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CENOZOIC DEPOSITS OF SOUTHEASTERN NEW MEXICO AND AN OUTLINE OF THE HISTORY OF EVAPORITE DISSOLUTION

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Abstract.—Sedimentary records of Cenozoic history in southeastern New Mexico begin with the Ogallala Formation of Miocene and Pliocene age. Later records include the Gatuna Formation of early or middle Pleistocene age, Mescalero caliche, an informal term, of middle Pleistocene age, and fluvial deposits of late Pleistocene age but there are many gaps in the record. The modern landscape is the result of erosion and deposition in climates that have ranged from semihumid to semiarid as well as dissolution of soluble rocks in Permian formations in the subsurface. This dissolution may have begun as early as Jurassic time and has continued intermittently to the present.

The geologic features discussed here are mostly in Eddy, Lea, and Chaves Counties of southeastern New Mexico (figs. 1, 2). This portion of New Mexico is in the southern part of the Pecos River section of the Great Plains physiographic province and, climatically, in the northern part of the Chihuahuan desert. The present climate is semiarid; however, climate has ranged from arid to semihumid during Cenozoic time.

Cenozoic history has been generally neglected in many of the previous studies of southeastern New Mexico but major contributions have been made by Fiedler and Nye (1933), Morgan (1942), Price (1943, 1958), Horberg (1949), Nicholson and Clebsch (1961), and Vine (1963). The purpose of this report is to summarize the present knowledge of Cenozoic stratigraphy and to outline the history of dissolution as a geologic process that has contributed to the formation of the modern landscape (table 1).

I worked in southeastern New Mexico during parts of 1972 and 1973 as part of a U.S. Geological Survey group studying underground beds of salt for disposal of nuclear waste. This work was supported by the Oak Ridge National Laboratory of the U.S. Atomic Energy Commission. Fieldwork consisted of reconnaissance geologic mapping from the Pecos River eastward to Grama Ridge and from the Querecho Plains southward to the New Mexico–Texas State line. Selected areas were mapped in detail. In addition to traverses on the ground, much of the area was observed during low-level flights in light aircraft.

Acknowledgments.—Many people contributed ideas to the basic concepts in this report. Among these, L. E. Gard, C. L. Jones, and P. W. Lambert discussed geologic relations with me in the field. During the 1973 field season I conferred with J. C. Frye, A. B. Leonard, C. C. Reeves, Jr., and J. W. Hawley, who contributed freely of their knowledge of the area. S. E. Galloway of the New Mexico State Engineers Office discussed ground-water relations and geology of the Roswell-Artesia basin. Subsurface information for the interpretation of parts of figure 8 was provided by C. L. Jones.

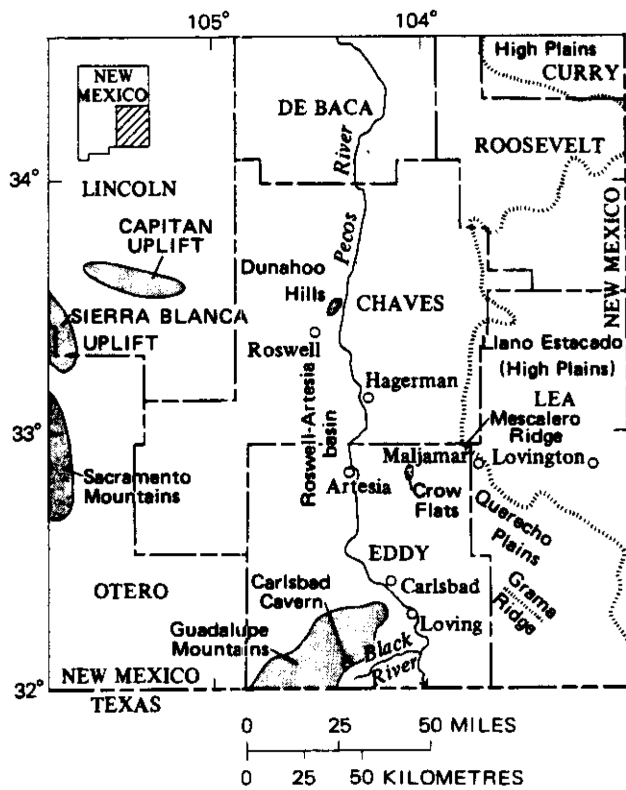


Figure 1.—Index map of southeastern New Mexico.

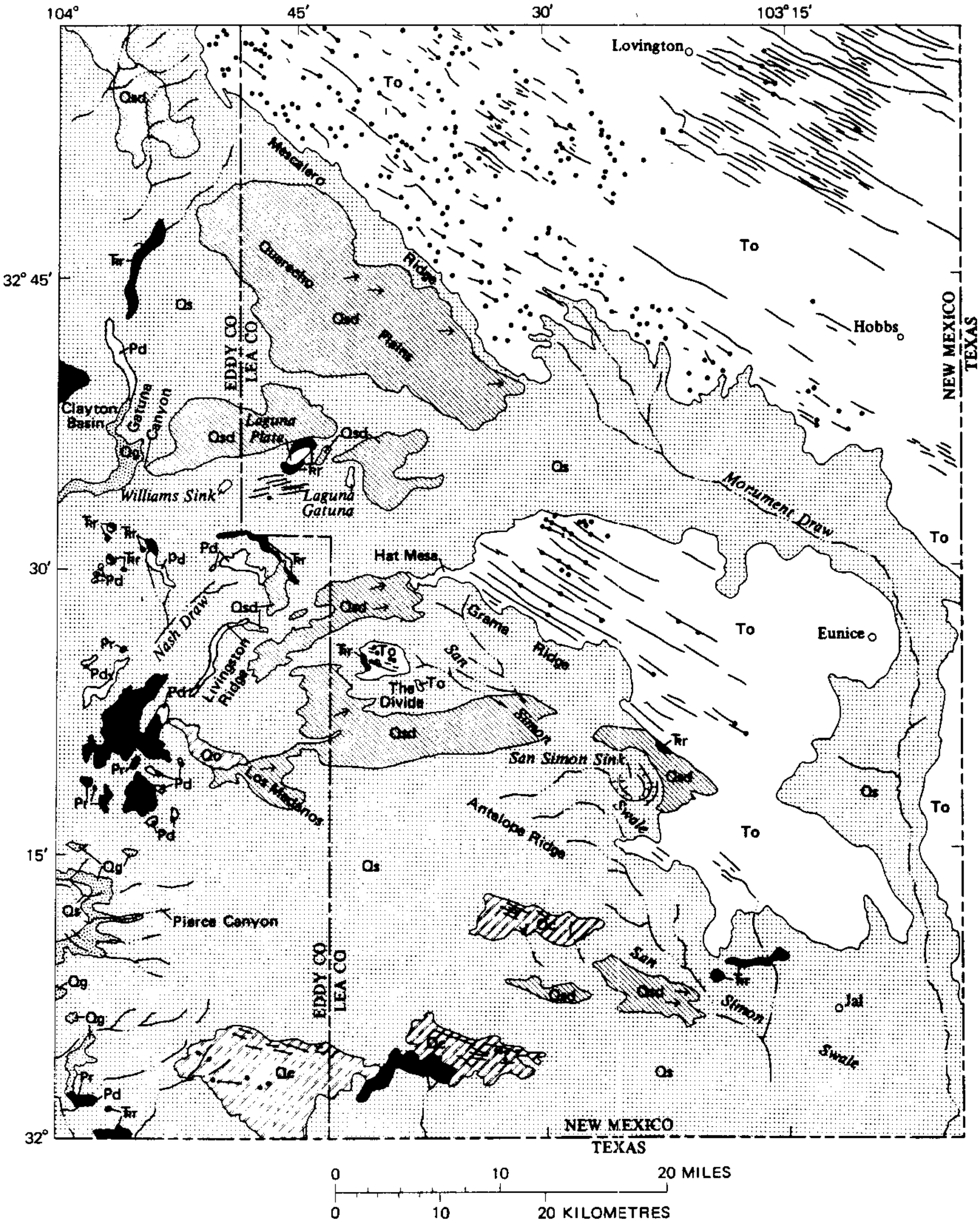


FIGURE 2.—Reconnaissance geologic map of surficial deposits, southern Lea County and eastern Eddy County, N. Mex. Base from U.S. Geological Survey Hobbs topographic quadrangle, scale 1:250,000, 1964–62.

