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GEOLOGICAL SURVEY

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GEOLOGIC PROCESSES AND CENOZOIC HISTORY RELATED TO SALT DISSOLUTION IN SOUTHEASTERN NEW MEXICO

By

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ABSTRACT

Salt of Permian age in the subsurface of an area near The Divide, east of Carlsbad, N. Mex., is being considered for a nuclear waste repository. The geologic history of the region indicates that dissolution of salt has occurred in the past during at least three distinct epochs: (1) after Triassic but before middle Pleistocene time; (2) during middle Pleistocene; and (3) during late Pleistocene. Thus, destructive geologic processes have been intermittent through more than 100 million years.

Nash Draw, near The Divide, formed during late Pleistocene time by the coalescing of collapse sinks. The rate of its subsidence is estimated to have been about 10 cm (0.33 foot) per thousand years. The immediate area of The Divide adjacent to Nash Draw has not undergone stress by geologic processes during Pleistocene time and there are no present indications that this geologic environment will change drastically within the period of concern for the repository.

INTRODUCTION

This report discusses the Cenozoic geology of a portion of southeastern New Mexico. The area is mostly in Eddy and Lea Counties, but some discussion of the Pecos River valley farther to the north is included (fig. 1). This portion of New Mexico is in the southern part of the Pecos River section of the Great Plains physiographic province. It is in the northern part of the Chihuahuan Desert and the climate is arid to semiarid.

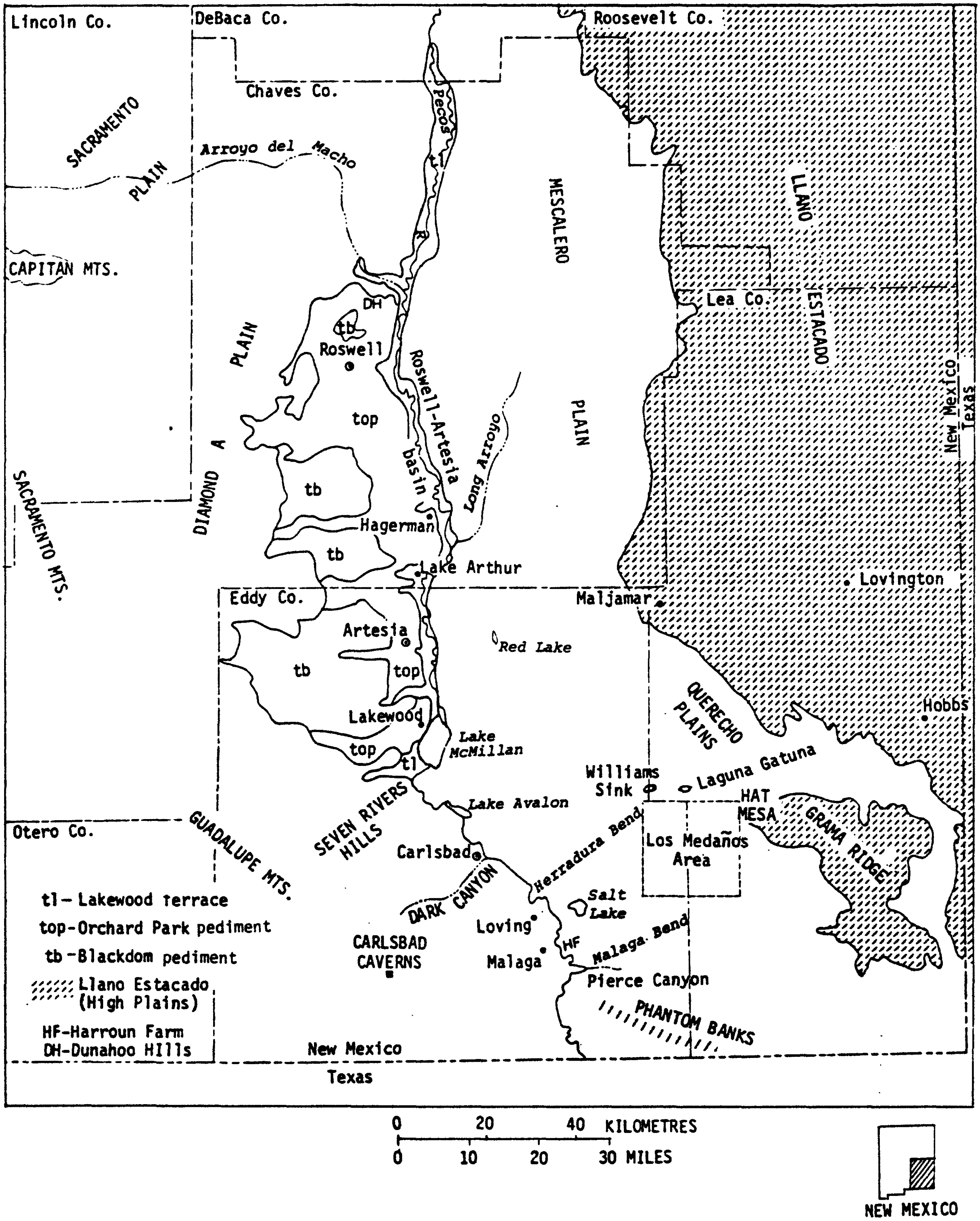


Figure 1.--Index map and Pleistocene features of southeastern New Mexico.

Southeastern New Mexico is underlain by Upper Permian salt-bearing rocks that have determined some features of the landscape. During Cenozoic time the climate varied from arid to relatively humid. During more humid times dissolution of subsurface salt and associated soluble rocks followed by collapse of the surface resulted in extensive karst plains. During the arid intervals large fields of windblown sand covered parts of the surface. These two features, karst plains and windblown sand, now dominate the landscape east of the Pecos River. West of the Pecos, karst topography is common but alluvial fans, pediments, and associated deposits form major parts of the landscape, and windblown sand is less common.

West of the Pecos River valley, the Guadalupe Mountains and, farther north, the backslope of the Sacramento Mountains have been major factors in the development of modern physiography. Drainage patterns are influenced by these uplifts. To the east of the Pecos the Staked Plains, or the Llano Estacado, are underlain by the sandy Ogallala Formation that has been a source of the large deposits of windblown sand in that area. Throughout this region the present landscape is visibly related to its geologic history.

Southeastern New Mexico is sparsely populated. The major town in the area is Carlsbad, which has a population of about 18,000. Farther to the north, and somewhat outside the area of this discussion, Roswell has a population of about 25,000. Carlsbad is a center of potash mining, petroleum production, and ranching. Development of these industries has been instrumental in the building of numerous secondary roads and jeep trails that give acess to much of the country.

Field work

The work in this area was done intermittently during 1972 and 1973 as part of a U.S. Geological Survey group studying problems of disposal of radioactive waste. This work was done on behalf of the Oak Ridge National Laboratory for the U.S. Atomic Energy Commission. Field work consisted of reconnaissance geologic mapping from the Pecos River eastward to Grama Ridge and from the Querecho Plains southward to Phantom Banks. Selected sites were mapped in detail. In addition to numerous traverses on the ground, much of the area was observed from low-level flights in light aircraft.

Acknowledgments

Many individuals contributed ideas and time to some to the basic concepts in this report. L. M. Gard, Jr., C. L. Jones, and P. W. Lambert visited localities in the field with me and discussed geologic relationships. During the 1973 field season I participated in a conference with J. C. Frye, A. B. Leonard, C. C. Reeves, Jr., J. W. Hawley and P. W. Lambert. These individuals contributed freely of their knowledge of the area. S. E. Galloway of the New Mexico State Engineers Office discussed ground-water relationships and geology of the Roswell artesian basin. Subsurface information for the preparation of figure 11 was provided by C. L. Jones.

STATEMENT OF PROBLEM

The possibility of constructing a nuclear waste repository in southeastern New Mexico within salt beds of the Salado Formation of Permian (Ochoan) age is being considered. One site under consideration is in Los Medaños area near the Eddy-Lea County line about 50 km (30 mi) east of Carlsbad. There, thick beds of salt are present at depths of about 600 m (2,000 feet).

The purpose of the present study is to help determine the geologic feasibility of such a repository. Many of the radioactive wastes to be stored in the repository are highly toxic for long periods of time. Of these wastes, plutonium-239 has the longest half life--24,000 years. This element must be contained for a period of about 10 half lives or about 250,000 years to decay to an innocuous level. Therefore, the period of concern for this repository is defined as 250,000 years. The problem is to determine if there are geologic processes or factors in southeastern New Mexico that might breach, disrupt, or otherwise disturb the repository within this period of concern.

In terms of human history 250,000 years is a long period of time, and it would appear to be impractical to attempt to predict events that far into the future. However, in terms of geologic processes 250,000 years is a relatively short time, and an attempt to predict geologic events that might occur within that time limit is not impractical.

The concept of uniformitarianism--that geologic processes operative in the past will continue to be operative in the future--is the basic assumption that predicates this study. Stable areas will remain stable for a period of time; whereas catastrophic geologic phenomena usually are confined to terrain having specific geologic prerequisites.

The prerequisites for catastrophic events such as violent earthquakes, volcanic activity, mountain building, and regional flooding are not known to be present in southeastern New Mexico. Instead, the geologic processes that might be potential hazards to a repository are more subtle and include erosion by streams and subsurface solution of salt by ground water. Collapsed sinks and associated features that indicate subsurface solution are present in a broad belt between Carlsbad and the site of the proposed repository. Nash Draw is one of these features and is about 12-13 km (7-8 mi) west of the proposed site. San Simon Sink in San Simon Swale is another solution feature about 25 km (15 mi) southeast of the proposed site. The geologic history of these features has been studied as part of this work.

The problem of predicting geologic events in southeastern New Mexico during the next 250,000 years has been approached by studying past geologic events recorded in preserved stratigraphic units. Active geologic processes have not changed since the close of Tertiary Ogallala time, about 3-4 m.y. (million years) ago. However, the rates of these processes have varied considerably. It is assumed that the rates of these processes will continue to vary and that prediction of future events can be made by assuming that the extremes of past conditions will not be exceeded in the future.

SUMMARY OF EROSION AND SALT DISSOLUTION

1. The western part of the Delaware basin (fig. 2) was exposed to erosion, and presumably salt dissolution, possibly as early as Triassic time and certainly as early as Jurassic time. This period of exposure

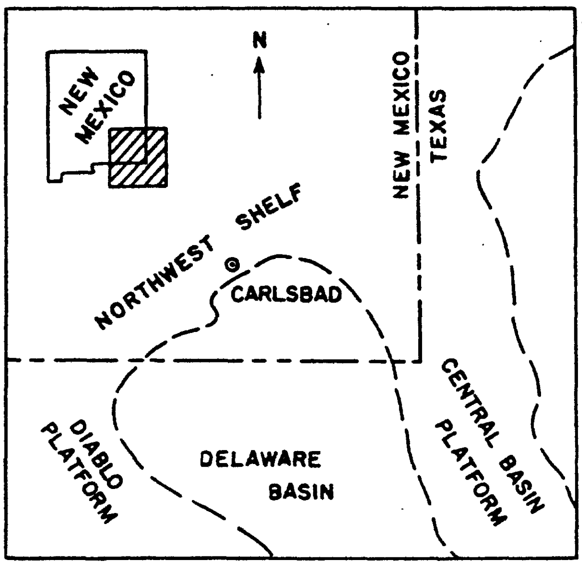


Figure 2.--Index map showing subsurface features in southeastern New Mexico.

may have been as long as 50 m.y. However, surface relief was probably low and erosion was not deep. Rocks of Triassic age covered much of the Delaware basin and helped to protect some of the underlying Permian beds. In the western part of the basin. however, Triassic rocks were stripped away, if they were ever deposized, and some erosion and dissolution of Permian rocks probably occurred.

2. During Cretaceous time the Delaware basin was submerged beneath the sea, but at the close of Cretaceous time regional uplift and major erosion occurred. This period of erosion lasted from the close of Cretaceous until late in Tertiary (Miocene) time, possibly a period of as much as 50 m.y. At the beginning of Tertiary time Cretaceous rocks blanketed the basin and protected the underlying rocks, but before the Ogallala Formation was deposited most of these Cretaceous rocks had been eroded away from the western half of the basin. Erosion again exposed the Permian rocks to dissolution. Some dissolution of Permian salt occurred at this time in the vicinity of San Simon Swale.

3. While the Ogallala Formation was being deposited there was very little, if any, erosion in the Delaware basin. During the past 3-4 m.y. since Ogallala time, wide fluctuations in climate have occurred and erosion and dissolution have been intermittent. The most humid climate and the greatest erosion were during middle Pleistocene time when the Gatuna Formation was being deposited. Then streams were capable of severely eroding the western escarpment of the High Plains as well as eroding and carrying pebble debris from as far to the west

as the Sierra Blanca and Capitan uplifts (fig. 9). Rainfall probably exceeded 600 mm (25 in.) per year and it is assumed that major dissolution of salt in the Delaware basin occurred at this time--more than 600,000 years ago.

4. After Gatuna time, but still during the middle Pleistocene, the region became more stable and semiarid. The Mescalero caliche accumulated in this climate. During late Pleistocene time, however, there were again periods of humidity accompanied by erosion and dissolution of salt. As a result of these processes the Mescalero caliche has subsided locally and collapsed into sinks.

5. Although erosion and dissolution are still active processes, the climate during Holocene time has been somewhat more arid than during the late Pleistocene. Present climate is neither as humid nor as arid as extremes of the past and it may represent an average of the past 1 m.y.

6. I have estimated that at one place in Nash Draw, dissolution of salt and accompanying subsidence of the surface has been about 58.5 m (180 ft) during the past 600,000 years.

GEOLOGIC SETTING

The production of oil, gas, and potash has been an economic incentive for the intensive study of pre-Tertiary stratigraphy and geologic history in southeastern New Mexico. Some of the major summary studies include the work of King (1942, 1948), Hayes (1964), and Jones (1973). Information from previous work is generally available; therefore, only a brief outline of major aspects of the pre-Tertiary history pertinent to the present study is presented here.

During the early part of the Paleozoic Era, the area of southeastern New Mexico was near sea level and periodically denuded by shallow seas. This raising and lowering of the sea level continued from Late Cambrian to the close of Mississippian time, a span of about 180 m.y. During Late Pennsylvanian and earliest Permian time an area of uplift, folding, and faulting--the Central Basin platform--developed along a north-trending belt near the present New Mexico-Texas State line (fig. 2). During Early Permian time this orogenic activity ceased and the entire region was again submerged beneath sea level.

