberson County, Texas, about 32 km (20 mi) south of the New Mexico-Texas State line. In that area only the lower part of the formation is exposed. In many areas in southeastern New Mexico much of the Rustler has been removed by dissolution and erosion and the only complete stratigraphic sections are encountered in drill holes.

The Rustler Formation may be divided into five natural parts. These include, in ascending order, an unnamed sequence of reddish-brown siltstone with interbeds of gypsum or anhydrite, the Culebra Dolomite Member, the Tamarisk Member, the Magenta Dolomite Member, and the Forty-niner Member. The Culebra and Magenta Members were named by W. B. Lang (Adams, 1944). The Tamarisk and Forty-niner Members were named by Vine (1963).

The basal unnamed member of the Rustler is about 37 m (120 ft) thick at the WIPP site (ERDA 9) and averages about 27 m (90 ft) thick in drill holes in the eastern part of Nash Draw. It consists of dark-reddish-brown to medium-gray and olive-gray siltstone, yellowish-brown to light-gray gypsum, and anhydrite.

The Culebra Dolomite Member is about 7.7 to 9.2 m (25-30 ft) thick and is a distinctive marker bed in the Rustler Formation. It is a medium- to brownish-gray, thinly bedded, finely crystalline dolomite. Many layers are characterized by abundant, distinctive vugs that range from about 2 to 10 mm in diameter. The vug rims are usually brownish and some contain minute crystals of selenite. The Culebra weathers to prominent ledges and is preserved in dissolution features as blocky collapse breccia.

The Tamarisk Member is preserved on the surface as massive light-gray gypsum and is not a distinctive lithologic unit. In the subsurface where dissolution has not altered its character the Tamarisk includes halite, anhydrite and traces of polyhalite. Near the WIPP site, it is 54.6 m (179 ft) thick.

The Magenta Dolomite Member is a distinctive, thinly laminated dolomite and anhydrite or gypsum. The laminae are generally less than 10 mm thick and at surface exposures are undulatory. The dolomite laminae are light reddish brown and the anhydrite or gypsum is gray. The Magenta ranges from about 6 m to 9 m (20-30 ft) thick. In drill hole P-18 near the WIPP site it is 8 m (26 ft) thick.

The Forty-niner Member is generally massive gray gypsum in surface exposures but locally includes reddish-brown siltstone. In the subsurface the member is composed of anhydrite, siltstone and halite. It is 23.8 m (28 ft) thick in P-18. The Forty-niner Member in parts of Nash Draw includes thin beds of moderate-reddish-orange siltstone mottled by greenish-gray reduction spots. At some exposures where gypsum is absent in the sequence it is impractical to separate this member from the overlying Dewey Lake Red Beds.

Walter (1953) discussed the fauna and age of the Rustler Formation in the area of the type locality. He studied fossils from the lower part of the formation including the Culebra Dolomite Member and concluded that the fauna may constitute the youngest Permian fauna in North America. He believed deposition was in a normal saline to hypersaline environment.

Dewey Lake Red Beds

The Dewey Lake Red Beds were named by Page and Adams (1940, p. 62-63) from a subsurface stratigraphic section in Glasscock County, western Texas. Previously this formation had been called the Pierce Canyon Red beds (Lang, 1935, p. 264) for exposures in the vicinity of Pierce Canyon southeast of Loving, New Mexico. However, owing to the poor definition of the Pierce Canyon and the wider acceptace of the term Dewey Lake among geologists, the U.S. Geological Survey has abandoned the Pierce Canyon and extended the term Dewey Lake to New Mexico for this stratigraphic interval.

The Dewey Lake Red Beds rest conformably on the Rustler Formation and consist mainly of alternating thin, even beds of moderate-reddish-brown to moderate-reddish-orange siltstone and fine-grained sandstone. There are occasional small-scale cross laminations and ripple marks. Many beds are mottled by greenish-gray reduction spots. Well-sorted quartz grains compose most of the rock. Cement is usually selenite or clay.

Rocks of Triassic age rest unconformably on, and overlap, the Dewey Lake Red Beds, and the thickness and regional distribution of the Dewey Lake is related directly to erosion before Late Triassic time. The Dewey Lake is thickest in the subsurface in eastern Eddy and western Lea Counties where it is as much as 172 m (560 ft) thick. It thins towards the west and is absent in some exposures where Triassic rocks lap across the westernmost line of outcrop.

Dewey Lake Red Beds may be distinguished from rocks of Triassic age by characteristics of bedding, color, and mineral content. These characteristics are compared in table 2.

Rocks of Triassic Age

Rocks of Triassic age are exposed along the northeastern rim of Nash Draw and northward along the Maroon Cliffs on the eastern side of Clayton Basin. These exposures are erosional remants of deposits that formerly extended continuously northward into east-central New Mexico. In that area, Triassic rocks have been divided into two formations: the Santa Rosa Sandstone at the base and the Chinle Formation above.

Table 2.--Lithologic characteristics of Dewey Lake Red Beds compared with Triassic rocks

Dewey Lake Red Beds	Triassic Rocks (Dockum Group)
1. Thinly and evenly bedded	1. Thin to thick bedded. Beds lenticular or irregular
2. Tints reddish orange	2. Tints dark reddish brown
3. Many beds mottled by greenish-gray reduction spots to about 1 cm diameter	3. May have large areas of greenish gray
4. Cross laminae, small scale, relatively uncommon	4. Cross laminae, large scale, common torrential cross-bedding
5. Relatively pure quartz sand	5. Conspicuous ferromagnesian minerals including biotite
6. Well sorted, well rounded, fine grained	6. Poorly sorted, many angular grains, may be coarse grained to conglomeratic

Triassic rocks were recognized by Cummins (1890) in western Texas and called the "Dockum Beds". Gould (1907) raised the Dockum to group status and divided it into two formations: a shaly Tecovas Formation at the base and the Trujillo Formation, dominantly sandstone, above. In east-central New Mexico Darton (1922) assigned the Triassic rocks to the Dockum Group and named the Santa Rosa Sandstone for a sequence of interbedded sandstone and shale at the base of the group. These beds are well exposed around Santa Rosa, New Mexico, about 290 km (175 mi) north of Carlsbad. Later workers have extended the term Chinle Formation from eastern Arizona for beds above the Santa Rosa and have retained the Dockum Group to include both formations.

Both formation names, the Santa Rosa and Chinle, have been extended to southeastern New Mexico but there is little justification for this practice. There are intricate facies changes and interfingering of lithologies within the Dockum Group over all of eastern New Mexico which lead to problems of correlation even in areas of relatively continuous exposures. The Dockum outliers in southeastern New Mexico are not traceable into the type areas of the Santa Rosa or Tecovas-Trujillo terminology; consequently these Triassic rocks are not subdivided into formations in this report and are here referred simply to the Triassic, or Dockum Group, undivided.

The basal beds of the Dockum Group in southeastern New Mexico are usually coarse, angular, conglomeratic sandstone but these beds interfinger locally with shale. Consequently, at places the basal beds are shaly and may be difficult to distinguish from the underlying Dewey Lake Red Beds. Lithologic characteristics of the Dockum Group are summarized and compared with the Dewey Lake Red Beds on table 2. The Dockum Group is exposed on the east side of Nash Draw where it is no more than 23 m (75 ft) thick but eastward in the subsurface in western Lea County it may be as much as 460 m (1500 ft) thick. Brecciated Triassic rocks are also present in isolated collapse sink deposits along the Pecos River drainage about 8 km (5 mi) northeast of Carlsbad and along the east side of Red Bluff Reservoir but none have been observed west of the Pecos River in Eddy County.

McGowen and others (1977) believe that the Dockum Group was deposited as a complex of fluvial-deltaic-lacustrine systems and the western depositional edge of the group was along a northerly trending line near the present limits of its preservation. This depositional edge is within, and approximately parallel to, the western edge of the Delaware Basin. This interpretation bears directly on the geologic history of dissolution of Permian evaporites discussed in the section on dissolution during geologic history. The position of the depositional edge of Triassic rocks overlying Permian evaporites indicates that the evaporites were exposed at the surface and available for dissolution during Triassic time.

Rocks of Cretaceous Age

There is a major hiatus between rocks of Late Triassic age and those of Early Cretaceous age in southeastern New Mexico. The region remained above sea level throughout intervening Jurassic time but rocks of Jurassic age have not been preserved, and presumably were never deposited, in this region.

During Early Cretaceous time the region subsided and the sea transgressed across southeastern New Mexico from the east and south. Lower Cretaceous marine rocks are present about 105 km (65 mi) east of Carlsbad. In the Cornudas Mountains about 120 km (75 mi) west of Carlsbad correlative marine Cretaceous rocks rest on Permian strata of Leonardian and Guadalupian age.

These regional stratigraphic relations indicate that the Early Cretaceous sea transgressed northwesterly over the WIPP site across progressively older rocks. These broad relations also indicate the low relief of the unconformity on which the Cretaceous rocks were deposited.

Rocks of Early Cretaceous age are preserved at a few localities in the Pecos drainage system as collapse debris in areas of dissolution. Lang (1947) reported an occurrence of fossiliferous Lower Cretaceous sandy limestone in Black River Valley about 9.6 km (6 mi) southwest of Whites City (NW 1/4 sec. 31, T. 25 S., R. 25 E., Eddy County, N. M.) (fig. 9).

These rocks containing Cretaceous marine fossils are scattered as collapse debris on the surface of the Castile Formation. This locality was examined during the present study and the Cretaceous debris appears to rest in a collapse sink about 60 m (200 ft) in diameter in the Castile Formation. Another occurrence of Cretaceous rocks and associated fossils resting on the Castile Formation is about 11.5 km (7.8 mi) southwest of Whites City (NE 1/4 sec. 1, T. 26 S., R. 24 E.). About 8.5 km (5 mi) northeast of Carlsbad (SW 1/4 sec. 12, T. 21 S., R. 27 E.), Lower Cretaceous rocks are mingled with debris of Culebra Dolomite Member of the Rustler Formation and Triassic conglomerate.

All these Lower Cretaceous rocks in southeastern New Mexico are of equivalent age. The locality northeast of Carlsbad contains the following marine fauna:

Echinoid (probably *Holectypus*)
Texigryphea washitaensis (Hill)
Ostrea quadriplicata Shumard

W.A. Cobban (written commun., Feb. 11, 1974) remarked that "this fauna matches the collection...at Black Mountain (Cornudas Mountains) which is Washita in age. Lang's collection from Black River Valley is also of Washita age".

Lang (1947) implied that Triassic rocks are absent south of Whites City and that Cretaceous rocks there rest on Dewey Lake Red Beds (fig. 10). However, examination of that locality did not reveal Dewey Lake rock types nor the preservation of other resistant rocks stratigraphically above the Culebra Dolomite Member. The interpretation of these stratigraphic relations proposed here is that Triassic rocks, Dewey Lake Red Beds, and strata in the Rustler Formation above the Culebra were removed by erosion, or never deposited, in the area south of Whites City and along the southwestern edge of the Delaware Basin before Cretaceous deposition. In addition, the fact that Cretaceous rocks in this area rest on gypsum of the Castile Formation suggests that the Salado Formation may also have been removed by dissolution before Cretaceous time.

