USGS
OFR-1973

OFR: 73-13

USGS-4339-8

USGS-4339-8

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

SURFICIAL FEATURES AND LATE CENOZOIC HISTORY IN SOUTHEASTERN NEW MEXICO

Open-file report
1973

Prepared under
Agreement No. AT(40-1)-4339
for the
Division of Waste Management and Transportation
U.S. Atomic Energy Commission

USGS-4339-8

USGS-4339-8

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

SURFICIAL FEATURES AND LATE CENOZOIC HISTORY IN SOUTHEASTERN NEW MEXICO

by

George O. Bachman

Open-file report
1973

CONTENTS

ILLUSTRATIONS

TABLES

SURFICIAL FEATURES AND LATE CENOZOIC HISTORY IN SOUTHEASTERN NEW MEXICO

By George O. Bachman

ABSTRACT

Since deposition of the Ogallala Formation during Pliocene time, southeastern New Mexico has been subjected to erosion, solution, subsidence, and widespread eolian activity. These processes have combined to influence the formation and morphology of major drainage systems. Alined drainage patterns resulted from solution of caliche localized by longitudinal sand dunes. San Simon Swale appears to have formed by processes of erosion and solution-subsidence of Permian evaporites, and was formerly an important tributary to the Pecos River. The combination of processes that formed San Simon Swale was similar to the combination of erosion and coalescing sinks that formed the lower Pecos Valley in southern New Mexico.

INTRODUCTION

The portion of southeastern New Mexico discussed here is in the southern part of the Great Plains physiographic province (figs. 1 and 2). The climate is arid to semiarid and the area is in the northern part of the Chihuahua Desert. Most of southeastern New Mexico is underlain by salt-bearing rocks of Late Permian age. The climate has varied from dry to moist during the Cenozoic, but at times high precipitation has partly dissolved the salt-bearing rocks and has participated in the formation of a unique physiography in this part of the Great Plains.

Previous work on the physiography of southeastern New Mexico includes studies by Price (1944, 1958), Frye (1970), and Frye and Leonard (1972). Mapping and studies of surficial deposits have been limited but include the work of Nicholson and Clebsch (1961) and Vine (1963). Bretz and Horberg (1949a and b) studied the Cenozoic history of the Pecos Valley on the west.

The author worked in this area intermittently during 1972 as part of a Geological Survey group that was studying problems of disposal of radioactive waste. This study was done on behalf of the Oak Ridge National Laboratory, United States Atomic Energy Commission. Fieldwork consisted of geologic mapping as well as ground and air reconnaissance between Livingston and Gramma Ridges southward from the Querecho Plains to the New Mexico State line.

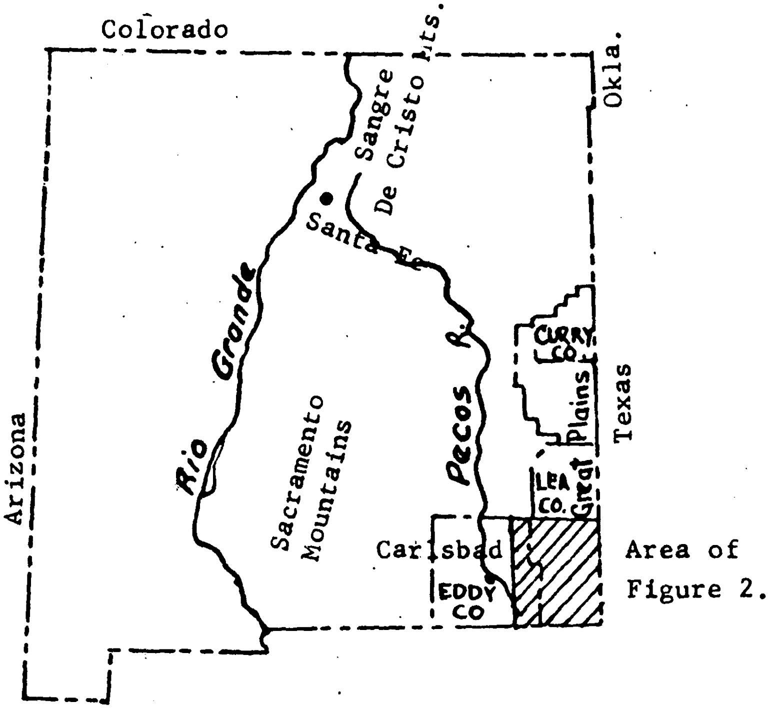

Figure 1.--Index map of New Mexico showing location of natural and cultural features mentioned in text.