During Late Permian time a sedimentary and structural basin, the Delaware basin, formed in western Texas and southeastern New Mexico. This basin was closed during parts of Late Permian time and therefore served as a hugh evaporating pan where salt and associated evaporites were deposited. This feature is now recognized in the subsurface where it is bounded by the Central Basin platform on the east, by the Northwest shelf, and by the Diablo platform on the southwest (fig. 2). At the surface it is bounded by the Guadalupe Mountains to the west. Rocks of Permian age are more than 3,000 m (10,000 ft) thick in the central part of the Delaware basin. Of these Permian rocks, only the upper part, the evaporite-bearing Ochoan Series, is of particular interest to the present study. Deposition of Permian rocks ended about 225 m.y. ago.

After the close of Permian time the region was uplifted above sea level, and during Late Triassic time stream and associated deposits accumulated over eastern New Mexico. These deposits include reddish-brown clays, sands, and gravels that cover the Permian rocks at many places in southeastern New Mexico. These Triassic rocks may have protected the underlying soluble Permian rocks from dissolution at various times in the geologic past.

It is possible that some dissolution of Permian soluble rocks occurred in the period of uplift during Triassic time. Far to the north in eastern New Mexico, in the vicinity of Santa Rosa, karst topography developed during Late Triassic time (about 190 m.y. ago). However, direct evidence for solution and collapse that occurred during Triassic time has not been found in southeastern New Mexico.

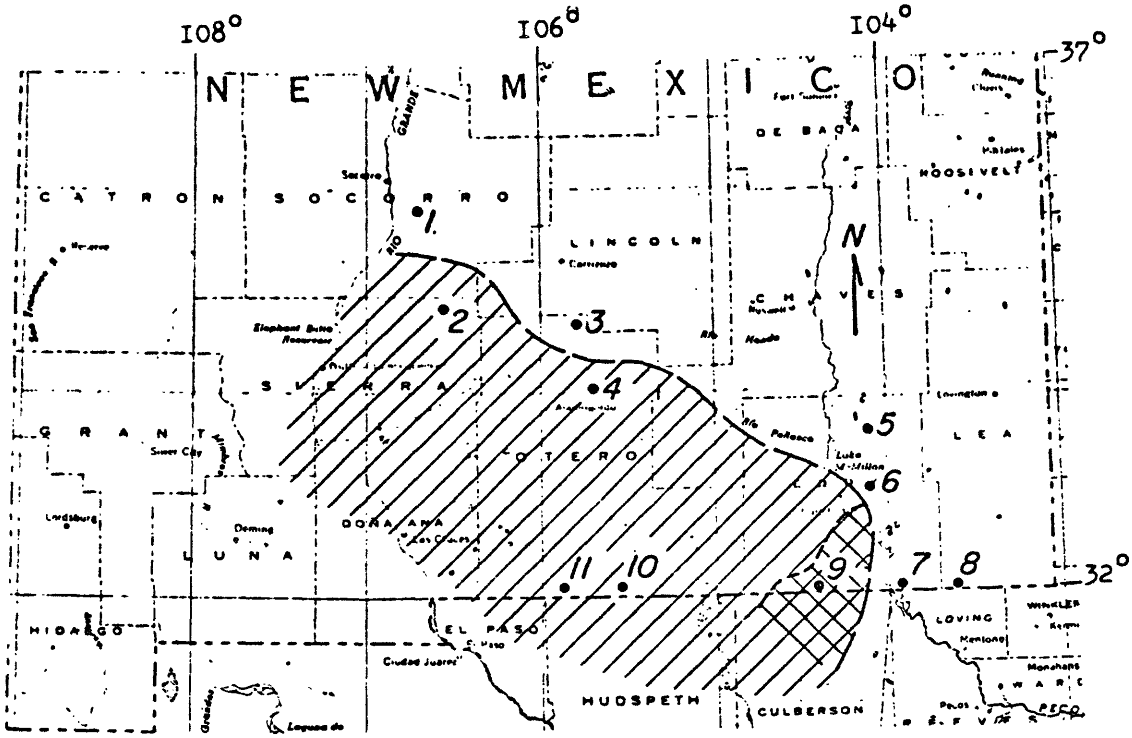
Most of southern New Mexico was probably above sea level and exposed to erosion from the close of Triassic time (about 190 m.y. ago) until Early Cretaceous time (about 136 m.y. ago). There is no evidence that sediments were being deposited in this area during the intervening Jurassic period. If rocks of either Jurassic or Triassic age were deposited in southern New Mexico they have since been eroded away.

Depositional characteristics and distribution of Jurassic rocks indicate that southern New Mexico was uplifted above sea level and was a region of low relief during Jurassic time. Continental Jurassic rocks preserved in central and northern New Mexico indicate that their source was from the south. Farther to the south in western Texas and northern Mexico, marine conditions prevailed during at least part of Jurassic time. In latitudes intermediate between the Jurassic continental deposits of central New Mexico and the marine deposits of northern Mexico, plutonism and volcanism in southeastern Arizona accompanied uplift and contributed sediments from that area (Hayes, 1970, p. 3).

In central and southeastern New Mexico where Triassic rocks are preserved they are overstepped by rocks of Cretaceous age. In general, these Cretaceous rocks rest on progressively older rocks toward the south and southwest. After cutting across the wedge edge of Triassic rocks the Cretaceous rocks rest on Permian or older strata at many places in southern New Mexico.

By plotting those localities where Triassic rocks are known to have been missing before Cretaceous time, along with localities where Triassic rocks are overlain by Cretaceous rocks, the general configuration of the erosional wedge edge of Triassic rocks is indicated. This plot also indicates the area that was subjected to erosion after Triassic and before Cretaceous time.

The accompanying map (fig. 3) summarizes the above information and shows that Permian rocks along the western edge of the Delaware basin were exposed to the atmosphere and presumably eroded during Jurassic time. Some dissolution of Permian salt deposits also probably occurred along the western side of the Delaware basin during this interval. Probably all of the Delaware basin area was eroded somewhat during this time, but Triassic rocks were present over most of the basin and served as a protective cover for the underlying Permian rocks.



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

Control Points

1. Carthage coal field (Triassic less than 500 feet 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 feet 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+ feet 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)

Figure 3.--Map showing extent of Jurassic erosion in southern New Mexico.

During Early Cretaceous (Washita) time a shallow sea transgressed across southern New Mexico. Only remnants of its deposits remain in parts of the region but they provide evidence for the extent of post-Cretaceous episodes of erosion. Some of these remnants are preserved only as fragments and blocks in collapse sinks (fig. 3). To the east, in Lea County, more continuous deposits of Cretaceous strata underlie the Tertiary Ogallala Formation (Ash and Clebsch, 1961). Far to the southwest, Cretaceous (Washita) rocks are also well preserved in the Cornudas Mountains (fig. 3, loc. 10). Present distribution of these remnants indicates that there has been extensive erosion in southeastern New Mexico since Cretaceous time.

At the close of Cretaceous time the western interior of the United States was uplifted and the seas withdrew. This marked the beginning of Tertiary time during which mountain building occurred in the Rocky Mountains. Although igneous activity occurred to the west in the Sierra Blanca (fig. 3, loc. 8) and Capitan Mountains during early Teritary time, extensive erosion was the dominant process in southeastern New Mexico. The Ogallala Formation of late Tertiary (Miocene and Pliocene) age is the earliest preserved sedimentary record in the vicinity of the Delaware basin that followed Cretaceous deposition. Late Tertiary and Quaternary events are summarized on table 1.

Table 1.--Summary of late Tertiary and Quaternary events in southeastern New Mexico

Age	Formation	Deposits	Events	Probable climate	Tentative correlations
Holocene	Young sand dunes Old soil Old sand dunes	Sand.	Working wind from southwest.	More dry than present. More moist than present. 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.	Wisconsinian.
	Orchard Park pediment deposits	Limestone-porphyry conglomerate. Caliche caprock.	Reworking of Blackdom deposits.	More moist than present. Probably cooler.	Probably early Wisconsinian.
	Blackdom pediment deposits	Limestone-porphyry conglomerate. Caliche caprock.	Major erosion of back slope of Sierra Blanca, Sacramento, and Capitan Mountains.	More moist than present. Probably cooler.	Probably early Wisconsinian.
	Hiatus				
	Mescalero caliche	Caliche.	Land surface stable. Soil development over much of southeast New Mexico.	More dry than present. Probably warmer.	Yarmouthian(?). Unnamed gravel surface west of Pecos.
Middle	Gatuna Formation	Unnamed gravel. Stream gravels, pond sediments, solution basin fill. Conglomerate, sand, silt, some gypsum.	Pediments formed Malaga area. 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 Ogallala Formation	Caliche.			

Tertiary Ogallala Formation

The Ogallala Formation of Miocene and Pliocene age is well exposed along Mescalero Ridge in the eastern part of Chaves County and in parts of Lea County. It rests unconformably on rocks of Permian, Triassic, and Cretaceous age in southeastern New Mexico and is the earliest Tertiary sedimentary formation preserved in that area. The Ogallala underlies the High Plains, the Llano Estacado of eastern and southeastern New Mexico; it provides much evidence for the interpretation of late Tertiary geologic history and climate.

At exposures along Mescalero Ridge northward from Maljamar for about 25 km (15 mi), the exposed part of the Ogallala typically includes three units as follows:

Top of exposures

1. 2.5-3.0 m (8-10 ft) caliche (caprock), light-gray to white, brecciated; densely pisolitic in upper part, dense and hard under hammer, forms prominent ledge.
2. 2.0-4.0 m (6.5-14 ft) sand, light-brown (5 YR 6/4)* fine-grained, well-sorted; grains subangular to well rounded, mostly quartz; forms vertical cliff at many places; weak calcareous cement, friable under hammer. Generally darker than underlying sand.

* Color notations are from Goddard, E. N., chm., and others, 1948, Natl. Research Council (rept. by Geol. Soc. America, 1951, 1970) 6 p.

3. 5-6 m (16-20 ft) sand, moderate-orange-pink (5 YR 8/4) to grayish-orange-pink (5 YR 7/2); fine grained, well rounded, well sorted, some grains frosted, mostly quartz; very friable, forms weak slope. Strongly cross laminated in places (apparently eolian origin). Some thin beds (less than 10 cm) have weak calcareous cement.

Base not exposed

The upper part of the caliche that caps these deposits, the "caprock" of local usage, has a distinctive pisolitic texture throughout its exposures along Mescalero Ridge and in exposures on Hat Mesa and The Divide. Exposures of the caprock farther north may not consistently have this texture but more observations are needed in that area. Examination of numerous deposits of caliche during the present work shows that pisolitic texture forms at a late stage of development and may indicate relatively old caliche deposits in this area. Although deposits other than the Ogallala caliche locally may contain pisolites, the pisolites in younger caliche beds are not as abundant, as widespread, or as well developed as those in the Ogallala.

Concentrically banded pisolites in the Ogallala vary in size even at the same locality; however, they generally average about 10-15 mm (0.3-0.7 in.) in diameter. They are usually closely spaced and may make up 50 percent or more of the rock. They vary from subround and ovoidal to elongate and irregular in form. The elongate axis is usually nearly normal to the bedding plain.

Microscopically the caliche is composed of variable proportions of micrite, sparry calcite, and scattered sand grains. Irregular masses of opal are common. The concentric structure of the pisoliths is usually composed of alternating bands of micrite and sparry calcite. Some micrite is clotted in structure, and the more dense portions may also be concentric or laminar. Rounded ooliths whose walls are composed of micrite surrounding minute masses of sparry calcite range from 0.10 to 0.30 mm or larger in diameter, and are common throughout the matrix. Horizontally banded, clotted to oolitic micrite having some layers of sparry calcite usually forms a laminar zone 5 mm or more thick at the top of the bed.

With the exception of the upper laminar zone, quartz grains are scattered throughout the Ogallala caliche. They range from about 0.08 to 0.30 mm in diameter. Many are well rounded, and concentric bands of sparry calcite surround some grains. Irregular masses of opal as large as 0.2 mm in diameter are common and are almost invariably surrounded by a fine mosaic of sparry calcite. In general, the quartz grains appear to float in a calcite matrix, as individual grains are not in contact. Calcite appears to etch and probably replaces some quartz grains.

The fine-grained sand that underlies the Ogallala caliche along Mescalero Ridge is remarkably uniform and well sorted. Although the upper part of the sand stands up as a vertical cliff, it is probable that the relatively weak cementation in that part is a result of the overlying calichification and not an indication of an environment of deposition different from the lower part. Similar sand is present in the Ogallala at Hat Mesa but at The Divide conglomeratic sandstone underlies the caliche. There pebbles of rounded quartzite and chert as much as 35-40 mm (about 1 1/2 in.) in diameter are present in lenticular beds.

In southeastern New Mexico the Ogallala Formation thins toward the south and southwest. Drill-hole information indicates that it is about 100 m (315-345 ft) thick in southeastern Chaves County (T. 15 S., R. 31 E.). In western Lea County (T. 16-17 S., R. 32 E.) the Ogallala ranges from about 75 to 90 m (245-300 ft) in thickness. At Hat Mesa it ranges from about 31 to 55 m (100-180 ft) in thickness and at The Divide in eastern Eddy County it is no more than 8.5 m (27 ft) thick. At all these localities the Ogallala caliche caps the formation. This indicates that the thinning occurred before formation of the caliche and suggests that the thinning is depositional.

Bretz and Horberg (1949a, p. 483) believed that the present Pecos River drainage southward from Roswell and in the vicinity of Carlsbad was of pre-Ogallala origin. They suggested that Ogallala fill might formerly have been as much as 400 m (1,300 ft) thick along the Pecos depression in this area. Although some form of major drainage may have been present in the vicinity of the modern Pecos River during pre-Ogallala time, the present work does not support an interpretation of thick Ogallala fill southwest of The Divide. In fact, the Ogallala Formation may not have been deposited in the Pecos depression southward from Carlsbad.

Much of the Ogallala Formation in eastern New Mexico was deposited as a series of complex alluvial fans by streams that flowed eastward from the Rocky Mountains. Deposition was on an irregular erosional surface and the alluvial fans coalesced as depressions were filled. Frye (1970) has reviewed problems pertaining to the Ogallala and has concluded that deposition ceased when the region was an extensive alluvial plain. By the end of Ogallala time the High Plains surface was probably continuous westward across the present Pecos River drainage to the backslope of the Sacramento Mountains. Although streams were responsible for some deposition in southeastern New Mexico, windblown sand also accumulated in thick deposits in that region.

