GEOLOGY AND REGIONAL HYDROLOGY OF THE PECOS RIVER BASIN, NEW MEXICO

by

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PURPOSE AND SCOPE

The Pecos River basin is an area of major economic importance to New Mexico (fig. 1). Irrigation is extensive; the State Engineer has

Figure 1 -- Pecos River basin in New Mexico

"declared" seven underground water basins -- including the famous Roswell Artesian basin -- within its borders. Many oil fields occur in the basin, many of them producing oil or gas from formations that produce fresh water elsewhere in the basin. Seven companies mine potash in the basin.

As a consequence, an amazing wealth of data has evolved for the basin. Hernandez and Eaton (1966?) have 399 entries in "A bibliography pertaining to the Pecos River Basin in New Mexico." Had they included all the literature related to the geology of oil and potash, they could easily have brought the total number of entries to 500.

Unpublished data fill many files in the offices of the state engineer, the U. S. Geological Survey, and the New Mexico Bureau of Mines and Mineral Resources.

This report summarizes the hydrogeology of the entire Pecos River basin in New Mexico -- from Truchas Peak to the State line, from the Sacramento Mountains to the Mescalero Escarpment.

It discusses the characteristics of the rocks of the Pecos River basin from the point of view of their hydrologic significance. Its primary purpose is to provide a geologic framework that hydrologists, engineers, and social scientists might use when they discuss the movement of fluids, especially water, within the basin.

Consequently, it has two aims: One is to describe the rocks of the basin in as quantitative a fashion as time and data allow; and the other is to describe the occurrence and distribution of water in the basin and relate it to the needs of man.

This report is then a synthesis of the material available as I interpret it.

Acknowledgments

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THE GEOLOGICAL APPROACH

As a geologist studies an area, he tries to picture the events that produced the rocks which he sees and to understand the processes that caused differences to develop within similar rock units. Then, he tries to describe how the rocks differ over the area and to predict their characteristics in those areas where they have not been exposed or tested.

For a study like this one, his ultimate aim is to describe the occurrence, distribution, and properties of the rocks as they affect the movement, occurrence and behavior of water.

In the Pecos River basin the bulk of the rocks is made up of lithified sediments that were deposited in marine seas. Therefore, I made an effort to understand the sequence of events that produced the sediments. This involved learning (from the evidence contained in the rocks) something about the source of the sediments, the size and shape of the sea floor, the salinity of the waters, plus such other factors as seemed pertinent.

The events which ultimately formed the rocks took place over a significantly long period of time, hence, we continually refer to geological time and subdivide rock units according to their position in geologic time. Table 1 gives the divisions and geologic time scale for the Pecos River basin.

Topography

The Pecos River basin occupies an area of slightly more than 26,000 square miles in eastern New Mexico. Figure 2 is a topographic

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Figure 2 -- Topographic map of the Pecos River basin, New Mexico

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map of the area, showing its asymmetrical palmate pattern in plan view. From the southern state line to the northernmost point in the basin is about 280 miles. At its widest point the basin is about 140 miles wide. More than half, perhaps as much as 75 percent of the basin's drainage area lies west of the river.

The divides follow the mountains on the west and the Mescalero Ridge or Mescalero Pediment on the east. The western divide follows the ridge line of the Sangre de Cristo Mountains south to Glorieta Mesa, continues southward through the Pedernal Hills, Sierra Blanca, and the Sacramento Mountains, then it jogs southeastward along the crest of the Guadalupe Mountains to the state line. The maximum altitudes in the mountains along the divides are:

Guadalupe Mountains	7444 feet
Southern Sacramento Mountains	9700
Sierra Blanca	12003
Tucson Mountain	8303
Carrizozo Mountain	9656
Patos Mountains	8505
Gallinas Peak	almost 9000
Pedernal Hills	6200 - 7600
Glorieta Mesa	6000 - 8000

Sangre de Cristo Mountains:

Glorieta Peak	10200 feet
Thompson Peak	10546
Baldy Peak	12629
Lake Peak	12409
Penitente Peak	12249
Santa Fe Baldy	12622
Capulin Peak	13221
Pecos Baldy	12500
South Truchas Peak	13102
Mid-Truchas Peak	13066
North Truchas Peak	13024
Jicarilla Peak	12944

The maximum altitude on the Mescalero ridge is 4754 feet Other prominent altitudes in the basin are:

Capitan Mountains	10205
Pajarito Mountain	8014
Elk Mountain	11561

The lowest altitude in the basin in New Mexico is about 2840 feet at the head of Red Bluff Reservoir.

Figure 3 is a hyposmetric curve of the basin in New Mexico based on table 2. It shows that 90 percent of the basin has an altitude of less

Figure 3 -- Hypsometric curve, Pecos River basin, New Mexico

than 7000 feet. It also shows that the remainder of the area below 7000 feet is linearly distributed with respect to altitude.

D r a i n a g e

The drainage pattern of the Pecos River is controlled by the fracture pattern of the underlying rocks.

From the headwater of the Sangre de Cristo Mountains the river flows southeastward. At Anton Chico it bends and flows east. At the confluence with Gallinas Creek it bends to flow southeast again. In central DeBaca County it bends again and flows generally southward until it reaches Lake McMillan where it again bends to flow southeastward to the state line.

Figure 4 is a profile of the river. The profile of the Pecos

Figure 4 -- Profile of the Pecos River

River shows the effect of the limestone of the Capitan Reef. The limestone apparently forms a sill which serves as a temporary base level, preventing the river from downcutting on the upstream side. On the downstream the rocks are relatively soft and have been removed, so that the gradient steepens near the reef.

For the purpose of discussing the drainage, the Pecos River basin divides into five parts:

1. The Sangre de Cristo drainage
2. The Pedernal Hills drainage
3. The Sacramento-Capitan drainage
4. The Guadalupe drainage
5. The Mescalero Ridge drainage .

In the <u>Sangre de Cristo drainage</u>, the Pecos and its two principal tributaries, Tecolote Creek and Gallinas River, flow southeast and south along steep gradients. These rivers drain relatively steep slopes with abundant precipitation and, as a result, are effluent perennial streams in their upper reaches.

From Anton Chico to Santa Rosa the Pecos River is an influent stream. The flow of the river in dry years diminishes to zero. Tecolote Creek and the Gallinas River are likewise influent in their lower reaches.

The Pedernal Hills drainage lies between the Pecos River and the Pedernal Hills and is south of Anton Chico and north of the Capitan Mountains. Only a few arroyos cross the area: Canyon Blanco, Pintada Arroyo, Salado Creek, Arroyo del Macho, and Salt Creek. The drainage pattern is discontinuous. Two sets of arroyos are evident; one set drains the mountains and terminates generally along the west edge of R. 19 E; the second set drains generally east of the east edge of R. 19 E. The area is pitted with many sink holes. Many of the drainageways reflect the fracture pattern of the underlying rock. No through streams exist in the area, and springs are rare. Two large closed basins (fig. 2) -- Pinas Wells basin and Encino basin -- occur in the Pedernal Hills drainage. The area of Pinas Wells basin is about 180 square miles; Encino basin is slightly larger.

The Sacramento - Capitan drainage extends southward on the west side of the river from the Capitan Mountains to the south side of the Rio Penasco basin. This area is crossed by several arroyos that can be traced continuously from the Pecos River on the east almost to the crest of the mountains on the west.