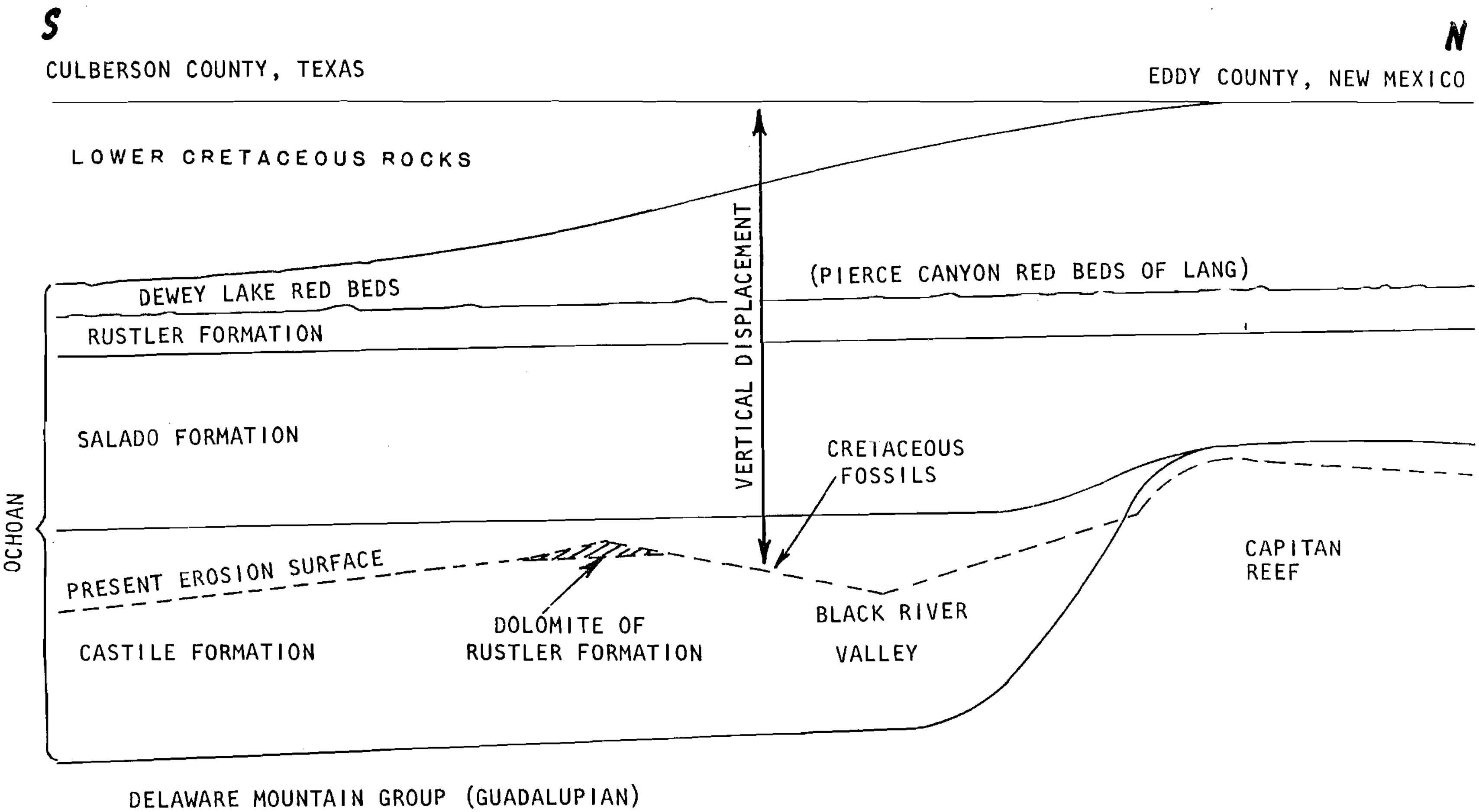

Figure 9 .--Diagram showing stratigraphic relations of Cretaceous and Permian rocks as interpreted by Lang. (Generalized from Lang, 1947, fig. 1.)

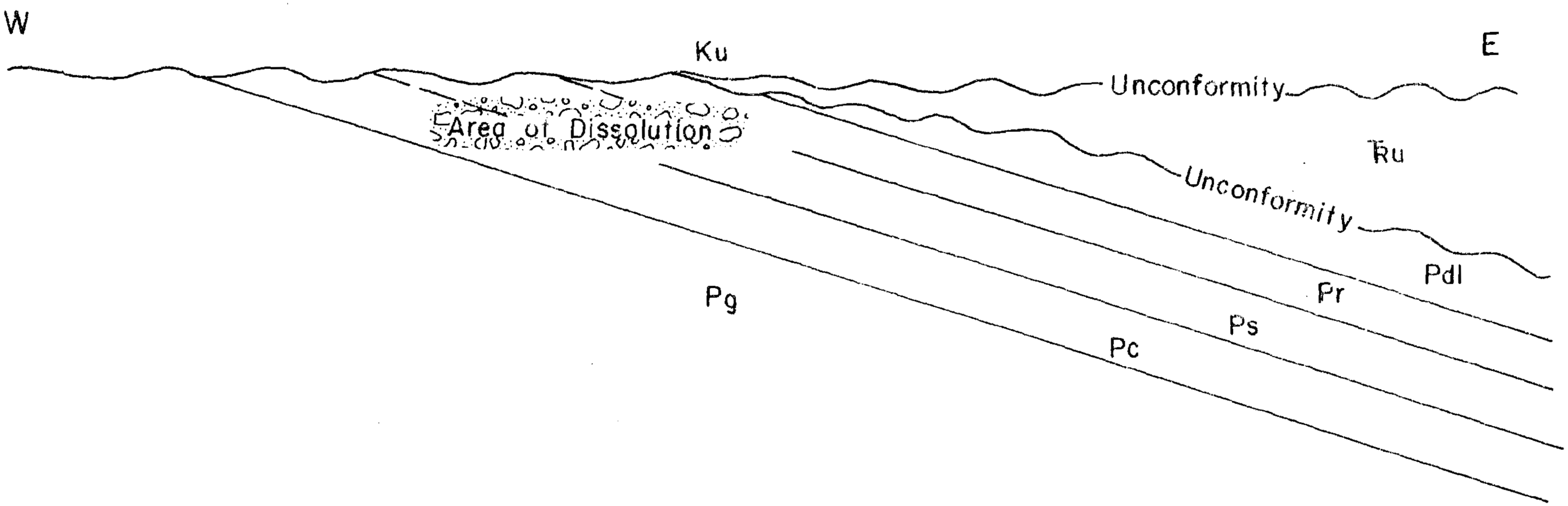

Figure 10.--Diagram showing interpretation of stratigraphic relations of Triassic and Permian strata on the western edge of the Delaware basin at the beginning of Cretaceous time. Pg, rocks of Guadalupian age; Pc, Castile Formation; Ps, Salado Formation; Pr, Rustler Formation; Pdl, Dewey Lake Red Beds; TRu , rocks of Triassic age, undivided; Ku, rocks of Cretaceous age, undivided.

Cenozoic Rocks

Other than a few thin intrusive igneous dikes about 30 million years old (Urey, 1936) rocks of early Tertiary age are not preserved in southeastern New Mexico. These igneous rocks include a lamprophyre dike which has been encountered in the underground workings at the Kerr-McKee Potash mine about 43 km (26 mi) east of Carlsbad, three deeply weathered dikes about 50 km (30 mi) southwest of Whites City, and another about 10 km (6 mi) southwest of Whites City (Pratt, 1954).

The nearest sedimentary rocks of Early Cenozoic age are in the Sierra Blanca region about 184 km (110 mi) northwest of Carlsbad where continental rocks of probable Paleocene or Eocene age are preserved. It is assumed all of southeastern New Mexico has been above sea level and subjected to erosion since Cretaceous time. Upper Tertiary and Quaternary formations are the only Cenozoic rocks preserved in southeastern New Mexico. These include the Ogallala Formation of Miocene and Pliocene age, the Gatuna Formation of Pleistocene age and various surficial deposits.

Ogallala Formation

The Ogallala Formation of Miocene and Pliocene age is the oldest record of Cenozoic depositional history and climate preserved in southeastern New Mexico. It is well exposed along Mescalero Ridge, at Hat Mesa, Grama Ridge, and at The Divide (fig. 2). The Geologic Atlas of Texas, Hobbs Sheet (Texas bureau of Economic Geology, 1976) indicates two areas of outcrop in southwestern Lea County, New Mexico, but I consider those rocks to be younger than Ogallala because they lack the distinctive Ogallala caprock. These surfaces are believed to be correlative with the Mescalero surface. During the present study the Ogallala Formation has not been recognized west of San Simon Swale except for the relatively thin exposures at The Divide.

The Ogallala Formation was derived from the west where sediments were eroded from the newly uplifted Rocky Mountains and was deposited on an irregular early Cenozoic erosion surface as a series of complex overlapping and coalescing alluvial fans. Frye (1970) concluded that Ogallala deposition ceased when the region was built to an extensive alluvial plain which was continuous westerly across much of the region of the Pecos River drainage to the backslope of the Sacramento Mountains. In the Pecos drainage in southern New Mexico, the Ogallala at The Divide could represent a depositional wedge-edge along the eastern limit of ancestral Pecos drainage or it could be a drainage divide that existed even in Ogallala time. However, there is no evidence for the position and extent of the ancestral Pecos River during Ogallala time and the character of the ancestral Pecos Valley is hypothetical.

At the termination of Ogallala deposition a pedogenic caliche, the Ogallala "climax soil" (Frye, 1970), accumulated on the High Plains surface, and the well-known "caliche caprock" was deposited as part of this process. This caliche has been dessicated, brecciated, and recemented through many generations until its present upper surface includes laminar deposits and pisoliths. Its texture and structure are distinctive characteristics of very ancient pedogenic caliche (Bachman and Machette, 1977).

In southeastern New Mexico the Ogallala Formation consists largely of well-sorted windblown sand. There are minor poorly sorted stream deposits and local carbonate pans. Generally the sediments suggest that the climate during Ogallala time was not much different from that in the region today. The pedogenic caliche caprock indicates a long period of quiescence during which constructive and destructive processes approached a steady state.

Although the upper surface of the Ogallala Formation is relatively smooth with only a slight southeasterly gradient, the irregular surface on which the Ogallala was deposited has resulted in irregular thicknesses. Generally it thins westerly and ranges from about 125 m (400 ft) in the vicinity of Mescalero Ridge to about 8 m (26 ft) at The Divide.

Since Ogallala time there has been large-scale realignment of drainage systems. During Pleistocene time the southward-flowing Pecos River captured the easterly flowing Ogallala streams and has become the major drainage system.

Gatuna Formation

The Gatuna Formation was named by Robinson and Lang (1938, p. 84-85) who defined it as "an assemblage of rocks of various kinds that were laid down in the Pecos Valley in post-High Plains time and apparently after the completion of the maximum cycle of erosion in this valley. The deposits are of terrestrial origin and with them began the process of refilling the Pecos Valley." The name is derived from Gatuna Canyon on the east side of the Clayton Basin, Eddy County, where the formation consists of light-reddish-brown sandstone and conglomerate more than 25 m (80 ft) thick.

Robinson and Lang did not designate a type section for the Gatuna Formation, but a reference stratigraphic section was designated and described by Bachman (1976, p. 140) from exposures in Gatuna Canyon. At that place the exposed portion of the formation consists of a pale-reddish-brown sandstone and conglomerate 16.8 m (54.7 ft) thick. The basal part of the formation is covered in colluvial slopes but is estimated to be about 7 m (23 ft) thick.

The Gatuna Formation is distributed intermittently over a braod area in the Pecos drainage system. It is recognized in areas east of Artesia and Hagerman, 48-80 km (30-50 mi) north of Carlsbad (Bachman, 1976). It is present along the east side of Clayton Basin and Nash Draw. It is especially well exposed in Pierce Canyon and its tributaries about 29-32 km (18-20 mi) southeast of Carlsbad. Along the New Mexico-Texas State line a gravel unit is assumed to belong to the Gatuna Formation.

In the vicinity of Pierce Canyon there are three facies in the Gatuna Formation. These include a pale-reddish-brown sand and sandy clay, light-yellowish, well-sorted sand and lenticular gravel. The reddish-brown facies is most widespread and is presumed to have been deposited on a flood plain. The well-sorted yellowish sand is thickest along the eastern margins of the gravel deposits and was deposited as sand dunes along the leeward side of stream channels. Locally along the east side of Nash Draw pods and veinlets of selenite are prominent in the Gatuna, but these are secondary and are not a depositional facies.