When Ogallala deposition began in the central Great Plains climatic conditions were somewhat moist, ground-water conditions were stable, and temperature may have been somewhat warmer than at present. As Ogallala time progressed the climate became more arid, the water table declined, and stream flow became irregular (Frye and Leonard, 1957, p. 8). It is probable that only the latter part of Ogallala time, the most arid, is represented by deposits in southeastern New Mexico.

When Ogallala deposition ceased at some time during late Pliocene time, the region was tectonically stable and the climate was semiarid to arid. Over the High Plains region an extensive featureless surface formed on which the Ogallala "climax-soil" (Frye, 1970) developed. The caliche caprock was deposited during this time of stability in the zone of illuviation in the soil profile. Late in this period of soil development and after the caliche was mature, a series of northwesterly trending longitudinal sand dunes formed on the caliche surface in southeastern New Mexico (Price, 1944, 1958). Dissolution of caliche in linear troughs between these dunes created systems of parallel swales and dolines (see p. 51) oriented northwesterly. Although the dunes have been removed by erosion, the swales and dolines are still visible and are especially apparent from the air. They have a relief of 3-5 m (10-15 ft) and some are as much as 16 km (10 mi) long. They probably formed on the High Plains (Llano Estacado) surface before Pleistocene time, because they are not present on Pleistocene surfaces.

Quaternary deposits

Following the late Pliocene stabilization of the High Plains, during early Pleistocene time parts of the Rocky Mountains were rejuvenated and a period of extensive erosion began. As glaciers accumulated at higher elevations and on the continent farther to the north, rainfall increased in the south. Climate fluctuated widely during Pleistocene time and the glaciers surged forward or withdrew accordingly. On the High Plains far to the south of the glaciers, climate varied from cool and moist to warm and semiarid or arid.

Pleistocene deposits in southeastern New Mexico include alluvium, lake and playa sediments, soils, caliche, travertine, and windblown sand. Although direct evidence for the age of these deposits has not been found within the study area, most of this sedimentary record is correlated with events in nearby areas during parts of middle and late Pleistocene time. Of these deposits only the Gatuna Formation has been given a formal stratigraphic name.

Erosion was widespread during early Pleistocene time and a hiatus represents that interval over much of southeastern New Mexico. At a few localities on the Mescalero plain east of the Pecos River, caliche is present on several small hills that rise above the Mescalero plain. These may be remnants of an early Pleistocene (Nebraskan) deposit (A. B. Leonard and J. C. Frye, written commun., 1974) that were not removed by middle Pleistocene erosion, but regionally these remnants are rare.

Gatuna Formation

The Gatuna Formation of Pleistocene age was named for exposures of light-reddish-brown sandstone and conglomerate more than 25 m (80 ft) thick in Gatuna Canyon, eastern Eddy County (Robinson and Lang, 1938, p. 84-85). A type section has not been described. The physical stratigraphy and field relationships of this formation indicate that it was deposited during the most moist conditions that prevailed in southeastern New Mexico during Pleistocene time. Because of the indications of climatic conditions inherent in the Gatuna Formation it was examined carefully at many exposures during the present study.

The Gatuna Formation is well represented along the east side of Clayton Basin where it rests on rocks of Permian age and is overlain by the Mescalero caliche that formed during Pleistocene time. The

Gatuna is also present around Nash Draw where it was mapped by Vine (1963, p. 31) who stated that Gatuna deposition "followed immediately after, or in part accompanied, a period of active solution in the Rustler and Salado Formations." In the vicinity of Crow Flats, Chaves County, the Gatuna Formation is also associated with extensive solution of gypsum and salt and subsequent collapse of the surface. The Gatuna is well exposed in Long Arroyo, Chaves County, and is present at many outlying localities along the Pecos River drainage.

The Gatuna Formation was examined in the type area during the present study. A stratigraphic section was measured on the north side of Gatuna Canyon (SW 1/4 SW 1/4 sec. 36, T. 19 S., R. 30 E.). Although the Gatuna is estimated to be thicker at other localities, this locality is the least disturbed by slumping and is one of the better exposed in Gatuna Canyon. For these reasons it is here proposed that this locality be regarded as a reference section for the Gatuna Formation in the type area; it can be described as follows:

Begin in arroyo bottom, base of formation not exposed.

4. 1.0 m (3.25 ft) sandstone, friable, moderate-reddish-orange (10 R 6/6) to pale-reddish-brown (10 R 5/4), fine- to medium-grained, subangular to subround, well-sorted. Grains are rock fragments, quartz, occasional flakes of biotite. Weak calcareous cement. Bedding irregular to indistinct. Beds about 10 cm thick.

3. 12.3 m (40 ft) conglomerate, poorly sorted, ranges from coarse sand to pebbles at base and grades upward into more coarse clasts. Clasts at base, subangular to subround, do not exceed 4 cm in diameter in basal metre of unit. Upper part of interval includes abundant subangular clasts as large as 25 cm in diameter, derived from Ogallala pisolitic caliche. Clasts consist of: Ogallala pisolite, 36 percent; sandstone, 10 percent; orthoquartzite, 14 percent; Tertiary porphyries, 16 percent (mostly Sierra Blancan rock types, one clast may be Capitan type); Permian limestone, 6 percent; quartz, 4 percent; chert, 2 percent; and jasper, 2 percent.

2. 3.5 m (11.2 ft) sandstone, pale-reddish-brown (10 R 5/4), medium-grained, subround to round, well-sorted, slightly calcareous; bedding indistinct; weathers into irregular masses. Top of unit engulfed by overlying Mescalero caliche.

   16.8 m (55 ft) total Gatuna measured. Estimated to be at least 6-7 m (20 ft) thick in covered slopes below this measured section.

1. 1.7 m (5.6 ft) Mescalero caliche. Nodular zone engulfs top of Gatuna, grades upward into plugged nodular zone. Caprock eroded at this place.

The Gatuna is slumped at most places but an estimated thickness of 16-30 m (50-100 ft) in Gatuna Canyon is reasonable. At a gravel pit on the north side of Gatuna Canyon (S 1/2 sec. 35, T. 19 S., R. 30 E.) the formation is at least 17 m (55 ft) thick in a slump block. There it consists of friable, calcareous, moderate-reddish-orange (10 R 6/6) conglomeratic sand. The sand grains are poorly sorted, medium to granular, and subangular to subround. Conglomeratic beds are lenticular and many layers are strongly crossbedded.

Clasts in the conglomerates at most places in Gatuna Canyon are largest near the base of the exposures where they average about 7-10 cm (3-4 in.) in diameter. Boulders as much as 20 cm (8 in.) in diameter are not uncommon. In the upper part of the Gatuna, cobbles are less than 9 cm (3.5 in.) in diameter. Rounded cobbles and boulders that have been derived from the pisolitic caprock caliche of the Ogallala Formation are common in the Gatuna at many places. At the gravel pit on the north side of Gatuna Canyon (S 1/2 sec. 35, T. 19 S., R. 30 E.) clasts derived from the Ogallala caliche are 7-20 cm (3-8 in.) in diameter and make up about 30 percent of the constituents. Quartzite and orthoquartzite are about 50 percent of the clasts and Tertiary porphyritic igneous rocks are about 10 percent of the clasts. The quartzites are generally much smaller in average diameter than the clasts derived from Ogallala caprock, which indicates that the quartzite clasts are at least of second-cycle derivation.

In Long Arroyo about 1 mile north of New Mexico Highway 31 (NW 1/4 sec. 14, T. 14 S., R. 27 E.) a conglomeratic channel deposit is well exposed in the Gatuna Formation along the west side of the arroyo. The base of the Gatuna is an uneven erosion surface on red beds of the Permian Artesia Group. Sandstone of the Gatuna, in which the channel deposit is preserved, is moderate reddish orange (10 R 6/6), fine to coarse grained, and poorly sorted. The channel deposit is generally pale red (5 R 6/2), poorly sorted, crossbedded, and lenticular in cross section. Clasts are as large as 15 cm (6 in.) in diameter and consist of about 45 percent quartzite and orthoquartzite, 33 percent Ogallala pisolitic caliche, 12 percent red sandstone, and almost 10 percent chert.

These exposures indicate that some of the Gatuna Formation was deposited by streams. However, in Nash Draw the sand is generally much finer grained, and clay and recrystallized gypsum are present in the Gatuna Formation. In the southern part of Nash Draw (SE 1/4 sec. 33, T. 23 S., R. 29 E.) yellowish-gray clays slumped into red silts and sands during Gatuna time. Beds of gypsum more than 2 m (6 ft) thick are associated with the yellowish-gray clays. In the vicinity of Red Lake and Pavo Mesa east of Artesia, N. Mex., the Gatuna Formation contains massive fine-grained beds. These exposures indicate that some parts of the Gatuna were deposited in a low-energy aqueous environment and probably in areas of sinking and collapse.

In southern Eddy County in Pierce Canyon and along Phantom Banks, the Gatuna contains fine-grained sediments as well as extensive blanket deposits of conglomerate. In this area the lower part of the Gatuna was probably deposited in collapsed basins and the upper part was deposited as alluvial gravels on a pediment surface. Here, in places, the alluvial gravels have been incorporated by the overlying Mescalero caliche. This has resulted in a lime-cemented conglomerate that is hard under the hammer. Clasts in this area are more than 50 percent Permian limestone, and the remaining constituents are quartz, orthoquartzite, and chert. Occasional Tertiary porphyritic igneous rocks and pink granite are present.

Some siliceous conglomerates are present along the present Pecos River and remnants of these gravels are along Black River (fig. 3, loc. 9). They were first described by Nye (in Fiedler and Nye, 1933, p. 35-38). Bretz and Horberg (1949) and Thomas (1972) have discussed these gravels and suggested that they are basal Ogallala. However, study of these pebbles as well as those of the Gatuna during the present work indicate that they are Gatuna Formation in place or remnants of the Gatuna Formation. Clasts derived from Ogallala pisolitic caliche are present in at least one of these outliers near Loving (SE 1/4 sec. 33, T. 23 S., R. 28 E.), and pebble counts at other places suggest pebble associations of the Gatuna.

Capping the Dunahoo Hills 19 km northeast of Roswell is an outlier of conglomerate that is probably equivalent to the Gatuna Formation. It is an irregular crossbedded channel deposit. Some interbeds consist of fine sand that was probably derived from strata of the underlying Permian Artesia Group. Clasts in the conglomeratic beds are subround to round, spherical to oblate, spheroidal forms. The most common size is 6-8 cm (about 3 in.) in diameter. A few rare clasts are as much as 20 cm (8 in.) in diameter. Permian limestone composes nearly 70 percent of these clasts. Orthoquartzite, chert, and Tertiary porphyritic igneous rocks make up the remainder. In roadcuts near the highway other rock types are present, but consideration of many exposures in this area indicates that these roadcuts have been contaminated by exotic debris during highway construction. In general, these conglomerates, as well as conglomerates of the Gatuna, are composed of an assemblage of relatively few rock types.

Sediments in the Gatuna Formation were derived from at least three major source areas: (1) the Ogallala Formation, (2) underlying Permian and Triassic rocks, and (3) uplifts of Permian limestones and Tertiary igneous porphyries west of the Pecos River valley. The underlying Permian and Triassic red beds supplied a major portion of the finer grained particles to the Gatuna Formation. The underlying Triassic conglomerates supplied some of the siliceous pebbles but many of these were derived from the Ogallala Formation along with pisolitic caliche from the Ogallala caprock. Permian limestone terrain was especially important as a contributor to the Gatuna Formation in southern Eddy County. There, in some places along the Phantom Banks, Permian limestones make up more than 50 percent of the clasts.

Limestone clasts, both Permian and Ogallala pisolitic caliche, are considered to be first-cycle deposition in the Gatuna Formation. Some Tertiary igneous porphyry clasts are probably also first cycle because they are of relatively large size in many places. Most siliceous clasts, however, appear to be of second-cycle deposition. Most of the siliceous clasts are as well rounded as the generally larger limestone clasts. In addition, it seems probable that the limestone clasts would be much smaller than the more durable siliceous clasts if the two constituents had traveled equal distances.

The Gatuna Formation was deposited during a much wetter climate than the present. There is no indication that modern drainage is carrying clasts of the size and quantity preserved in Gatuna stream deposits. (In fact, modern arroyos are frequently choked with windblown sand in southeastern New Mexico).

There are no pebbles in the Gatuna Formation that definitely indicate an axial Pecos gravel. All the pebbles could have been derived locally in southeastern New Mexico. The rare rock types (pink granite) that must have been derived from masses of Precambrian rock far to the north in the Sangre de Cristo Mountains region or the Pedernal Hills are probably second-cycle elements that were reworked from the Ogallala Formation. Fresh feldspars that might be expected in an axial gravel derived from the Sangre de Cristo Mountains are indeed rare to nonexistent at most Gatuna exposures.

Discovery of Ogallala pisolitic caliche debris in the Gatuna Formation in its type area clarifies one aspect of the Gatuna's age. The Gatuna is post-Ogallala and, therefore, Pleistocene. It has been suggested by other workers that the Gatuna could be pre-Ogallala (Kelley, 1971, p.30) or that siliceous gravels along the Pecos River alley, herein correlated with part of the Gatuna, could be Ogallala (Thomas, 1972, p. 17) or possibly pre-Ogallala (Bretz and Horberg, 1949a, p. 487).

Fossils have not been found that would permit definitive correlation with other areas, but on the basis of analogies with other areas it is possible to make tentative correlations. As the

Gatuna appears to have been deposited during the most humid climatic conditions that have existed in this area since Ogallala time, it is necessary to examine evidence for climatic conditions in adjacent areas.

Other workers have regarded Kansan time as the most humid of Pleistocene stages. Frye and Leonard (1965, p. 211) have stated that "molluscan and vertebrate faunas clearly indicate that ecological conditions in the Great Plains reached their Quaternary optium during the Kansan Stage. The trend toward greater precipitation and lower average annual temperatures began in the Nebraskan and culminated in the Kansan." In a discussion of a Kansan fauna from Texas, Hibbard (1970, p. 401) has stated that "the diversity of large grazers in the fauna indicates the presence of tall grasses in the valleys. The presence of browsers indicates the occurrence of shrubs and a good stand of small trees.... The fauna indicates more effective moisture and temperatures not below freezing...."

On the basis of the many stream and pond deposits in the Gatuna and the evidence for widespread solution and collapse, Gatuna time represents the most humid Pleistocene stage in southeastern New Mexico. Therefore, the Gatuna Formation is here tentatively correlated with the Kansan Stage.