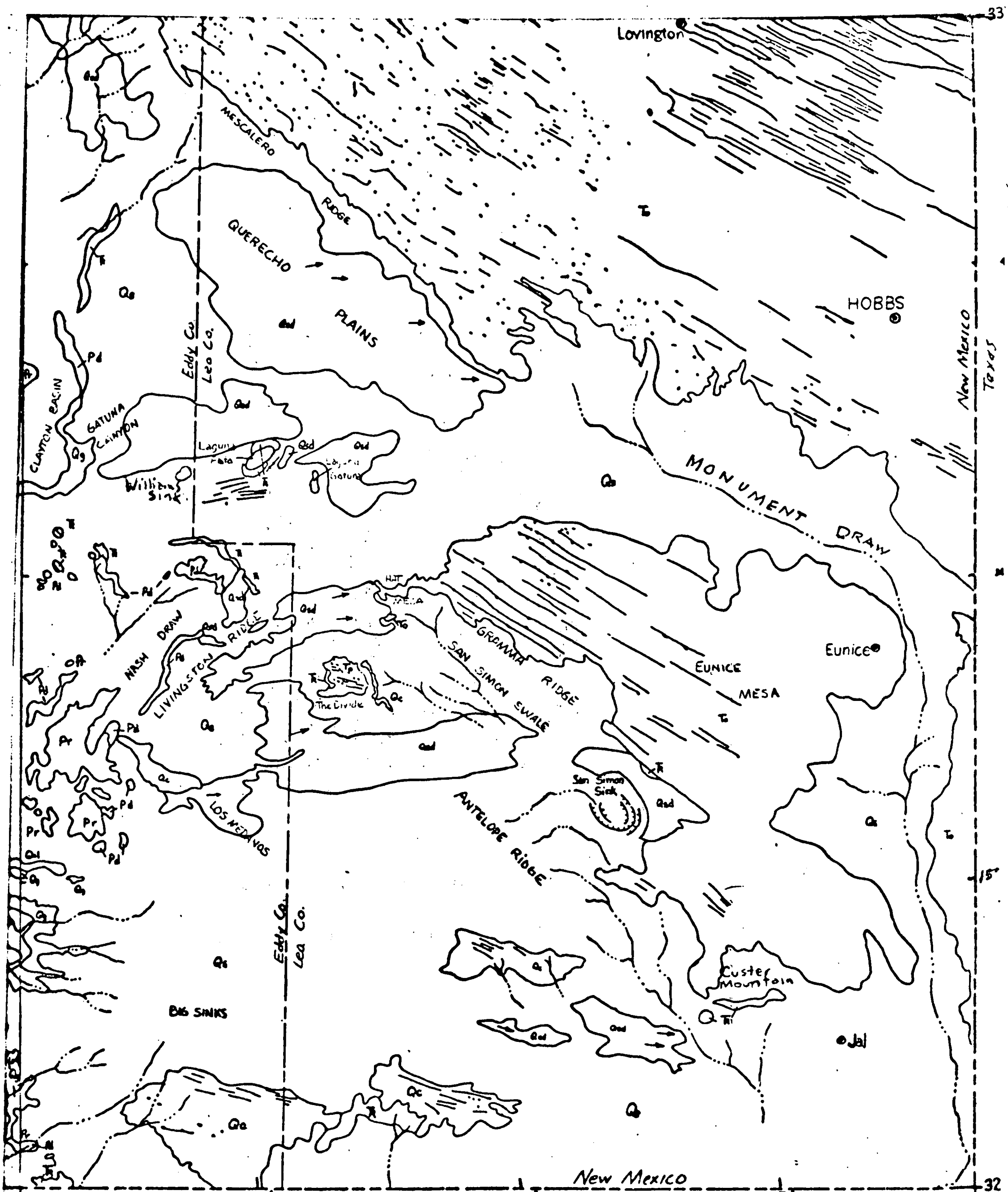

Figure 2.--Geologic map of southeastern New Mexico showing selected surficial features.