Many conglomeratic beds in the Gatuna Formation contain pebbles of quartz and quartzite reworked from Triassic conglomerates, and in isolated exposures it may be difficult to distinguish conglomerates of these formations. In addition, the reworked Triassic conglomeratic beds in the Gatuna usually contain pebbles derived from Tertiary igneous masses far to the northwest in the Sierra Blanca and Capitan Mountains. Clasts of pisolitic caliche may also be present in the Gatuna. At the reference section in Gatuna Canyon, more than one-third of the clasts in the conglomeratic unit were derived from the pisolitic caliche of the Ogallala caprock. Shale beds in both the Gatuna and Triassic have subtle, but distinctive, characteristics. Shale in the

Gatuna Formation is more massive, stained with manganese oxide and lacks the large greenish-gray reduction spots usually associated with Triassic shale.

The upper part of the Gatuna Formation is middle Pleistocene in age. A bed of volcanic ash present near the top of the Gatuna Formation on the east side of Nash Draw (SE 1/4 NW 1/4 sec. 36, T. 21 S., R. 30 E.) has been identified on the basis of mineralogy and fission-track dating as a Pearlette type "O" ash (G.A. Izett, written commun., 1978). The indicated age of this ash fall which was derived from the Yellowstone region, north-central Rocky Mountains, is about 600,000 years.

Soils

Soils are not usually mapped in great detail in geologic studies but soil accumulation results from processes which are extremely sensitive to climatic conditions and landscape stability. If either erosion or deposition exceed the rate of soil formation, a relatively slow process, soil cannot accumulate. Because of the value of soils as indicators of climate and stability, they were examined in detail during the present study.

Soil profiles are commonly divided into three mineral horizons designated, in descending order, A, B, and C (U.S. Department of Agriculture, 1975). The A horizon at the surface is characterized by the presence of organic material which coats mineral grains or darkens the mass relative to underlying horizons. The A horizon is not present in ancient soils (paleosols) and is commonly poorly developed in modern soils in semiarid regions such as those in southeaster New Mexico. In temperate climates the B horizon underlies the A horizon and is broadly characterized by illuvial concentrations of clay (where it is termed an argillic horizon), iron or related minerals and compounds, or by residual concentrations of sesquioxides adequate to give a darker color to the horizon. The C horizon is that weathered part of the profile overlying bedrock where soil-derived cements accumulate. These cementing substances include calcium carbonate which is a conspicuous light-gray to white deposit capping stable geomorphic surfaces in many parts of the semiarid world.

The carbonate deposit in the C horizon has received numerous provincial names such as caliche, calcrete, and croute calcaire. All these names have been used imprecisely in the literature. In this report the term caliche is used to designate those calcium carbonate deposits which are generally parallel to topography, have a distinctive morphology which increases in complexity from the base to the top, and are believed to have been deposited by soil processes.

Mescalero caliche

The Mescalero caliche is an informal stratigraphic unit named for the Mescalero Plain, a broad geomorphic surface, which lies east of the Pecos River and west of the High Plains in southeastern New Mexico (Bachman, 1976, p. 141). The Mescalero caliche caps the gecmorphic surface and is overlain by soil and windblown sand.

Where completely preserved the Mescalero caliche includes two major parts: a basal earthy to firm nodular calcareous deposit and an upper well-cemented caprock. These units correspond to the K horizon of Gile and others (1966) and include their K3 and K2 horizons, respectively. The two units commonly weather to a ledge in which the caprock overhangs the nodular base. Together the two parts range in thickness from about 3 to 13 ft (1-4 m) with the caprock usually making up about one-third to more than one-half of the total thickness.

Although both parts of the Mescalero may engulf underlying bedrock, most commonly this phenomenon is more apparent in the basal part. Near the base of the caliche, irregular masses of bedrock may be partially surrounded or completely engulfed by the caliche. In the caprock where calcium carbonate content is highest, scattered quartz pebbles and masses of sand grains may be the only vestige of the engulfed bedrock. However, fine well-rounded sand grains are common throughout the matrix of the caliche.

The Mescalero caliche appears to have accumulated in the C horizon of an ancient soil during an interval of climatic and tectonic stability that followed deposition of the Gatuna Formation. Carbonates in the caliche were deposited in an aggrading eolian environment from windblown sand, dust, and rainwater. Small quantities of the calcium carbonate are leached from the sand and dust during wet seasons and are deposited in the underlying soil horizons by downward percolating solutions. During dry seasons the sand and dust are reworked and moved about on the surface and a new source of calcium carbonate is constantly introduced into the region.

Owing to the fact that pedogenic caliche is deposited only on a relatively stable land surface it is important to learn the amount of time required for a deposit of caliche of a given thickness, carbonate content and morphology to accumulate. Such knowledge provides evidence for the length of time that the terrain has been stable.

Many workers have attempted to develop techniques for measuring the rate of carbonate accumulation in pedogenic caliche (Arkley, 1963; Gardner, 1972; Goudie, 1973; Szabo, 1969; Bachman and Machette, 1977). Of the various methods studied the most promising is a technique which measures uranium series disequilibrium. This technique has been applied to the Mescalero caliche with notable results (table 3). Using this technique it has been determined that the Mescalero began to accumulate about 510,000 years ago (J.N. Rosholt, written commun., 1979). The upper crust of this caliche formed about 410,000 years ago.

These dates are compatible with other known facts and previous estimates. The Pearlette type "O" volcanic ash in the Gatuna Formation is about 600,000 years old and underlies the Mescalero caliche. The Mescalero has been estimated previously to be middle Pleistocene in age (Bachman, 1976).

Berino soil

The Berino soil is an informal stratigraphic unit, but the term "Berino series" is used by the U.S. Department of Agriculture for mapping soils in Eddy County (Chugg and others, 1971). As used in this report the Berino is a dark red, sandy argillic paleosol which overlies the Mescalero caliche at some places in the vicinity of the WIPP site. It is usually overlain by windblown sand, but it is exposed along pipeline roads and at other construction sites. It varies in thickness but is rarely more than 1 m thick.

It is probable that the Berino soil represents a remnant B horizon of the underlying Mescalero caliche. The Berino is noncalcareous which suggests that the carbonates have been leached. The uranium-series disequilibrium technique indicates that the Berino began to form about 350,000 (±60,000) years ago (J.N. Rosholt, written commun., 1979) (table 3).

Table 3.--Palesols in the Vicinity of the WIPP Site

Sample	Thickness[1]	Description	Age[2]
A		Modern Dune Sand	
B-E	0-48 cm	Bt horizon (Berino soil). fine to medium grained well sorted, mostly quartz grains. Firm. Does not effervesce in 10% HCl. Peds blocky, angular to weakly columnar (2.5 YR 4/6).	350 ± 60 x 10^3 yrs
F-G	48-73 cm	BTca horizon (Berino soil). Sand, fine to medium grained, well sorted, mostly quartz. Slightly clayey and calcareous. Rests with sharp contact on Mescalero caliche.	
H-1	73-121 cm	K^2mb (Mescalero caliche). Platy, very firmly cemented. Peds platy, angular, sandy. Many veinlets.	Samples HIK-M 410 x 10^3 yrs
J-M	121-233 cm	K^3mb. Peds blocky, angular. Very firmly cemented. Nodular at base. Engulfs underlying Triassic sandstone.	Samples J-M 420 x 10^3 yrs. Samples L-M 510 x 10^3 yrs.

1/Measured from top downward.

2/J. N. Rosholt, written commun. 1979

DISSOLUTION AND KARST

Soluble rocks considered in this report include limestone, dolomite, gypsum, anhydrite, halite and associated potassium-bearing salts. Dissolution of these rocks can occur at any place in the environment where they come in contact with an open system of chemically unsaturated water. Dissolution occurs in the phreatic zone below the water table as well as in the vadose zone above the water table.

Karst is a type of topography which develops in regions overlying soluble bedrock. It is characterized by sinkholes, caves, valleys without stream channels, and underground drainage. Dissolution is the most dynamic process in producing karst. The most effective part of the process is the removal of material from rocks to increase permeability. Karst topography began to develop along the western edge of the basin at least as early as Triassic time (fig. 10).

The classic karst area of the world is in the limestone region in Slovenia, northern Yugoslavia, and much karst terminology has its roots in Slavik languages. However, karst regions in many other countries have attracted observation and a cumbersome regional terminology has evolved. Owing to the complexities that affect terminology, a brief glossary is provided here to define terms as used in this report. These definitions are based on consideration of work by Jakucs (1977), Jennings (1971), Monroe (1970), Sweeting (1973), and Thornbury (1969).

Glossary

Breccia chimney

A variety of collapse sink which penetrates one or more major stratigraphic units. It may have roots deep in the subsurface. A "breccia pipe".

Cockpit karst

Tropical karst topography containing many closed depressions surrounded by conical hills.

Collapse sink

A closed depression formed by the collapse of the roof of a cave. Also called collapse doline by some writers.

Doline

A basin, or funnel-shaped hollow, in limestone or other soluble rock ranging in diameter from a few meters to a kilometer.

Flute

Small, shallow, oval-shaped, closely spaced hollows formed by dissolution of surfaces of soluble rock. They are separated by parallel crests. They resemble current ripple marks in sand and are thought to indicate direction of flow.

Grike

A vertical or subvertical fissure in a limestone pavement developed by solution along a joint (Monroe, 1970). Grike-like features are also present along fractures in bedded gypsum in southeastern New Mexico. Their walls are characterized by extensive fluting.

Karst dome

Term introduced in this report for structural dome in karst terrain presumed to be formed by karst processes. The central core is believed to be analogous in structure and form to a tower which has been buried by collapse breccia.

Karst mound

Term introduced in this report for erosional remnant of collapse breccia.

Kegelkarst (German)

General term for several types of tropical humid karst characterized by numerous, closely spaced, cone hemispherical or tower-shaped hills having intervening closed depressions. See also cockpit karst, mogote, tower karst.

Mogote

A steep-sided hill of limestone, generally surrounded by nearly flat alluviated plains; karst inselberg.

Pepino

Rounded or conical hill resulting from karst action. A mogote. Elongate hill or ridge capped by mogotes.

Tower karst

Karst topography characterized by isolated limestone hills separated by areas of alluvium or detrital sand. The term tower karst is used in this report to include those features called cockpit karst, Kegelkarst, and mogotes.

Types of Dissolution

Most observations on karst decribed in the literature have been in limestone regions; whereas much of the karst in the Delaware Basin is developed on gypsum, anhydrite, and halite. These rocks are much more soluble than limestone and the dissolution processes are more direct. Carbon dioxide in the atmosphere and organic compounds on the Earth's surface combine with water to form acids which dissolve lime carbonates. These acids do not attack sulfates or chlorides which constitute gypsum and halite. Circulating fresh water is the primary solvent which produces karst in gypsum and salt.

Three general types of dissolution occur in the Delaware Basin in differing geologic environments. These are:

1. Local dissolution near the surface in the vadose zone. Sinkholes and some caves form in this zone.

2. Regional, or bulk, dissolution that may occur either in the vadose or phreatic zone. Some caves and solution breccias which develop regionally at a stratigraphic horizon are in this category.

3. Deep-seated dissolution which may be generated in the phreatic zone. Some caves such as Carlsbad Caverns are in this category. All these types of dissolution in gypsum, anhydrite,

and halite are dependent on the proximity of the soluble rocks to an open system of conduits, usually fractures, which allow free movement of fresh water.

Local Dissolution

Near-surface dissolution occurs where surface and ground waters penetrate soluble rocks through joint systems and related fractures. The fractures are further widened by dissolution to form trenches or grikes. Such trenches may be so deepened that their walls collapse to form collapse sinks filled with breccia (fig. 11).