Mescalero caliche

The Mescalero plain is a geomorphic surface that lies generally east of the Pecos River and west of the High Plains in southeastern New Mexico (Bretz and Horberg, 1949a, p. 481). It extends from the vicinity of Fort Sumner on the north to beyond the New Mexico-Texas State line on the south. It is covered at many places by windblown sand, but everywhere the surface is observed it is underlain by a prominent deposit of caliche. This caliche has been traced over a broad area during the present work. It is here treated as an informal stratigraphic unit and called the Mescalero caliche.

The Mescalero caliche consists of two parts: a basal earthy-to-firm nodular calcareous deposit and an upper dense laminar caprock. The caliche commonly weathers to a ledge where the caprock overhangs the nodular base. The two parts range from about 1 to 4 m (3 to 13 ft) in thickness, the caprock usually making up about one-third to over one-half of the total thickness.

Although either part of the Mescalero caliche may engulf underlying sediments, most commonly it is the basal part that has the greatest effect. Near the base of the caliche profile, irregular masses of bedrock may be engulfed, or partly surrounded, by caliche. In the upper part of the profile, scattered siliceous pebbles may be the only vestige of the engulfed surface.

The Mescalero caliche has undergone a long history of dessication and recementation; however, breccia and pisolitic texture are not as commonplace as in the Ogallala caliche along Mescalero Ridge. Breccia is generally rare; whereas, pisoliths are common in the Mescalero. Both are concentrated in limited areas. The most characteristic feature of the Mescalero caliche is the prominent laminar texture throughout much of the caprock. These laminae are generally less than 5 mm thick and are parallel to the surface. They may be weakly crenulated or even disrupted by pisoliths.

Microscopically the carbonate of the caprock is mostly micrite having lesser amounts of sparry calcite, which occurs as veinlets, replacements, and irregular laminae. The micrite commonly has a clotted texture which emphasizes the laminar structure. Although chemical studies were not made during the present work, the micrite frequently occurs as yellow bands in areas of secondary accumulation, which suggests the presence of iron oxide.

Sand grains are common in most parts of the caliche profile. In the caprock, subangular to rounded quartz grains that range from about 0.1 to 0.3 mm in diameter are an integral part of the micritic matrix. Some of these grains are etched and are being replaced by sparry calcite. However, sand grains are conspicuously rare in the laminar zones. Some very fine silt grains (<0.01-0.02 mm in diameter) are not uncommon in these zones, but it appears that the larger grains have been pushed aside by the process that deposited the laminae. It is here suggested that this fact is one of the strongest indications that the laminar zone was deposited by a separate process from that which deposited the matrix. It is believed that the laminar zone represents dissolution and reprecipitation of the matrix during a period of climatic change from the ideal climate suitable for the formation of caliche.

The Mescalero caliche was formed during an interval of climatic and tectonic stability that followed deposition of the Gatuna Formation. The Mescalero engulfs the upper part of the Gatuna Formation in the Gatuna Canyon and Nash Draw areas and at most other places where the Gatuna is present. However, the Mescalero is not confined to places where the Gatuna is present. It oversteps to older formations in the region and at various places has engulfed a planar surface on Triassic and Permian rocks.

The Mescalero caliche formed mainly in a semiarid environment that followed the moist conditions of Gatuna time. By comparison with Pleistocene events in other parts of the Southwest and the Rocky Mountains, the Mescalero is tentatively correlated with the Yarmouthian interglacial stage.

Pleistocene deposits and geomorphic features

Five physiographic surfaces have been recognized in southeastern New Mexico west of the Pecos River. Horberg (1949, p. 464 summarized the work 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 (Bretz and Horberg, 1949b, fig. 1). Although the Sacramento and Diamond A plains represent part of the early history of the Pecos River drainage, limited time did not permit their close examination during the present study. The Blackdom, Orchard Park, and Lakewood surfaces are more closely related to the modern Roswell alluvial basin and were examined in detail at some places.

Sacramento plain: The Sacramento plain was described by Nye (in Fiedler and Nye, 1933, p. 14-15) as a highly dissected plain about 40 km (25 mi) west of the Roswell basin that extends westward to the Sacramento Mountains. Horberg (1949, p. 464-465) suggested that this plain is correlative with the surface of the High Plains on the Ogallala Formation to the east of the Pecos and stated that the Sacramento plain is probably equivalent to the upland surface on the Guadalupe Mountains.

Diamond A plain: The Diamond A plain was named by Nye (in Fiedler and Nye, 1933, p. 14), and other workers have followed this nomenclature. Remnants of the Diamond A plain are present about 32-40 km (20-25 mi) west of the Pecos River. This plain is much 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 well-developed beds of caliche. The caliche has a laminar caprock and is very similar to the Mescalero caliche to the east of the Pecos River.

Blackdom pediment gravel: The Blackdom pediment gravel was first named the Blackdom terrace by Nye (in Fiedler and Nye, 1933, p. 12, 32-35), and this nomenclature has been followed by other workers in the area (Morgan, 1938, p. 9-17; Morgan and Sayre, 1942, p. 35; Horberg, 1949, p. 464-465, 470-471). It is implicit in the descriptions of these workers that the Blackdom deposits rest on a surface cut on older rocks. However, for the purposes of the present discussion it is desirable to separate pediment gravels from the terrace gravels related to the axial drainage of the Pecos River. Field work by the writer indicates that Pleistocene drainage of the Pecos River included major tributaries from the west. Thus, the Blackdom pediment gravels are interpreted to have been deposited by these western tributaries during an early stage in the development of the modern Pecos drainage.

Blackdom pediment gravels are restricted to areas west of the Pecos River. They have been traced during the present work from a point about 16 km (10 mi) south of Roswell southward intermittently for about 64 km (40 mi) to the Seven Rivers Hills 20 km (12 mi) northwest of Carlsbad. These gravels, or their equivalents, appear to extend northward from Roswell at least as far as Arroyo del Macho but have not been examined in that area. Motts (1962) recognized a "Blackdom plain" in the vicinity of Carlsbad and along Dark Canyon east of the front of the Guadalupe Mountains, and Horberg (1949, fig. 3) recognized a "Blackdom plain" in the vicinity of the Carlsbad Caverns. These "plains" may be underlain by some equivalents of the Blackdom pediment gravel but they appear to be part of a more extensive fan system that formed locally to the east of the Guadalupe Mountains.

Between Roswell and the Seven Rivers Hills the Blackdom pediment gravel rests on a planate surface that cuts across Permian rocks. Almost 100 percent of the constituents of the Blackdom pediment consists of limestone and dolomitic limestone of the underlying Permian rocks. Progressively northward along its exposures, scattered porphyries derived from Tertiary intrusives to the west are more common.

The limestone clasts vary considerably in size and shape but generally range from about 6 to 8 cm in diameter. The range from lime sand to scattered boulders 0.5 m in diameter indicates the poor sorting and extreme variations in size. Clasts are subangular to round and vary from spherical to oblate spheroidal. Many clasts are solution faceted and calcareous cups have formed on their lower surfaces.

The matrix of the gravel is commonly a white earthy textured caliche, but at many places the gravel is well cemented. Cemented horizons usually occur near the top of the gravel, but they may be present as isolated zones at any place within the deposit. The calcareous cement is hard under the hammer and, unlike pedogenic caliche, has a relatively uniform density throughout the cemented zone. A weak nodular zone similar to the underlying pedogenic laminar zones in caliche may underlie the more dense layers, but the nodules in the Blackdom gravel commonly are solution-faceted pebbles. Laminar zones in the dense caliche of the Blackdom are weakly developed, and pisolitic texture was not observed.

The Blackdom pediment gravel averages about 6.0-8.5 m (20-30 ft) in thickness. Its surface is hummocky to rolling and is scarred by small dolines. It is more uneven than the younger Orchard Park gravel surface. About 3.2 km (2 mi) and 8.8 km (5.5 mi) north of Lakewood are two low outliers that rise above the younger Orchard Park gravel but are not as uneven and pocked as the Blackdom gravel surface. These are presumed to represent a local deposit intermediate between the Blackdom and the Orchard Park.

Nye (in Fiedler and Nye, 1933, p. 12) stated that the "Blackdom terrace rises 30 to 50 feet [9 to 15 m] higher than the Orchard Park terrace along its eastern margin and is generally 60 to 80 feet [18 to 24 m] higher than the stream channels. It has an eastward gradient of 30 to 40 feet [9 to 12 m] to the mile and is therefore 50 to 60 feet [15 to 18 m] higher than the Orchard Park terrace in the valleys of the major tributaries of the Pecos in its western margin." The present work indicates that these observations are generally accurate.

Orchard Park pediment gravel: The Orchard Park pediment gravel was named the Orchard Park terrace by Nye (in Fiedler and Nye, 1933, p. 11-12, 31-32) and this terminology has been generally followed by later workers. From the present work, however, the Orchard Park pediment gravel is believed to be deposited on an erosion surface related to the cutting of the Blackdom surface. Therefore, it is treated as a younger part of the erosional cycle that accompanied the development of the western part of the Pecos River drainage system.

Orchard Park pediment gravels are restricted to areas west of the Pecos River from Arroyo del Macho north of Roswell southward to the vicinity of Lakewood. Equivalent gravels may be present in the fan complex east of the Guadalupe Mountains and south of Carlsbad but they cannot be distinguished with certainty.

The Orchard Park pediment gravel contains both limestone and porphyry clasts. In a gravel pit near Orchard Park (SE 1/4 SE 1/4 sec. 21, T. 12 S., R. 25 E.) gravel clasts consist of 58 percent Tertiary porphyry and 42 percent Permian limestone. The porphyries were derived from the Capitan and Sierra Blanca uplifts to the west. The clasts at this locality are subround to round and average about 3-4 cm in diameter. A maximum diameter of about 15 cm was observed at this locality. The deposit is poorly sorted and the matrix is light gray, earthy, and calcareous.

About 45 km (28 mi) south of Orchard Park and 3.2 km (2 mi) east of Artesia, the Orchard Park gravel is composed of 100 percent Permian limestone clasts. They are subround to round, average about 2-5 cm in diameter, and have maximum diameters of about 8 cm. Some clasts are oblate spheroids. Solution faceting is common and limestone cups have formed on the base of clasts. This faceting is not as advanced as that in the Blackdom gravels and the matrix clasts are easily recognized as detrital limestone. Wherever the Orchard Park gravel was examined, its constituents were generally smaller than those of the Blackdom.

At the above-mentioned locality near Orchard Park a bed of caliche 0.5 m (1.5 ft) thick overlies the gravel. It is moderately indurated and structureless except for a weakly laminated plane at one horizon. It has engulfed scattered cupped pebbles near the base.

Nye (<u>in</u> Fiedler and Nye, 1933, p. 11) stated that the "Orchard Park terrace rises 5 to 10 feet [1.5 to 3 m] above the Lakewood terrace and is 20 to 35 feet [6.1 to 10.7 m] above the present stream channels." It is difficult to estimate the thickness of the Orchard Park gravels because exposures are limited to gravel pits and other artificial cuts, and much of the surface is farmed by irrigation. An incomplete stratigraphic section in the gravel pit at Orchard Park is 3.8 m (12.5 ft) thick. In the vicinity of Lakewood the Orchard Park gravel is estimated to be about 6-9 m (20-30 ft) thick.

<u>Lakewood terrace</u>: The Lakewood terrace, named by Nye (<u>in</u> Fiedler and Nye, 1933, p. 10) is present as a narrow strip along the Pecos River from the vicinity of Roswell as far south as Carlsbad. It represents a former flood plain of the Pecos and is about 3-9 m (10-30 ft) above the present channel. It is present westward along some of the tributaries to the Pecos and is especially prominent between Lake Arthur and Lakewood. This terrace can be traced along the Pecos for about 6 km (4 mi) downstream from Carlsbad but there it loses its identity. Southward from Herradura Bend there are surfaces that lie near the Pecos channel, but these are here interpreted as exhumed collapsed surfaces and should not properly be called Lakewood terrace.

Constituents of the Lakewood terrace deposits are variable throughout the length of their exposures. The northernmost exposures in the Roswell basin contain a great variety of rock types that reflect the many source areas of the Pecos River far to the north in the Sangre de Cristo Mountains.

At the south end of the Roswell basin, Lakewood deposits are generally fine grained and indicate the effectiveness of the Roswell basin as a settling basin during Lakewood time. In the vicinity of Carlsbad the Lakewood terrace sediments are mainly limestone sand and gravel, which indicate local sources.

About 22 km (14 mi) northeast of Roswell (SW 1/4 NE 1/4 sec. 3, T. 9 S., R. 25 E.), gravels in the Lakewood terrace contain subround to round pebbles that average about 3 cm in diameter; but some clasts are as much as 10 cm in diameter. These pebbles consist of:

Orthoquartzite	22 percent
Permian limestone	22
Chert	16
Sandstone	12
Quartz	12
Granite, pink, medium-grained, crystalline, epidote	6
Granite, pink, coarsely crystalline, prominent feldspars	4
Schist (mica, hornblende, quartz)	2
Yellow granite, coarsely crystalline	2
Diorite(?)	2
Feldspar, fresh	Rare
	100 percent

These constituents are the most diverse observed in any conglomerate along the Pecos River from the Roswell basin southward to the

New Mexico-Texas State line. The granites and feldspars are similar to those in Pecos River gravels along the Pecos River in the vicinity of Fort Sumner about 100 km (63 mi) to the north. It is noteworthy that Tertiary porphyries from the Capitan Mountains to the west are apparently absent in the Lakewood terrace deposits in the Roswell basin, although these porphyries are common in the older Orchard Park pediment gravels in the same area. This shift indicates that the Pecos River drainage changed its characteristics between Orchard Park and Lakewood time.

Fanglomerates east of the Guadalupe Mountains: Lime sand and lime pebble conglomerate cover an extensive area of low relief in Eddy County east of the Guadalupe Mountains and west of the Pecos River. These deposits are continuous from the vicinity of Carlsbad southward nearly to Black River. They are present also in an elongate belt about 6.5-16 km (4-10 mi) wide southwestward from Black River (fig. 3, loc. 9) along the eastern front of the Guadalupe Mountains. Some of this clastic debris has been described as an alluvial apron (Hayes and Koogle, 1958). It has also been mapped simply as "younger" and "older" alluvium and correlated with the Lakewood terrace and Orchard Park and Blackdom "plains" (Motts, 1962).