EXPLANATION

Symbol	Unit	Epoch	Period
Qs	Surficial sand and sandy soil	Holocene and Pleistocene	QUATERNARY
Qsd	Sand dunes	Holocene and Pleistocene	QUATERNARY
Qc	Caliche	Holocene and Pleistocene	QUATERNARY
Qg	Gatuna Formation	Pleistocene(?)	QUATERNARY(?
To	Ogallala Formation	Pliocene	TERTIARY
Ꞧr	Rocks of Triassic age	Triassic	
Pd	Dewey Lake Red Beds	Permian	
Pr	Rustler Formation	Permian	
	Contact		
	Surficial depressions		
	Alined depressions or swales		
	Traces of annular collapse		
	Dominant wind direction-- Indicated by orientation of sand dunes		

PRE-TERTIARY ROCKS

Permian rocks are important to the consideration of surficial geology of southeastern New Mexico because they include salt, gypsum, anhydrite, and other soluble constituents that have been subject to solution and subsidence during Cenozoic time. However, the stratigraphic relationships of these rocks are complex and it is not the purpose of this report to discuss them. The rocks' main characteristics are summarized on table 1. Of these Permian formations only the Rustler Formation is exposed in the study area. Other pre-Tertiary rocks exposed are the Dewey Lake Redbeds and undifferentiated rocks of Triassic age.

Salt-bearing Permian rocks underlie the Pecos Valley to the west of the study area and account for solution-subsidence features there as well as in Clayton Basin and Nash Draw. The gentle eastward dip of these Permian rocks places them at least 2,000 feet below the surface at places along the Texas State line. Despite this great depth solution has caused subsidence in the overlying Triassic and Cenozoic deposits at San Simon Sink.

Table 1.--Pre-Tertiary Upper Permian (Ochoan) and Triassic rocks in southeast New Mexico (Brokaw and others, 1972)

Age	Formation	Thickness (feet)	Lithology
Late Triassic	Undifferentiated rocks of Triassic age	50-1,500	Moderate-reddish-brown to yellowish-brown conglomeratic sandstone, siltstone, and shale. Equivalent to Santa Rosa Sandstone and Chinle Shale in other parts of New Mexico.
Triassic or Permian	Dewey Lake Redbeds	200-250	Light- to moderate-reddish-brown, thin-bedded shale, siltstone, and fine-grained sandstone. Formerly the Pierce Canyon Formation.
Late Permian (Ochoan)	Rustler Formation	200-500	Mostly anhydrite and rock salt in subsurface. Minor amounts of shale, siltstone, and fine-grained sandstone and dolomite. Thickness varies because of leaching of salt and hydration of anhydrite.
	Salado Formation	0-2,500	A complex assemblage of halite and potash minerals with minor amounts of anhydrite, claystone, siltstone, and fine-grained sandstone. Where exposed at the surface, all salt has been removed by solution and anhydrite has been altered to gypsum. Alteration of evaporites occurs from surface to 1,600 feet below surface.
	Castile Formation	910-2,180	Mostly anhydrite and rock salt with minor amounts of limestone.

TRIASSIC-CENOZOIC HIATUS

After Triassic time there is a long hiatus and little of the geologic record is preserved for the interpretation of events in southeastern New Mexico. During Early Cretaceous time a sea occupied the area. Isolated slump blocks of limestone and shale that contain Early Cretaceous marine fossils in Lea County east of Eunice (Nicholson and Clebsch, 1961, p. 37) and in the Pecos River drainage (Lang, 1947) are the only evidence of the sea's advance. Horberg (1949, p. 475) suggested that an ancestral Pecos River developed near the course of the present river and that some gravels in the Pecos River drainage may be pre-Ogallala in age. Some subsurface solution of Permian salt occurred in the vicinity of The Divide before Ogallala deposition. The timing and extent of the episodes of subsurface solution, erosion, and deposition after Triassic and before Ogallala time is largely conjectural.

CENOZOIC DEPOSITS

Ogallala Formation

The Ogallala Formation of Pliocene age is the earliest definite deposit of Cenozoic age preserved in southeastern New Mexico. The Ogallala was deposited on a sloping plain as coalescing fans largely by streams that flowed southeasterly from the Rocky Mountain uplift. It is preserved as a thick blanket of gravel, sand, and caliche that underlies much of the southern Great Plains and is well exposed along Mescalero Ridge, Hat Mesa, and at The Divide. The Ogallala covers a large area of Eunice Mesa west and southwest of Eunice where it is only poorly exposed.