The Rio Hondo has in its headwaters two effluent perennial streams that become influent near Hondo. The Rio Hondo, the Rio Felix, and the Rio Penasco are the most important drainageways crossing the area. Their drainage pattern is more of a trellis type, but still shows the influence of the fractures in the underlying rocks. Figure 5 is a profile of the Rio Penasco. The definition of the drainageways is much more

Figure 5 -- Profile of the Rio Penasco

precise than in the Pedernal Hills drainage area just to the north. The area contains many sinks and much of the surface runoff is to these sinks.

The Guadalupe drainage lies between the Rio Penasco basin and the state line. On the north side of the Guadalupe Mountains many arroyos flow out of the mountains and have an almost dendritic pattern. Most of the arroyos are well defined from the river to the mountains. A few areas of sinks exist.

South of the mountains, the drainage is dominated by the Black River and the Delaware River, both tributary to the Pecos. Both are perennial streams but the Delaware tends to become dry during drought years. The area has numerous sinks and some surface drainage to sinks is evident. Springs are common.

The Mescalero Ridge drainage is east of the river and south of Santa Rosa. Relatively few arroyos drain the area. Those with the best defined drainage pattern are in the nothern third of the area above Fort Sumner.

South of Fort Sumner only Taiban Creek, Buffalo Creek, and Long Arroyo are significant. All other arroyos are short and many terminate in sinks which are common throughout the southern two-thirds of the area. Some sinks are sufficiently deep to continuously intersect the water table so that they form year round lake basins. These lakes are for the most part highly saline.

Physiography

The Pecos River Basin is in the Great Plains Province of Fenneman (1931). It forms the Pecos Section of this physiographic province and has received considerable attention from physiographers. Figure 6 shows the physiographic setting of the area. Fenneman wrote

Figure 6 -- Physiographic setting of the Pecos River basin

(p. 47),

> "The Pecos section is a long trough lying between the High Plains on the east and the Basin and Range province on the west. Its boundaries are marked almost throughout by steep slopes 500 to 1,500 feet high, but within these clearly marked limits the topography varies from flat plains to rocky canyon lands. The unity of the section consists in this, that the whole has been eroded below the once continuous level of the High Plains and of the Raton Section. The Llano Estacado, surfaced with wash from the mountains on the west, must have been continuous across what is now the Pecos section."

Several investigators (Nye, 1933; Leonard and Frye, 1962; Morgan and Sayre, 1942) recognize five cyclic erosion surfaces in the Pecos section. These surfaces are best defined in the south half of the basin. In topographic order from highest to lowest they are in the Roswell - Artesia area (Figure 7).

Figure 7 -- Profiles of erosion surfaces in the Pecos River basin

1. The Sacramento Plain. This is an erosional surface in the Sacramento Mountains to the west of the Pecos River that is correlated with the constructional surface of the Ogallala Formation of the High Plains west of the Mescalero Ridge.

2. The Diamond A - Mescalero Plain. Diamond A is the name given to surface on the west side of the river and Mescalero to the corresponding surface on the east side. This surface is a pediment that lies from 400 to 1300 feet below the level of the Sacramento Plain; the Mescalero Plain is the much more extensive of the two pediments. Morgan (1942) estimated that about 95 percent of the excavation that has taken place in the Pecos River basin occurred during the Diamond A-Mescalero erosion cycle.

3. Along the Pecos River, Nye (1933) recognized three gravel-capped pediments which he named the Blackdom (highest), Orchard Park, and Lakewood (lowest) terraces.

Unquestionably the Ogallala Formation once extended across the Pecos River valley. The headward cutting Pecos River removed these sediments. And, as Thornbury says, " .... in so doing it apparently performed a notable case of stream piracy". The original drainage of the area that is the upper Pecos River basin today was eastward across the high plains (Figure 8 - A). The Pecos River was initially only a short

Figure 8 - A -- Probable drainage pattern of Southern High Plains before developments of Pecos River

tributary of the Rio Grande, but it cut its way headward and one by one pirated the eastward flowing streams (Figure 8 - B).

Figure 8 - B -- Present drainage pattern of the Southern High Plains

Geologic History

The next few pages outline in limited detail the sequence of events that produced the physical geography of the Pecos River basin.*

Although we read the sequence from the rocks, not all the rocks have been studied in the detail we need to speak with absoluteness. To confuse matters further, the histories of some rocks have been studied in detail by several people who came to different conclusions. Nonetheless, by establishing even this sketchy sequence of events, we provide a basic frame work that we can work within.

Most of the earth's history is included in the Precambrian period. Yet, our knowledge of New Mexico during Precambrian time is exceptionally limited. Seas covered the area several times, igneous rocks were emplaced, and both sediments and igneous rocks were deformed and subjected to heat and pressure by burial and for several hundreds of million years prior to the close of Precambrian time New Mexico was a stable platform similar to the Canadian Shield of today.

During Cambrian time the area that is the Pecos River basin continued as a land mass of low relief. To the south and east a marine sea extended into central Texas and northern Mexico.

Very late in Cambrian time this sea encroached upon the land, depositing a thin blanket of sand and mud (the Bliss Sandstone) over the old land surface.

*We use the word basin in two senses. One is the sense of the Pecos River "drainage" basin. The other is the sense of sedimentary basin, which is a segment of the earth's crust which has been downwarped and which, therefore, collected the detritus washed in from subaerial land masses. When we refer to a drainage basin, the name of an exant river is always included.

From that time until the end of Mississippian time the old land mass was periodically covered by the sea. The sediments deposited were, for the most part, those of a shallow shelf -- largely carbonate rocks with some sands and muds.

The shore line -- where the sea met the land -- was some distance west and north of the Pecos River area. Each time the sea withdrew, the newly deposited sediments were gently eroded and beveled by the streams that developed on the emerging land. During Mississippian time sink holes developed in the limestone during periods of emergence in the northern part of the Pecos River basin.

An island archipelago of Precambrian-age rock persisted in these Cambrian to Mississippian age seas in the Matador uplift area of southern Roosevelt County.

At the close of Mississippian time the area was uplifted, tilted to the south, gently folded, and faulted. The Central basin platform began to rise from the sea floor. Erosion on a major scale took place. Streams removed large volumes of the new sediment and carved a new landscape as they dissected the relatively soft rocks.

Upon this surface the sediments of Pennsylvanian age were deposited. The area that now includes the Pecos River basin contained both positive and negative elements. The positive elements included the Pedernal uplift, the Matador uplift and the Central basin platform. The negative elements included the (1) Oregrande basin and the associated Sacramento shelf west of the Pedernal uplift, and (2) the Permian basin and the Tucumcari basin east of the Pedernal uplift. The Permian basin and the Tucumcari basin are separated by the Matador uplift.

Geologists generally divide the Permian basin into several parts. These include: (1) the Northwest shelf, (2) the Central basin platform which separates (3) the Midland basin of west Texas from (4) the Delaware basin of southeastern New Mexico and west Texas.

The development of the basins took place slowly, the postitive areas formed were exposed to erosion and contributed fine sediment to the adjacent seas.

The sediments of Pennsylvanian age were deposited in a tidal-flat shallow marine sea environment. In the deeper water of the basin the sediments were thin layers of black organic mud. On the shallow shelf areas thick lime muds developed.

To complicate the picture the area was in a continuing state of adjustment so that freshly deposited sediments were very often exposed to erosion and redeposited in the sea nearby. Thus sediments of one age may rest upon sediments which are only slightly older than themselves or they may rest on rock as old as Precambrian.

This final period of adjustment continued into Permian time, producing faults and folds that can be recognized in the Guadalupe Mountains, the Sacramento Mountains, and the southern Sangre de Cristo Mountains. Even so, over large areas of New Mexico sedimentation continued without a break from Pennsylvanian time into Permian time (Bursum, Laborcita, and Sangre de Cristo Formations).