EXPLANATION

Qs	Surficial sand	Holocene and Pleistocene	QUATERNARY
Qsd	Sand-dune deposits	Holocene and Pleistocene	QUATERNARY
Qc	Caliche	Holocene and Pleistocene	QUATERNARY
Qg	Gatuna Formation	Pleistocene	QUATERNARY
To	Caliche caprock and Ogallala Formation	Pliocene and Miocene	TERTIARY
	Sedimentary rocks		TRIASSIC
Pd	Dewey Lake Red Beds		PERMIAN
	Rustler Formation		PERMIAN

Contact

Depressions

Swales or depressions

Trace of annular collapse

→ Dominant modern wind direction – Indicated by orientation of sand dunes

PRE-TERTIARY ROCKS

The oldest rocks exposed in southeastern New Mexico are of Permian and Triassic age. These rocks contribute to the physiographic relief, but the Permian rocks are especially noteworthy because the included evaporites have been dissolved at various times causing subsidence of younger deposits. The evaporite-bearing Permian rocks were deposited in shallow basins (fig. 3)

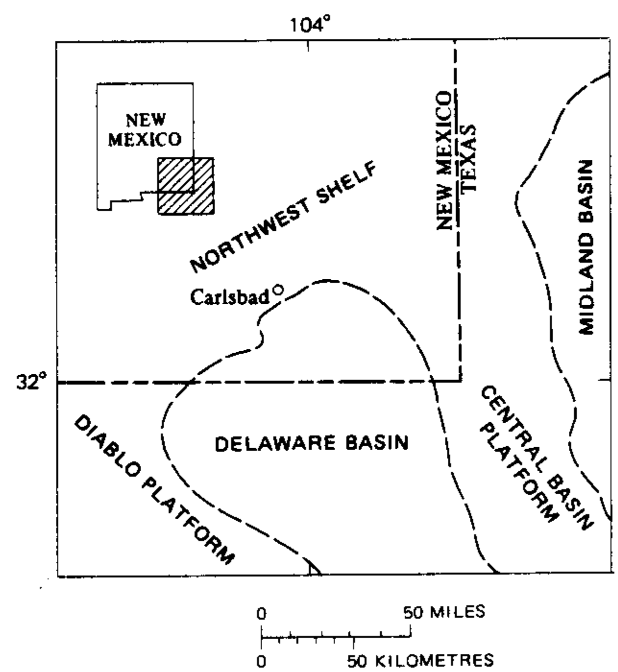


FIGURE 3.—Index map showing subsurface Permian features in southeastern New Mexico.

and have been discussed by King (1942, 1948), Hayes (1964), and Jones (1973). These rocks include the Castile, Salado, Rustler, and Dewey Lake Formations. Of these Permian formations, only the Rustler Formation and the Dewey Lake Red Beds are exposed in the study area.

OGALLALA FORMATION

The Ogallala Formation of Miocene and Pliocene age is the oldest record of Tertiary history and climate preserved in southeastern New Mexico. It underlies the High Plains and is well exposed along Mescalero Ridge, at Hat Mesa, Grama Ridge, and The Divide. Along Mescalero Ridge it typically includes the following three units, in descending order:

	Thickness in metres	(ft)
1. Caliche (caprock), brecciated, light-gray to white, densely pisolitic in upper part. Dense and hard under hammer. Forms prominent ledge	2.5–3	(8–10)
2. Sand, light-brown, fine-grained; grains are mostly quartz, subangular to well rounded, and well sorted. Cement is weak and calcareous. Forms vertical cliff in places	2–4	(6.5–14)
3. Sand, very friable, moderate orange-pink to grayish-orange-pink, fine-grained; grains are mostly quartz, well rounded, and well sorted. Strongly cross laminated in places. Forms gentle slope	5–6	(16–20)

Because the base of the Ogallala Formation commonly is covered, these three units do not represent the total thickness along Mescalero Ridge.

Much of the Ogallala Formation in eastern New Mexico was deposited on an irregular erosional surface as a series of complex alluvial fans. Frye (1970) concluded that deposition ceased when the region was covered by an extensive alluvial plain. By the end of Ogallala time the High Plains surface probably was continuous westerly across the region of the present Pecos River drainage to the backslope of the Sacramento Mountains.

When Ogallala deposition began in the central Great Plains, climatic conditions were somewhat moist, streamflow was regular, and temperature may have been somewhat warmer than at present. As Ogallala time progressed the climate became drier, the water table declined, and streamflow became intermittent (Frye and Leonard, 1957, p. 8). The thick deposits of sand along Mescalero Ridge probably accumulated as eolian deposits during this dry period.

When Ogallala deposition ceased during late Pliocene time the region was tectonically stable and the

TABLE 1.—*Summary of late Tertiary and Quaternary events in southeastern New Mexico*

Age		Stratigraphic unit	Deposits	Events	Probable climate	Tentative correlations
Holocene		Young sand dunes	Sand	Working wind from southwest.	More dry than present.	
		Old soil			More moist than present.	
		Old sand dunes			More dry than present.	
Pleistocene	Late	Lakewood terrace deposits.	River conglomerate, pond, marsh, and lake silts.	Pecos River developed as axial stream from Fort Sumner to Roswell.	More moist than present. Probably cooler.	Wisconsin.
		Orchard Park alluvial deposits.	Limestone-porphyry conglomerate. Caliche caprock.	Reworking of Blackdom deposits.	More moist than present. Probably cooler.	Probably early Wisconsin.
		Blackdom alluvial deposits.	Limestone-porphyry conglomerate. Caliche caprock.	Major erosion of back slope of Sierra Blanca and Sacramento and Capitan Mountains.	More moist than present. Probably cooler.	Do.
		Hiatus				
	Middle	Mescalero caliche, an informal name.	Caliche	Land surface stable. Soil development over much of southeast New Mexico.	More dry than present. Probably warmer.	Yarmouth (?). Unnamed gravel surface west of Pecos.
	Middle or early	Gatuna Formation	Gravel. Stream gravels, pond sediments, solution basin fill. Conglomerate, sand, silt, some gypsum.	Pediments formed in area between Carlsbad and San Simeon Swale. Streams cut High Plains escarpment eastward. Extensive solution of salt and gypsum in subsurface. Collapse of Nash Draw and Clayton Basin. San Simon Swale may have been of major stream.	Much more moist than present. Probably cooler.	Analogous to Kansan deposits in Trans-Pecos Texas.
	Early (?)	Hiatus				
Pliocene		Ogallala "climax-soil."	Caliche	Land surface stable. Soil development.	Similar to, or more dry than, present.	
Pliocene and Miocene		Ogallala Formation.	Gravel, sand, silt			

climate was semiarid to arid. The High Plains were extensive and featureless. In southeastern New Mexico the High Plains surface slopes southeastward about 2.1 m/km (10 ft/mi) and this slope is presumed to reflect the original depositional surface. On this surface a pedocal soil, the Ogallala "climax-soil" (Frye, 1970), formed and the present caliche caprock accumulated in the zone of illuviation.