The Ogallala Formation consists of lenticular beds of medium- to yellowish-gray conglomeratic sandstone and fine- to medium-grained well-sorted sandstone. These deposits are overlain by distinctive beds of light-gray sandy, pisolitic limestone--the caliche "caprock" of the High Plains. On the southern part of Hat Mesa and at Custer Mountain the formation consists only of silica-cemented sandstone. In southeastern New Mexico the Ogallala Formation ranges in thickness from a featheredge to about 300 feet (Nicholson and Clebsch, 1961, p. 31). It thins toward the west due to post-Ogallala erosion. At The Divide the Ogallala is 27 feet thick and on the north side of Hat Mesa it is 20-25 feet thick. At the south end of Hat Mesa, where the formation is cemented by silica, it is only 12-15 feet thick.

Ogallala deposition ceased before the end of Pliocene time. The pisolitic limestone that caps the Ogallala over much of the High Plains is generally regarded as being part of a pedocal soil profile (the Ogallala-Climax soil) that developed over the region near the close of Pliocene time (Bretz and Horberg, 1949a and b; Swineford and others, 1958; Frye, 1970). It ranges in thickness from about 5 feet to as much as 60 feet in southeastern New Mexico (Nicholson and Clebsch, 1961, p. 39).

The top of the Ogallala Formation, where not extensively eroded, is a constructional physiographic surface that has been called the High Plains, or Llano Estacado. At many places the top is obscured by thin soils and windblown sand. In southeast New Mexico the High Plains descend from 4,400 to 3,100 feet in altitude and slopes southeasterly about 10 feet per mile with numerous minor irregularities. It has been correlated to the west of the Pecos River with the Sacramento Plain (Horberg, 1949). The High Plains surface is presumed to be of late Pliocene age.

Oriented drainage and depressions of the Ogallala Formation

The High Plains surface on the caliche caprock of the Ogallala Formation in Lea County is marked by numerous alined drainages and depressions (fig. 3). As seen from the air these alined drainages form broad swales that are 100-300 feet wide and about 3 miles long (figs. 2 and 3); some are as much as 10 miles long. The swales are closely spaced east of Lovington; west of Lovington they are widely spaced and are marked by internally drained ponds. These features are oriented about N. 60° W.

Most of these depressions are less than 40 feet deep in southeastern New Mexico. The caliche thins toward the depressions then evidently pinches out. Trenches from 3 to 5 feet deep within a depression but below the caliche exposed at the margins do not encounter caliche at depth. Havens (1966, p. F8) also reported that drilling in depressions west of Lovington indicates that caliche "thins toward or is absent beneath the central part of the depressions." Most of the depressions are partly filled by soil.

Some swales have become incised in places and are now occupied by several minor drainages in eastern Lea County. Monument Draw, northwest of Eunice, and San Simon Swale are parallel to existing swales on the High Plains surface, and it is possible that these depressions began as drainages in etched swales. Drainage has developed along similar swales to the north on the High Plains in Curry County, N. Mex. (Price, 1958, p. 63).

Figure 3.--Aerial view of oriented drainage on Eunice Plain, Lea County, N. Mex. View is toward the west-northwest. Swales are marked by darker vegetation. Caliche of the Ogallala surface is exposed along the margins of the swale in the foreground. These swales are 100-300 feet wide and about 3 miles long. Internally drained depressions are visible in the distance.

These oriented depressions are believed to have formed by the etching of caliche between former longitudinal dunes (Price, 1944; 1958, p. 63) that have since disappeared. Hack (1941, p. 243) has described longitudinal dunes in the Navajo country of Arizona where "the troughs between the ridges, as well as the flanks of ridges, are covered with vegetation; only the long ridge tops are bare." Plants that grow between longitudinal dunes would accelerate the etching process of the underlying caliche by chemical action, release of carbon dioxide by growing roots, and decay. Erosion by wind and water could remove sediment from these etched swales.

A late Pliocene or early Pleistocene age is suggested for these swales and longitudinal dunes because winds were from the west-northwest, as indicated by alinement of swales, rather than from the west or southwest as shown by younger dunes. Evidence of these wind directions is preserved uniquely on the oldest preserved physiographic surface in the region, the High Plains surface. Almost all criteria for wind directions on younger surfaces indicate that later dominant winds have been from the west or southwest.

PLEISTOCENE AND HOLOCENE DEPOSITS

At the close of Ogallala time the Ogallala Formation extended far to the west of the study area and probably abutted against the eastern slope of the Sacramento and Rocky Mountains. During Pleistocene and Holocene time erosion removed large areas of the Ogallala, the Pecos River and its tributaries were entrenched, and both wind and solution-subsidence were quite active. Quaternary deposits include the Gatuna Formation, caliche, and windblown sand.