As the period of crustal adjustment closed, uplift of the Pedernal ceased. The younger rocks were completely stripped off, exposing the Precambrian core. Sediment, derived in part from the Pedernal itself, buried it as the seas of the Northwest shelf gradually covered it. Thus, the sediments (Abo and Sangre de Cristo Formations) covering the Pedernal were partly deposited by wind and stream and are primarily continental rather than marine. The other uplifts behaved in a similar fashion except that they were not all completely stripped to their Precambrian cores and for the most part shallow seas covered them almost continuously. In the deeper waters a carbonate sediment (Hueco Limestone) formed.

After about one quarter of Permian time had elapsed, the area was completely covered by a sea whose shore was some distance north and west. But the land mass which drained into it probably had fair relief. The region was semi-arid.

Sediment poured into the sea from the distant land mass. Mud and sand (Yeso Formation) from the tidal flat-lagoonal area interfingered with the carbonate (Bone Springs Limestone) deposits building up to the south in the Delaware basin. Gypsum, anhydrite, and even rock salt developed. At the margin of the Delaware basin, a lime bank (Victorio Peak Limestone and Abo Reef) developed between the clastic shoreward deposits and the basin carbonates. The sea was approaching the largest areal extent it was to have. To the north a great influx of clean quartz sand built up a tidal flat that was underlain by as much as 300 feet of clean white sand (Glorieta Sandstone). This sand was washed clean probably because there was no restriction of circulation and the mud that would have been deposited behind the reef could now be washed out into deeper water.

About the time the sea achieved its greatest areal extent, a great barrier reef (the Goatseep-Capitan) started to develop around the perimeter of the Delaware basin. This reef controlled sedimentation during much of the remainder of Permian time. On the shoreward side open sea (lower San Andres carbonates) gave way in time to closed basin and lagoonal deposits (middle and upper San Andres and Artesian Group); on the seaward side typical marine sediments evolved (Delaware Basin Group). Apparently the areal extent of the sea diminished gradually, but the reef continued to grow because the basin subsided. At maturity the crust of the reef could have stood in places as much as 1800 feet above the basin floor. Eventually in late Permian time the sea shrank and became ultrasaline. The reef organisms probably died not because of the high salinity but because the reef was choked with sand.

At this time the sea occupied a closed basin, similar to the Dead Sea, whose only loss of water was to the atmosphere. Thick deposits of evaporites developed (Castile, Salado, and Rustler Formations), which were finally covered by sands, silts, and clays (Dewey Lake Red Beds and basal Santa Rosa Sandstone) from the eroding land mass the sea had left behind. The thickness of these clastic deposits is unknown, but we think they were very thick, for following their deposition there came a long period of erosion during which they were not breached.

The Appalachian Orogeny that followed Permian time and built the mountains of the eastern United States seems to have affected the Pecos River basin area very little. The sea withdrew and the new land mass was subjected to erosion but the rocks themselves were only slightly folded and faulted.

During Triassic time the area was covered by extensive continental deposits (Santa Rosa and Chinle Formations) -- debris from the mountain highlands to the north and west piled onto a dry land surface. In all probability the area was crossed by braided streams and a depositional pattern that carried the sediment and sorted it into the beds we see today. At the close of Triassic time they were again subjected to erosion and were unevenly removed so that the Jurassic sediments were deposited upon a truncated surface.

During Jurassic time continental deposits (Entrada Sandstone and Morrison Formation) formed in the north part of the basin, but in the south part deposition ceased and erosion began again, continuing through all of the Jurassic Period into the Cretaceous Period. For a short time an arm of Jurassic sea or salt lake covered the northern part of the Pecos River basin and in it was deposited a thin layer of limy, silty, sandy mud (Todilto Limestone). This sea withdrew after occupying the area for a short interval and subaerial deposition continued to the end of Jurassic time.

Cretaceous time saw the return of a marine sea. The west central part of New Mexico was a highland mass and the Pecos River area served as a zone of transition from near shore sedimentation where deposits of sand and mud were building up to the deeper water sediments where the lime muds accumulated. The Cretaceous Period closed with a period of upheaval during which the Rocky Mountains and the Basin and Range Province began to form.

In early Tertiary time well to the west the Basin and Range mountains were uplifted substantially and to the north the Rocky Mountains had formed. These highland areas provided sediment (Cub Mountain Formation) that covered at least the western part of the Pecos River basin with more than 2000 feet of gravelly sediment. The Sierra Blanca volcanic terrain developed upon these sediments. The pile of volcanic rock was more than 4000 feet thick.

During early Tertiary time large masses of molten rock from depths were intruded into the sedimentary rocks. These intrusions ranged in size from the huge mass of Capitan Mountain to dikes a few feet wide and only a few hundred feet long. Except for the two long dikes north and northeast of Roswell, a few reported occurrences in wells of southeastern New Mexico and west Texas, and two horseshoe-shaped dikes -- one west, and one northwest of Roswell -- this igneous activity was centered along the west side of the Pedernal uplift.

The intrusion of the Capitan Mountain had a twofold effect on the older sediments. (1) The more competent limestone beds (San Andres) were bowed up, but (2) the sandstone, shales and gypsum-anhydrite beds (Yeso Formation) were literally pushed out of the way with a resulting folding of these beds in the immediate area of the intrusion.

In late Tertiary time the Guadalupe-Sacramento-Pedernal area was uplifted . . . sliding upward along a nearly vertical fault plane. At the same time long northeast-southwest trending structural zones developed. The west slope of the uplifted mountain was extremely steep, the east slope comparatively gentle. Erosion stripped the young volcanics and the sediments, and aggrading eastward-draining streams redeposited them as a thin layer of sand and gravel (Ogallala Formation) that not only covered most of the Pecos River basin but extended far into Texas. These eastward-draining streams are the ancestors not only of the Pecos River, but also the Colorado, the Barzos and Red Rivers of Texas. As these rivers developed, erosion by the Pecos took the stream northward into the softer, more easily attacked sands and gravels, removed them and exposed the rocks beneath and in part removed them. Where the soluble rocks were exposed a karst topography developed and speeded the erosion process.

At first the river followed a course parallel to but several miles west of its present position in New Mexico. Gradually it eroded eastward "sliding" down the competent rock surface as it eroded the unconsolidated sand and gravel and the poorly consolidated rocks. Large areas collapsed from the removal of underlying evaporites, preserving large volumes of Ogallala sediments in apparent drainageways. In the mountains glaciers accelerated erosion during Pleistocene time. The glaciers have disappeared but the headward erosion continues and the build-up and erosion of the alluvial plain goes on.

Tectonic Setting and Structural Features of the Pecos River Basin

INTRODUCTION

Source of the data

This section of the report is based on:

1. Published reports, cross sections, and maps,
2. Open file reports of the U. S. Geological Survey, Albuquerque,
3. Theses and dissertations in geology,
4. Electric log interpretations by the Stratigraphic Studies Committee, Roswell Geological Society, and
5. Well logs, sample suites, and scout reports filed with the PetroleumSection, New Mexico Bureau of Mines and Mineral Resources, Socorro.

Problems in defining structure

We use structure contour maps to define the attitude (or position) of stratigraphic units. Using structure contour, we predict the location of the particular unit involved over the area in which it occurs.

We use structural cross sections to show the relation of several stratigraphic or lithologic units in the vertical plane.