Local, near-surface, dissolution includes the process of "solution-and-fill" described by Willis T. Lee (1925). Lee worked along the Pecos River in New Mexico and observed some of the spectacular karst features. He was impressed by the considerable volume of rock that was being removed by dissolution and the fact that dissolution cavities were being filled rapidly by sediments eroded from the surface. He estimated that on one occasion nearly 30,000 cubic yards of surficial sediments disappeared into a cavern during a storm in a single night (Lee, 1925, p. 117). He recognized the quantitative importance of the combined processes of dissolution and erosion in the formation of stream valleys.

The process of solution-and-fill occurs at relatively shallow depths and is an active process in gypsum terrain in southeastern New Mexico. At many places in Nash Draw arroyos disappear into caves. Commonly Permian gypsum in these caves has collapsed over Pleistocene or Holocene fill which results in an anomolous stratigraphic sequence. Dissolution is especially active near the surface in the north-central part of Nash Draw

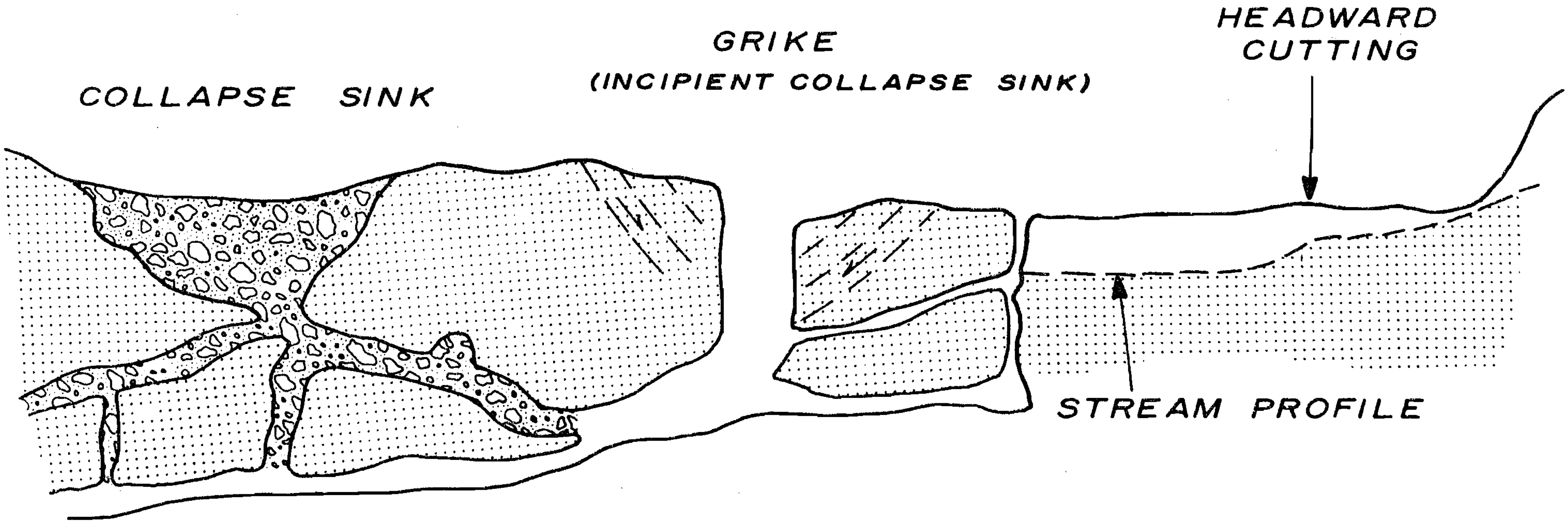

Figure II.--Erosion by solution and fill.

(SE1/4 sec. 33, T. 21 S., R. 30 E.). In that area, dissolution is removing the Forty-niner Member which underlies the main drainage system. Numerous collapse sinks pock this area. This dissolution is increasing the gradient of the drainage which results in active headward cutting of the arroyos in the upper reaches of Nash Draw.

Regional Dissolution

Blanket" or "regional" dissolution, occurs where chemically unsaturated water penetrates to a permeable bed through which it migrates laterally. Soluble rocks adjacent to the permeable beds are dissolved. This process is active in the central part of Nash Draw (S1/2 sec. 18, T. 22 S., R. 30 E.) where fractures in the Rustler Formation penetrate the Forty-niner Member to the Magenta Dolomite Member. Although the Magenta is not a major aquifer in the region, it carries enough water in Nash Draw to dissolve the superjacent Forty-niner in places. Tunnels, caves, and collapse sinks result at these localities.

Results of regional dissolution have been described in various rock types. Generally the resulting dissolution breccias are intraformational and are at stratigraphic positions which correspond to known evaporite intervals. They are described as "evaporite solution breccias" in the Devonian dolomite of Montana "for breccias which can be demonstrated to have resulted from the removal of evaporites" (Sloss and Laird, 1947, p. 1422-1423). Similar breccias have been described in Mississippian limestone and dolomite in Montana (Middleton, 1961; Roberts, 1966).

The process of regional dissolution has removed large volumes of rock in the Delaware Basin. Comparison of thicknesses of units within the Rustler Formation in Nash Draw and at the WIPP site indicate the effectiveness of this process. For example, in well-preserved stratigraphic sections in the subsurface at the WIPP site, anhydrite of the Tamarisk Member as much as 37 m (120 ft) thick separates the Culebra and Magenta Dolomite Members of the Rustler Formation. In the southern part of Nash Draw and near Malaga Bend brecciated Magenta may be separated from brecciated Culebra by no more than 1 m of insoluble clayey residue. At places the Magenta and Culebra are in direct contact. The intervening sulfates have been removed by dissolution.

This relationship between the Magenta and Culebra is portrayed by isopachs drawn on the Tamarisk Member between the two units (fig. 12, in pocket). This map shows a maximum thickness for this interval in the vicinity of the WIPP site where the interval is composed mostly of anhydrite and minor amounts of halite. Dissolution of the Tamarisk has occurred west of the site where the interval thins. Along the eastern edge of Nash Draw there is a thickening of the Tamarisk which may be attributed to expansion of the sulfates by hydration of anhydrite to gypsum. Southwesterly, the interval thins abruptly by dissolution, and in the vicinity of Malaga Bend the Magenta and Culebra are essentially in contact.

The net result of this regional dissolution is the subsidence of beds overlying the evaporites. Dissolution of gypsum in the Rustler Formation by this process accounts for some of the karst topography and rolling relief in Nash Draw and southward to the New Mexico State line along the Pecos River.

Solution breccias that result from regional dissolution may be distinguished from products of solution-and-fill by the absence of exotic fill debris in association with the breccia. At places where the Magenta rests directly on the Culebra, eroded surficial deposits do not replace the missing gypsum. This indicates that the path of dissolution was subterranean and was not open to the surface in the immediate vicinity.

The dissolution that removed gypsum from the Rustler Formation is presumed to be a continuing process in the subsurface but it can be observed only indirectly. Chemical analyses of ground water indicates that water in the Magenta may carry as much as 3,600 mg/L dissolved sulfate and 15,000 mg/L dissolved chloride. The water in the Culebra carries as much as 11,000 mg/L dissolved sulfate and 49,000 mg/L dissolved chloride (Mercer and Orr, 1979, table 2). Stratigraphic relations in the southern part of Nash Draw indicate that regional dissolution occurred there before Middle Pleistocene time. The Gatuna Formation of middle Pleistocene age (at least 600,000 years old) rests undisturbed in places on chaotic solution breccias of the Magenta and Culebra .

Anderson and others (1978) have proposed that regional breccias have formed in the Castile Formation in the subsurface at stratigraphic horizons corresponding to major halite beds. They propose that dissolution is an active process in the Delaware Basin beneath the main body of the Salado Formation. According to this hypothesis unsaturated ground water moves through the Capitan reef system or along "predisposed horizons within the evaporite body" (Anderson and others, 1978, p. 49) to dissolve the halite interbedded with anhydrite.

An open hydraulic system through which unsaturated water moves to dissolve soluble rock and to carry the solute away is a prerequisite for the formation of regional breccias. Such a hydraulic system does not appear to be in contact with the halite beds in the Castile Formation. Study of numerous geophysical logs of the Castile Formation in the Delaware Basin indicates that major beds of halite in the Castile have never been in close proximity to the Capitan reef system (fig. 12). Instead the halite beds in the Castile have been deposited in individual and discrete subbasins within the larger Delaware Basin. These halite beds are well preserved in the subsurface and have been protected from dissolution since their deposition by relatively impermeable enclosing beds of anhydrite. The hydraulic conductivity of the Delaware Mountain Group underlying the Castile is only 4.9 mm (0.016 ft) per day (Hiss, 1975) which is not conducive to the removal of a large volume of solutes. In addition, the halite beds in the Castile are also protected from the underlying Delaware Mountain Group by a basal anhydrite in the Castile.

At outcrops of the Castile Formation along the western edge of the Delaware Basin, minor intraformational breccias are commonly present at the approximate stratigraphic horizon of halite beds in the subsurface. These Castile breccias are not comparable with the large-scale, chaotic breccias common at the outcrop of the Salado Formation where major halite beds have been dissolved. It is here proposed that some dissolution of halite in both the Castile and Salado Formations occurred along the western and southwestern margins of the Delware Basin soon after the deposition of these formations. Removal of moderate amounts of halite could have occurred while the region was nearer to sea level and before it was loaded by deposits of sediments in Cretaceous seas (fig. 4). The time during which dissolution has occurred in the Delaware Basin is discussed in more detail later in this report.

Deep-seated Dissolution

Deep-seated dissolution in the phreatic zone forms some types of caverns. These caverns are dissolved in soluble rock below the water table by an open system of circulating fresh water. It has been postulated that Carlsbad Caverns in the Capitan and Tansill Formations southwest of Carlsbad was dissolved in the phreatic zone (Bretz, 1949, p. 451). The stalactites, stalagmites, and other cave formations were not deposited until after the cave complex was uplifted above the water table. Cave formations are deposited from saturated solutions by evaporation in the vadose zone above the water table.

Other karst features in southeastern New Mexico have been formed by deep-seated dissolution. Some of these features were first described as "structural domes" (Vine, 1960). However, there are great variations in the characteristics of so-called structural domes and in this report they are divided into three types as follows:

1. Breccia chimneys, or breccia pipes, are characterized by brecciated cores of rock that have collapsed into the chimney. Relatively younger rocks are collapsed into a chimney, or fissure, in older rocks.

2. Karst domes are true structural domes. Relatively older rocks form the center of the dome and strata are progressively younger outward from the center of the dome.

3. Breccia mounds are positive topographic features that result from differential erosion of regional breccia. Resistant portions of solution breccias survive as mounds. These features are not deep seated and may or may not be engulfed by caliche.

Breccia Chimneys

Breccia chimneys, or breccia pipes, are vertical cylindrical fissures which are filled with collapse breccia. Collapse of these features appears to have been initiated in a deep-seated aquifer system. In addition to fresh water, breccia chimneys appear to require a hydrostatic head which forces water up through fractures. Superficially these chimneys resemble collapse sinks but their vertical dimensions are distinctive. They may penetrate downward from the surface through several hundred meters of various rock types. Known breccia chimneys in the Delaware Basin are columnar bodies no more than 245 m (800 ft) in diameter at the surface.

Landes (1945) described breccia chimneys in the northern part of the Michigan salt basin. These breccia bodies range from a few feet to several hundred feet in diameter and are estimated to penetrate 425 m to 457 m (1,400-1,500 ft) of limestone, dolomite, and dolomitic sandstone of Devonian and Silurian age. They are believed to have formed during Devonian time.

Miotke (1971) described brecciated pipes in Keuper gypsum (Triassic) southwest of Hannover in West Germany. These features are less than 50 m (160 ft) in diameter and estimated to be about 140 m (455 ft) deep. They are recent features and are active at present. Other brecciated pipes, some of which are actively subsiding, have been described in West Germany by Prinz (1973) and Grimm and Lepper (1973).