Gatuna Formation

The Gatuna Formation consists of light-reddish-brown friable sandstone and conglomerate more than 80 feet thick in Gatuna Canyon (Robinson and Lang, 1938, p. 84-85). The conglomerate consists of chert and siliceous pebbles 1-2 inches in diameter that may have been reworked in part from the Ogallala Formation. In the type area and in the vicinity of Nash Draw where the Gatuna is readily recognized it is overlain by a prominent caliche that marks the Mescalero surface (see below).

Vine (1963, p. B31) suggested that Gatuna deposition "followed immediately after, or in part accompanied, a period of active solution in the Rustler and Salado Formations." This observation was further confirmed during the present work. The Gatuna thickens toward areas of solution and subsidence in Nash Draw and is absent to the east of Nash Draw between Livingston and Antelope Ridges. There the caliche of the Mescalero surface rests on Dewey Lake Redbeds and undivided rocks of Triassic age.

Bretz and Horberg (1949b, p. 483-486) suggested that some gravels along the Pecos River could be Ogallala but deposited in a pre-Ogallala ancestral Pecos drainage. They assumed "that no postconglomerate deformation has occurred" and that "a former Ogallala fill of more than 1,300 feet" accumulated along the Pecos depression (Bretz and Horberg, 1949b, p. 483). Subsidence has occurred after deposition of some conglomerates, and both conglomerates and overlying caliche may be tilted. In view of the complex history of solution and subsidence it is probable that the gravel deposits represent several intervals of deposition. Kelley (1971, p. 31) suggested that the Gatuna Formation is Pliocene or pre-Ogallala, and he extended the formational name northward along the Pecos depression to other gravel and sand deposits. However, some sedimentary structures in the type area of the Gatuna indicate that its source was from the east. This evidence is local but it suggests derivation from the Ogallala and a post-Ogallala age for the type Gatuna. It is herein suggested that the Gatuna be restricted to the type area and the adjacent Nash Draw exposures until more definite age determinations can be made.

Residents[1/] in Carlsbad discovered a partial skeleton of a mammoth 2 1/2 miles south of Gatuna Canyon in 1961 (newspaper story in the Carlsbad Current-Argus, August 13, 1961). I have attempted to recover this locality in the field. Stratigraphic relationships are not clear at the locality but it is possible that the specimen occurred in the Gatuna Formation. Later, the remains of a second mammoth (Carlsbad Current-Argus, February 17, 1963) were discovered about 3 miles northeast of Gatuna Canyon. Field relationships here indicate that these remains were in gravels younger than the Gatuna Formation. Mammoths are considered to be post-Pliocene.

The Gatuna Formation is presently considered to be Pleistocene(?) by the U.S. Geological Survey. In view of the uncertainties outlined above it is logical to retain this designation until more positive evidence is available.

1/ I wish to thank Mr. W. H. Balgemann, Sr., of Carlsbad for the information he provided me on the remains of these mammoths which were discovered in the vicinity of Clayton Basin.

Caliche on the Mescalero Plain

A prominent caliche formed on deposits overlying the Mescalero Plain is the most extensive physiographic surface in southeastern New Mexico. The surface is an uneven one that has been disrupted by solution-subsidence. It is about 150-250 feet above the floodplain of the Pecos on the west and rises gradually toward the High Plains on the east. To the northeast, near Mescalero Ridge, the surface rises to 3,800-4,100 feet in altitude; south of Big Sinks, it descends to about 3,100 feet.

Caliche on the Mescalero Plain is 3-5 feet thick, light gray to white, and sandy. The beds are nodular, with some concretionary growth on the nodules; but the concretionary growth is not as pronounced as on the pisolitic limestone of the Ogallala. Most of the nodules are randomly oriented, but the long axes of some are horizontal. Vertical caliche veinlets indicate several generations of solution and recementation. Occasional pipes 1 foot in diameter or more penetrate 2 or 3 feet into the caliche from the top and are filled with light-reddish-brown sandy soil. Some of these pipes pass entirely through the caliche bed. They presumably represent the former position of roots. Dissolution of this caliche is greater at the depressions. At numerous places on the Mescalero Plain the caliche thins towards depressions, and in some of these depressions the caliche is entirely absent.

The caliche on the Mescalero Plain is the remnant of an extensive soil profile. At places a younger sandy soil is preserved above the caliche but the surface is covered over broad areas by Pleistocene or Holocene windblown sand. This surface is correlative with Surface II of Leonard and Frye (1962, p. 11-12) in the Pecos region of Texas. The Mescalero Plain is analogous to the Jornada-La Mesa surface in the Rio Grande trough in southern New Mexico. Faunal remains indicate that rounded gravels on the Jornada-La Mesa surface are Kansan or younger (Ruhe, 1962, p. 163). Owing to lack of more positive evidence, it is here suggested that the Mescalero Plain formed in early to middle Pleistocene time.