Using available information to interpret structure, to draw contour maps, or to construct cross sections has its drawbacks. Published and open file reports generally provide interpretations rather than "raw" data, and interpretations differ because investigators stress different "facts." For example, geologists using different logs picked the tops of critical formations at different altitudes because their criteria were necessarily different, e.g., some used electric logs, others used radioactivity logs, and still others drillers' logs. Difficulties also arise because: data are lacking where rocks are not exposed or test holes have not been drilled; and data are misleading where samples are mislabeled or locations are incorrect (owing primarily to typographical errors). Thus, available data may suggest structural features where none exist in fact. Our interpretations of structure is confused by two other factors -- erosion and facies.

Subaerial erosion of once continuous surfaces creates three problems:

First, structure contours on the eroded surface reflect, of necessity, the topography developed on that surface as well as the attitude of the beds that developed as a consequence of tectonic forces. Thus, mapped slopes may differ from the actual slope of the beds because rocks on the mapped surface are not all the same age.

Second, erosion removed some rocks from some areas entirely, before the overlying rocks were deposited, thus precluding their use to define structure in the denuded area.

Third, erosion of the rock from the present outcrop precludes the use of any unit in the area of its outcrop except where the overlying unit is present.

Facies changes make the preparation of structure contour maps difficult. If we choose as a mapping unit a stratigraphic horizon over which the character of the sediments reflects a wide range of depositional environments at a given time, we may not always be able to recognize the horizon of our choice in the rocks or to pick it with the data available. In such rocks the slope of a persistent lithology does not necessarily reflect the attitude of the beds in the area mapped. The actual dip of the beds may be either greater or less than the slope mapped. In general, we believe the difference between the attitude of the beds at a specific locality and the slope of a persistent lighology is usually small.

Facies differences may preclude the use of some horizon for defining structure because the surface at the time of deposition was itself so irregular. In the vicinity of reefs, for example, the surface at any time has a distinct topographic expression which if mapped would not describe the attitude of the underlying beds.

We drew the structural contour maps presented here with a 250 to 1000-foot contour interval to minimize the effects of using different criteria for picking unit tops and of facies changes. We have smoothed or generalized because the data can be interpreted in many ways. We have adopted the attitude, therefore, that the simplest explanation is the best explanation. When data becomes available for the whole basin in the detail that is available for part of it now, more complex interpretation will be practical.

Structural features

In the Pecos River basin we recognize these structural features: faults, folds, and structural zones.

Faults are fractures in the rocks along which movement has occurred so that particles which were initially adjacent have been measurably displaced. The west side of the Sacramento Mountain is a fault scarp. Beds which occur in the mountain at elevation of 8-9000 feet occur in the Tularosa basin at elevation of less than 4000 feet -- more than 4000 feet of vertical displacement. The horizontal displacement is unknown.

Folds occur when the tectonic forces have warped, but not broken the beds. Anticlines are elongate upwarps; domes are circular upwarps, synclines are elongate downwarps, structural basins are circular downwarps.

Structural zones include both faulting and folding. This term is generally used either (1) because neither fault nor fold adequately describes the situation, or (2) because the evidence is insufficient to adequately determine the structural feature.

REGIONAL SETTING

The Pecos River basin has had a complex history of uplift and subsidence. The west and north part of the area has been primarily positive; the south and east primarily negative. In general, the sediments which make up the rocks were derived from the positive areas and deposited in the negatives. We infer, therefore, that the sediments were deposited upon a surface which generally sloped downward from north and west to south and east. We cannot define the slope at the time of deposition with any precision, however we do presume that it was not generally steep and probably was similar to the slopes of the land surface we see today around the Gulf of Mexico and along the Atlantic Coast, that is, a few feet per mile.

Although the north and west parts of the basin are primarily positive areas, they were covered by marine seas part of the time and were also the continental lowlands upon which the debris derived from high land masses still farther west or north was deposited.

From Cambrian to Mississippian time no area within the basin stood out as a source of sediment. During Pennsylvanian and Permian time, however, the area of the Pecos River basin was strongly differentiated into positive and negative areas. Figure 9 shows the dominant tectonic

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Figure 9 -- Tectonic Features during late Paleozoic time in Southeastern New Mexico

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features during Pennsylvanian and Permian time.

During Mesozoic time the basin area alternated between being a source for sediment deposited south and east and a site of deposition for sediments derived from sources west and north. In early Cenozoic time mountains began to take shape. Large fractures developed in the rocks. Igneous rocks were emplaced. The region was generally uplifted and tilted, modifying the attitude of the rocks extensively. In middle and late Cenozoic time the mountains attained their present attitude. Thus the rocks of the Pecos River basin were deformed significantly during Pennsylvanian and early Permian time and during Cenozoic time.

We can divide the discussion of the structure of the basin into three parts, one part being a discussion of the structures of the mountains that form the western periphery of the basin, the second being a discussion of the structures in the northern part of the basin that includes the Pedernal Hills, Glorieta Mesa, and the Sangre de Cristo Mountains, and the third being a discussion of structures of the interior and eastern periphery of the basin.

Figure 10 shows the location of structural features in the Pecos River basin.

Figure 10 -- Location of principle structural features in the Pecos River basin, New Mexico

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THE WESTERN PERIMETER

Guadalupe Mountains

The following commentary is digested from Hayes (1964, p. 40 -46): The principal structural feature of the Guadalupe Mountains is the Guadalupe Mountains uplift. This uplift is a gently northeastward tilted block bounded on the west by a zone of nearly en echelon normal faults of late Cenozoic age and on the east by a monoclinal fold of Cenozoic age, the Huapache monocline. The monocline apparently is superimposed on a zone of late Paleozoic thrust faults. The southeast margin of the Guadalupe Mountains uplift concides with the Reef Escarpment which may be resulted partly from Cenozoic rejuvenation of a Late Paleozoic fold, the Bone Spring monocline. Adjacent to this moncline on the northwest is a zone 5 miles wide characterized by the broad northeastward plunging Walnut Canyon syncline and Guadalupe Ridge anticline.

West of the Guadalupe Mountains is a graben area occupied by Big Dog and Upper Dog Canyons. This area is bounded on the west by a north-northwestward-trending zone of normal faults of late Cenozoic age in and adjacent to the Brokeoff Mountains. Strata to the northeast and southeast of the Guadalupe Mountains are relatively undistrubed and, in general, dip gently east to northeast.

The only pre-Permian structural element known in Guadalupe Mountains is a buried fault zone along the east side of the main Guadalupe Mountains block. The displacement, attitude, trend and age of the fault zone are suggested by logs of deep oil tests. The nature and thickness of Mississippian, Pennsylvanian, and Lower Permian rocks penetrated in several wells indicate that the fault zone is very nearly coincident with the present east boundary of the northern Guadalupe Mountains, that it was apparently intermittently active through all or most of Pennsylvanian time and possibly Early Permian time, and that the fault zone defined the east boundary of a rising positive area.

The dips of the fault planes cannot be determined, but the faults are known to be reverse in attitude with rocks on the west sides of the faults being upthrown. The strike of the fault zone is about N. 35° W. The apparent dip is 45° to 85° westward. The rocks dip eastward as much as 60° and possibly much more, throughout a vertical interval of nearly 4,000 feet. Because this seems excessive for drag folding along a fault, the dipping rocks have been interpreted to be part of a thrusted fold.

Mississippian rocks underlying the area show no important lithologic change from one side of the fault zone to the other, but they are vertically displaced by as much as 4,000 to 6,000 feet and are found twice in one well. The Permian San Andres Limestone, which lies at the surface over the fault zone, is not ruptured; so the faulting must be pre-Guadalupe in age.

The fault zone is reflected today on the surface by the low eastward-dipping Huapache monocline. Inasmuch as the Huapache monocline affects rocks of late Guadalupe age, it appears that minor post-Guadalupe, probably Tertiary, movement has taken place along the old zone of weakness.