Crater Lake in southeastern Saskatchewan is well documented as a chimney-shaped collapse structure (Christiansen, 1971). The feature is the result of downfaulting of two concentric fault zones which form an inner and outer cylinder of collapse beneath the lake. The inner cylinder is about 100 m (300 ft) in diameter and collapsed about 43 m (140 ft) before late Pleistocene time. The outer cylinder is about 213 m (700 ft) in diameter and collapsed 15-30 m (50-100 ft) during the last deglaciation about 13,600 years ago. This structure is believed to be the result of dissolution of salt in the subsurface.

Hill A

Hill A of this report was designated "Dome A" by Vine (1960, p. 1905). It is in Eddy County about 38 km (18.5 mi) east of Carlsbad on U. S. Highway 62-180 (SW1/4 sec. 35, T. 20 S., R. 30 E.). It is about 0.4 km (0.25 mi) north of the highway and is transected by a spur of the Atchinson, Topeka and Santa Fe Railroad. It is expressed as a low, circular breached hill with relief of about 12-15 m (40-50 ft) and about

370 m (1,200 ft) in diameter. During the present study, Hill A was mapped at a scale of 30 m to 25 mm (100 ft equals 1 inch) and the map was reduced for presentation in this report (fig. 12, in pocket).

The central part of Hill A has been eroded to form a shallow basin with an outlet to the west. The rim of the hill is capped by Mescalero caliche which engulfs slopes dipping rather uniformly about 15^{0} away from the rim.

Dewey Lake Red Beds are exposed in the east, north, and west sides of the shallow basin. These beds are lithologically typical of the formation and dip away from the center of the hill. These dips average about 15° but locally steepen to 20°-22°. Rocks of the Triassic Dockum Group are well exposed along the east and south side of the basin with dips approximately parallel to the underlying Dewey Lake Red Beds.

Superficially Hill A has some of the characteristics of a collapse sink. Within the basin, brecciated debris composed of angular blocks of Triassic claystone, sandstone, and conglomerate are confined within a circular area about 245 m (800 ft) in diameter. The circular contact surrounding the central brecciated core is a fracture and was termed a "peripheral fault or ring-fault" by Vine (1960, p. 1905). He stated that the brecciated core is composed of blocks similar to the Triassic beds exposed around the flanks of the hill but with greater range in lithologic character. He indicated that some breccia was derived from rocks stratigraphically higher than any now exposed around the flanks. Mapping completed during the present study is in agreement with Vine's observations but some details can now be added. The collapse breccia at the surface in Hill A is composed largely of clay, coarse sandstone, and conglomerate derived from Triassic rocks. All fragments of the breccia had been lithified before collapse. The breccia debris ranges in size from small fragments to large angular blocks 4 to 5 m in diameter.

An exposure of gravel in the Gatuna Formation no more than 0.5 m (1.5 ft) thick fills a minor channel on the north side of Hill A. This gravel cuts across the peripheral faults and rests unconformably on the brecciated central core. Clasts in that gravel are as much as 5 cm in diameter and include abundant fragments of pisolitic caliche similar to the Ogallala caprock caliche exposed along Mescalero Ridge to the east. In addition there are clasts of quartzite and chert pebbles similar to those in Triassic rocks and presumably are recycled from those older conglomerates.

Overlying the Gatuna gravel is a structureless caliche with abundant root casts. The Mescalero caliche is usually a pedogenic deposit that accumulated on physiographic surfaces after Gatuna time; whereas the structureless caliche at Hill A appears to have been deposited in a small, relatively moist, closed basin. This caliche is laterally continous with the Mescalero caliche and is presumed to have been deposited contemporaneously.

Both the Gatuna gravel and the structureless caliche overlying the Gatuna were deposited in a basin that formed after the central portion of Hill A had collapsed. This interpretation of Hill A as a depositional basin requires topographic conditions to have been much different in the past. The Gatuna gravel is now at a higher elevation than the surrounding terrain which indicates substantial differential movement since Gatuna time.

The locus of this movement was around the rim of Hill A where the structure of the Mescalero caliche indicates that the adjacent terrain has subsided relative to the rim. Columnar structures at the base of the Mescalero on the east side of Hill A are tilted about 15^{o} from vertical. This indicates that tilting occurred after deposition of the caliche because columnar soil structures are normally oriented vertically. The subsidence of the surrounding terrain is believed to result from regional dissolution of soluble rocks from the underlying Rustler Formation after collapse of the chimney.

Normally in this region the Mescalero caliche has a distinctive morphology with nodular carbonate at the base grading upward in turn into columnar, massive and laminar caliche. Around Hill A, this morphology has been disrupted by repeated dissolution and recementation. At places on the south flank of Hill A the Mescalero is a network of pipes and fracture fillings. This suggests dissolution of the caliche on a slope after its formation.

It is also significant to the interpretation of geologic history that at Hill A neither Gatuna gravel nor Mescalero caliche are intermingled with the collapse breccia. Instead, both the gravel and the caliche rest undisturbed on the collapse breccia which indicates that the major collapse occurred before either gravel or caliche were deposited.

Mapping indicates that the fracture along which collapse occurred is circular in plan and essentially vertical. The depth to which collapse has occurred is notable. A hole (WIPP 31) has been drilled in Hill A from the surface to a total depth of 258 m (820 ft). Nearby exploration holes for potash indicate that the Salado Formation should be no more than 215 to 221 m (700-720 ft) below the surface. The Salado Formation was not encountered in the drilling at Hill A. Instead, the entire interval from the surface to total depth was composed of collapse breccia of Dockum, Dewey Lake, and Rustler.

At 231 to 232 m (751-754 ft) below the surface a block of anhydrite was encountered. It is presumed that this block was derived from the Rustler Formation which would normally be at least 7.7 to 15 m (25-50 ft) above this level. There is no evidence that the anhydrite had been even partially hydrated to gypsum. This suggests that the collapse was abrupt. At places in the subsurface selenite veinlets cut across breccia fragments indicating that sulfate-bearing solutions were present after brecciation and collapse.

The history of Hill A may be summarized as follows:

1. Major collapse dropped Triassic rocks stratigrahically below the surrounding terrain during early Gatuna time. Collapse breccia of Triassic rocks are in contact with Dewey Lake Red Beds of Permian age. No sediments are present representing the time from Triassic to Gatuna. This collapse occurred while Triassic rocks were thicker in the vicinity of Hill A. The nearest continuous exposures of Triassic rocks at present are along the western edge of Nimenim Ridge about 1.6 km (1 mi) north of Hill A.

2. The area surrounding the collapse was eroded and the Gatuna gravel was deposited in a closed depression which formed as a result of the collapse.

3. Following Gatuna time the region was relatively stable and the Mescalero caliche formed as part of a soil profile over an extensive area. A shallow pond was present periodically over the collapse feature indicating it was still a local basin.

4. The area surrounding Hill A subsided, probably as a result of regional dissolution. During this subsidence the Mescalero caliche was tilted as much as 15°.

5. Hill A was breached by erosion which is a continuing process.

Hill B

Hill B is adjacent to Hill A (fig. 12). It is a dome-shaped prominence with about 15 m (50 ft) relief. It is mostly engulfed by Mescalero caliche but it is breached on the west and south sides where underlying rocks are exposed. Its internal structure is not apparent but some pre-caliche rocks are brecciated.

Rocks exposed in the breached part of Hill B include Dewey Lake Red Beds, undifferentiated Triassic rocks, and the Gatuna Formation. Some Triassic rocks in the center of the hill and Gatuna rocks along the northern edge of the hill are extensively brecciated; whereas at other localities these rocks appear to be folded but unbroken. A collapse fracture system similar to the circular system in Hill A was not detected.

Hill C

HIll C is a dome-shaped feature about 0.5 km (0.3 mi) west of the Maroon Cliffs (fig. 13). It has relief of about 30 m (100 ft) and is deeply breached at several places. It is flanked by the Mescalero caliche which engulfs the Gatuna Formation and brecciated Triassic rocks with angular blocks of conglomeratic sandstone 3 or more meters (10 ft.) across.

The Triassic rocks are brecciated wherever they are exposed on Hill C. In an arroyo on the western edge of the hill, Triassic rocks have collapsed against the Dewey Lake Red Beds. This is the only locality at the surface where at least a segment of a possible ring fracture may be observed. Other minor fractures offset the Mescalero caliche, but these do not follow a ring-like pattern. Locally on the south and west sides of Hill C, the Mescalero caliche has been displaced as much as 3 to 4 m (10-13 ft).

Underground workings at the Mississippi Chemical mine are in the potash ore zone beneath Hill C. At a point underlying the hill, a well-cemented breccia occupies a cylindrical, chimney-shaped body. This breccia consists of angular blocks of anhydrite and halite which have collapsed from overlying beds. It is assumed that this body of breccia is continuous from the mine workings to the surface.

The history of Hill C is similar to Hill A:

1. Rocks of Triassic age collapsed into a circular chimney. Neither the Gatuna Formation nor the Mescalero caliche were involved in this major event.

2. The Gatuna Formation was deposited in depressions overlying the area of collapse.

3. The Mescalero caliche was deposited across the entire area about 500,000 years ago.

4. The area surrounding Hill C subsided as a result of regional dissolution.

5. The Mescalero caliche has been fractured over parts of the area of collapse as a result of readjustment of the brecciated mass.

Origin of Breccia Chimneys

The only features in the vicinity of the WIPP site which can be proved to be breccia chimneys are Hills A and C. Both these features are expressed at the surface and have collapsed through more than one formation. It is presumed that both features bottom beneath the Salado Formation and that the chimney penetrates the entire formation.

It has been proposed that many and varied features in the Delaware Basin have been formed by brine density flow (R. Y. Anderson, written commun., 1978). According to this hypothesis, unsaturated water from underlying aquifers (Bell Canyon Formation and Capitan Limestone) rises through fractures in the Castile and Salado Formations from a hydrostatic head. Dissolution of salt increases the water density which causes the downward flow of brine. This initiates a flow cycle which dissolves chambers in the salt. Collapse of these chambers results in the formation of breccia chimneys.

This hypothesis outlines a feasible mechanism for explaining the origin of Hills A and C. Both of these features are superimposed on the Capitan aquifer system. In the area of these features, the Salado Formation rests on the Capitan Limestone or its backreef equivalents. Ground water flows easterly in this aquifer, but the easterly flow is retarded by fine-grained sediments filling the submarine canyon complex at Laguna (fig. 3).

During Pleistocene time the regional drainage system was at higher elevations than at present. About 2 miles north of Carlsbad (NE1/4 sec. 19, T. 21 S., R. 27 E.) collapsed blocks of cross-bedded Gatuna sandstone and conglomerate are at least 15 m (50 ft) above the present level of the Pecos River. In Pierce Canyon Gatuna channel gravels are more than 30 m (100 ft) above the Pecos. These relationships indicate the minimum altitude of the drainage system during Pleistocene time. It also indicates an increased hydrostatic head as compared with the present drainage system.

It is here suggested that the hydraulic head in the Capitan aquifer system was higher during Gatuna time which caused easterly movement of fluids in the system. The restriction of this flow by the submarine canyon complex at Laguna (fig. 3) resulted in upward migration of unsaturated ground water in fractures at the points now represented by Hills A and C. These fluids dissolved halite and allowed collapse at these points.

The relatively low transmissivity of the Capitan aquifer system in the vicinity of the submarine canyon complex at Laguna has been documented (Hiss, 1975, p. 181-199). Observation wells in the Capitan aquifer system which straddle this submarine canyon complex (Hiss, 1973) indicate that the hydraulic head in the Capitan aquifer system has been reduced in the vicinity of the Laguna submarine canyon and the transmissivity is the lowest known in the system.