Stages of formation of pedogenic caliche in southern New Mexico have been described by Gile, Peterson, and Grossman (1966). Similar stages are present in southeastern New Mexico where the caliche varies from weak calcareous accumulations in youthful soils through nodular and laminar deposits on older geomorphic surfaces, and finally to the brecciated and pisolitic caliche of the Ogallala. The pisolitic texture forms during late stages of caliche genesis after repeated solution and desiccation. Caliche deposits younger than the Ogallala may contain pisoliths locally but on younger geomorphic surfaces the pisoliths are not as abundant, widespread, nor as completely formed. I used this distinctive aspect of the Ogallala caliche in extreme southeastern New Mexico to identify clasts in later deposits that have been eroded from the Ogallala caprock.

Bretz and Horberg (1949, p. 483) suggested that the Pecos River system near Carlsbad is of pre-Ogallala origin and that "if it be assumed that no postconglomerate deformation has occurred, a former Ogallala fill of more than 1,300 feet [425 m] along the Pecos depression is indicated." My work does not support this hypothesis. Instead, the Ogallala Formation thins towards the south and southwest from the High Plains. Drill-hole information indicates that the Ogallala Formation is about 102–112 m (315–345 ft) thick along Mescalero Ridge north of Maljamar. At Hat Mesa it ranges in thickness from about 33 to 60 m (100–180 ft) and on the west side of The Divide it is no more than 9 m (27 ft) thick. At all these localities the pisolitic caliche caps the Ogallala Formation which indicates that the southwesterly thinning must have occurred before the caliche formed. Erosion probably was not the cause of regional thinning because other evidence points to a progressive desiccation as Ogallala deposition ceased. Much of the lowering of the Pecos River valley has occurred as a result of dissolution of evaporites in the underlying Permian rocks since Ogallala time.

THE PLIOCENE-PLEISTOCENE HIATUS

The Ogallala "climax-soil" (Frye, 1970) formed after most Ogallala deposition and before the extensive erosion that characterized Pleistocene time. Late in this period of soil formation and after the caliche was indurated, northwest-trending fields of longitudinal, or seif, dunes probably formed on the High Plains surface in southeastern New Mexico. These dune fields have since been eroded away but oriented depressions remain on the High Plains surface that are believed to have formed by the etching and removal of the Ogallala caliche between the former longitudinal dunes (Price, 1943; 1958, p. 3). Havens (1966, p. 8) reported that drilling in depressions west of Lovington indicates that caliche "thins toward or is absent beneath the central part of the depressions." The depressions are partly filled by alluvial and lacustral sediments, and plant growth is relatively more abundant within them. Flint (1955, p. 156–160) reviewed various concepts of the origin of parallel drainage on shale and concluded that some form of eolian control was probable, but that the mechanism of stream development was not clear.

These alined swales and dolines are especially common in the vicinity of Lovington (fig. 2). They are commonly about 35–100 m (100–300 ft) wide and about 3–5 km (2–3 mi) long, although some are as much as 16 km (10 mi) long. These depressions have gentle relief (fig. 4) and most are less than 13 m (40 ft) deep. They are generally oriented about N. 60° W. This orientation indicates that effective winds were from the northwest during late Pliocene or early Pleistocene time which contrasts with the dominant southwesterly winds of present time.

FIGURE 4.—Aerial view of alined drainage on the mesa west of Eunice, Lea County, N. Mex. View is west-northwestward. 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 30–90 m (100–300 ft) wide and about 5 km (3 mi) long. Internally drained depressions are visible in the distance.

In areas of longitudinal dunes in the Navajo country of Arizona "troughs between the ridges, as well as the flanks of ridges, are covered with vegetation; only the long ridge tops are bare" (Hack, 1941, p. 243). In other modern dune fields, plant growth is more abundant in troughs between dunes than on the dunes themselves. Plant growth between longitudinal dunes on the High Plains probably accelerated the etching of the underlying Ogallala caliche by chemical action that included the release of humic acids. Erosion by wind and water could then more effectively remove sediments from these etched swales.

Some swales are locally minor drainages in eastern Lea County. Monument Draw, northwest of Eunice, and San Simon Swale (fig. 2) are parallel in part to the system of swales on the High Plains surface. These drainages may have begun in etched swales on the Ogallala caliche. Drainage has developed along similar swales about 240 km (150 mi) farther north on the High Plains in Curry County, N. Mex. (Price, 1958, p. 63).

PLEISTOCENE AND HOLOCENE DEPOSITS

In Pleistocene time large areas of Ogallala deposits were removed or reworked by water and wind. The Pecos River and its tributaries became entrenched;

some underlying Permian evaporites were dissolved, resulting in surface collapse. Pleistocene deposits found in this region are presumed to represent parts of early or middle Pleistocene time. They include the Gatuna Formation and the Mescalero caliche.

GATUNA FORMATION

The Gatuna Formation was named for exposures of light-reddish-brown sandstone and conglomerate more than 25 m (80 ft) thick in Gatuna Canyon, eastern Eddy County, by Robinson and Lang (1938, p. 84–85), who did not describe a type section. The formation is well exposed along the east side of Clayton Basin (fig. 2), where it rests on rocks of Permian age and is overlain by the Mescalero caliche, an informal name. Although the Gatuna is estimated to be thicker at other localities, it is better exposed and less disturbed by slumping on the north side of Gatuna Canyon. The following stratigraphic section is here proposed as a reference section for the Gatuna Formation.

Reference section of the Gatuna Formation
[North side of Gatuna Canyon, SW¼SW¼, sec. 36, T. 19 S., R. 30 E. Color notations are from Goddard and others (1948)]

	Thickness in metres	(ft)
Mescalero caliche:		
5. Caprock is eroded. Well-cemented nodular zone grades downward to nodular zone that engulfs top of Gatuna	1.7	(5.5)
Gatuna Formation:		
4. Sandstone, pale-reddish-brown (10*R* 5/4), slightly calcareous, medium-grained; grains are subround to round and well sorted; weathers to irregular masses. Bedding is indistinct	3.5	(11.4)
3. Conglomerate, poorly sorted. Upper part of unit includes abundant coarse subangular clasts as much as 25 cm (9.8 in) in diameter which are derived from Ogallala pisolitic caliche; grades downward to less coarse sand and pebbles. Clasts at base are subangular to subround and do not exceed 4 cm (1.6 in) in diameter in basal metre of unit	12.3	(40.0)
2. Sandstone, friable, moderate-reddish-orange (10*R* 6/6) to pale-reddish-brown (10*R* 5/4), fine- to medium-grained; grains are subangular to subround, well sorted, and include rock fragments, quartz, and sparse biotite. Cement is weak and calcareous. Beds in unit are about 10 cm (4 in) thick, and are irregular to indistinct	1.0	(3.3)
Total Gatuna Formation	16.8	(54.7)
1. Covered; in slopes below base of measured section (estimated thickness)	7	(23)

The Gatuna Formation is extensively slumped in Gatuna Canyon. Its thickness there is estimated to range from about 15 to 30 m (50–100 ft). At a gravel pit on the north side of Gatuna Canyon (S½ sec. 35, T. 19 S., R. 30 E.) it is well exposed and is at least 17 m (56 ft) thick in a slump block.

Although much of the Gatuna Formation is fine grained, the conglomeratic beds have provided most of the evidence for the history of the formation. The conglomerate comprising unit 3 of the reference section contains the following types and percentages of clasts:

Ogallala pisolitic caliche	36
Sandstone	10
Orthoquartzite	24
Tertiary porphyries (mostly Sierra Blanca rock types, but one clast noted may be from Capitan Mountains)	16
Permian limestone	6
Quartz	4
Chert	2
Jasper	2

Clasts in the conglomeratic sand in Gatuna Canyon are largest in the basal part of the formation where they average about 7–10 cm (3–4 in) in diameter, with clasts as much as 20 cm (8 in) not uncommon. In the upper part of the formation in Gatuna Canyon, clasts are generally less than 9 cm (3.5 in) in diameter.