Vertical movement along the Huapache thrust zone was greater in the vicinity of Texas Hill than it was to the south near Last Chance Canyon.

Late in Leonard time and early in Guadalupe time a broad southeastward-dipping fold, the Bone Spring monocline, formed along the south side to the Victorio Peak Limestone.

Two systems of folds involving the San Andres Limestone and Artesia Group at the surface interrupt the northeastward regional dip of about 1° to 2°. These are the north-northwestward-trending Huapache monocline and its related structures and the northeastward-trending folds that parallel the Reef Escarpment on its northwest side.

The east-northeastward-dipping Huapache monocline is a prominent fold that extends from the Reef Escarpment between Rattlesnake and Slaughter Canyons to a point beyond the north edge of the mapped area. It resulted from post-Permian flexing along the trend of the late Paleozoic Huapache thrust zone. Maximum dips along the monocline in the San Andres Limestone and younger rocks that form the surface generally range from 5° to 8°. The width of the fold is generally less than 2 miles, and the difference in elevation of equivalent beds on opposite sides is about 1, 000 feet.

Closely associated with the Huapache monocline is the asymmetrical Texas Hill dome. Its axis is parallel to the trend of the Huapache monocline, and the relatively steep east flank of the dome merges with the monocline. The west flank of the dome is formed by a slight reversal of the gentle regional dip. The total structural closure on the dome at the surface is apparently less than 100 feet.

Three folds that parallel the Reef Escarpment on its northwest side may be indirectly related to the older structural feature, the Bone Spring monocline of Early Permian age. (1) The Walnut Canyon syncline, whose axial trace is about 1 mile northwest of the crest of the Reef Escarpment, extends from Big Canyon to near the mouth of Walnut Canyon, a distance of nearly 25 miles. The maximum dips on the northwest flank of the syncline average 6° and locally are as great as 9°; the southeast flank rarely dips more than 1° or 2°. For much of its length, the axial trace of the Walnut Canyon syncline nearly coincides with West Slaughter, South Rattlesnake, and Walnut Canyons. (2) The steeper northwest limb of the Walnut Canyon syncline is the southeast limb of the asymmetrical northeast-plunging Guadalupe Ridge anticline whose axial trace is near the crest of Guadalupe Ridge. Dips on the northwest limb of this anticline are also very gentle and barely exceed 1°. (3) Structural contours indicate one more indistinct shallow, northeast-plunging syncline adjacent to the Guadalupe Ridge anticline on the northwest.

These three folds that parallel the Reef Escarpment are presumed to be Laramide in age. The open joints that controlled the solution of the Carlsbad limestone are probably tension joints that formed during the folding. Kelley (1971, p. 40) thinks, " * * * they may be due to something in the progression of reef growth in early Capitan time over which later compactive folds would form."

Other small undulations in the carbonate surface rocks in the northern part of the Guadalupe Mountains are probably tectonic in origin. Undulations in the outcrop areas of the evaporite member of the Seven Rivers Formation and the Castile Formation are probably at least partly due to solution and collapse of evaporite beds.

Many closely spaced faults trend north to northwest along the west edge of the Guadalupe Mountains. Several faults of small displacement also parallel the Reef Escarpment.

The faults on the west side of the area are assigned to three groups: (a) those along the Guadalupe Mountains scarp north of Stone Canyon, (b) those parallel to the Shattuck Valley scarp south of Stone Canyon, and (c) those in and north of the Brokeoff Mountains.

The Guadalupe Mountains scarp from Stone Canyon northward is characterized by numerous closely spaced high-angle faults which are parallel or subparallel to that scarp. Dip slip is probably predominant. Nearly all these faults are downthrown on the west, but a few short faults have the opposite displacement. Stratigraphic displacements of faults high on the scarp rarely exceed 100 feet but two faults that are mostly buried beneath alluvium in Big Dog Canyon have maximum stratigraphic displacements of about 800 feet where they are exposed low on the scarp.

The faults paralleling the Shattuck Valley scarp are separated from the faults at the south end of the main Guadalupe Mountains scarp by an unfaulted monoclinal fold about 1-1/2 miles wide. Most of the displacement on the Shattuck Valley scarp is along one long fault high in the scarp, although some displacement is taken up by a smaller fault. The larger fault can be traced for about 13 miles from north of El Paso Gap southward into a fault called the Dog Canyon Fault. It has an arcuate trace convex to the east, and the average strike is a little east of north. The fault plane probably dips to the west at a high angle. Stratigraphic displacement along the fault is as much as 800 feet locally. Adjacent to the fault, beds on the down-dropped side dip sharply to the west with dips as great as 70° and are cut by strike faults of small displacement. The steep westward-dipping beds on the west side of the fault flatten out under the alluvium of Shattuck Valley and, on El Paso Ridge on the west side of the valley, the dip is as much as 14° to the east, thus forming a syncline. On the west side of Upper Dog Canyon near the southwest edge of the mapped area is another arcuate fault, downthrown on the east, which parallels the fault on the Shattuck Valley scarp. Upper Dog Canyon, therefore, is a combination graben and syncline.

The faults in and north of the Brokeoff Mountains are a closely spaced complex of northwestward-striking faults, particularly toward the north, are downthrown on the west so that the area contains several narrow grabens and horsts. Stratigraphic displacement on the faults range from a few feet to as much as 600 feet. Two of the fault planes dip 60° and 80° ; dips of the others could not be measured. Most of the faults appear to be normal faults that dip at high angles. The Brokeoff Mountains fault zone and the main fault zone of the Guadalupe Mountains are separated by a graben occupied by Big Dog Canyon. The two fault zones merge and form a profusion of subparallel faults along the Guadalupe Mountains scarp.

The Capitan Limestone and adjacent parts of the Artesia Group contain a conspicuous system of nearly vertical joints that parallel the Reef Escarpment. Associated with these are less conspicuous joints that trend at right angles to the Reef Escarpment. These intersecting joints formed the avenues for solution of such caves as Carlsbad Cavern and New, Goat, and Lechuguilla Caves (see Table 1). Many of the joints parallel to the Reef Escarpment contain sandstone dikes of probable Cretaceous age. Numerous small drainage courses are controlled by this set of joints. Among these are Calamity Cove and Lefthook, Yucca, Nuevo, and Fence Canyons.

The fact that these joints are everywhere parallel or at right angles to the Reef Escarpment, no matter what its trend, suggests a relation between the Capitan Limestone and the joints. Sandstone dikes of probable Cretaceous age in some of the joints indicate that they were opened before late Early Cretaceous time. Possibly they were formed soon after deposition of the Permian rocks by differential compaction of rocks in the northwest-shelf area and the Delaware basin, or they may have been formed during post-Permian regional uplift by tensional stresses resulting from differential movement between the shelf and the basin. Some of the joints may have been enlarged and others may have formed concurrent with the folding of the Walnut Canyon syncline and related structures in Tertiary time.

Another type of jointing that is peculiar to the Capitan Limestone is sheeting parallel to the present erosion surface. Sheeting occurs locally along the Reef Escarpment and on the walls of some of the canyons which cut through the escarpment. The sheeting can be easily confused with the crudely developed bedding in the breccia member, which is subparallel to the surface of the Reef Escarpment. The type of sheeting or exfoliation noted in the Capitan Limestone is often well developed in granitic rocks, but it is rarely observed in sedimentary rocks.

Other joints in the area are more obviously directly related to structural features of Tertiary age. Along the west edge of the area are numerous closely spaced joints parallel to the faults there. These are particularly prominent along The Rim on the west edge of the Guadalupe

Mountains. Less closely spaced joints of north-northwesterly trend are present in limestone and dolomite throughout the Guadalupe Mountains.