Since Gatuna time, the Pecos River system has eroded downward to the Capitan aquifer system in the vicinity of Carlsbad. Although hydraulic heads in this aquifer system are nearly horizontal east of the Pecos as far as the Laguna Canyons, there is now intermittent flow to the west. This system is now at the surface near Carlsbad Springs along the Pecos, and these springs provide a mechanism for releasing the pressure of the hydraulic head. So long as this present natural balance is maintained, it is improbable that other breccia chimneys will form over the reef aquifer.

The hypothesis of brine density flow is not adequate to explain other domal features within the Delaware Basin. As noted elsewhere in this report, the Bell Canyon Formation underlying the Castile Formation is of low permeability. Owing to this low permeability, it is improbable that porosity and permeability of the Bell Canyon has ever been adequate to initiate brine density flow. In addition, this hypothesis does not provide for the disposition of large quantities of brine in the subsurface within the basin. In the vicinity of Hills A and C brine could pass through the Capitan aquifer in places and move ultimately outside the Delaware Basin; whereas brine within the basin would become trapped and immobile.

The Bottomless Lakes near Roswell, New Mexico, about 120 km (75 mi) north of Carlsbad, have some characteristics analogous to Hills A and C. These lakes occupy a cluster of collapse sinks in gypsum in the Artesia Group, a back-reef facies of the Capitan Limestone (fig. 5). The Artesia Group is underlain by the San Andres Limestone of Leonardian age which is a major artesian aquifer in that area.

One of the lakes, Lea Lake, flows at the surface with an artesian head. This lake is about 150 m (500 ft) wide, 290 m (950 ft) long, and 27 m (90 ft) deep (Barker and Navarre, 1959). The depth to the San Andres Limestone at Lea Lake is about 260 m (850 ft). Structure contour maps indicate several closed basins on the upper surface of the San Andres (Welder, 1980, p. 25, fig. 3). Some of these basins underlie similar features in valley fill and Lea Lake coincides with the eastern margin of such a closed basin. Welder (1980) attributes these basins to solution and subsidence.

It is improbable that ground water at Hills A or C ever came to the surface as springs similar to those at Bottomless Lakes. Anhydrite is preserved in the breccia at Hill A and was observed in the drill core. Blocks of halite are preserved in the brecciated core of Hill C in the underground workings of the Mississippi Chemical mine. The presence of these rocks indicates that sufficient water was never available to hydrate the anhydrite to gypsum or to dissolve the halite.

Karst Domes

Domes may be defined as roughly symmetrical structural features whose beds dip away in all directions from a central point. The strata in the central core of the dome are older than those on its flanks. In plan, domes may range from circular to elongate. The term "karst dome" is introduced in this report to designate unique structural domes which develop in a karst terrain as a result of dissolution and subsidence in salt and associated highly soluble rocks.

As here defined, karst domes are best developed in an area along the west side of the Pecos River near Malaga Bend (fig. 15, in pocket). Although much of this area is underlain by chaotic breccia of the Rustler Formation, some domes are symmetrical and nearly circular in plan. They are conspicuous features viewed from the air. At other places in this area, the domal structure is disrupted and indistinct. The presence of older rocks surrounded by younger strata can be observed only by tracing and mapping rock types on the ground.

An example of a symmetrical karst dome is about 1.4 km (0.8 mi) west of the Pecos River near Malaga Bend. (The southwest corner of sec. 19, T. 24 S., R. 29 E. is near the center of this dome.) This is about 200 m (650 ft) in diameter and nearly circular in plan. It rises about 10 m (35 ft) above the surrounding terrain. Pink to dark red gypsum and associated insoluble residues of the Salado Formation are exposed in the core. Chaotic breccia of the Rustler Formation caps the Salado core and the Culebra Dolomite Member of the Rustler is draped around the rim of the dome. Variations of these relationships are displayed on several dozen features in the vicinity of Malaga and Malaga Bend.

A search of the literature has failed to locate previous descriptions of karst domes elsewhere in the world. The domes near Malaga Bend have been included with breccia chimneys and karst mounds as "structural domes" (Vine, 1960). Although all these features are superficially similar, the structure, geologic setting, and origin of karst domes are distinctive.

Origin of karst domes: Although the nature and origin of karst domes are unique, they can be compared with so-called "towers" which develop by dissolution on limestone terrains in tropical regions. Such terrain has been called "tower karst", "cockpit karst" or "Kegelkarst". Tower karst has been described in Puerto Rico (Monroe, 1976), Brazil (Tricart and da Silva, 1960), Malaysia (Wilford, 1964) and China (Silar, 1965). Towers in these regions vary considerably in form, and the types of relief encountered have been summarized by Balazs (1973).

Tower karst is characterized by steep-sided discrete limestone hills which rise from 100 m to more than 300 m above the surrounding terrain. They may be 200 to 300 m in diameter at the base and rise to sharp cones at their peaks. Towers are of many shapes and forms which have given rise to many local terms for these features. Other names for associated tower-like features include pepinos and mogotes (Monroe, 1976; Miotke, 1973) (fig. 16).

Towers may be as closely spaced as 5 to 20 full tower forms per square kilometer (Balazs, 1973, p. 21). In some regions, towers are so closely spaced that colluvial debris chokes the valleys between them to form an impenetrable mass of broken rock.

Towers form in relatively pure limestone in tropical regions of high rainfall. Karst domes are here compared with towers. Although these domes are in a temperate region of moderate rainfall, they are formed in much more soluble rock salt. The karst domes are considered to have

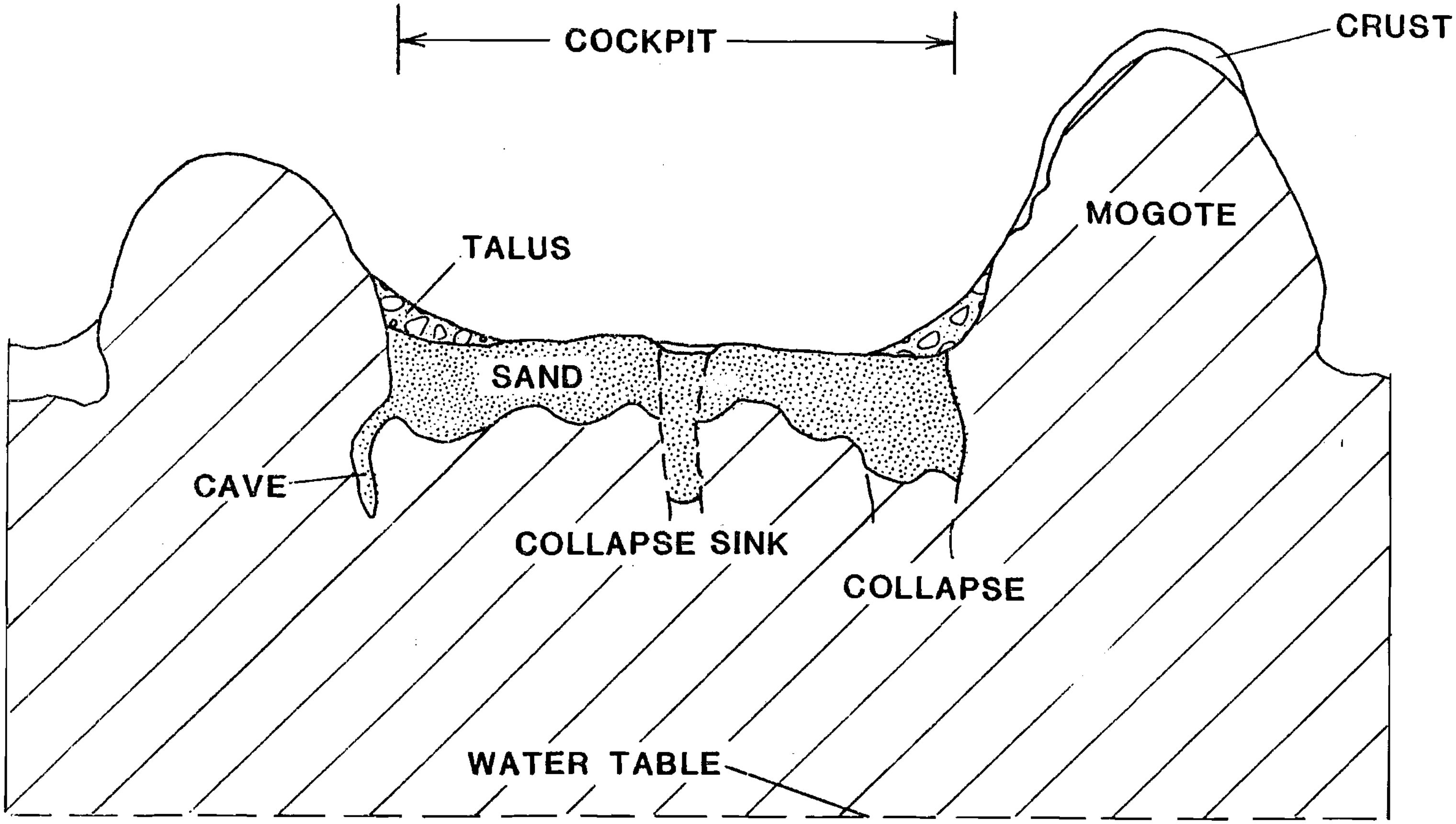

Figure 16.--Diagram of mogotes, Puerto Rico. Mogotes may be as much as 200 meters high (modified from Miotke, 1973).

formed in the subsurface near the dissolution front of the Salado Formation. Near this front the upper surface of the Salado is highly irregular and dissected by dissolution channels. Insoluble residues of the Salado Formation and overlying Rustler Formation subside into these channels to bury and protect the core of the karst dome as it develops.

Some workers have considered that towers in the tropics develop along faults and joints where dissolution forms deep trenches or grikes. However, in many areas there is no evidence that dissolution is related to a joint system (Sweeting, 1973, p. 276). In the vicinity of Malaga Bend the distribution of karst domes appears to be random and they are presumed to have been initiated on an irregular dissolution surface.

Karst Mounds

Both karst domes and karst mounds form in areas where regional dissolution breccias are extensive. It is presumed that karst domes have been modified somewhat by erosion, but erosion is a secondary process in their origin. However, karst mounds are primarily erosional features. They are residual hills of dissolution breccia which have been carved almost entirely by erosion.

Many karst mounds are present along the Pecos Valley, particularly on the east side of the Pecos River (fig. 17 in pocket) from Malaga Bend southward to near Red Bluff. They are roughly circular to elongate and highly irregular in plan. Many are capped by Mescalero caliche or Culebra Dolomite Member, some are no more than mounds of brecciated debris derived largely from insoluble residuum of the Rustler Formation. They vary from circular features less than 100 m in diameter to discontinuous masses more than a kilometer in length. Their relief varies from about 3 m to as much as 10 m.

Karst mounds appear not to have roots below the surficial dissolution breccia of the Rustler Formation, whereas both karst domes and breccia chimneys are deeply rooted in the Salado or older formations. A karst mound in Nash Draw (fig. 18) was drilled to determine the nature of its lower limits (WIPP 32, SE 1/4 sec. 33, T. 22 S., R. 29 E.). This drill hole (WIPP 32) may be compared with a drill hole about 1,000 m to the east (WIPP 29, SE 1/4 sec. 34, T. 22 S., R. 29 E.). WIPP 29 was drilled to determine subsurface stratigraphy and examine evidence for dissolution above undisturbed salt in the Salado Formation. At that place markers in the Salado Formation from the 101 marker bed downward through its Vaca Triste Sandstone Member (Adams, 1944) and including the 118 marker bed are present. These beds are present likewise in WIPP 32. This proves that the hill where WIPP 32 was drilled is not a deep-seated dissolution feature. At WIPP 32, beds are brecciated in the Rustler Formation but this results from blanket, near-surface dissolution. Many of the prominent hills and mounds that have surficial resemblance to breccia chimneys and karst domes are only mounds of surficial breccia.