The clasts in these deposits are derived almost entirely from Permian limestones and associated sedimentary rocks along the eastern side of the Guadalupe Mountains. Many of the limestone pebbles are strongly solution faceted, and calcium carbonate cements the deposit at many places. Although some of this calcium carbonate cement may represent pedogenic caliche, it is generally structureless and most was probably deposited from surface-water solution. A dense caliche caprock usually less than 0.5 m (18 in.) thick is present at some places but it, too, is structureless and appears to be a cement derived locally from the solution of limestone clasts.

Although the surface on which these deposits accumulated is not well exposed, it appears to be an irregular erosional and karst topography. Southward from Carlsbad Caverns lenticular beds of conglomerate fill channel-shaped depressions along the tops of ridges. Northward from Black River the deposits appear to fill collapse sinks and at some places the surficial deposits themselves are marked by minor solution and collapse features. Low discontinuous ridges radiate eastward from the Guadalupe Mountains parallel to modern drainages. These features, as well as the general configuration of these deposits, indicate that they are fanglomerates deposited on an irregular land surface.

The age of these fanglomerates has not been determined. They may represent deposits as old as the Blackdom pediment or earlier, but they cannot be traced northward into the well-defined pediments along the west side of the Roswell artesian basin. Northeast of Loving along the west side of the Pecos River, remnants of these fanglomerates rest on probable Gatuna and Mescalero beds. In this same vicinity near the Pecos River, a geomorphic surface is present at some places that are overlain by other remnants of the fanglomerate. This surface is distinguished from the fanglomerate by the numerous Tertiary porphyry and siliceous pebbles cemented in its caprock. This surface is here interpreted as an exhumed surface on the Mescalero caliche where the Mescalero has collapsed along the course of the Pecos River. Therefore, at least the eastern fringes of the fanglomerate are assumed to be post-Mescalero in age. Fill in modern arroyos on the surface of the fanglomerate indicates that parts of it are Holocene.

Windblown sand: Windblown sand blankets much of the area east of the Pecos River. Some of these sand deposits occur as coppice dune fields which have received local names such as Los Medaños and Mescalero sands. Most of these dunes are relatively inactive at present but they have been active during Holocene time and local blowouts suggest that they would soon become reactive if the present plant cover were to be disturbed.

At many places in coppice dune fields at least two distinct deposits of windblown sand are present. Regionally, 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 windblown sand as much as 6-8 m (20-25 ft) thick. Locally, very weakly developed soils are present on some deposits of windblown sand but the relationship of these soil deposits to regional deposits is not yet understood. However, it is apparent that there have been Holocene intervals when the climate was more stable and humid than at present.

The widespread deposits of windblown sand are indicative of a large source of fine sand as well as of the extreme fluctuations of climate that have occurred during Pleistocene time. There is very little evidence that much sand has been derived from the Pecos River.

It is suggested here that most of the windblown sand in areas such as Los Medaños has been derived from deposits in the Ogallala Formation. During humid intervals in Pleistocene time the sand has been eroded from the Ogallala, and during arid intervals the wind has moved this sand across the Mescalero plain.

Although these deposits of windblown sand are quite visible, they are more valuable as records of past climate than as indicators of the permanence or long history of the present landscape. Some of this sand may have been moving about intermittently since middle Pleistocene time but the eolian process itself has destroyed much of the Pleistocene record. The piecing together of this record will require more time than has been currently available for this study.

GEOLOGIC STRUCTURE

The structure of the Delaware basin and adjacent uplifts has been discussed in the literature by other workers (King, 1948; Haigler, 1962; Hayes, 1964; Kelley, 1971). They have described the Delaware basin as a structural feature in which the rocks of Permian age dip gently eastward from the Guadalupe Mountains toward the Central Basin platform. Except for a belt of relatively steep dips along the front of the Guadalupe Mountains, regional dips within the Delaware basin are generally less than 2° toward the east and southeast. Locally, intraformational warping is complex within the evaporite sequence of the Permian rocks (Jones, 1973, p. 31-33).

On the basis of geometric relationships of strata, Kelley (1972) has suggested the probability of faulting along the front of the Guadalupe Mountains at their juncture with the Delaware basin. This faulting can be neither proved nor disproved, but its probability has been questioned by Smith (1973).

Large-scale geologic structures in surficial deposits are difficult to establish. During the present work, both surface and subsurface information was used to compile a structure contour map using the Mescalero caliche as a datum (fig. 4). Although the Mescalero caliche was not definitely identified to the east of San Simon Swale, it is present over an extensive area westward from Antelope Ridge across Nash Draw and along Quahada Ridge. It is also well exposed to the north along Nimenim Ridge and it underlies the Querecho Plains.

The Mescalero caliche presumably formed on an undulatory stable surface; but the contour interval on this map is sufficient to discount local primary slopes. These are apparent in the field along Livingston, Quahada, and Nimenim Ridges where the caliche dips abruptly into the adjacent depressions. The crowding of contours, the presence of fractures, and the uniform thickness of the caliche along these ridges indicate that Nash Draw and Clayton Basin were subjected to collapse after the formation of the Mescalero caliche.

On the other hand, the relatively uniform spacing of contours underlying the Querecho Plains suggests that this is an original slope on the Mescalero surface. This surface dips southwesterly toward

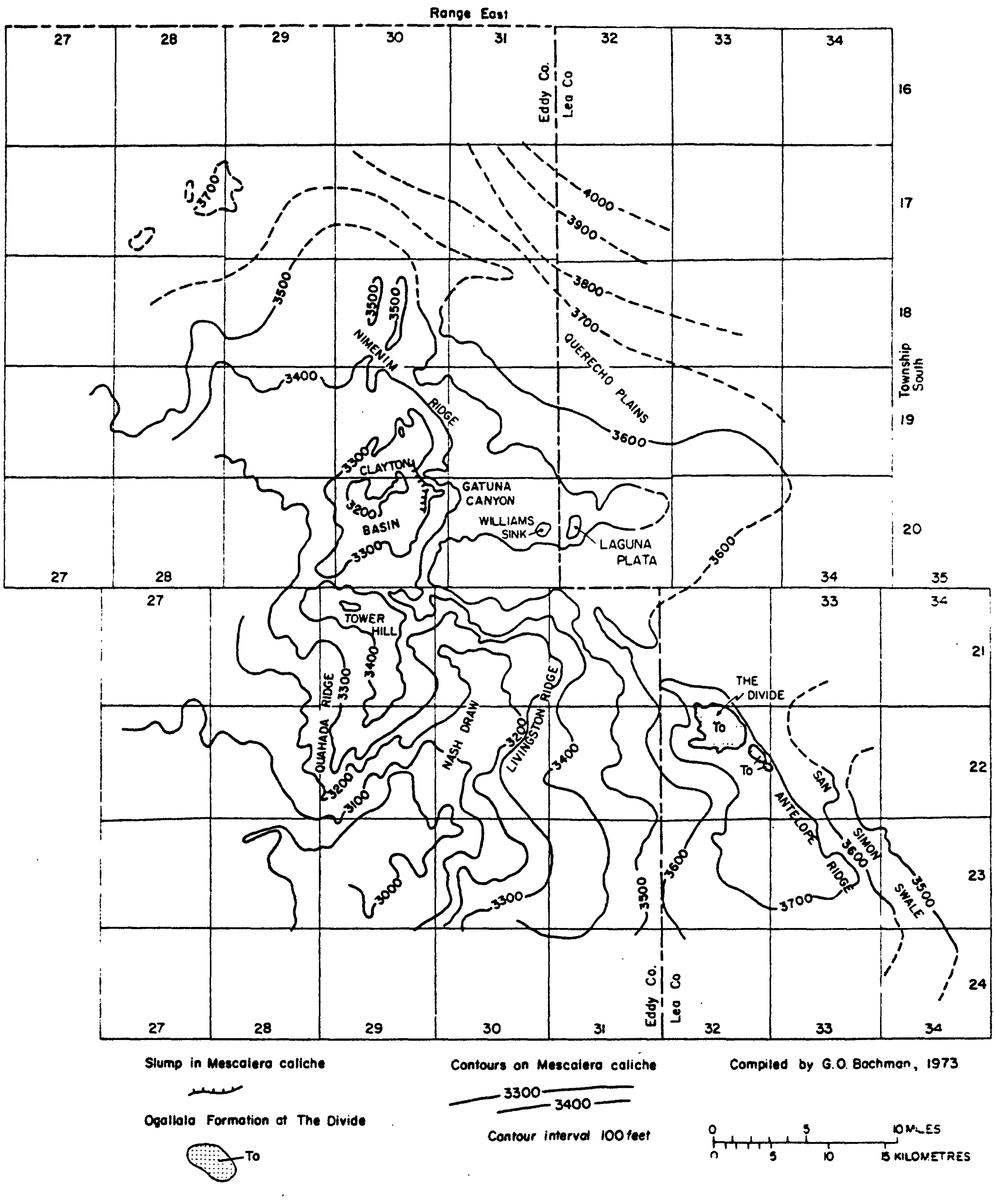


Figure 4.--Structure contour map of Mescalero caliche.

Nimenim Ridge about 5.5-7.5 m/km (30-40 ft/mi). Eastward from Gatuna Canyon the contours indicate a prominent swale. This could be reflecting an easterly trending drainage system that survived briefly from Gatuna time. At present the area of this swale is occupied by several prominent depressions that include Williams Sink and Laguna Plata.

The uniform spacing of the contours in the area of The Divide between Livingston and Antelope Ridges suggests that this surface also approaches its original slope. The closed contour at the 3,700-foot elevation indicates that this has been a drainage divide between San Simon Swale and Nash Draw at least since Mescalero time.

RADIOMETRIC AGES

Relatively young (Pleistocene) volcanic ash falls are widespread over the central and western parts of the United States. Formerly reference was made to many of these ash falls under the common name "Pearlette ash" and it was assumed that they represented a concentrated volcanic event. On the basis of this supposition many questionable correlations of stratigraphic units were made over the High Plains region.

Recently some of these ash beds have been studied intensively and it has been learned that they are not all part of the same volcanic event (Izett, Wilcox, and others, 1970; Izett, Wilcox, and Borchardt, 1972). Instead, they have volcanic sources as widely separated as Yellowstone National Park, eastern California, and northern New Mexico. Radiometric ages have been determined for many of these ash falls and they range from about 2 million to 600,000 years ago. As a result of these determinations a reevaluation of correlations is being made and a time scale for geologic events on the High Plains is being constructed. At present this time scale is incomplete and much work remains to be done. However, some generalizations can be made that are useful to understanding the relative intervals of late Tertiary and Quaternary time on the High Plains.

Correlation of North American and European late Pliocene and Pleistocene events has been discussed extensively in the literature and will not be reviewed here. However, some European geologists have estimated that four major alpine glacial events occurred during the past 600,000 years. Other estimates have varied from 300,000 to about 1 million years for these glacial events. None of these estimates is compatible with recent work in the Western United States. Here, major glaciation of the Pleistocene is considered to have begun much earlier (see Cooke, 1973, for review of this problem). Only those radiometric dates that can be correlated with events in southeastern New Mexico are considered here.

The youngest fauna present in the Ogallala Formation is of Kimball age. This fauna may be as old as 4.6±1.0 m.y. (G. A. Izett, written commun., 1974). The next youngest formation in the High Plains region that has been dated radiometrically is the Blanco Formation of west Texas. The Blanco was deposited after stabilization and some dissection of the Ogallala Formation that underlies the High Plains surface. The Blanco at its type locality has a minimum age of 1.4 m.y. (Izett, Wilcox, and Borchardt, 1972). The Blancan fauna are generally considered to be early Pleistocene (Nebraskan) in age. Therefore, the hiatus that separated the youngest deposits of Ogallala time from earliest Pleistocene deposits may have spanned as much as 3 m.y. Because this deduction is based on the fortuitous preservation of beds of volcanic ash, this estimate of time is considered to be conservative. The period of time during which the High Plains were stabilized after Ogallala deposition and before erosion of early Pleistocene time spanned less than 3 m.y.

Other ash falls have dated a pre-Kansan event at 1.2 m.y. ago and a post-Kansan (Yarmouthian(?)) event at 600,000 years ago (Izett, Wilcox, and Borchardt, 1972, p. 562). This is a broad span of time but it is useful for assigning minimum and maximum ages of Kansan time. It is here assumed that the Gatuna Formation and the overlying Mescalero caliche in southeastern New Mexico were deposited as much as 600,000 years ago.

Deposits that represent the time interval between middle (Mescalero caliche) and late Pleistocene (alluvial terraces) have not been recognized. However, late Pleistocene deposits are widespread in the Pecos River valley. Some of these deposits have been dated by radiocarbon and they include terraces as old as 17,180±140 years (Glass and others, 1973, p. 8). Therefore, it is assumed that erosion and nondeposition were prevalent in southeastern New Mexico for a period of about 500,000 years between middle and late Pleistocene time.

GEOLOGIC PROCESSES

Active geologic processes in southeastern New Mexico during late Tertiary and Quaternary time that have been considered during the present study are:

1. Alluvial processes including erosion, and formation of fans, pediments, and river terraces.
2. Dissolution of evaporite deposits and associated collapse and formation of karst topography.
3. Formation of playas and other enclosed depressions.
4. Formation of caliche.
5. Eolian activity and deflation.
6. Mass wasting.

Of these processes erosion, dissolution, and collapse of the surface overlying solution chambers are destructive and potentially the most hazardous to beds of salt in the subsurface. Some alluvial processes and all caliche formation are constructive and can form protective covers over evaporite deposits. Eolian activity, formation of playa deposits, and mass wasting are less effectual either in deeply sculpturing or protecting the surface.

Solution and collapse

The term karst refers to the distinctive pitted topography that has poorly developed surface drainage resulting from solution of soluble rocks in areas underlain by limestone, gypsum, and rock salt.

Karst plains are extensive in southeastern New Mexico and indicate the prominence of rock solution as a geologic process.

In this report the terminology of karst features generally follows that of Thornbury (1954). A sinkhole results from the collapse of the roof over an underground solution cavity. Compound sinkholes result from coalescing collapse sinks. The term doline applies to relatively shallow solution sinks that form on the surface beneath the soil mantle without physically disturbing underlying rocks. Dolines are not underlain by subsurface solution cavities. They are very common in southeastern New Mexico where they form on limestone bedrock as well as on caliche surfaces.

Collapse sinks are common along the Pecos River valley southward from Roswell. Many of these have collapsed within historic time. One collapse sink formed at the edge of the town of Lake Arthur in June 1973 (fig. 5). That feature is circular in plan and about 40 m (125 ft) in diameter. It collapsed an estimated 10-13 m (30-40 ft) below the surface. The underground solution chamber is not visible because it is filled by roof debris. Fractures that are circular in plan formed around the outer margins of the collapse sink.