Low scarps in the Castile Formation trend about N. 75 E. across the Yeso Hills in the southwestern part of the Castile outcrop area. Some of the scarps are several miles in length and are as high as 50 feet. They face south or north and bound relatively flat valleys or ridges that resemble horsts or grabens ranging from a few hundred feet to more than a mile in width. Such linear features are present in the Castile Formation for nearly 30 miles south into Texas.

The scarps are apparently the traces of shallow faults of small displacement. Olive (1957) has described the grabens between the scarps as "solution-subsidence troughs." He believes that gypsum is dissolved along underground drainage channels following fractures that closely parallel the regional dip direction and that when the roofs over the channels can no longer be supported, collapse ensues. In Olive's words (p. 357) -- 'The collapse debris forms a barrier across the channels and causes the underground drainage to seek passage * * * along nearby fractures, which also approximate the trend of the regional dip. Subsidence that gives rise to troughs probably is not the result of a single cavern but of several.' The presence of small caverns and sinks, the irregular topography in the troughs, and the existence of gypiferous springs (Ben Slaughter, Cottonwood, and Jumping Springs) to the east of the troughs in a downdip direction all support Olive's theory on the origin of the troughs.

Sacramento Mountains

The following commentary is summarized from Otte (1959, p. 78-87) and Pray (1961, p. 123-131):

The Sacramento Mountain range is essentially a block that has been uplifted, with respect to the Tularosa basin, along a fault zone on the west and tilted eastward. The western part of the range is structurally similiar to the scarps of the Basin and Range province. The eastern portion possesses many structural features characteristic of the Great Plains region. From the crest of the mountains, the strata dip one to two degrees eastward and can be traced in that direction with only a few structural deviations for more than 50 miles.

The uplift of the Sacramento Mountains was during the latest period of tectonic activity in this area and apparently occurred in late Cenozoic time. Earlier periods of crustal deformation are recorded in the rock units. There is evidence of a late Pennsylvanian and early Permian period of deformation, referred to as the pre-Abo deformation. Evidence of post-Abo gentle folding was observed in the area south of Laborcita Canyon. Owing to the absence of sedimentary strata area younger than the Yeso Formation, and older than the Quaternary surficial deposits, this period of deformation could not be dated more closely. At least three periods of tectonic activity can be distinguished in the northern part of the Sacramento Mountains.

One of the major angular unconformities within the Paleozoic sequence of the Sacramento Mountains occurs at the base of the Abo Formation. The pre-Abo deformation caused major folding and faulting.

Resistant strata of the Bug Scuffle Limestone members of the Gobbler Formation rise abruptly above the less resistant strata of the Holder and Laborcita Formations in the southeastern part of the map area. This is mainly a result of pre-Abo high-angle normal faulting. Between Fresnal Canyon and Salada Canyon displacement occurred on a system of two essentially parallel faults, with the western sides downthrown. The western fault, called the Salada Canyon fault, extends for about 1-1/2 miles from Salada Canyon to Fresnal Box Canyon and may extend farther south. The Fresnal Canyon fault is the eastern fault and is exposed continuously for about five miles between Salada Canyon and Arcente Canyon to the south. There is evidence that the faults occur as buried structural features at least as for north as La Luz Canyon. These faults probably are parts of one major fault zone at depth and movement probably took place along these various branches at different times during late Pennsylvanian and early Permian time. Parts of this fault system are reactivated in post-Abo time.

Folds resulting from pre-Abo deformation occurred in the southeastern part of the northern Sacramento Mountains in a zone that extends for about 3 miles northward from Salada Canyon to about one mile north of La Luz.

Evidence of post-Abo deformation occurs south of Laborcita Canyon where three gentle folds, the La Luz anticline, the Dry Canyon syncline, and the Maruchi Canyon arch, are believed to be results of post-Abo deformation. Both the Dry Canyon syncline and the Maruchi Canyon arch occur in strata of the Abo Formation, but the age of this deformation is poorly defined, as the folding is younger than the Abo Formation and older than the Quaternary surficial deposits. Strata as young as the San Andres Formation are gently folded in other parts of the Sacramento Mountains escarpment, which suggests a post-San Andres age for this deformation.

The margin between the mountains and the Tularosa basin is locally marked by scarps up to 20 feet high and about 2 miles long. These Piedmont scarps are considered to mark the surface trace of the major boundary fault. Most occur within a few hundred feet of the base of the escarpment and separate alluvium on the west from bedrock on the east.

Between Cottonwood and Tularosa Canyons, two normal faults near the frontal escarpment are interpreted as step faults. The faults dip westward at an angle of about 70°, and the west side is downthrown, with a dominant dip-slip movement. The western fault has an approximate displacement of about 300 feet and is characterized along its entire length of about seven miles by a narrow zone of fault drag about 100 feet wide. These two step faults merge with the frontal fault near Tularosa Canyon, and farther to the north the escarpment appears caused by displacement on a single boundary fault.

In the area between Laborcita and La Luz Canyons, the step faults are not as well defined as separate faults, but there are numerous high-angle normal faults. These faults are in general nearly vertical, and the displacements appear to be largely dip-slip, averaging about 100 feet. Locally, displacements up to 400 feet have been measured. As these faults offset the folded strata of the La Luz anticline, they are younger than the post-Abo deformation. A few affect the Tertiary (?) intrusive rocks and associated features.

The regional dip of the beds in the Sacramento Mountains is one to two degrees to the east. In the relatively undeformed parts of the northern Sacramento Mountains, such as in the area north of Laborcita Canyon, the amount of east dip increases toward the front of the escarpment, and in the area north of Tularosa Canyon, dips as steep as 25 to 30 degrees have been recorded. This gradual steepening of the strata generally occurs within a zone about half a mile wide. The feature is common along the Sacramento Mountains escarpment. It is probably the result of fault drag on the major boundary fault as a result of relatively recent subsidence of the main mountain block with respect to the Tularosa basin.

Sierra Blanca

The following discussion summarizes the work of Griswold (1959, p. 14-15), Bodine (1956, p. 13-14), Knapp (1933), Griswold and Missaghi (1964, p. 4-8), and Thompson (1966):

Sierra Blanca is an igneous complex resting on a structural basin. The igneous complex consists primarily of basaltic andesite flows, breccias, and agglomerates, into which numerous stocks and dikes have been intruded.

The structural basin upon which this volcanic pile "rests" trends north-northeast, is 40 miles long and 20 miles wide. Some investigators have attributed the origin of the basin to the extrusion of the Sierra Blanca volcanic rocks, which, in effect, removed the underlying foundation of the area, allowing the volcanic rocks to settle to form a basin structure. This reasoning, while plausible, is not proven.

Capitan Mountains and the Lincoln fold system

The following discussion summarizes Griswold (1959, p. 14-15), Knapp (1933), Craddock (1960), and Allen and Kottlowski (1958, 1967):

They believe the Capitan Mountains were formed by a laccolithic intrusion of alaskite.

Figure 11a shows diagrammatically the relation of the intrusive

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Figure 11 -- Diagrammatic cross-sections through the Capitan, Carrizo, and Vera Cruz Mountains

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igneous rocks to the sedimentary rocks, both at the time of emplacement and as we see them now.

Around the margin of the laccolith, the beds of the Yeso Formation are strongly folded. These folds do not occur in the overlying San Andres Limestone. However, there seems to be no distinct break between the San Andres Limestone and the Yeso Formation. Thus, some observers believe the intraformational folding occurred when the intruded magma pushed the incompetent Yeso beds aside, the more competent overlying limestone was simply uplifted by and domed over the igneous mass.