Age of Brecciated Topographic Features

As indicated above, the major collapse of breccia chimneys occurred during or near the end of Gatuna time and before the formation of the Mescalero caliche. Karst domes and karst mounds appear to have formed about the same time. Although the Mescalero caliche commonly caps both karst domes and karst mounds, the Mescalero is not brecciated at any of these localities, nor are fragments of the Mescalero mixed with the breccia. At all localities where the Mescalero is observed around the features, it engulfs the underlying breccia.

At two localities near Malaga Bend, the Gatuna Formation is intermixed with some breccia and may itself be brecciated in karst domes. At both localities, the Mescalero engulfs the Gatuna Formation and its breccia. For these reasons, breccia chimneys, karst domes, and karst mounds are believed to have formed during Gatuna time but before the beginning of deposition of the Mescalero caliche.

Miscellaneous Karst Features

Other topographic prominences in southeastern New Mexico have been shown as structural domes or related features on index maps of other workers (Vine, 1960). Although all these features are conspicuous on aerial photographs and are easily located on the ground, field examination indicates that some are no more than caliche-capped hills which were carved before Mescalero time.

One of these hills is in the northwestern part of Nash Draw (fig. 19). There caliche covers Dewey Lake Red Beds which are gently folded but not brecciated. Dips as much as 19° were measured but there is no regular pattern to the folding. These folds are presumed to result from dissolution and hydration of evaporites in the underlying Rustler Formation rather than being related to local pipe formation. Some caliche-capped hills southeast of Malaga Bend (fig. 17) are similar features, although many of these are karst mounds.

In the southern part of Nash Draw a prominent hill has been indicated as a "structural dome" (Vine, 1960). Complex folding and brecciation at this locality is the result of collapse into local caverns which have since been exhumed (fig. 20). This is an example of ancient "solution and fill" which occurred during Gatuna time. The Gatuna Formation is brecciated and overlain in places by remnants of collapsed Magenta Dolomite Member of the Rustler. This prominence is somewhat unusual because it is not now capped by caliche.

Dissolution During Geologic History

Major dissolution occurs while land masses are above sea level. Regional uplifts have occurred in southeastern New Mexico following both Permian and Cretaceous times. Consequently, there is a long history of dissolution in the Delaware Basin. Although Castile and Salado rocks are transitional in the central part of the basin, some dissolution occurred locally after Castile and before Salado time (Adams, 1944, p. 1622-1624). Dissolution occurred again along the western edge of the basin after Salado and before Rustler time and during Triassic time (Adams, 1944, p. 1622-1624). In addition to being above sea level throughout Triassic time the region was above sea level through Jurassic and again from the beginning of Tertiary time to the present. In summary, the region has been above sea level for a minimum of 154 million years and below sea level less than 71 million years since the end of Permian time (see table 1).

Adams (1929, p. 1050) believed that as much as 123 m (400 ft) of upper Permian beds may have been removed from the Delaware Basin by erosion during Triassic time. McGowen and others (1977, fig. 3.42) indicate the depositional wedge-edge of the Dockum Group along a line trending northeasterly through Eddy County, New Mexico, near the present westernmost outcrops of the Dockum. They also indicate stream deposits trending easterly across the Delaware Basin from a highland in the vicinity of the present Sacramento uplift. These stream systems would have eroded and dissolved parts of the Permian evaporite sequence along the western margin of the basin.

Stratigraphic relations of Triassic rocks preserved in the western part of the Delaware Basin also indicate that erosion and regional dissolution in the area of the present Pecos drainage occurred before and during Triassic time. Triassic rocks rest on the Permian Culebra Dolomite Member of the Rustler in an area of collapse breccia about 8 km (5 mi) northeast of Carlsbad (secs. 12 and 13, T. 21 S., R. 27 E.). Along the east side of the Pecos River near Red Bluff Reservoir (NE 1/4 NW 1/4 sec. 21, T. 26 S., R. 29 E.) blocks of Triassic conglomerate about 150 to 180 m (500-600 ft) across rest on, or adjacent to, the Culebra. The Magenta Dolomite Member of the Rustler is absent.

These relations suggest that Triassic rocks were deposited on an erosion surface which cut across the Rustler Formation. It is assumed that dissolution accompanied this erosion (fig. 10). Some of the dissolution breccias described in the Castile and Salado in the western and southwestern part of the Delaware Basin (Anderson and others, 1978) may have formed at this time. The areas where Triassic rocks appear to have lapped across the Rustler coincide remarkably with the areas of halite dissolution in the subsurface.

During the Jurassic Period that followed, southeastern New Mexico continued to be above sea level and was an area of nondeposition. Although erosion was a dominant process, there is no evidence for mountain building in the region during this time.

Much evidence for Jurassic paleogeography lies outside southeastern New Mexico. The nearest deposits of Jurassic age are in the Upper Jurassic Malone Formation in the Malone Mountains, Hudspeth County, Texas, about 177 km (110 mi) southwest of Carlsbad. These rocks were deposited in a near-shore marine environment (Albritton, 1938, p. 1764) in a sea that extended far to the south in Mexico. Continental deposits, including windblown sand, of Jurassic age are present about 282 km (175 mi) north of Carlsbad in east-central New Mexico. These sediments were derived from the south. These paleogeographic relations indicate that southeastern New Mexico was above sea level during all of Jurassic time (at least 54 m.y.).

Lang (1947) implied that Cretaceous strata south of Whites City rested on Dewey Lake Red Beds (fig. 9). However, regional geologic relations do not support his interpretation. Lang's diagram (1947, fig. 1) is drawn along a north south line but his interpretation of the stratigraphic relations may be compared with figure 10 of this report. At Lang's locality, resistant debris from the Rustler, Dewey Lake, or Triassic units is not observed. The gravel he described appears to be derived entirely from conglomeratic Cretaceous rocks. About 2 km south of Lang's locality angular blocks of Culebra Dolomite Member are mingled with Cretaceous debris and there is an exposure of Culebra apparently resting on Castile gypsum, nearby. A careful search was made in this immediate area for other rock types but they were not observed.

These field relations suggest the following conditions along the western edge of the Delaware Basin in New Mexico:

1. The Salado Formation has been removed completely from this area allowing the Culebra Dolomite Member of the Rustler Formation to rest on the Castile Formation.

2. Rocks above the Culebra Dolomite Member and below Cretaceous strata were never deposited or were removed before Cretaceous deposition.

3. Cretaceous rocks lap westward across the Culebra Dolomite Member to rest on earlier Permian rocks in the Cornudas Mountains to the west.

The above evidence is presented to show that major dissolution and erosion occurred in the Delaware Basin before Cretaceous time (fig. 10). However, erosion and dissolution did not cease with the advance and withdrawal of Cretaceous seas. The collapse sink occupied by Cretaceous debris at Lang's locality formed after lithification of the Cretaceous sediments, presumably during Cenozoic time.

The many active, shallow karst features in the Delaware Basin indicate that dissolution is continuing in the region today, but there is no positive evidence that deep-seated dissolution is an active process within the basin. However, owing to the long history of dissolution in this region, it appears impractical to estimate a rate of dissolution or a rate of withdrawal of halite along a hypothetical front. The rates of dissolution proposed previously by Bachman and Johnson (1973, p. 21) and Bachman (1974, p. 68-71) were based on the assumption that all measurable dissolution occurred during Cenozoic and Quaternary time. Those estimates are now considered to be invalid because a consideration of the amount of dissolution which probably occurred during Triassic and Jurassic time would derive a much slower rate of dissolution for the region.

The estimates for the age of Nash Draw proposed by Bachman (1974, p. 68-71) are also too young. More recent work indicates that much of Nash Draw formed by solution-and-fill before Mescalero, and even Gatuna, time. Although there are places in Nash Draw where the Mescalero caliche has slumped since its deposition, there are many localities along the east side of Nash Draw where the caliche was deposited on the slopes and in the bottom of an ancient topographic basin. This caliche has been weathered and eroded but remnants of depositional morphology are present.

PALEOCLIMATE

Over long intervals of geologic time climate, particularly rainfall and evaporation, influences the ground-water regime which in turn is the major factor in evaporite dissolution. The present climate in southeastern New Mexico is warm semiarid to arid. Records over the past 60 years at Lake Avalon near Carlsbad indicate that average annual rainfall is about 280 mm (11 in.). During the past 20-30 years the annual mean temperature has been about $17^{o}C$ ($62.8^{o}F$) and annual pan evaporation has been about 2,500 mm (98 in.) (Gabin and Lesperance, 1977, p. 123).

Climate fluctuates from year to year, but cumulative effects of long-range variations are imperceptible because they span longer time than recorded history. For this reason the study of paleoclimate is dependent on observations in many disciplines. These include the study of isotopes such as radiocarbon and uranium series, paleobotany and pollen records, geomorphology and soils (Lamb, 1977).

Climate during Triassic time fluctuated from arid to humid, tropical. During arid intervals Dockum lakes were reduced in size and their sediments contain gypsum crystals and salt hoppers (McGowen and others, 1977, p. 39). During humid phases streams meandered across the terrain which supported a tropical to subtropical flora (Ash, 1972, p. 127). The humid tropical climate would have been particularly conducive to the dissolution of evaporites.

Hallman (1975, p. 178) believes that during Jurassic time world-wide climate was more equable than climate today. There were no polar ice caps and there was a more modest decline of air and sea temperatures with increasing latitude. Widespread deposits of Lower and Middle Jurassic eolian sand and Middle and Upper Jurassic gypsum in northern New Mexico indicate a warm arid climate in that area. Jurassic time may have ended with an increase in humidity because stream deposits with some interbeds of carbonaceous shale from late in the Jurassic Period trend northerly from central New Mexico.

In both Europe and North America climate deteriorated through the Tertiary. There was a cooling trend throughout the period (West, 1977, p. 212-213; Wolfe, 1978), and near the end of Tertiary time polar ice caps formed. The first appearance of ice-rafted debris in the North Atlantic was about 3 million years ago, but this may not have marked the first expansion of ice sheets over Europe and North America (Berggren and Van Couvering, 1974, p. 150-151). However, this Tertiary ice-rafted debris indicates that ice caps began to form before Pleistocene time. In the southwestern United States there was progressive deterioration during Miocene and Pliocene time from mild climate with arboreal flora through lush grasslands which were in turn dessicated by extreme lowering of the water table. Windblown sand with interbedded carbonate pans is a major facies of Ogallala sedimentation in southeastern New Mexico.

Quaternary Climate

The Quaternary Period includes the Pleistocene and Holocene Epochs. Pleistocene time began about 1.8 million years before the present (BP). It was a time of world-wide lowering of temperatures, accumulation of massive ice sheets, and advance and retreat of glaciers on the continents. Distribution of plants and animals changed with the wide fluctuations in climate.

The time-stratigraphic classification of the Quaternary generally accepted in the glaciated regions of the central United States is shown on Table 4. Each glaciation stage was accompanied by multiple glaciations (Frye and Willman, 1965, p. 86; Frye and others, 1965). Some of these individual glaciations are marked by the formation of interglacial soils. All the major glaciation stages are marked by long interstadial intervals of climate moderation and soil formation.

Correlation of these classic units within parts of the central United States as well as to events in the Southwest is tentative except for localities where absolute ages are comparable. "Some classic concepts of Quaternary stratigraphy developed elsewhere are not applicable to the arid regions of the southwestern United States" (Hawley and others, 1976, p. 243), and "interpretation of Quaternary history in much of the lower Pecos Valley... is complicated by the long history of subsidence resulting from dissolution of evaporites" (Hawley and others, 1976, p. 246).