Pleistocene and Holocene drainage

It is not possible to date precisely the entrenchment of the present Pecos River in southern New Mexico. The river may have begun to form as a tributary at the time of the removal of the blanket of Ogallala deposits east of the Sacramento Mountains. However, solution and subsidence were major processes in the lower Pecos Valley in New Mexico and it is equally possible that some of this early Pleistocene drainage was internal. The Pecos Valley has been regarded as having been formed in part by the coalescing of trains of sinks (Lee, 1925; Morgan, 1942). Nash Draw and Clayton Basin appear to have formed in this way and each is characterized by numerous later and smaller internal sinks, which indicates that the process is continuing. It is probable that the Pecos River entrenched itself as a tributary to the Rio Grande by a combination of the processes of headward cutting, piracy, and continuing solution-subsidence.

San Simon Swale has been an area of both subsidence and stream erosion and was probably the former site of a major drainage in southeastern New Mexico. It appears to have been a tributary that joined the Pecos in western Texas. More than 500 feet of Cenozoic sediments fill San Simon Sink (C. L. Jones, U.S. Geological Survey, written commun., Jan. 15, 1973) (fig. 4). Southward in Texas, about 2 3/4 miles from the State line along San Simon Swale, some 580 feet of Cenozoic fill has been reported in a test well (Cities Service Beckham No. 1) (Garza and Wesselman, 1962, p. 2). To the east and west of this channel fill the Cenozoic deposits are less than 100 feet thick. A thickness map prepared by Maley and Huffington (1953) shows Cenozoic fill as much as 1,500 feet thick farther south, in Winkler County, Tex., that defines a narrow and thick deposit of Cenozoic fill that trends southeasterly to, and beyond, the present Pecos River.

Figure 4.--Oblique aerial photograph of San Simon Sink, Lea County, N. Mex. This is a large collapse feature that has continued to subside in historic time. It is more than 3 miles across and is surrounded by numerous dark annular rings that mark fractures. This subsidence resulted from solution of salt in the underlying Rustler and Salado Formations.

The stream that probably once occupied San Simon Swale would have supplied water for the solution of salt in subsurface Permian rocks. An isopach map on the salt in the Castile and Salado Formations shows that salt is absent in a belt corresponding to the narrow thick deposit of Cenozoic fill that trends southward from San Simon Swale in western Texas (Maley and Huffington, 1953, pl. 2). Salt has been leached from the upper part of the Salado Formation as well as from the Rustler Formation in San Simon Swale, New Mexico (C. L. Jones, U.S. Geological Survey, written commun., Jan. 15, 1973). Possibly solution began in this area before Ogallala time, but Ogallala deposits have been removed from San Simon Swale and solution-subsidence has been active "as recently as 25 or 30 years ago" (Nicholson and Clebsch, 1961, p. 14). Thus, processes that have formed San Simon Swale appear to be similar to those that formed the lower Pecos Valley in New Mexico.

Windblown sand

Windblown sand covers much of southeastern New Mexico. Only two types of deposits are shown on the geologic map: sheetlike deposits of surficial sand, sandy soil, and sand dunes. The sheetlike deposits are usually 5 feet or more thick and may include local hummocky areas of stabilized dunes. The areas indicated as dune fields are larger, partially stabilized, or active dunes. Many of these dunes are more than 20 feet high. Most are barchans but some transverse dunes were observed (fig. 5).

Windblown sand has accumulated at least twice since the formation of the Mescalero Plain (since middle Pleistocene time) in southeastern New Mexico. In many dune fields a layer of semiconsolidated sand 2 inches or more thick underlies the active portion of the field. This layer is slightly darker than the overlying sand, and at places the grains are weakly bonded by a calcareous cement. Mechanical analyses indicate that the basal unit is somewhat finer grained (table 2). A similar basal unit in the Monahans dunes area of west Texas, about 40 miles southeast of Jal, N. Mex., has been named the Judkins Formation, and the overlying windblown sand was named the Monahans Formation (Huffington and Albritton, 1941). The dune stratigraphy is complex, and more than two units may be present. Green (1961) has recognized seven informal units in the Monahans area.