Rounded cobbles and boulders derived from the pisolitic caprock caliche of the Ogallala Formation are widespread and common in the Gatuna. Gravel in a pit on the north side of Gatuna Canyon contains the following percentages and types of clasts: 35 percent are derived from the Ogallala caliche, 50 percent are quartzite and orthoquartzite, 10 percent are Tertiary porphyries, and 5 percent are red sandstone. The clasts derived from the Ogallala caliche are 7–20 cm (3–8 in) in diameter which indicates that they have been transported shorter distances than the quartzite and porphyry clasts which have a generally smaller average diameter.

A conglomeratic, lenticular channel deposit is well exposed in the Gatuna Formation along the west side of Long Arroyo about 13 km (8 mi) east of Hagerman. There the Gatuna rests on an uneven erosion surface on Permian red beds. The sandy matrix is pale red, poorly sorted, and crossbedded. The clasts are as much as 15 cm (6 in) in diameter. Of the clasts in the deposit, 45 percent are quartzite and orthoquartzite, 35 percent are Ogallala pisolitic caliche, 10 percent are red sandstone, and 10 percent are chert. In the southern part of Eddy County conglomerates are widespread in the upper part of the Gatuna Formation where they were deposited as alluvial gravels on a piedmont surface. More than 50 percent of the clasts in the gravels of this area are of Permian limestone and the rest of the clasts are of quartz, orthoquartzite, chert, and Tertiary porphyries.

Conglomerates with quartzite clasts are common along the Pecos and Black Rivers and remnants are widespread in the Pecos River Valley. They were first described by Nye (in Fiedler and Nye, 1933, p. 35–38). Bretz and Horberg (1949) and Thomas (1972) have suggested that these gravels are basal Ogallala, but clasts derived from the Ogallala pisolitic caliche are present in at least one outlier west of the Pecos River near Loving (SE¼ sec. 33, T. 23 S., R. 28 E.). Pebble counts at other places suggest pebble associations found in the Gatuna Formation; therefore I consider these gravels to be remnants of the Gatuna.

Underlying the caliche caprock of the Dunahoo Hills (fig. 1) is an outlier of conglomerate that also may be part of the Gatuna Formation. It is an irregular, cross-bedded channel deposit with some interbeds of fine sand. Clasts in the conglomeratic beds are subround to round and spherical to oblate spheroidal. Most commonly they are 6–8 cm (about 3 in) in diameter but a few are as much as 20 cm (8 in) in diameter. Nearly 70 percent of these clasts were derived from Permian limestone; the remaining 30 percent are orthoquartzite, chert, and Tertiary porphyries. Rare clasts of Ogallala pisolitic caliche were observed in these exposures. In roadcuts near the highway other rock types are present, but many roadcuts were contaminated by exotic debris during highway construction.

Fine-grained deposits in the Gatuna are well exposed in Nash Draw, Pierce Canyon, and at Crow Flats. In the southern part of Nash Draw (SE¼ sec. 33, T. 23 S., R. 29 E.) thin, even beds of yellowish clay and silt dip steeply into a sink that formed during Gatuna time. At this place a bed of gypsum 2 m (6 ft) thick is intercalated with the yellowish clays. Near Crow Flats (figs. 1, 7) east of Artesia the Gatuna includes massive fine-grained beds which locally fill sinks of Gatuna age.

The Gatuna Formation was derived locally and was deposited before the Pecos River had cut headward to the Sangre de Cristo Mountains. Sources for the Gatuna include: (1) The Ogallala Formation, (2) Permian and Triassic rocks, and (3) Tertiary porphyries in the Capitan and Sierra Blanca uplifts west of the Pecos River. Apparently there are no clasts derived from the Sangre de Cristo Mountains or Pedernal uplift to the north. The pink, alkalic feldspars that might be expected in such a gravel are abundant only in the much younger (Wisconsin) Lakewood terrace along the Pecos River near Roswell.

Other workers have suggested that the Gatuna Formation could be pre-Ogallala (Kelley, 1971, p. 30), or that some siliceous gravels in the Pecos River valley, herein correlated with part of the Gatuna, could be Ogallala (Thomas, 1972 p. 17) or pre-Ogallala (Bretz and Horberg, 1949, p. 487). The Ogallala pisolitic caliche clasts in the Gatuna Formation in its type locality are evidence for its post-Ogallala age. More specific evidence of age has not been found.

The Gatuna Formation is here considered to be early or middle Pleistocene in age. The widespread channel deposits as well as the sink fillings indicate that the climate was unusually wet. Other workers have regarded middle Pleistocene (Kansan) time as the wettest time in the Pleistocene in the High Plains (Frye and Leonard, 1965, p. 211; Hibbard, 1970, p. 401), and probably the Gatuna was deposited at this time. In addition, the Gatuna is almost everywhere overlain by an extensive, indurated caliche (the Mescalero caliche). This caliche covers a geomorphic surface that is analogous in extent and maturity to high surfaces along the Rio Grande in southern New Mexico which are believed to have developed during middle Pleistocene time (Kottlowski and others, 1965, p. 292).

MESCALERO CALICHE

The Mescalero plain lies generally east of the Pecos River and west of the High Plains in southeastern New Mexico (Bretz and Horberg, 1949, p. 481). It extends southward from the vicinity of Fort Sumner to the New Mexico–Texas State line. Wherever the surface can be observed beneath the widspread deposits of windblown sand, it is underlain by a distinctive caliche. I observed this caliche at many places and treated it as an informal stratigraphic unit, here called the Mescalero caliche.

The Mescalero caliche consists of two parts: a basal, earthy to firm, nodular calcareous deposit, and an upper well-cemented laminar caprock. These units correspond to the K zone of Gile, Peterson, and Grossman (1966) and include the K_3 and K_2 zones, 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 1 to 4 m (3–13 ft) with the caprock usually making up about one-third to more than one-half of the total thickness.

Although both parts of the Mescalero caliche may engulf underlying sediments, most commonly this 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 diagenesis is most advanced, scattered quartz pebbles and sand grains may be the only vestige of the engulfed sediment.

Prominent laminations throughout much of the caprock characterize the Mescalero caliche. These laminae consist of alternating dark and light layers generally less than 5 mm thick and parallel to the land surface. They may be weakly crenulated or even disrupted by pisoliths. The pisoliths are common only locally and are less common and less well developed than in the

Ogallala caliche along Mescalero Ridge. Brecciation is rare in the Mescalero caliche.

Microscopically the carbonate of the caprock is mostly micrite with subordinate sparry calcite in veinlets, replacements, and irregular masses. The dark layers are clotted micrite. The micrite occurs in places as yellowish bands around pisoliths which suggest the presence of iron oxide.

Sand grains are common in both the lower nodular zone and the caprock of the caliche. However, in the caprock, sand grains are abundant in the massive, unlaminated part but are rare in the laminae. More commonly, detrital grains in the laminated zones are very fine silt (0.01–0.02 mm in diameter). Sand grains in the massive parts of the caprock are subangular to rounded quartz that range in diameter from about 0.1 to 0.3 mm. Some of these grains are etched and replaced by sparry calcite. The general absence of sand grains in the laminated zones suggests that processes of solution and reprecipitation that formed the laminae separated the carbonate from larger detrital grains.

The Mescalero caliche was formed during an interval of climatic and tectonic stability that followed deposition of the Gatuna Formation. The Mescalero caps the Gatuna Formation almost everywhere that the Gatuna is exposed. It locally caps Triassic and Permian rocks as well. The Mescalero caliche formed in the semiarid environment that followed the moist conditions of Gatuna time. It is analogous in maturity and extent to the caliche that caps the La Mesa surface along the Rio Grande valley in southern New Mexico (Gile and others, 1966, p. 348), and is considered to be middle Pleistocene in age.