It is here suggested that the course of the Pecos River southward from Carlsbad to the proximity of the New Mexico-Texas State line lies in a major belt of collapsed sinks. At many places the river follows broad meanders yet the flood plain is unusually narrow or lacking. At places adjacent to the Pecos River, intermittent tributaries follow

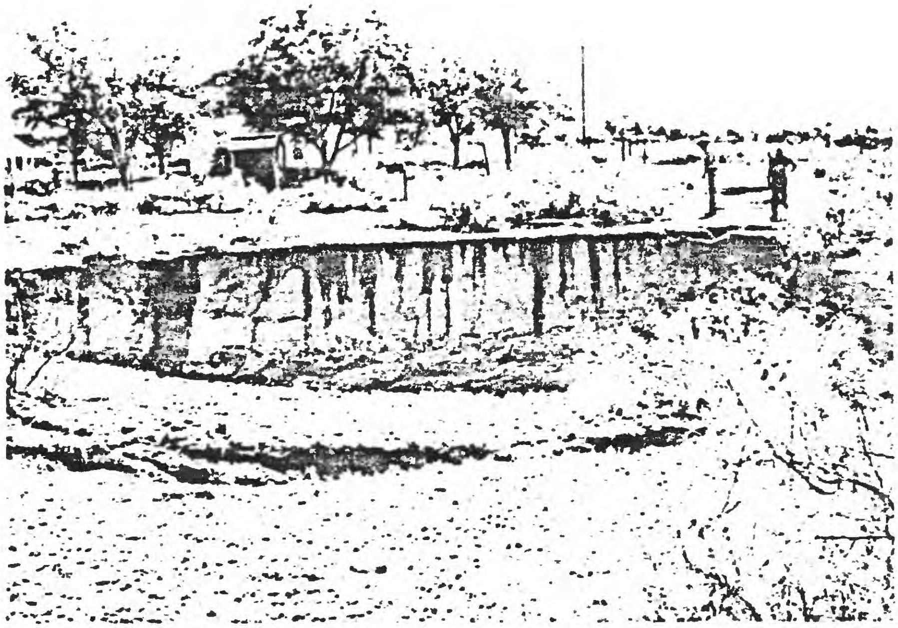


Figure 5.--Collapse sink near Lake Arthur, N. Mex.
Collapse occurred in June 1973.

semicircular collapse valleys (fig. 6). Along the east side of the Pecos River southeast of Carlsbad a linear scarp is believed to have formed along a collapse structure that is now occupied by the river (fig. 7).

Other major collapse features include Clayton Basin and Nash Draw. These features formed as coalescing sinks, probably during Pleistocene time. At the south end of Nash Draw a sink collapsed during Gatuna time but was stable during Mescalero time. It has since been partially exhumed. An even longer history of solution and collapse is suggested for part of Clayton Basin where blocks of Cretaceous and Gatuna rocks have been preserved as sinkhole debris. San Simon Sink has collapsed many times during its formation and may have had a long history during Tertiary time. The last recorded episode of its collapse was "as recently as 25 or 30 years ago" (Nicholson and Clebsch, 1961, p. 14).

Crow Flats

Crow Flats is part of a collapse feature north of Clayton Basin and about 24 km (15 mi) east of Artesia. It is of particular interest to this study because at least three episodes of solution and collapse in geologic history are indicated. These episodes occurred (1) after Triassic and before Gatuna time; (2) contemporaneous with, or after, Gatuna time; and (3) after Mescalero time. This geologic history suggests the complexity that probably accompanied the formation of

Figure 6.--Oblique aerial photograph of collapse features near Harroun. N. Mex. Some meanders of the Pecos River may have originated as similar semicircular features. View is toward the northwest; the Pecos River is in the background.

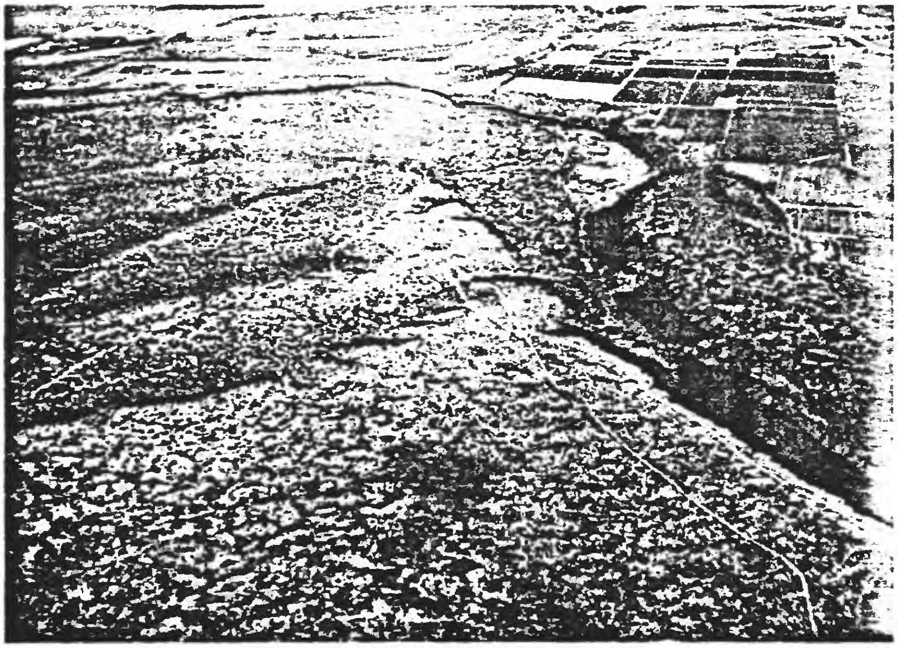


Figure 7.--Oblique aerial photograph of Pecos River showing linear scarp along the eastern bank near Malaga Bend. View is southwesterly.

such features as Clayton Basin and Nash Draw. For this reason the Crow Flats area was studied in some detail (fig. 8).

In this area 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 late Triassic age. Owing to local structure it is difficult to estimate the thickness of the Triassic but these beds may not exceed 15 m (50 ft). These beds are overlain at many places by the Gatuna Formation, which consists of pale-reddish-brown thinly laminated sandstone in this area and ranges from a featheredge to about 20 m (65 ft) in thickness. The Gatuna Formation is in turn overlain by the Mescalero caliche. At places the Mescalero overlaps the Gatuna and rests on Triassic or Permian beds. The Mescalero caliche ranges from 1-2.5 m (3-8 ft) in thickness.

South of Pavo Mesa and along the east side of Crow Flats, Triassic and Permian rocks are contorted, fractured, and exposed as chaotic, angular blocks for a distance of about 11 km (8 mi). At many places Triassic rocks fill collapse sinks in Rustler gypsum and are slumped at least 15 m (50 ft) below the top of the Rustler. These chaotic structures formed during the earliest recognizable episode of solution and collapse in this area. They formed after the Triassic rocks were deposited and indurated and it is possible that they formed as early as Triassic time when the entire region was uplifted and subjected to erosion. The Gatuna Formation rests unconformably on this chaotic structure; therefore, this episode of collapse occurred before Gatuna time.

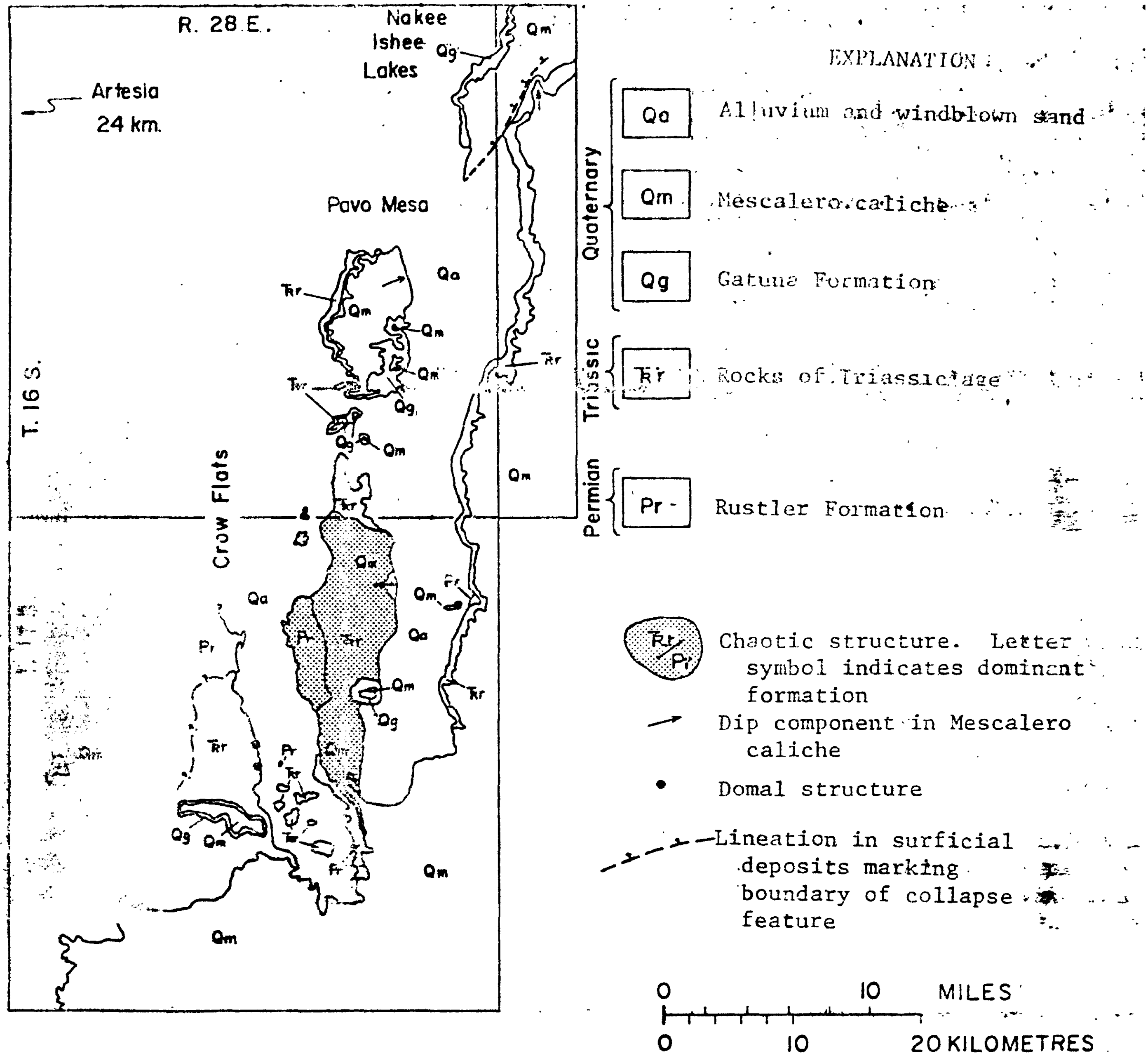


Figure 8.--Geologic sketch map of Crow Flats area east of Artesia.

Along the northern and western sides of Pavo Mesa the Gatuna Formation dips persistently to the northeast toward the Nakee Ishee Lakes. Apparent dips are as much as 20°. The Mescalero caliche cuts across these steeply dipping beds. Along the eastern and southeastern sides of the Nakee Ishee Lakes the Gatuna is relatively flat lying. The steep dips in the Gatuna at Pavo Mesa are interpreted as being in part depositional and in part a result of collapse after Gatuna but before Mescalero time.

At one place along the eastern edge of the chaotic exposure (NW 1/4 sec. 14, T. 17 S., R. 28 E.) the Gatuna Formation is exposed in an interval of at least 10 m (40 ft) below the uppermost exposures of Triassic rocks. At this place the exposures of Gatuna are about 700 m (2,000 ft) across and roughly circular in plan. These exposures are capped by relatively undisturbed Mescalero caliche. The Gatuna at this place represents a collapse-sink fill that was deposited before the Mescalero caliche was formed. This sink fill contrasts with those described above that are filled with chaotic Triassic rocks because the Gatuna here is fine grained and unfractured. It was probably deposited in a low-energy environment within a preexisting collapse sink.

The Mescalero caliche is well developed on Pavo Mesa and on adjacent mesas and buttes. At the north end of Pavo Mesa the Mescalero crosscuts dipping beds of the Gatuna Formation and, along the east side of Pavo Mesa, it dips steeply toward the east and northeast in the direction of the Nakee Ishee Lakes. These dips range from about 10° to nearly vertical. On Pavo Mesa the Mescalero caliche is at 3,700 feet elevation. Along a low escarpment southeast of the Nakee Ishee Lakes the Mescalero is fractured and is at 3,590 feet elevation. This indicates a displacement of at least 30 m (110 ft) since the caliche formed.

Mass wasting

Mass wasting comprises the movements of masses of rock and soil down slopes by gravity. Included under this broad heading are landslides, creep, earthflows, mudflows, and sheet flooding. Erosion is sometimes considered a process of mass wasting but is discussed separately herein. Owing to the relatively low relief of the study area, massive landslides and mudflows have had little effect on the landscape; however, minor landslides into solution cavities are common. Small slides have also occurred along the Pecos River, especially along the steep eastern bank south of Carlsbad and along the margins of Clayton Basin and Nash Draw.

The subtle processes of creep and sheet flooding contribute to the formation of planate surfaces. These are not major processes of destruction but they are significant in southeastern New Mexico where they contribute to the formation of extensive geomorphic surfaces.

Alluvial processes and the history of modern drainage

Geologic records of early Tertiary time are sparse in southeastern New Mexico. If rocks of this age were ever deposited, most of them have since been destroyed by erosion. A small area of sedimentary deposits far to the west around the Sierra Blanca uplift, igneous masses of the Sierra Blanca and Capitan uplifts, and isolated intrusive dikes are the only records from Cretaceous to late Tertiary (Pliocene) time. This represents a span of at least 57 m.y. during which regional uplift occurred and erosion was probably the dominant geologic process. Cretaceous rocks, except for minor remnants, as well as some Triassic and Permian rocks were eroded away in parts of southeastern New Mexico. It is assumed that some dissolution of salt in the Delaware basin occurred during this time span.

According to Bretz and Horberg (1949a, p. 487) a pre-Ogallala ancestral Pecos River lay along the present course of the Pecos. They assumed that a continuous geomorphic surface extended from the summit of the Guadalupe Mountains eastward to the High Plains. They also suggested that if no post-Ogallala deformation had occurred "a former Ogallala fill of more than 1,300 feet along the Pecos depression is indicated" (Bretz and Horberg, 1949a, p. 483). However, during the present work some of the conglomeratic beds they studied were found to contain pebbles derived from the Ogallala caprock caliche. The conglomerate was deposited after Ogallala time.