Kelley (1971) says the nature of the Capitan is largely indeterminate (p. 43). Of the Lincoln fold system he writes,

> "Some of the folds are undoubtedly related to the larger tectonic features of the area; some are due to surficial slump; some are caused by intrusions of sills or dikes; some to solution collapse; some to volume changes accompanying hydration; and some to gravity tectonics arising out of regional tilt. Above all else they are to be classed as incompetent folds by their abundant confinement to the Yeso or a small part of it. They are erratic in form and distribution and clearly could have formed at almost anytime from shortly after Yeso deposition to the present."

Vera Cruz, Tucson, Carrizo, Patos, Jicarilla, and Gallinas Mountains

The Tucson, Carrizo, Patos, Jicarilla, and Gallinas Mountains are also laccoliths (Kelley, 1946). The sedimentary rocks around Carrizo Mountain dip inward, suggesting a structural basin (Fig. 11b).

The overlying rocks have been removed by erosion but they probably were domed upward in the same fashion as those of the Vera Cruz (Fig. 11c) and Gallinas Mountains.

NORTHERN THIRD OF THE BASIN

Pedernal Hills

The Pedernal Hills are an upland of Precambrian igneous and metamorphic rocks. Sedimentary rocks are draped over this central core. In addition to being a dominant positive area which influenced the structure of the overlying beds, the Pedernal Hills are bounded on the western side by a fault zone of Tertiary age.

Glorieta Mesa

The beds of the Glorieta Mesa are uplifted in a broad, nearly flat-topped arch. The axis of this arch trends slightly west of north.

Gorman and Robeck (1946) describe the structure of Guadalupe County as follows:

> "The mapped area lies near the western edge of the High Plains. The strata in general have a low regional dip to the east and southeast, although local reversals of dip are common. The Esterito dome, the Guadalupe anticline, and the Bar Y dome are three major folds that interrupt the regional dip. Several minor folds were also mapped. No faults were observed in the mapped area.
>
> "Esterito dome is an elongated domal structure, whose crest lies about 5 miles southeast of Dilia. It has a closure of about 400 feet.
>
> "Guadalupe anticline is a broad south-trending fold, whose axis passes about 3 miles west of Las Colonias. It has been traced to the south edge of the mapped area and may be connected by a fold that is visible near San Ignacio in Pintada Canyon. The continuation of this axis north of the Pecos River is suggested by the pattern of outcropping formations.
>
> "Bar Y dome is an elongated domal feature whose crest is located about 3 miles west of the Bar Y ranch headquarters. The closure is about 100 feet."

Sangre de Cristo Mountains

The structure of the Sangre de Cristo Mountains appears to be more complex than the structure of the other mountains that border the Pecos River basin. The reason for this is: we are able to define the structures of the Precambrian rocks in greater detail, because they are better exposed.

The pertinent events in the structural history of the range are:

1. Intensive folding of metasedimentary rocks during Precambrian time.
2. Generation of the Picuris-Pecos fault during Precambrian time.
3. Uplift on the west side of the Picuris-Pecos fault during Pennsylvanian time (at least two distinct phases).
4. Renewed uplift of the west side of the fault and general uplift of the entire area during the late Cretaceous-early Tertiary Laramide orogeny.
5. Middle and late Cenozoic deformation resulting in the uplift of the mountians.

Sutherland (1963, p. 47) called the Picuris-Pecos fault a <u>geofracture</u>, a major, ancient <u>fracture</u> zone along which current movement has taken place. The rocks along the east side of this fault form the northwestern divide of the Pecos River basin. Sutherland describes the structure of the rocks in the Pecos Valley area. A summary of his [illegible] follows:

The area around the valley of the upper Pecos River and east of the Picuris-Pecos fault is characterized primarily by a major south-plunging syncline and a similar eastward-adjacent anticline. These two broad folds with north-south-trending axes originated during Laramide deformation. The syncline, here named the Holy Ghost syncline, trends north-south with its axis less than one mile east of the Picuris-Pecos fault zone, which it parallels, and about two to three miles west of the Pecos River south of Cowles. It crosses near the head of Holy Ghost Canyon about four miles northwest of Tererro. This syncline can be traced northward for about ten miles from the south edge of the map and appears to have its northern terminus in the sharp synclinal structure immediately west of Pecos Baldy.

The anticline to the east, the Elk Mountain anticline, is sharply asymmetrical to slightly overturned eastward. It trends north-northeastward and its axis coincides for four miles north of the south edge of the map with the crest of the Elk Mountain (East) Divide. Beds in the west limb of this anticline dip gently westward, averaging five to ten degrees, and occupy most of the Pecos drainage area. A southward plunge of about two to three degrees for beds in this west limb can be noted at many exposures along the Pecos River valley. Bedding in much of the east limb of the Elk Mountain anticline is steeply inclined eastward to vertical to slightly overturned. Minor displacements occur locally along the overturned synclinal axial plane adjacent to the east. Most of the sedimentary strata occupying the east flank of the Elk Mountain anticline have been removed by erosion, exposing Precambrian rocks in the deep canyons and on most of the sharp east-west ridges separating Burro, Hollinger, and Beaver Canyons.

Minor normal faults are common throughout the area of Pennsylvanian outcrop. These faults generally strike north-south, parallel to the major faults of the region, but poor exposures make lateral tracing of most of them impossible. One of the larger of these faults, with a throw of about 60 feet, named the Cowles fault, is along the Pecos River valley at Cowles. The fault plane appears to be vertical and beds are downthrown to the west. This fault can be traced for about one and one-half miles and may be a primary factor in the north-south location of the Pecos River along the Pecos Valley, but its trace is lost in the Precambrian rocks exposed in the bottom of the Pecos Canyon. Such faults are presumed to have developed during Laramide deformation.

Along the eastern side of the mountains the sedimentary Paleozoic and Mesozoic rocks have been folded into nearly vertical attitudes so that width of their trace on a geologic map is very nearly their thickness. These steeply dipping beds form the hogback ridges which are the eastern foothills of the Sangre de Cristo Mountains. East of the mountains the dip of the beds diminishes as the distance from the mountain increases. In general, all over most of the area east of Las Vegas, including the Las Vegas Plateau, these rocks are nearly horizontal although slightly warped and folded.

INTERNAL AND EASTERN PERIPHERAL STRUCTURES

Introduction

The bulk of the rocks of the Pecos River basin dips east or southeastward at relatively low angles, 1-2°. These dips are interrupted by local structures of small relief, including anticlines and domes, synclines, and igneous intrusions. Kelley (1971) discussed the structural features of this area in great detail.

The major structural features within the basin are northeast-trending structural zones, some of which have been named.

Secondary structural features in the basin include collapse features associated with the removal of underlying rocks by solution. In all probability many of the surfical structural features are the direct result of or are considerably modified by solution phenomenon in the subsurface.

Anticlines, domes, and synclines

East of the mountains the outcropping rocks are gently folded and several of these have been named by various investigators. They include McDaniel anticline, Tinnie fold zone, Picacho anticline, McKnight anticline, Manning anticline (dome) (Bluewater anticline and syncline of Bean, 1949, p. 19), Black Hills (Cuevo) anticline, and Dunken dome. These features generally show low relief and low dips of less than ten degrees. Kelley (1971, p. 40-41) refers these folds to the Dunken uplift and the Tinnie fold belt and describes them in some detail.

The so-called Artesia-Vacuum trend had the aspects of an eastward plunging anticline. The sedimentary beds also have an anti-domal configuration over the Matador uplift and the central basin platform. The San Simon syncline is the only synclinal feature east of the river. Numerous low relief domes, anticlines, and rocks have been mapped in the search for oil east of the river.