PLEISTOCENE DEPOSITS AND THE DEVELOPMENT OF MODERN DRAINAGE

Major drainage was probably eastward to southeastward during early Tertiary time and this continued to be the dominant direction of drainage while the Ogallala Formation was being deposited during late Tertiary time. Bretz and Horberg (1949, p. 487) postulated an early Tertiary ancestral Pecos drainage, and there may have been a local Pecos drainage but this southward-flowing system was limited in extent and its headwaters may have extended no farther north than the vicinity of Carlsbad and San Simon Swale. Streams probably flowed eastward from the Capitan and Sierra Blanca uplifts, but the pattern of that drainage system is not known.

Southeasterly flowing streams formed at least three major drainage systems in eastern New Mexico during late Pliocene and early Pleistocene time (fig. 5). The Canadian River system to the north cut through the Ogallala Formation and flowed eastward into the Red River system. A second major system drained southeastward towards the Portales valley and finally into the Brazos drainage in western Texas (Baker, 1915, p. 52–54). The third system generally followed the southern part of the Pecos River valley. Igneous debris was carried from the Sierra Blanca and Capitan uplifts eastward down the Rio Penasco, Rio Hondo, and other valleys west of the Pecos into the southward-flowing Pecos River. By middle Pleistocene time a stream system also flowed westward from the High Plains toward Clayton Basin and deposited portions of the Gatuna Formation.

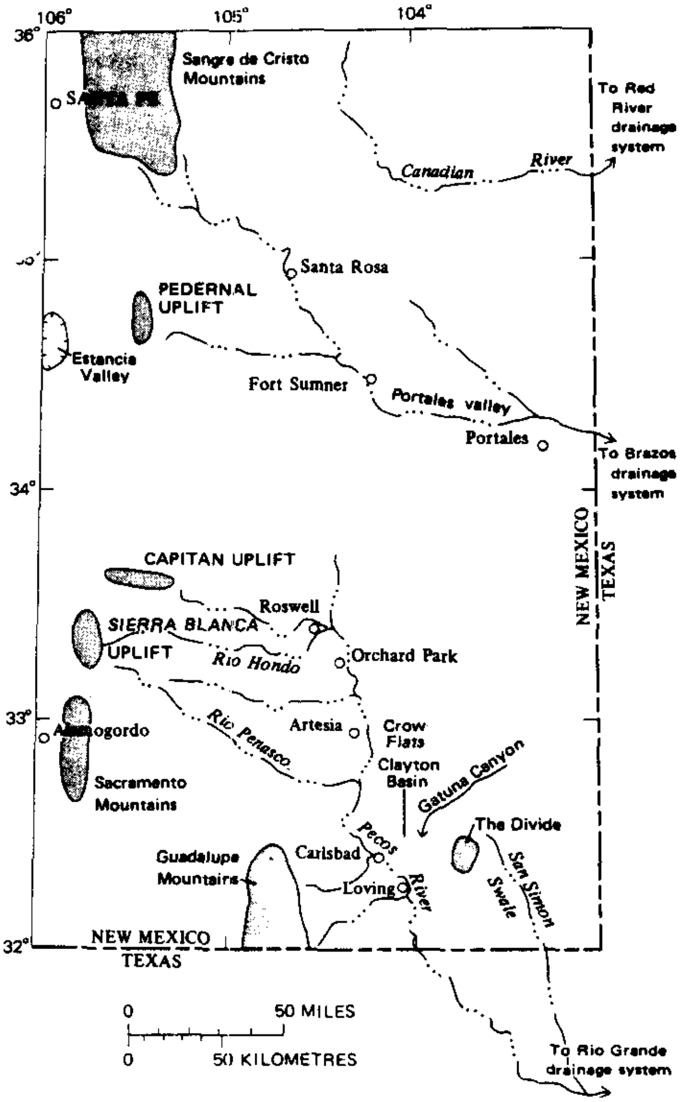


FIGURE 5.—Map showing probable drainage in eastern New Mexico during middle Pleistocene time.

After Gatuna time there was a period of tectonic stability during which the Mescalero plain formed and extensive deposits of caliche accumulated in a semiarid climate. Streams were smaller than in Gatuna time but the pattern of their drainage is not known.

After Mescalero time pediment surfaces were cut east of the Sacramento Mountains, and the Pecos River entrenched itself near its present channel along the toes of these pediments. The wetter climate that contributed to the formation of pediments also caused widespread solution and collapse in the Roswell-Artesia basin and probably farther to the south. Stream gradients and sediment-carrying capacity thus decreased along the Pecos River during most of late Pleistocene and Holocene time.

During early and middle Pleistocene time sediments were derived largely from the Sierra Blanca and Sacramento and Capitan Mountains, but in late Pleistocene (post-Mescalero) time the Pecos River intersected the Portales valley drainage system near Fort Sumner. The Pecos River thus became a permanent stream flowing from the southern Rocky Mountains to the Rio Grande.

Part of the history of the Pecos River drainage is recorded in five physiographic surfaces that have been recognized in southeastern New Mexico west of the Pecos. Horberg (1949, p. 464) summarized the studies of previous workers and enumerated these surfaces, from oldest to youngest: (1) The Sacramento plain, (2) the Diamond A plain, (3) the Blackdom terrace, (4) the Orchard Park terrace, and (5) the Lakewood terrace. A tentative correlation of these physiographic features and their accompanying deposits is proposed in table 2.

TABLE 2.—*Tentative correlation of Quaternary features and formations in southeastern New Mexico*

West of Pecos River	East of Pecos River	Age
Lakewood terrace deposits.	Playa deposits ----	Woodfordian Substage (late Pleistocene).
Orchard Park alluvial gravel.	Not recognized ---	(?).
Blackdom alluvial gravel.	Not recognized ---	(?).
Diamond A plain -	Mescalero caliche -	Middle Pleistocene.
Gatuna(?) Formation, locally.	Gatuna Formation.	Early or middle Pleistocene.
Sacramento plain --	High Plains surface.	Late Pliocene to early Pleistocene.

At the close of Ogallala time an extensive physiographic surface extended from the High Plains to the Sacramento Mountains. In the Sacramento Mountains this surface is highly dissected and has been named the Sacramento plain (Fiedler and Nye, 1933, p. 14–15). The limits of this plain have not been defined, but Horberg (1949, p. 464, 465) suggested its correlation with the High Plains surface and also believed it to be equivalent to the upland surface on the Guadalupe Mountains.

Remnants of a lower physiographic surface, the Diamond A plain (Fiedler and Nye, 1933, p. 14), are present about 32–40 km (20–25 mi) west of the Pecos River. This surface is less dissected than the older Sacramento plain, but it is hummocky and marked by numerous dolines. It is well preserved about 37 km (23 mi) west of Hagerman, where it is capped by caliche. This caliche has a prominent laminar caprock and is morphologically very similar to the Mescalero caliche east of the Pecos River.

The next lower surface has been named the Blackdom terrace (Fiedler and Nye, 1933, p. 12, 32–35), and this usage has been followed by other workers in the area (Morgan, 1942; Horberg, 1949, p. 464–465, 470–471). The Blackdom alluvial deposits are coalesced fans that rest on a broad surface cut on older rocks and it seems more proper to refer to these deposits as the Blackdom alluvial deposits. They were deposited by aggrading western tributaries of the Pecos River during an early stage of formation of the Pecos drainage before the river was entrenched in its present course. The Blackdom, as well as the younger Orchard Park alluvial deposits, should be distinguished genetically from the Lakewood terrace deposits. The latter contain clasts from the Sangre de Cristo Mountains and are related genetically to the modern Pecos River.

Blackdom alluvial deposits occur only west of the Pecos River. They are present intermittently from about 16 km (10 mi) south of Roswell to the Seven Rivers Hills. These deposits appear to be present in the vicinity of Arroyo del Macho but have not been examined in that area.