It is more probable that major drainage was eastward to southeastward rather than southward during early Tertiary time. During late Tertiary time, while the Ogallala Formation was being deposited, the dominant direction of drainage was southward. The original thinning of the Ogallala Formation toward the southwest, described elsewhere in this report, suggests that there may have been a local Pecos drainage system in southeastern New Mexico during or before Ogallala time, but this southward-flowing system was limited in extent and its headwaters may have been no farther northward than the vicinity of Carlsbad and San Simon Swale. There were probably eastward-flowing streams from the Capitan and Sierra Blanca uplifts but the details of that system are not known.

The easterly and southeasterly stream systems that were present in eastern New Mexico during Ogallala time entrenched themselves during late Pliocene and early to middle Pleistocene time in three major systems (fig. 9): these are the Canadian to the north, which cut through the Ogallala Formation and flowed eastward into the Red River system; a major drainage system from the Sangre de Cristo Mountains, which flowed southeasterly toward the Portales Valley and finally into the Brazos drainage in western Texas (Baker, 1915, p. 52-54); and a third system, which 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. At this time the Gatuna Formation was being deposited and a stream system also drained westward in the vicinity of Gatuna Canyon to the vicinity of Clayton Basin and finally into the Pecos Valley.

During middle Pleistocene (Gatuna) time extensive pediments were formed in the vicinity of Pierce Canyon (fig. 10) and along the

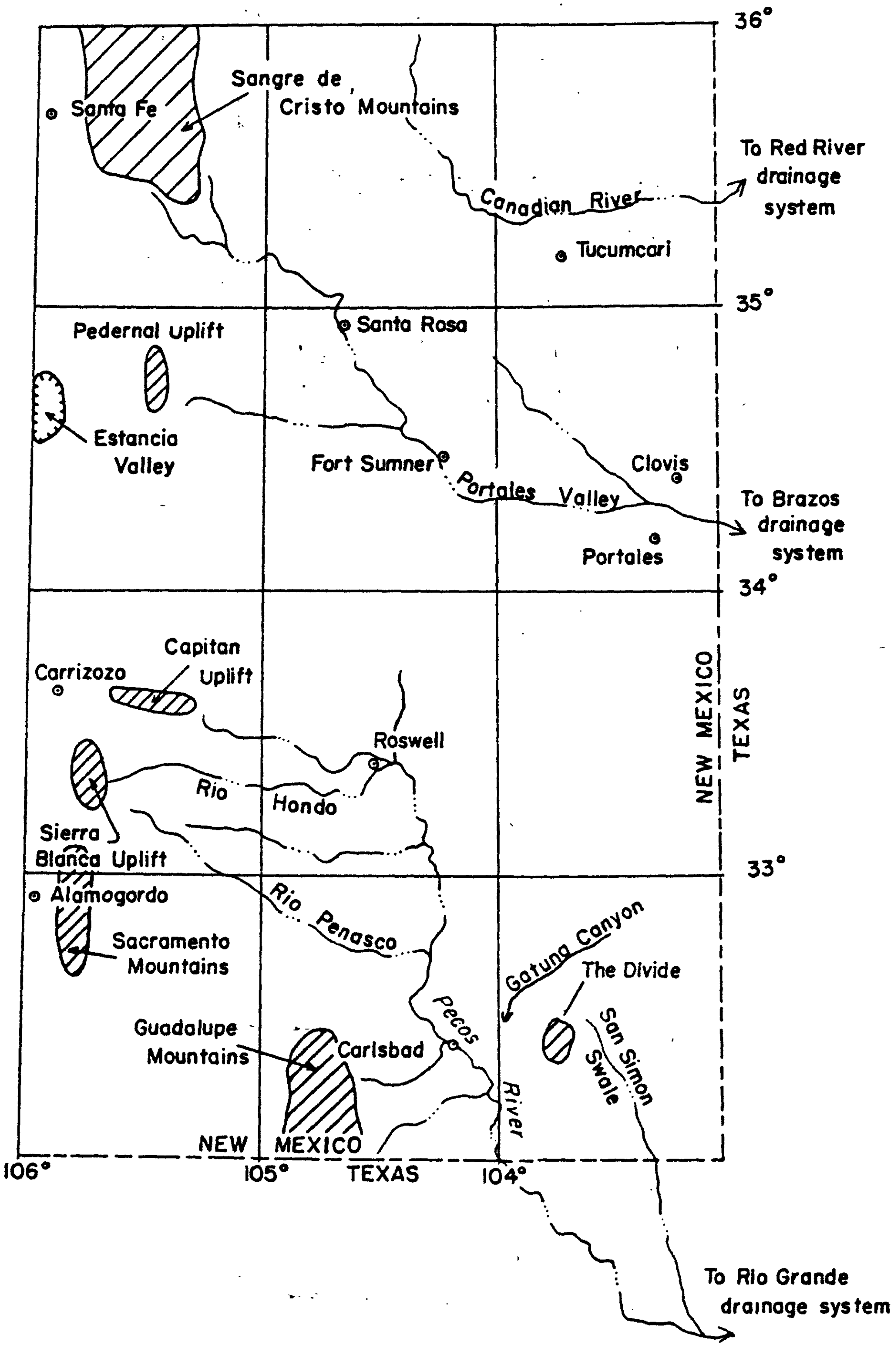


Figure 9.--Map showing middle Pleistocene drainage systems in southeastern New Mexico.

Figure 10.--Oblique aerial photograph showing channel filling and caliche-cemented pediment surface that caps the mesa south of Pierce Canyon. Channel deposit exposed in south wall of canyon is about 240 m (780 ft) across and is as much as 24 m (78 ft) thick. It consists of rounded clasts that average 2-3 cm in diameter, but some are as large as 7 cm. They are 80 percent Permian limestone, 10 percent quartzite, 8 percent Tertiary porphyry, and 2 percent chert.

New Mexico-Texas State line. Some meanders of the Pecos may have been 8-16 km (5-10 mi) east of the present channel. Distribution of conglomerates that fill channels, as well as local fine-grained sediments that were deposited in marshy areas and sinkholes, indicates that a broad flood plain occupied parts of the Pecos River valley in southern New Mexico.

Following Gatuna time there was a period of regional stability, and extensive deposits of caliche accumulated in a semiarid climate on the Mescalero plain. Drainage during this part of Pleistocene time was greatly diminished from that during Gatuna time but its details are not known.

After Mescalero time the Blackdom and Orchard Park pediment surfaces were cut and the Pecos River entrenched itself in the vicinity of its present channel near the toes of these pediments. The increased humidity of Blackdom and Orchard Park time caused solution and collapse to become major processes in the Roswell artesian basin. These processes resulted in reduced stream gradient that had a low sediment-carrying capacity in that area during most of late Quaternary time.

During Blackdom and Orchard Park time the source of sediments was mainly to the west in the Sacramento, Sierra Blanca, and Capitan uplifts. An increase in the proportion of Tertiary porphyry clasts in the Orchard Park gravels suggests that headward cutting into the Sierra Blanca and Capitan uplifts reached an optimum at that time. The widespread pedimentation of bedrock west of the Pecos indicates that erosion was much more effective in that area during Blackdom and Orchard Park time than at present.

During late Pleistocene time the Pecos River cut headward and intersected the Portales Valley drainage system in the vicinity of Fort Sumner. This piracy initiated the present Pecos River as a permanent stream flowing from the southern Rocky Mountains to the Rio Grande.

The precise time of piracy of the Portales Valley by the Pecos is not known but it is presumed to have occurred long before the deposition of the Lakewood terrace. However, the Lakewood terrace is the oldest deposit in which rock debris from the Sangre de Cristo Mountains or the Pedernal uplift has been recognized in the Roswell artesian basin. Clasts from these uplifts have been found only in the vicinity of Roswell at the north end of the basin. This may reflect the low carrying capacity of the modern Pecos River more than its unaccessibility to those uplifts.

The age of pediment gravels and major alluviation in southeastern New Mexico is not known but rock units and pediments west of the Pecos are correlated tentatively as follows:

Table 2.--Correlation of Pleistocene formations and geomorphic features

West of Pecos River	East of Pecos River	Age
Lakewood terrace	Some playa deposits	Woodfordian[1/]
Orchard Park pediment gravel	Not recognized	(?)
Blackdom pediment gravel	---do--------------	(?)
Diamond A plain	Mescalero caliche	Yarmouthian(?)
Gatuna Formation(?), locally	Gatuna Formation	Kansan
Sacramento plain	High Plains surface (Llano Estacado surface)	Late Pliocene-early Pleistocene

1/ Glass and others, 1973, p. 8

Enclosed basin deposits

The karst topography of southeastern New Mexico has resulted in numerous closed basins. However, all basins in this region have not been formed by solution and collapse. Some have been formed by wind blowouts and others are the result of solution or etching of the carbonate surface. They range in size from small depressions no more than a few metres in diameter to large features such as Salt Lake, Laguna Gatuna, and Williams Sink, which are several kilometres in diameter. These depressions are partially filled with water during rainy seasons and many contain fine sand, clay, salines, and related playa deposits.

Salt Lake, southeast of Carlsbad, is one of the largest playas that occupies an area of coalesced collapse sinks in the region. It has an irregular plan and is about 3.2 km (2 mi) wide and 4.8 km (3 mi) long. Modern Salt Lake, as well as other larger playas in the vicinity, has retreated from the higher levels it attained in the past when it was a more permanent lake. Deposits of caliche and other lime-cemented sands at the north end of Salt Lake, as well as beach rubble along the southwest side, indicate that water formerly filled this depression to a level about 3 m (10 ft) above its present level. This former level increased the area of the lake approximately 30 percent. Its maximum width was about 4.8 km (3 mi) and its length was about 6.4 km (4 mi). Wave-cut benches are not present at higher levels around the lake because a rise of more than about 4-5 m (13-17 ft) would have caused the lake to overflow into the nearby Pecos River. However, the lake has probably undergone numerous cycles of filling and evaporation. Caliche along the margins of the playa deposits is more pisolitic than other caliche in the vicinity, which indicates that many extremes of wetting and dessication have occurred in the vicinity of the lake. Other playa deposits that occupy collapse sinks in southeastern New Mexico include San Simon Sink and numerous small depressions in Clayton Basin.

Williams Sink and other nearby depressions, such as Laguna Gatuna, appear to have formed as blowouts in windblown sand deposits. Although clay and saline deposits are present in these depressions, they are surrounded by windblown sand. Dune fields exist along the northeastern and eastern margins of these depressions where sand has fallen out of the prevailing winds on the lee side of the depressions. These depressions are situated in the vicinity of a Pleistocene drainage system that flowed westward from the High Plains. It is probable that large quantities of fine sand, derived from the Ogallala Formation to the east, were carried into this drainage system, helped to choke the system, and since have been moved about locally by the wind. Thus, the process of deflation produces shallow depressions that may be filled with water during rainy seasons.

Dolines are common on limestone and caliche surfaces in southeastern New Mexico. They are shallow surficial depressions that formed by local dissolution, or etching, of the surface. They may become small lakes during rainy seasons, and a few contain playa deposits.

Elongate depressions on the surface of the High Plains are closely related genetically to dolines. These features are oriented about N. 60° W. and were formed by etching the caliche between former logitudinal, or seif, dunes that were present on the High Plains surface during late Pliocene or early Pleistocene time (Price, 1944, 1958; Bachman, 1973).

Calichification

As used in this report the term "caliche" refers to an accumulation of calcium carbonate that may form either as a process of soil formation or by direct precipitation from ground water. Where possible throughout this work pedogenic caliche has been distinguished from other varieties because it forms within predictable geologic and climatic limits. Therefore, deposits of pedogenic caliche are of value for the interpretation of geologic history, paleoclimate, and structural stability. Pedogenic caliche is also of importance as a caprock, or protective cover, for underlying rocks during some climatic conditions.

In general, pedogenic caliche forms and is best preserved in arid to semiarid regions where annual rainfall is less than 625 mm (25 in.) and where annual evaporation exceeds the rainfall. The formation of pedogenic caliche also follows the general precepts of other soil formation. Its maximum development occurs on planar or undulatory surfaces where carbonate parent material is readily available and where plant growth is generally sparse. Thick and well-developed accumulations of pedogenic caliche appear to indicate regional tectonic stability as well as relative climatic stability.

RATE OF SALT DISSOLUTION

A study of the literature has resulted in an estimated rate of lateral dissolution of salt in the western part of the Delaware basin at about 9.5-13 km (6-8 mi) per m.y. (Bachman and Johnson, 1973, p. 41). This has been translated into a rate of vertical dissolution of about 150 mm (0.5 ft) per 1,000 years (Jones, 1973, p. 21). However, the present study shows that fundamental assumptions underlying these estimates are faulty. It was assumed that all dissolution had occurred since the close of Ogallala time. Now it is known that dissolution has occurred at other times in the geologic past. The rate of salt withdrawal is much slower than previously estimated.

Collapse of the Mescalero caliche along the margins of Nash Draw indicates that this depression has formed, at least in part, since the deposition of the caliche. A body of brine is present in the subsurface beneath Nash Draw and may be additional evidence that this is geologically a relatively young feature. "It seems likely that the structural conditions that caused the development of Nash Draw might also control the position" of the brine beneath it (Robinson and Lang, 1938, p. 86).

Along Livingston Ridge on the east side of Nash Draw the Mescalero caliche is undeformed at elevations above 3,300 feet. It dips steeply into the depression along the ridge and occurs at elevations of 3,200 feet and less within the depression. Along Quahada Ridge on the west side of Nash Draw the Mescalero is likewise undeformed at elevations above 3,300 feet but it dips steeply into Nash Draw and it occurs as collapsed fractured masses within the depression (NE 1/4 sec. 1, T. 22 S., R. 29 E.).

A cross section through drill holes in Nash Draw indicates the approximate extent of salt dissolution in the Salado Formation since Mescalero time (fig. 11). This cross section shows that along Livingston Ridge on the east side of Nash Draw the Salado salt is relatively undissolved (drill hole U134). There is a thickness of 245 m (750 ft) between the top of the Salado Formation and the top of marker bed 124 within the Salado Formation. Westward, this interval diminishes to 71.5 m (220 ft) on Quahada Ridge (drill hole I127). At both these localities the Mescalero caliche is undisturbed at the surface. It is, therefore, assumed that 172 m (530 ft) of Salado salt was removed from the vicinity of Quahada Ridge before Mescalero time.