Figure 5.--Aerial view of transverse dunes along the north side of Los Medaños area, Eddy County, N. Mex. This is a small dune field only about one-quarter mile wide and three-quarters mile long. Individual dunes are about 15 feet high. Typical stabilized dunes of Los Medaños are in the foreground.

Table 2.--Mechanical analysis of sand. (1) Sandy "soil" underlying dunes, Sec. 27, T. 21 S., R. 31 E., Eddy County, N. Mex. (2) Sand from small barchan, Sec. 35, T. 21 S., R. 31 E., Eddy County, N. Mex.

Size		Percent weight	
Inch	Millimeter	(1)	(2)
0.0394	1.00	0.2	0.0
.0197	.500	.5	.4
.0098	.250	33.8	23.4
.0070	.178	38.5	53.0
.0059	.150	11.6	11.7
.0041	.104	9.8	9.4
.0029	.074	5.3	1.9
-.0029	-.074	.3	.2

The widespread deposits of windblown sand indicate intermittent periods that have been even more arid than the present climate. Most of the dune fields are presently stabilized, although they were probably more active during the past few hundred years: pre-Columbian Indian artifacts are found partially covered by dunes. In fact, wind action has been very strong in the past at some places. Williams Sink, Laguna Plata, and Laguna Gatuna are primarily blowouts with accompanying fields of dunes. There is no indication that solution of underlying salt has contributed to the formation of these large depressions (C. L. Jones, U.S. Geological Survey, written commun., Jan. 15, 1973).

SUMMARY AND CONCLUSIONS

Early Cenozoic time may have been a period of nondeposition or of deposition and erosion in southeastern New Mexico. Some solution of salt beds in the subsurface Permian Rustler Formation near The Divide suggests pre-Ogallala solution but pre-Ogallala physiography can only be conjectured. Recorded Cenozoic history begins with fluvial deposition of the Pliocene Ogallala Formation.

During Ogallala time streams flowed eastward and southeastward from the Rocky Mountains, and the Ogallala Formation was deposited as coalescing fans on a pedimentlike plain over the area of the Great Plains. Locally, eolian activity was a factor in deposition and, periodically, widespread soils formed (Frye, 1970, p. 7). At the close of Ogallala time a widespread soil formed on the Great Plains and the caliche zone of this soil profile forms the present caprock. The caliche caprock has since undergone a complex history of brecciation, solution, and recementation.

Probably during late Pliocene or early Pleistocene time desert conditions prevailed over the southern Great Plains and fields of longitudinal dunes were formed. The alinement of swales between these dunes indicates that dominant winds were from the west and northwest, in contrast to late Pleistocene and Holocene winds from the west and southwest.

Erosion was widespread in southeastern New Mexico during early and middle Pleistocene time and solution and subsidence were active processes. Large areas of Ogallala deposits were stripped away and Pecos River drainage was entrenched. A tributary to the Pecos occupied San Simon Swale. Also during early and middle Pleistocene time Nash Draw, Clayton Basin, and probably San Simon Sink underwent extensive subsidence and partial filling.

Intermittently during Pleistocene time caliche formed in southeastern New Mexico. Some of these caliche deposits are useful planes of reference for relative dating of geologic events. The most widespread caliche horizon on the Mescalero Plain, was formed during early or middle Pleistocene time after a period of extensive erosion along the Pecos River.

During late Pleistocene and Holocene time climatic conditions were variable, but there was a tendency towards aridity. Sheetlike deposits of sand and fields of sand dunes have accumulated over much of southeastern New Mexico. These reflect a dominant wind direction from the west or southwest. Major erosion has been confined to the Pecos Valley and solution and subsidence have been at a slower rate than during early Pleistocene time. Intermittently, ponds have formed in blowouts during relatively humid intervals.

This study results in the following general conclusions:

1. Deep-seated solution and subsidence are minimal processes in areas now overlain and protected by the Ogallala Formation.
2. Solution-subsidence and erosion have shaped the present landscape in southeastern New Mexico. These combined processes were instrumental in forming both the lower Pecos River Valley and San Simon Swale.
3. Factors of microclimate are important in southeastern New Mexico. In an area of such widespread windblown sand, decreasing or minor changes in the distribution of rainfall may decrease the plant cover and reactivate wind erosion. Conversely, greater rainfall may increase plant cover and change blowouts into playas.

REFERENCES CITED

Bretz, J. H., and Horberg, C. L., 1949a, Caliche in southeastern New Mexico: Jour. Geology, v. 57, p. 491-511.