The Blackdom deposits are about 6.0–8.5 m (20–30 ft) thick. The surface of the deposits slopes eastward about 5.5–7.5 m/km (30–40 ft/mi), is hummocky to undulating, marked by small dolines, and is more uneven than the younger Orchard Park surface. The gravel in the deposits consists mostly of limestone from the underlying Permian rocks but clasts of porphyries derived from the Sierra Blanca and Capitan uplifts increase in abundance in exposures toward the north. The clasts average about 6–8 cm (2.4–3.2 in) in diameter but sorting is poor and some clasts are as much as 0.5 m (1.6 ft) in diameter. Clasts are subangular to round and are cemented by an earthy to well-indurated caliche. Many of the limestone clasts are solution faceted. Laminar zones in this caliche are poorly developed and pisoliths were not observed.

The Orchard Park alluvial deposits (the Orchard Park terrace of Fiedler and Nye, 1933, p. 11–12, 31–32) occur west of the Pecos River between Roswell and Lakewood. They represent a later stage of the erosional cycle that abraded the Blackdom deposits. Some clasts are reworked from the Blackdom and they are generally smaller than clasts in the Blackdom. In a gravel pit near Orchard Park (SE¼SE¼ sec. 21, T. 12 S., R. 25 E.) clasts average about 3–4 cm (1.2–1.6 in) in diameter with some as much as 15 cm (6 in) in diameter. At this quarry, 58 percent of the clasts are of Tertiary porphyry derived from the Sierra Blanca and Capitan uplifts to the west, and 42 percent are of Permian limestone. About 45 km (28 mi) south of Orchard Park and 3.2 km (2 mi) east of Artesia, the Orchard Park deposits are composed entirely of Permian limestone clasts, many of which are solution faceted. The matrix is structureless caliche that is poorly to moderately indurated. The incomplete exposures at the quarry near Orchard Park are 3.8 m (12.5 ft) thick. Near Lakewood the Orchard Park deposits are estimated to be 6–9 m (20–30 ft) thick.

The Lakewood terrace is the youngest named physiographic feature along the Pecos River (Fiedler and Nye, 1933, p. 10). It is present in a narrow strip along the river from the vicinity of Roswell to about 6.4 km (4 mi) south of Carlsbad where it loses its identity. Surfaces near the Pecos channel east of Loving are here interpreted as older collapsed surfaces which have been exhumed and are not properly a part of the Lakewood terrace. The Lakewood terrace is present westward along some of the tributaries to the Pecos and is especially prominent in the Roswell-Artesia basin.

The Lakewood terrace deposits are widely varied along the Pecos River. The northernmost exposures near Roswell contain a large variety of rock types that reflect the source areas of the Pecos River as far north as the Sangre de Cristo Mountains. For example, about 22 km (14 mi) northeast of Roswell (SW¼NE¼ sec. 3, T. 9 S., R. 25 E.), gravels in the Lakewood terrace contain subround to round pebbles that average about 3 cm (1.2 in) in diameter, with some clasts as much as 10 cm (4 in) in diameter. The types and percentages of clasts in the gravels are:

Orthoquartzite	22
Granite, pink to yellow, medium- to coarse-crystalline	12
Chert	15
Quartz	12
Permian limestone	22
Sandstone	12
Schist, mica, hornblende, quartz	2
Diorite (?) weathered	2
Pink alkalic feldspar, "fresh," sparse fragments	1
Total	100

This is the most heterogeneous conglomerate observed along the Pecos River from the Roswell-Artesia basin southward to the New Mexico–Texas State line. The granites are similar to those in gravels along the Pecos River near Fort Sumner about 100 km (63 mi) north. It is noteworthy that clasts of the Tertiary porphyries exposed farther west are apparently absent, although such clasts are commonly represented in the older Orchard Park alluvial deposits in the same area.

At the south end of the Roswell-Artesia basin, Lakewood deposits are generally fine sand, silt, and clay. The size of the material in the deposits reflects the low gradient of the Pecos River south of Roswell and the effectiveness of the Roswell-Artesia basin as a settling basin. Near Carlsbad the Lakewood terrace deposits are mostly sand and gravel derived from Permian limestones, which indicate local sources.

FANGLOMERATES EAST OF THE GUADALUPE MOUNTAINS

Lime sand and limestone pebble fanglomerates cover an extensive area of low relief between the Guadalupe Mountains and the Pecos River. These deposits are continuous from Carlsbad southward nearly to Black River and in a narrow belt in the Black River drainage along the eastern front of the Guadalupe Mountains. Some of this clastic debris has been described as an alluvial apron (Hayes and Koogle, 1958). Horberg (1949, fig. 3) recognized a "Blackdom plain" south of Carlsbad, and Motts (1962) mapped "younger" and "older" alluvium which he correlated with the Lakewood terrace and with the Orchard Park and Blackdom "plains." These plains may be underlain by some equivalents of the Orchard Park and Blackdom alluvial deposits but they are part of an extensive fan system east of the Guadalupe Mountains, and this system has not been traced with certainty north of Carlsbad.

Clasts in these fanglomerates are derived from the Permian limestones and other rocks from the Guadalupe Mountains. Most of the limestone pebbles are solution faceted, and caliche cements the deposit at many places. The caliche is generally structureless and was probably deposited from surface water solutions.

These fanglomerates appear to be deposited on an erosional and karst topography. South of Carlsbad Caverns lenticular beds of conglomerate fill channel-shaped depressions along the tops of ridges. North of Carlsbad Caverns the fanglomerates appear to fill sinks, and, at places, the surface itself is locally marked by dolines and sinks. Modern drainage on these fanglomerates generally parallels low discontinuous ridges that radiate from the Guadalupe Mountains. This suggests that the fans are now being dissected.

The age of these fanglomerates is not known. They may be as old as the Blackdom deposits, or older. However, northeast of Loving, along the west side of the Pecos River, remnants of these fanglomerates rest on probable Gatuna Formation and Mescalero caliche. Here the underlying deposits are distinguished from the fanglomerate by the many Tertiary porphyry and siliceous pebbles cemented in the caprock. This caprock is here interpreted as an exhumed Mescalero caliche surface that has collapsed along the Pecos River. Therefore, at least the eastern fringes of the fanglomerate are assumed to be post-Mescalero in age.

WINDBLOWN SAND

Windblown sand is widespread over much of the area east of the Pecos River. Some of these deposits occur as coppice dune fields with local informal names such as Los Medanos and Mescalero sands. Most of these dunes are relatively inactive, but they have been active during Holocene time and local blowouts suggest that they would soon be reactivated if the plant cover were disturbed.

At least two distinct deposits occur at most places in coppice dune fields. These include a lower deposit of compacted, somewhat clayey sand that may be as much as 0.5 m (1.5 ft) thick and an overlying deposit of loose blow sand as much as 6–8 m (20–25 ft) thick. Locally, soils are very poorly formed on some deposits of blow sand.

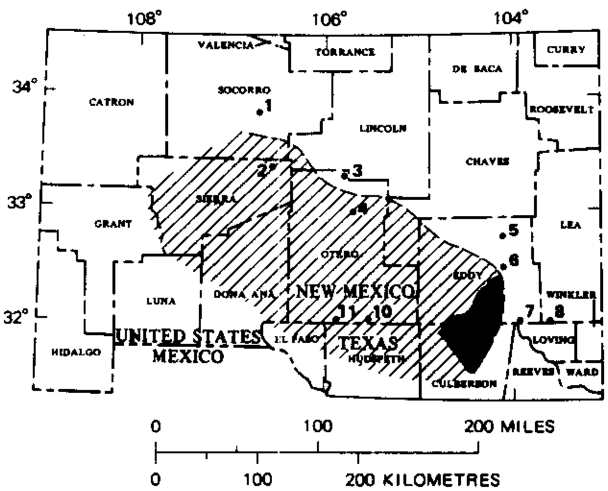
The widespread deposits of windblown sand indicate a large source of fine sand. Sand deposits are discontinuous along the banks of the Pecos River and there is very little evidence that much sand has been derived from there. I believe that most of the windblown sand in areas such as Los Medanos was derived from the Ogallala Formation. During wet intervals in the Pleistocene the sand was eroded from the Ogallala, and during arid intervals it was blown across the Mescalero plain.