Table 4.--Quaternary geologic-climate and time-stratigraphic units in the central United States and correlations to southeastern New Mexico (modified from Hawley and others, 1976, table 3)

CENTRAL UNITED STATES	SE NEW MEXICO	AGE (yrs BP)
Holocene	Playas, windblown sand	10,000
Wisconsinan (G)	Streams, springs, lakes	75,000
Sangamon (I)	?	
Illinoian (G)	?	
Yarmouth (I)	Berino soil	300,000
	Mescalero caliche	500,000
Kansan (G)	Gatuna Formation	600,000
Aftonian (I)	?	
Nebraskan (G)	?	

G-Glacial; I-Interstadial

There is a major hiatus between Pliocene and Pleistocene deposits in southeastern New Mexico and early Pleistocene time apparently is not represented. The Gatuna Formation may represent part, or all, of early and middle Pleistocene time but there is no direct evidence for this range in age. The presence of Pearlette type "O" volcanic ash in the upper part of the Gatuna indicates only that the upper Gatuna is equivalent to middle Pleistocene, late Kansan, time.

Kansan time in the Great Plains region of western Texas, Oklahoma, and Kansas was marked by deep stream incision, and Kansan alluviation in that area displays a coarse texture (Frye and Leonard, 1957, p. 6). In southeastern New Mexico the Mescalero scarp east of the Pecos River was carved (Frye, 1972). Moist climate which supported prairie grasses and belts of trees and shrubs along valleys characterized this time (Frye and Leonard, 1957, p. 9).

Coarse gravels in the Gatuna Formation suggest that during its deposition streams had more carrying capacity than at any time since. Overbank and flood plain deposits in the Gatuna commonly have abundant molds of grasses and reeds which indicate more widespread bodies of water than at present. Collapse sinks in the Gatuna indicate that dissolution was an active process in Nash Draw and elsewhere in southeastern New Mexico.

On the Great Plains to the east "the buried Yarmouth soil profile reflects development under grasslands cover" (Frye and Leonard, 1957, p. 10). The Mescalero caliche and Berino soil reflect similar conditions on the geomorphic surface across the WIPP site. The physical characteristics of these two soils indicate continuous semiarid climate during the past 300,000 to 500,000 years. There has been adequate rainfall to leach all carbonates through the Berino soil and into the underlying Mescalero caliche. There has not been enough rainfall to leach away the Mescalero. The preservation of these two soils suggests annual rainfall of not less than 75 to 100 mm (3 to 4 in) nor more than about 750 mm (30 in) over extended periods. Extreme humidity would have served to dissolve the caliche; extreme aridity would have dessicated the Berino soil.

Wisconsin climate has been studied extensively through various disciplines, and there is an overwhelming mass of literature on this time interval. Even with all these studies there is not a unanimous opinion on the nature of that climatic regime. Berggren and Van Couvering (1974, p. 148) state that "past climates are beyond our grasp...." After studying ancient plant communities Van Devender and others (1979, p. 28) suggest that it is the present climate which is unusual. They state that most biota have lived longer under Pleistocene glacio-pluvial climates than under the present interglacial conditions.

Many attempts to decipher Pleistocene climates have concentrated on the last full-glacial interval about 25,000 to 13,000 years BP. It has been commonly accepted that glaciation stages in the northern and central United States have been accompanied by periods of higher rainfall, or "pluvial" periods (Leopold, 1951; Antevs, 1954; Reeves, 1966, 1973); but this concept of "pluvial" periods has recently been challenged. Galloway (1970) believed that precipitation during the last full-glaciation in the southwestern United States was from 80 to 90 percent of present amounts. Brackenridge (1978) calculated water budgets and recorded lowest elevations of downslope movements of saturated regolith (permafrost or cryogenic deposits) and concluded that the last full-glacial climate was cold and dry. However, Reeves (1973) studied playa depressions on the High Plains and believes that during late Pleistocene time increased runoff was necessary to maintain lake levels. Dury (1973) reconstructed the paleohydrology of closed lake basins in New South Wales, Australia, and rejected any hypothesis that former lakes were associated with reduced precipitation.

Two recent symposia on biotic communities in the Chihuahuan Desert and the Guadalupe Mountains provide basic data for interpreting the Wisconsin and Holocene climatic fluctuations in southeastern New Mexico. Only the general interpretations presented in those symposia are outlined here.

From a fauna in Dry Cave about 25 km (15 mi) west of Carlsbad, Harris (1977, p. 38) deduced that before the last full glacial (more than 25,000 years BP) temperatures were less extreme, summer temperatures cooler, and moisture was more effective. The peak of the late Wisconsin pluvial may be represented by another fauna in Dry Cave (about 15,030 ± 210 BP).

From this fauna Harris (1977, p. 38-46) suggests southeastward migration of species from the Great Basin region and a different seasonality of precipitation. He believes that a low precipitation was uniformly distributed throughout the year.

Elsewhere Harris (1970) has compared the fauna and flora of Dry Cave with the present Transitional Life Zone of central Wyoming. He believes the biotic community included sagebrush (Artemesia tridentata) intermingled with grasses on gentle north-facing slopes. South-facing slopes carried a well developed grassland with occasional Ponderosa pine. The presence of prairie dog bones indicates deeper soil mantle than found today in that area (Harris, p. 1970, p. 17).

Logan and Black (1979, p. 156) postulate that approximately 11,000 years ago climatic conditions in the southern Guadalupe Mountains may have been similar to present climatic conditions in the Black hills of South Dakota. Van Devender and others (1979, p. 26) reject the concept of extreme Pleistocene timberline depression of 1300 to 1400 m proposed by Galloway (1970).

In east-central New Mexico Leonard and Frye (1975) studied late Pleistocene molluscan faunas and concluded that they indicate a pluvial period from 18,000 to 13,000 BP. At that time numerous small lakes and ponds dotted that region. They observe that the volume of present lakes in that region fluctuates with seasonal precipitation, temperature and air movements but that the lakes seem to be in equilibrium with runoff and evaporation. They state that this delicate balance can be disturbed by changes in precipitation, fluctuations in rates of evaporative loss or a combination of these two factors. "Loss from a lake surface is...not closely related to mean annual temperature, but responds to extremes." They conclude that the small pluvial lakes of the 18,000 to 13,000 BP period maintained their levels by decreased evaporation during lowered summer extreme temperatures and by increased precipitation (Leonard and Frye, 1975, p. 30).

Wells (1966, 1977, 1979; Wells and Berger, 1967) has developed a regional approach to late Quaternary climate through the study of pack rat (Neotoma) middens. These middens are compacted refuse heaps of plant food debris, fecal pellets and dried urine. Older deposits are dark brown or amber-colored masses veneered by wood rat urine. They are amenable to study by radiocarbon dating and analysis of plant communities. Radiocarbon dates show ages from modern, Holocene, through the last full glacial to more than 40,000 BP.

Pack rat middens have been studied over many parts of the southwestern United States from Frenchman Flat in western Nevada (Wells and Berger, 1967) to the Chisos Mountains in the Big Bend region, Texas (Wells, 1966). In the Chisos Mountains there was a downward displacement of woodland vegetation (pinyon-juniper-oak) as much as 800 m (2620 ft) during the Wisconsin pluvial, but there was a lack of displacement of montane species (Ponderosa pine, Douglas fir and broad-leaf deciduous trees) (Wells, 1966). In the latitude of Frenchman Flat, Nevada, there was a similar displacement of about 600 m (1970 ft) of juniper woodlands as late as 9000 to 10,000 BP (Wells and Berger, 1967). In both the Chisos Mountains and at Frenchman Flat there was coexistence of some desert or semi desert species with the woodland flora.

In summarizing data from many localities in the southwestern United States Wells (1979, p. 324) believes that there was a northwest to southeast increase in the monsoonal gradient of summer rain with a relatively cool dry Mojave region on the northwest and a relatively warm moist Chihuahuan province on the southeast. This monsoonal gradient was similar to the present gradient, but the Wisconsinan gradient was somewhat steeper. In the northern Chihuahuan Desert there was a dominance of pinyon, juniper and scrub oak over the region but there was no trace of creosote bush (Larrea divaricata) in deposits of pluvial age (Wells, 1977, p. 79). The present desert flora with its dominance of creosote bush evolved less than 11,500 years ago (Wells, 1977, p. 82).

Observations during the present study confirm more humid conditions--a "pluvial period"--near the end of Pleistocene time in the vicinity of the WIPP site. A perennial lake in Clayton Basin to the north of the site covered at least 18 sq km (7 sq mi). Apparently the waters of this lake were high in sulfates and the only abundant inhabitant was a common snail (Physa virgata). The shells are thin-walled, but this species is hardy and wide spread (A. L. Metcalf, written commun., July 24, 1980).

Fossil clams (Megalonaias gigantea) are common in gravels in the bed of the Pecos River near McMillan Dam (NW1/4 sec. 11, T. 20 S., R. 26 E.). These shells have been dated 13,620 ± 300 BP (E. Spiker, USGS Radiocarbon Determ. 12/7/78, W-4182). They lived in relatively clear, running water following an influx of carbonate gravel derived from the northern Guadalupe Mountains. The gravels in the river bed are assumed to be late Pleistocene and indicate that the Pecos River had incised to its present position before the end of Pleistocene time.

In summary, the concept of pluvial periods in southern regions which accompanied glaciations in the north has more basis than the concept of cold, dry full glacial periods. During periods of glaciation temperatures, although cooler throughout the year, may not have been as extreme. Annual rainfall was somewhat higher but distributed throughout the year and more effective. Evaporation was lower and runoff increased. Some life zones were considerably depressed in elevation as compared with present zones and pinyon-juniper-oak woodland species mingled with semidesert species.

It may be assumed that dissolution of evaporites was more intense during pluvial periods. Erosion is an effective agent during periods of aridity because vegetation which holds soils and promotes infiltration is more sparse. Infiltration and dissolution are processes which accompany periods of effective moisture.

SUMMARY AND CONCLUSIONS

The purpose of this study has been to determine if there are continuing geologic processes in the Delaware Basin which may pose a threat to the proposed WIPP site. The preserved geologic record of erosion and dissolution have been examined to learn the pattern of these processes in geologic history.

The salt beds at the proposed site have been preserved for about 225 million years. Some dissolution, in places of major proportions, has occurred in the Delaware Basin intermittently during this long period of time. The Salado Formation itself has been dissolved and preserved only as a mass of chaotic breccia along its western line of outcrop. The nearest exposures of this breccia to the WIPP site are in karst domes in the vicinity of Malaga Bend 19 km (12 mi) southwest of the proposed WIPP site. The main belt of outcrop of Salado breccia is 24 km (15 mi) to the west of Malaga Bend.

Evidence is presented here that dissolution of the Salado Formation along its western belt of outcrop began at least as early as Triassic time more than 190 million years ago. Dissolution in the subsurface near this belt of outcrop is presumed to be continuing today. This dissolution has been intermittent throughout its history, and it is unrealistic to attempt to calculate an average rate of dissolution for the region. However, if dissolution continues to be no more severe than during the time since the formation of the Mescalero caliche about

500,000 years ago there is no reason to believe that the repository horizon will be threatened by dissolution for another 500,000 years.

Deep-seated breccia chimneys collapsed over the Capitan aquifer system about 600,000 years ago. Dissolution is presently an active process over the Capitan aquifer system along San Simon Swale about 32 km (20 mi) east of the WIPP site. However, this aquifer system does not underlie the site and there is no presently known aquifer system or process of dissolution in this area which is undermining the site. Near-surface dissolution has been and is presently active along Nash Draw about 10 km (6 mi) west of the site but this dissolution has not penetrated the major salt bodies in the Salado Formation.

Fluctuations in climate have not greatly accelerated the process of dissolution in terms of geologic time and the longer history of the salt bodies. Dissolution during past glacio-pluvial intervals was probably at a more rapid rate than today but the present state of the evaporite deposits is a summation of the processes operating on them throughout 225 million years. It is improbable that a continuation of these fluctuations on their past scale will pose a threat to the deposits during the life of the WIPP repository.

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