__________ 1949b, The Ogallala formation west of the Llano Estacado [N. Mex.]: Jour. Geology, v. 57, p. 477-490.

Brokaw, A. L., Jones, C. L., Cooley, M. E., and Hays, W. H., 1972, Geology and hydrology of the Carlsbad potash area, Eddy and Lea Counties, New Mexico: U.S. Geol. Survey open-file report (USGS-4339-1), 86 p.

Frye, J. C., 1970, The Ogallala formation; a review: in Ogallala Aquifer Symposium, p. 5-14, Int. Cent. Arid Semi-arid Land Stud., Lubbock, Texas.

Frye, J. C., and Leonard, A. B., 1972, Structure of Ogallala Formation in east-central New Mexico: New Mexico Bur. Mines and Mineral Resources Target Exploration Rept. E-6, 8 p.

Garza, Sergio, and Wesselman, J. B., 1962, Geology and ground-water resources of Winkler County, Tex.: U.S. Geol. Survey Water-Supply Paper 1582, 162 p. [1963].

Green, F. E., 1961, The Monahans Dunes area, in Paleoecology of the Llano Estacado: Fort Burgwin Research Center Pub. 1, p. 22-47.

Hack, J. T., 1941, Dunes of the western Navajo country: Geog. Rev., v. 31, p. 240-263.

Havens, J. S., 1966, Recharge studies on the High Plains in northern Lea County, N. Mex.: U.S. Geol. Survey Water-Supply Paper 1819-F, p. F1-F52.

Horberg, C. L., 1949, Geomorphic history of the Carlsbad Caverns area, New Mexico: Jour. Geology, v. 57, p. 464-476.

Huffington, R. M., and Albritton, C. C., Jr., 1941, Quaternary sands on the southern High Plains of western Texas: Am. Jour. Sci., v. 239, p. 325-338.

Kelley, V. C., 1971, Geology of the Pecos country, southeastern New Mexico: New Mexico Bur. Mines and Mineral Resources Mem. 24, 75 p.

Lang, W. T. B., 1947, Occurrence of Comanche rocks in Black River Valley, New Mexico: Am. Assoc. Petroleum Geologists Bull., v. 31, p. 1472-1478.

Lee, W. T., 1925, Erosion by solution and fill: U.S. Geol. Survey Bull. 760-C, p. 107-121.

Leonard, A. B., and Frye, J. C., 1962, Pleistocene molluscan faunas and physiographic history of Pecos Valley in Texas: Texas Univ. Bur. Econ. Geology Rept. Inv. 45, 42 p.

Maley, V. C., and Huffington, R. M., 1953, Cenozoic fill and evaporate [evaporite] solution in the Delaware Basin, Texas and New Mexico: Geol. Soc. America Bull., v. 64, p. 539-545.

Morgan, A. M., 1942, Solution phenomena in New Mexico, in Symposium on relations of geology to the ground-water problems of the Southwest: Am. Geophys. Union Trans. [23d Ann. Mtg.], Pt. 1, p. 27-35.

Nicholson, Alexander, Jr., and Clebsch, Alfred, Jr., 1961, Geology and ground-water conditions in southern Lea County, New Mexico: New Mexico Bur. Mines and Mineral Resources Ground-Water Rept. 6, 123 p.

Price, W. A., 1944, Greater American deserts: Texas Acad. Sci. Proc. and Trans. 1943, v. 27, p. 163-170.

__________ 1958, Sedimentology and Quaternary geomorphology of south Texas: Gulf Coast Assoc. Geol. Socs. Trans., v. 8, p. 41-75.

Robinson, T. W., and Lang, W. T. B., 1938, Geology and ground-water conditions of the Pecos River Valley in the vicinity of Laguna Grande de la Sal, New Mexico, with special reference to the salt content of the river water: New Mexico State Engineer 12th-13th Bienn. Rept. 1934-38, p. 77-100 [1939].

Ruhe, R. V., 1962, Age of the Rio Grande Valley in southern New Mexico: Jour. Geology, v. 70, p. 151-167.

Swineford, Ada, Leonard, A. B., and Frye, J. C., 1958, Petrology of the Pliocene pisolitic limestone in the Great Plains [Kans.-Okla.-Texas]: Kans. Geol. Survey Bull. 130, pt. 2, p. 97-116.

Vine, J. D., 1963, Surface geology of the Nash Draw quadrangle, Eddy County, N. Mex.: U.S. Geol. Survey Bull. 1141-B, B1-B46.