HISTORY OF EVAPORITE DISSOLUTION

The parts of southeastern New Mexico underlain by salt, gypsum, and other soluble Permian rocks near the surface attract popular interest because of the widespread karst topography that has formed on modern surfaces. The removal of these soluble rocks by dissolution has caused subsidence and collapse of the surface at many places (Lee, 1925). However, my work indicates that dissolution and collapse have not been confined to the modern landscape but have been active processes in this area for long intervals in geologic time.

In east-central New Mexico near Santa Rosa, karst topography developed during Late Triassic time, but evidence for Triassic karst development in southeastern New Mexico has not been seen. However, dissolution of Permian salt in the western part of the Delaware basin may have begun as early as Jurassic time. During this time southern New Mexico was above sea level and there was probably considerable erosion. South of New Mexico, in western Texas, near-shore marine conditions prevailed during at least part of Jurassic time (Albritton, 1938, p. 1764). In central New Mexico continental Jurassic rocks were derived from the south. These relations, as well as the regional pattern of thinning of Triassic rocks, indicate an area of extensive erosion in southern New Mexico during Jurassic time (fig. 6).

Rocks of Triassic age wedge out to a featheredge on Permian rocks in southern New Mexico. Rocks of Cre-



EXPLANATION

Rocks of Triassic age absent – Rocks of Cretaceous age rest on rocks of Permian age or older

Part of Delaware basin subject to erosion during Jurassic time

.10 Control point

FIGURE 6.—Map showing extent of Jurassic erosion in southern New Mexico. Control points: 1, Carthage coal field (Triassic less than 500 ft thick; Wilpolt and Wanek, 1951). 2, North San Andres Mountains (Triassic absent, Cretaceous rests on Permian; Bachman and Harbour, 1970). 3, Southern Sierra Blanca (Triassic about 100 ft thick; G. O. Bachman, unpub. data). 4, North Sacramento Mountains (Triassic absent, Cretaceous rests on Permian; Pray and Allen, 1956). 5, Crow Flats (Triassic about 50+ ft thick, chaos structure). 6, Northeast Carlsbad (Triassic remnants present in sinkholes). 7, Red Bluff Reservoir (Triassic present). 8, South Lea County (Triassic present). 9, Black River valley (Triassic absent, Cretaceous remnant present in sinkhole; Lang, 1947). 10, Cornudas Mountains (Triassic absent, Cretaceous rests on Permian). 11, Otero Mesa (Triassic absent, Cretaceous rests on Permian).

taceous age lap across this wedgeout at some places. These places indicate the configuration of the line of pre-Cretaceous zero thickness of Triassic strata and outline the area of southern New Mexico, including a portion of the Delaware basin, where Permian rocks were unprotected by Triassic strata during Jurassic erosion. Probably some dissolution of Permian salt and gypsum occurred in the western part of the Delaware basin at this time. During Cretaceous time the entire region was submerged below sea level and presumably neither erosion nor dissolution was an effective process.

Extensive erosion, presumably accompanied by dissolution of Permian salts, occurred during parts of Tertiary time. However, there are no sedimentary records of these events that can be related directly to the formation of modern karst topography.

The earliest and most widespread datum for determining the relative time of solution and collapse of many modern karst features is the Pleistocene Mescalero caliche. I believe that the Mescalero caliche is pedogenic and that it formed on an undulatory, stable surface. Pedogenic caliche—like other soils—probably would not form on steep slopes. However, along the margins of some major depressions the Mescalero dips steeply—nearly vertically in places; yet this caliche is comparable in thickness and morphology to adjacent horizontal profiles. In addition, fracturing and slumping of the Mescalero along the margins of these depressions indicate collapse after Mescalero time. Major solution and collapse of the surface preceded and followed the accumulation of the Mescalero caliche in Nash Draw, Clayton Basin, and at Crow Flats.

Crow Flats is a large collapse feature about 24 km (15 mi) east of Artesia (fig. 7). Evidence for at least three episodes of solution and collapse is preserved there. These episodes occurred (1) after Triassic and before Gatuna time, (2) during or after Gatuna time, and (3) after Mescalero time.

At Crow Flats dolomite and gypsum of the Permian Rustler Formation are the oldest rocks exposed. These rocks are overlain by conglomeratic, crossbedded, dark-reddish-brown sandstone of the Upper Triassic Dockum Group. South of Pavo Mesa for about 11 km (8 mi) along the east side of Crow Flats, Triassic and Permian rocks are contorted and fractured and exposed as chaotic, angular blocks. At many places Triassic rocks fill collapse sinks at least 15 m (50 ft) deep in Rustler gypsum. These sinks formed after the Triassic rocks were indurated and possibly as early as Jurassic time when the entire region was uplifted and eroded. Certainly this collapse occurred before Gatuna time because the Gatuna Formation rests unconformably on these chaotic structures.

Southwest of the Nakee Ishee Lakes the Gatuna Formation itself dips persistently northeast with apparent dips of as much as 20°. East and southeast of the lakes the Gatuna is relatively flat lying and cuts unconformably across the steeply dipping Gatuna beds. The steep dips in the Gatuna are interpreted as partly depositional and partly a result of collapse before Mescalero time.

At another place along the eastern edge of the exposure of chaotic rocks (NW¼ sec. 14, T. 17 S., R. 28 E.), the Gatuna Formation is at least 10 m (33 ft) below the uppermost exposures of Triassic rocks. These exposures of Gatuna are about 700 m (2,000 ft) wide and are roughly circular in plan. They are sinkhole fillings capped by relatively undisturbed Mescalero caliche.

At the north end of Pavo Mesa the Mescalero caliche is relatively flat lying and truncates dipping beds of the Gatuna Formation. However, along the east side of Pavo Mesa the Mescalero dips east and northeast; dips range from about 10° to nearly vertical. On Pavo Mesa the Mescalero caliche is at the 3,700-ft contour. Along a low escarpment southeast of the Nakee Ishee Lakes the Mescalero is fractured and is at the 3,590-ft contour. This indicates a displacement of 30 m (110 ft) since the caliche formed. Observations of similar displacements indicate that Clayton Basin has subsided more than 30 m (100 ft) and parts of Nash Draw have subsided as much as 55 m (180 ft) since Mescalero time.

Surface measurements and drilling data were used to compile a contour map with the Mescalero caliche as the datum for an area in eastern Eddy and western Lea Counties (fig. 8). This map shows gross topographic features of both Mescalero and post-Mescalero time and delineates some areas that have collapsed since Mescalero time. Relatively uniform spacing of contours beneath the Querecho Plains suggests that this represents an original slope on the Mescalero surface. The Mescalero surface dips southwestward, away from the High Plains, about 5.5–7.5 m/km (30–40 ft/mi). The uniform spacing of contours between The Divide and Livingston Ridge suggests that this surface also approaches its original slope. The closed contour at 3,700 ft around The Divide indicates that this area has been a drainage divide between San Simon Swale and Nash Draw at least since Mescalero time. A prominent swale east of Gatuna Canyon may indicate a relict Gatuna drainage system. At present this swale is occupied by several prominent depressions that include Williams Sink and Laguna Plata. These depressions do not appear to be collapse features and there is no evidence in the subsurface for dissolution of salts beneath these depressions. They are here interpreted as