Nash Draw appears to have subsided between Livingston and Quahada Ridges as much as 58.5 m (180 ft) since Mescalero time. At one locality (drill hole U26) the surface of Nash Draw is 58.5 m (180 ft) below the projected altitude of the Mescalero caliche. However, the interval between the top of the Salado Formation and the top of marker bed 124 is 136 m (420 ft), or 107 m (330 ft) less than at Livingston Ridge. It is, therefore, interpreted that about 48.7 m (150 ft) of Salado salt was removed before Mescalero time and about 58.5 m (180 ft) of Salado salt has been removed since Mescalero time. At another locality, Nash Draw subsided approximately 52 m (160 ft) below the projected elevation of the Mescalero caliche while about 39 m (120 ft) of Salado salt was being removed (drill hole 1 James "A"). There is a discrepancy here of about 13 m (40 ft) that could be explained by surficial erosion.

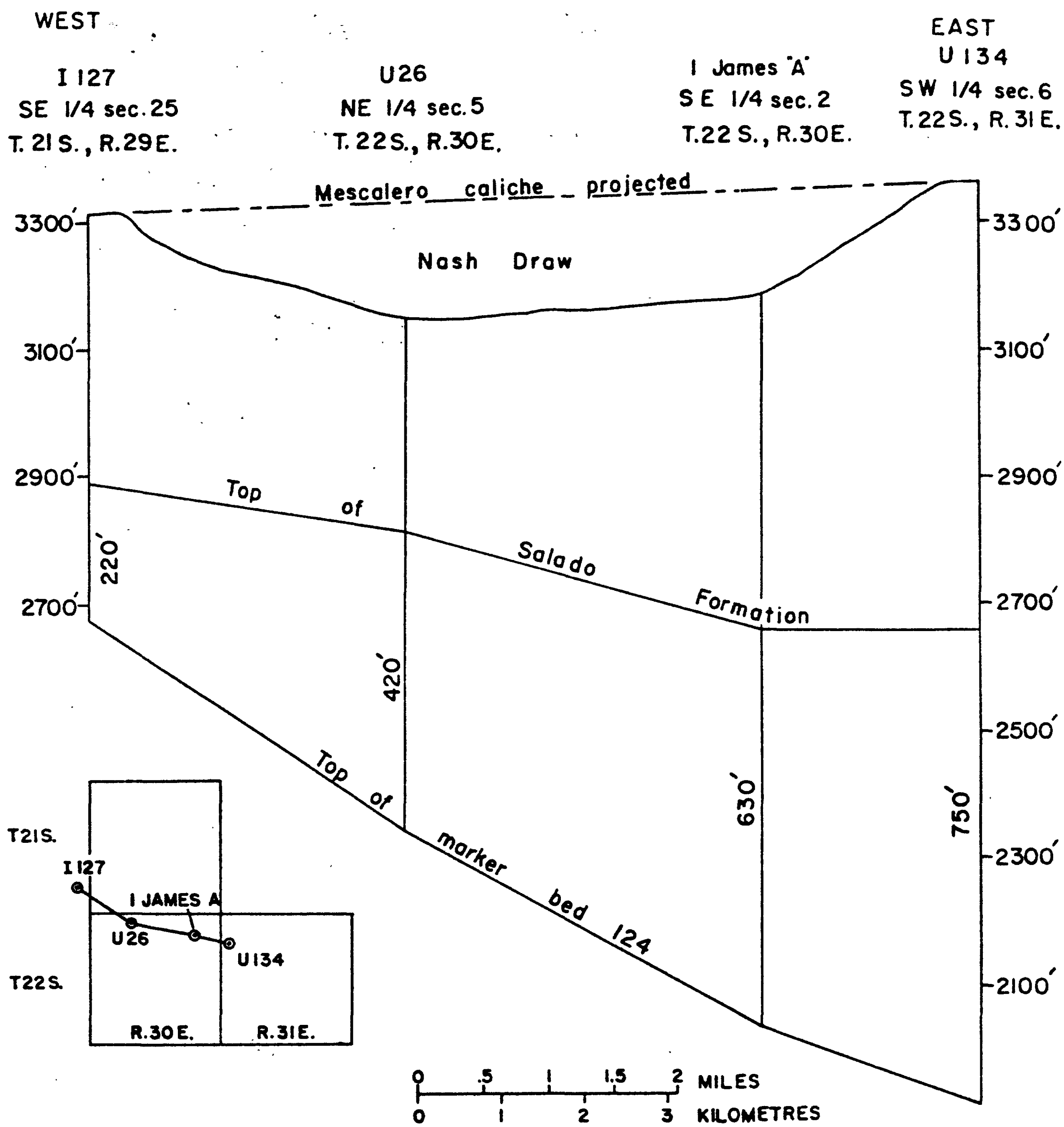


Figure 11.--Cross section showing relationship of subsidence in Nash Draw to dissolution of salt in Salado Formation.

If it is assumed that the Mescalero caliche was deposited during a stable part of the Yarmouthian Stage of the Pleistocene, the caliche accumulated about 600,000 years ago. Thus, at one place in Nash Draw there has been about 58.5 m (180 ft) of subsidence during the past 600,000 years. This is equal to about 10 cm (0.33 ft) per 1,000 years.

These conclusions are based on the available geologic evidence, but the assumption should not be made that this rate of dissolution is a constant for the region. At least two other factors must be considered in this interpretation, but geologic information is not currently available to permit evaluation of these factors. They are:

1. Subsidence probably has not been constant in Nash Draw during the past 600,000 years. A major part of this subsidence may have occurred during periods of humidity in late Pleistocene (Wisconsinan time).
2. The subsidence in Nash Draw, whenever it occurred in the Pleistocene, is not an average rate for the region. In the area of The Divide, between Antelope and Livingston Ridges, the Mescalero caliche is relatively undisturbed and probably no dissolution has occurred there since Mescalero time.

PROJECTED COURSE OF FUTURE GEOLOGIC EVENTS

Present knowledge of Cenozoic history of southeastern New Mexico indicates that the area of The Divide, between Antelope and Livingston Ridges, has been subjected to the least erosion and salt dissolution of any area west of the escarpment of the High Plains. Contours drawn on pre-Ogallala bedrock indicate that a southeast-flowing Cenozoic stream, probably Pleistocene, may have eroded San Simon Swale (fig. 12) but that this erosion did not cut headward to The Divide. To the west there has been dissolution of salt in Nash Draw. This dissolution has ceased its eastward migration in the vicinity of Livingston Ridge.

It is probable that the area of The Divide will remain the least affected by erosion and dissolution of any area in the vicinity for the longest period of time. Permian rocks are overlain by Triassic rocks which are locally overlain by thin deposits of the Ogallala Formation. Both of the latter units are protective covers for the underlying salt. Additionally, this area is encased on the surface by relatively thick accumulations of caliche. Under present climatic conditions of low rainfall and high rates of evaporation this caliche will remain intact and serve as a protective cover. Erosion of the caliche under present conditions is ineffectual and a complete and prolonged change in climate from present semiaridity to extreme humidity would be required to alter these conditions.

If the Holocene is an interglacial stage and future stages of glaciation are to be anticipated, the regional climate will change. However, under the most severe climatic conditions of late Pleistocene time Nash Draw subsided less than 61 m (200 ft). If the climate becomes more humid in the future it is presumed that the most stress will again be placed on Nash Draw and San Simon Swale because these depressions

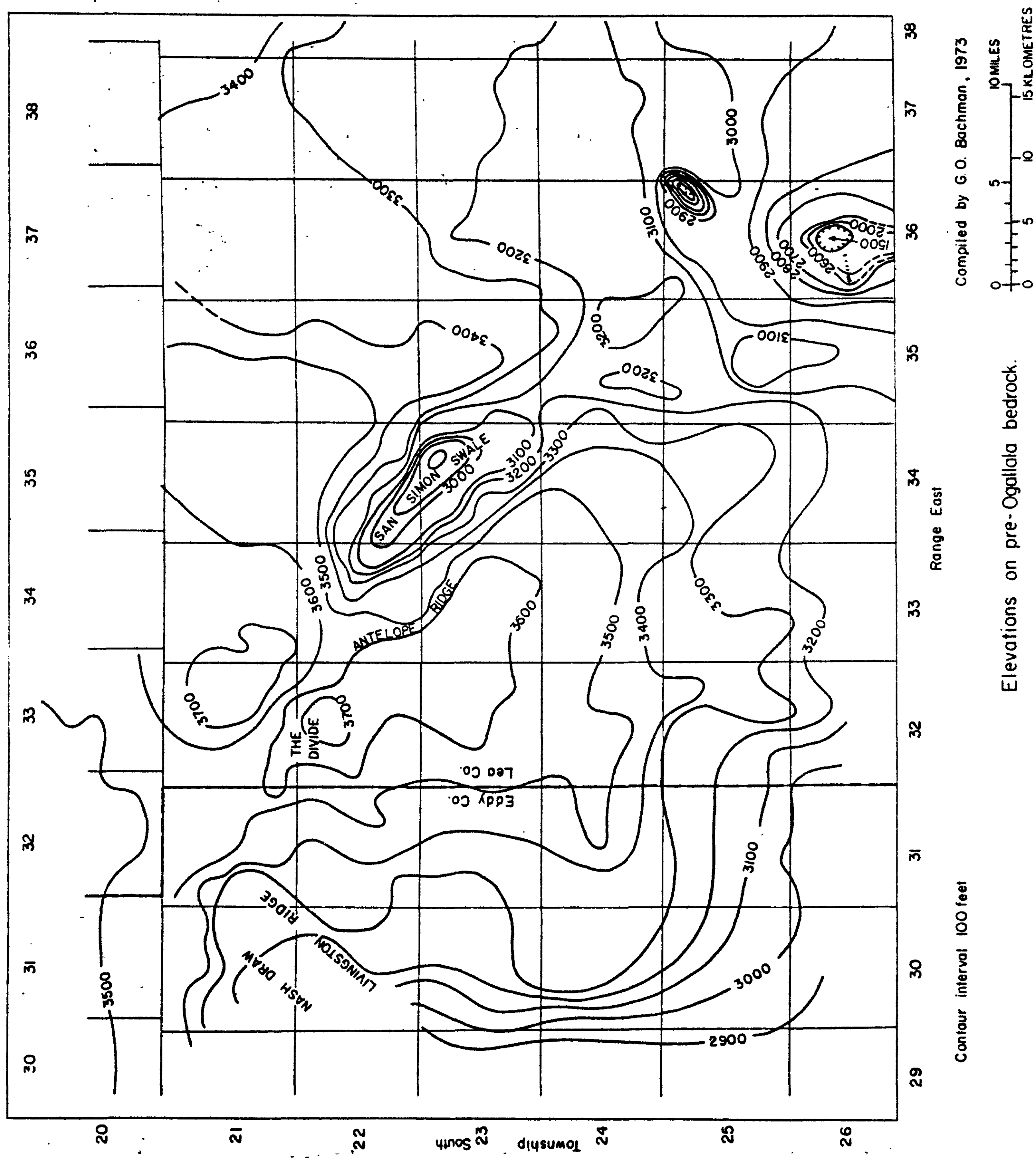


Figure 12.--Map showing contours drawn on surface of bedrock in The Divide-San Simon Swale area, New Mexico.

will attract runoff. Retreat of Antelope and Livingston Ridges will maintain the area of The Divide as a drainage divide. Therefore, The Divide will be least attacked by processes of erosion and dissolution.

PROPOSALS FOR FUTURE WORK

This report establishes a framework of geologic history and paleoclimate based on available evidence from the literature and reconnaissance field observations within the immediate area of the proposed repository. However, this study also serves to point out problem areas where information is lacking and where intensive special-purpose studies should be made. There has been very little interest in surficial geology in southeastern New Mexico in the past and there have been no detailed studies from which this information may be drawn.

The present work points out the need for intensive studies in the following problem areas:

1. Further study of the erosional history of the Pecos River and its tributaries.

The Pecos River drainage from the Roswell basin northward to Fort Sumner is relatively young (late Pleistocene). The modern Pecos River, which flows into the Rio Grande, captured a major drainage that flowed southeastward from the Rocky Mountains through the Portales Valley and eastward across Texas into the Brazos River drainage. Before that capture there was extensive erosion in southeastern New Mexico.

Erosion in southeastern New Mexico probably began during Jurassic time but was intensive during Tertiary time. Field studies during the present work indicate that headwaters of the ancestral Tertiary and Pleistocene Pecos River were in the Sierra Blanca and Capitan Mountains. One tributary of the ancestral Pecos drainage was in San Simon Swale. The present gradient of the Pecos River is not adequate to carry heavy loads, and erosion in southeastern New Mexico has been less severe since the Pecos captured the Portales Valley drainage and settled into its modern course.

It would be informative to make further studies of ancient river gravels and soils to learn the details of geography and paleoclimate that preceded the modern Pecos drainage. The erosional history of the Estancia Valley and the southern Rocky Mountains is part of this problem. Both areas are sources of distinctive suites of rocks that can be used to trace ancient drainage systems. Ancient soils, many with prominent caliche horizons, are present over much of the region and can be used to correlate remnants of former stabilized erosional surfaces. By linking these drainage systems and related soils from areas where they are better preserved to those drainages and soils now recognized in the vicinity of the proposed repository, it may be possible to fill in many gaps in Tertiary-Pleistocene history and climate.

2. Study of collapse history of playas and salt lakes in southeastern New Mexico, their climatic implications, and their rates of subsidence.

Adjacent to The Divide are numerous collapse sinks in which playas or lakes have formed and sediments have accumulated. These include Salt Lake in Nash Draw to the west, San Simon Sink on the east, and numerous sinks to the north in Clayton Basin. Other playas that do not appear to be related to collapse but which have extensive sedimentary deposits include Williams Sink and Laguna Gatuna to the north.

Much evidence for Pleistocene history and climate is preserved in these playa deposits; but these deposits have never been studied. Neither facilities nor funds were available for their study during the present work. Study of these deposits should include trenching and drilling of shallow holes to obtain samples of sediments. Besides mineralogic and chemical studies, these sediments should be examined for pollen and other fossil remains. Pollen is almost invariably present in lake deposits and shows sequential changes in plant assemblages that indicate changes in past climate.

It would be most advantageous to carry on these two studies--the erosional history of the Pecos River and the history of lake deposits--concurrently. They are complementary studies in that each would contribute evidence for the substantiation of results in the other.

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