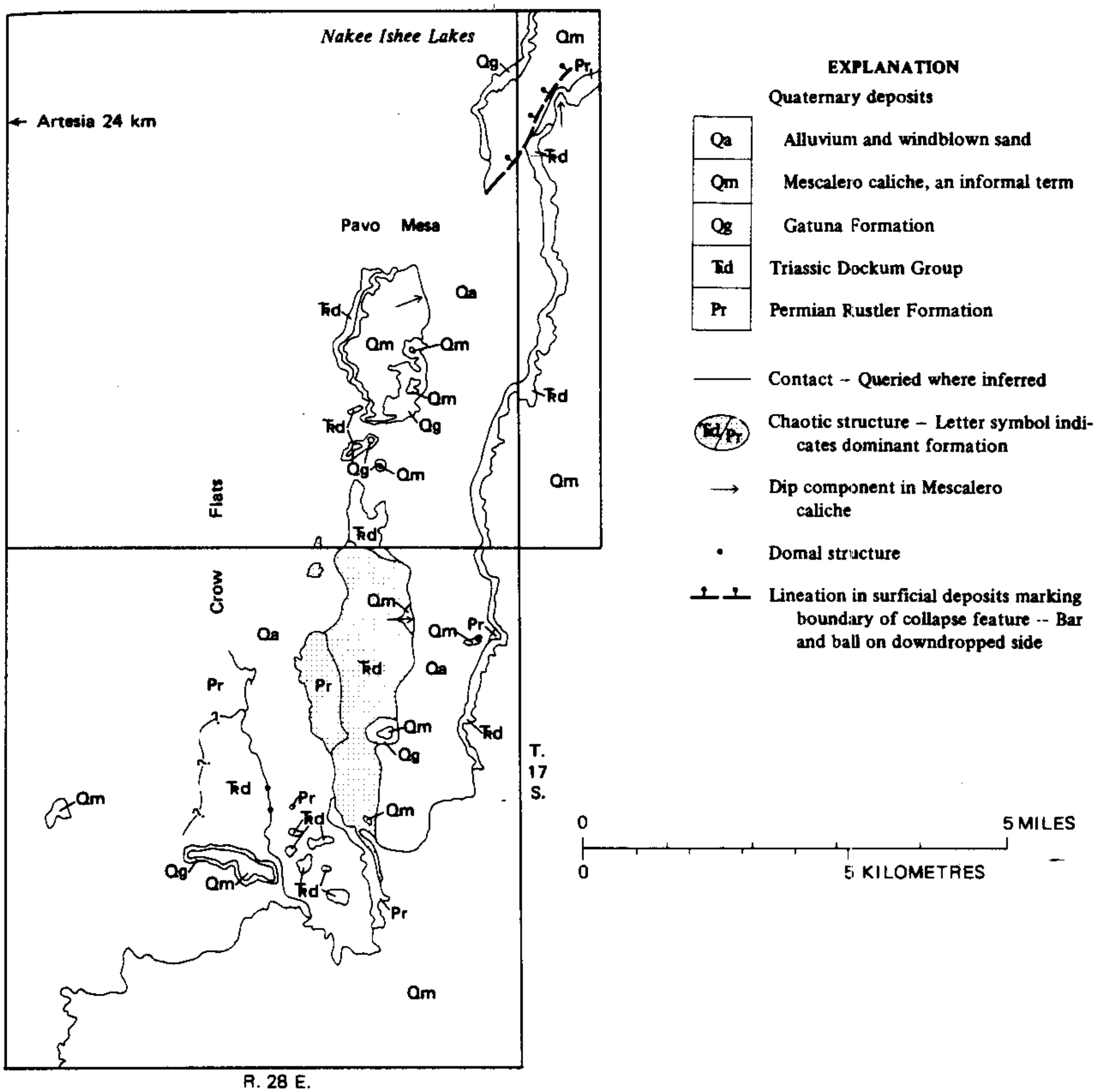


FIGURE 7.—Geologic sketch map of Crow Flats area east of Artesia, N. Mex.

blowouts within the relict drainage. Closely spaced contours around Clayton Basin and Nash Draw delineate these post-Mescalero features.

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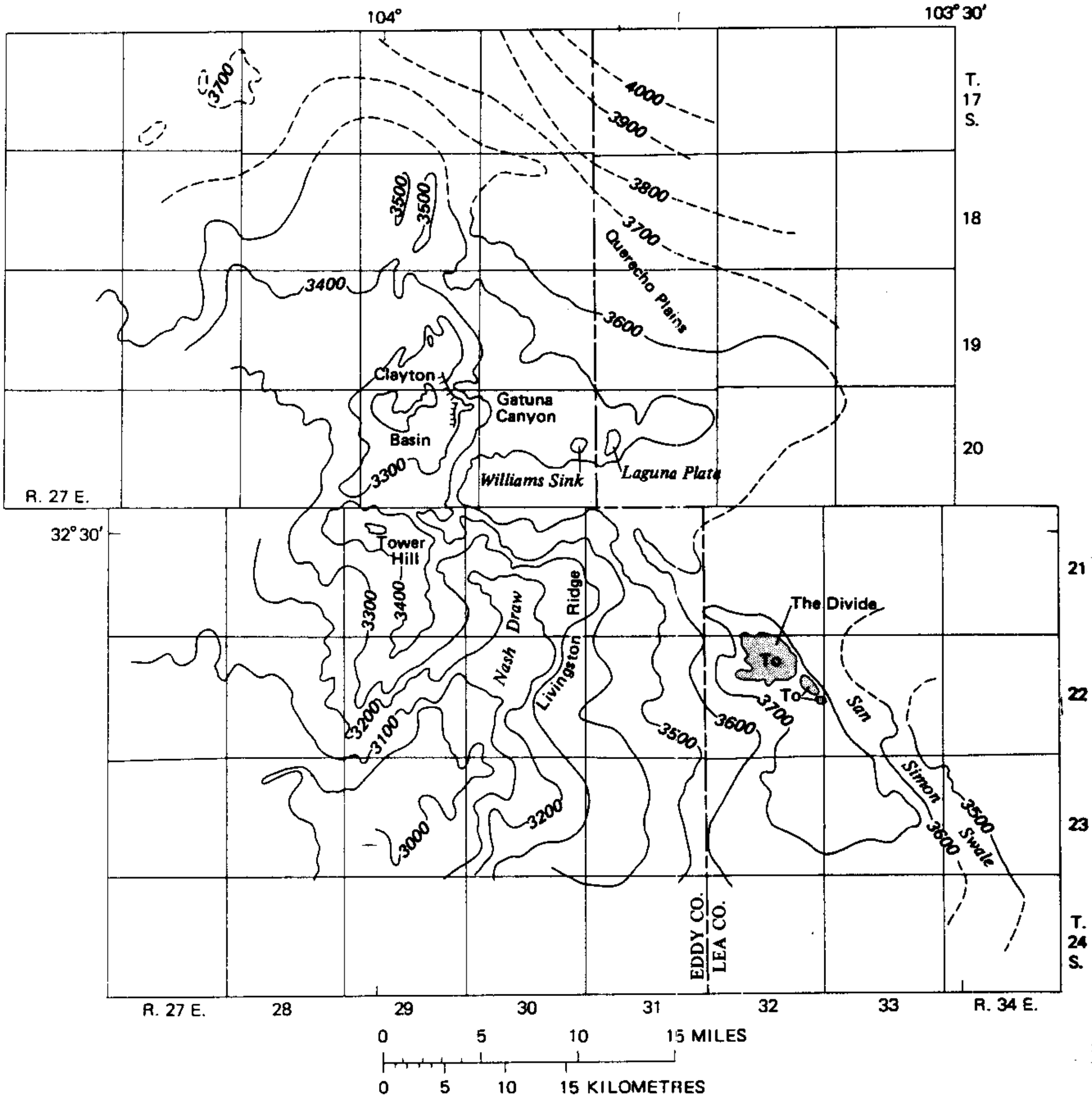

EXPLANATION

Slump in Mescalero caliche

To — Ogallala Formation at The Divide

—— 3300 —— Structure contours on Mescalero caliche —
- - - 3200 - - - Dashed where control is sparse. Interval is 100 feet (30.5 m)

FIGURE 8.—Structure contour map of Mescalero caliche.

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