Structural zones

The structural zones that strike approximately N 45° E are shown in their simplest format on Figure 10. They are in fact complicated features (Fig. 12). They have been called anticlines,

Figure 12 -- Plan view of structural zones (after Bean, 1949)

faulted anticlines, faults, and buckles. The three most obvious are referred to as the Six-Mile Hill, Y-O, and Border Hills zones. The three zones are very similar. Each is a straight, narrow ridge or a series of narrow ridges and hills in a line. More recently the term KM Fault has been applied to a zone southeast of the Y-O zone. The KM zone is defined by subsurface information only. Other zones seem apparent on the high level areal photography.

High level aerial photography of the basin shows clearly the three zones we can see at the surface and also shows several other linear features which might be construed as structural zones. One of these aligns with the KM. Stipp (1956, p. 17) believes the Border Hills and Six-Mile Hill structural zones are surface expressions of faults extending up from the Precambrian basement rocks.

Kelley (1971) uses the term buckle to describe these features. As he puts it,

> "The term buckle is used here owing to the fact that their surface expressions are in some places folds, elsewhere faults or combinations of the two. Furthermore, there is much evidence that they have experienced strike movement. Both sides are generally turned up sharply in a zone that may range from a few tens of feet to 4,000 feet wide. In many places there is wider uplifting outside a narrow zone of intense de-

"formation. This is the case along the Six Mile buckle west of Roswell where the anticline may be as much as 4 miles wide. The buckles plunge northeastward diagonally across the easterly regional dip. As a result of this relationship there generally is a plunging syncline on the northwest side of the fault or buckle and a synclinal bend on the southeast side, and these axes are mapped. Where the buckle is a fault one buckled-up limb may have a bed separation in the vertical of as much as 500 feet without the beds outside the buckled zone being measurably up or down with respect to each other. Elsewhere, however, key beds away from the buckle are observed to be lowered or raised relatively by 50 to 100 feet.

"Along the strike of a buckle the nature of a deformation may change markedly in a short distance. This is strikingly demonstrated by comparing the cross section of the Border buckle in the north wall of Hondo Canyon with roadcut exposure 3 miles to the northeast on U. S. Highway 70. Only a small quantity of breccia is present in the fine exposures on the Hondo. However, the great quantity and chaotic distrubance revealed in the highway cut is not believed to be too unusual.

"The evidence for wrenching action along the faults falls into two principal categories (1) steeply plunging drag folds and left-branching spur faults along the axis or fault, and (2) echelon diagonal folds of some length between the buckles."

Border Hills Structural zone

According to Nye (1933, p. 78),

> "The Border Hills are formed by a combination of a narrow anticlinal fold and a fault of moderate displacement, which in the canyon of the Rio Hondo appears to be a thrust fault. For several miles north of the Rio Hondo, at least, the beds on the west side are downthrown relative to those on the east side. According to K. H. Crandall, who made a detailed study of it, the fault reverses itself at several places, and for a few miles south of the Rio Hondo the beds on the west side are upthrown relative to those on the east side. As a topographic feature the Border Hills fault dies out in T. 9 S., R. 21 E., but evidence of its continuation northeastward beyond Salt Creek is said to have been found. According to Merritt, it extends southwestward as far as T. 16, R., 16 E."

Paul. NcCune told Nye,

> " *** that it changes into a narrow anticline and ends near the Manning dome, in T. 15 S., R. 17 E., which together with the fact it is not clearly seen to be a fault where the Roswell-Alamogordo road crosses it, may account for the fact that Merritt described it solely as an anticline."

Bean (1949, p. 18) wrote,

> "The Border Hills structure is expressed as a ridge of that name which Highway 70 crosses about 25 miles west of Roswell. The structure is clearly a narrow

Bean (1949, p. 18) continued

" faulted anticline throughout most of its extent, although the fault does not show distinctly in road cuts at the highway and may die out to the north. The structure is well exposed in the walls of Rio Hondo Canyon between 2 and 3 miles south of Highway 70. There it is clearly a narrow anticline, broken at the crest by a nearly vertical fault. Very surprisingly, the vertical component of the fault reverses itself across the river. North of the river the east limb is upthrown and on the south the west is upthrown. This observation was first made by Nye (Fiedler and Nye, 1933, p. 79) with some question, but is was checked by the present writer who corroborates Nye's tentative finding. Two excellent sketches of the structure here are included in Nye's work (Fig. 13).

Figure 13 -- Diagrammatic sections across the Border Hills

There is a pronounced horizontal bend or offset in the fault where it crosses the river, the southern part of the structure being displaced to the west.

"The Glorieta (?) sandstone member of the San Andres formation is exposed in many places near the axis of the structure, and on the north side of the Hondo another sandstone which is probably in the Yeso formation appears below it. These markers are very useful in determining the upthrown side of the fault, but the writer was unable to find them opposite each other in the same locality to determine the amount of displacement. Dips on either side of the anticline are as steep as 50° but are mostly about

Bean (1949, p. 18) continued

"half that amount. The base of the eastern limb particularly is very sharp, and massive horizontal beds assume a dip of more than 20° in a very few feet. A well-developed joint system parallels the structure.

"The Border Hills structure is not a typical thrust-faulted anticline. Instead it evidently was formed by forces that pinched the rocks into a very narrow fold which broke nearly vertically along the axis, further relief from the stresses being gained by relative displacement of the two limbs. Displacement was partly vertical but may have included a comparable horizontal component as well. The total throw along this fault was not great, and probably did not exceed 300 feet anywhere along the structure. The zone of crushing and brecciation along the axis of the anticline is very wide; however, in the saddle 300 yards south of the Rio Hondo, for example, its width is 200 feet.

"The trend of the Border Hills structure varies considerably, but it averages about N. 32° E. Its northeastward limit as mapped in this report is in sec. 5, T. 10 S., R. 21 E., where available aerial photograph coverage ends, but it undoubtedly extends into the Salt Creek area, for a monocline directly in line with the structure was found in the banks of Salt Creek in sec. 22, T. 8 S., R. 22 E.

Bean (1949, p. 18) continued

> "South of the Rio Hondo, valleys parallel the structure along much of its extent. These commonly lie a little west of the fault, which is often marked by less conspicuous saddles. Six and a half miles southwest of the point where it crosses the Rio Hondo, the Border Hills structure is again bent to the west, and again the bending takes place at a water gap, here occupied by a tributary of the Rio Felix. On the south side of this water gap the structure bifurcates. The east branch is mainly a fault, and it dies out in about 3-1/2 miles. The west branch continues as a faulted anticline to T. 14 S., R. 18 E., and Merritt (1920, p. 55) states that the structure continues southwestward as far as 'a point below Elk' in T. 16 S., R. 16 E."

McClure (1939, p. 65 - 66) wrote,

> "The Hondo River in its course crosses a prominent displacement known as the Border Ridge Fault, the strike of which is approximately North 35° East. The Border Ridge Fault is the most conspicuous structural feature in the region for it persists for many miles as a prominent narrow anticlinal fold and a fault of moderate displacement. The beds on the west side are down-thrown relative to those on the east side. These structural relations are well shown at the Border Ranch where the Rio Hondo has cut through the ridge."

Mourant (1963, p. 32) believes it to be "a very narrow fold combined with a thrust fault."

Kelley (1971, p. 46) wrote

"The Border buckle has an exposed length of about 60 miles and extends from a splayed termination at the northern end of the Dunken uplift into the eastward turned Five Mile Draw buckle in T. 7 S., R. 23 E. It is a stronger zone of buckling than any of the other similar features. The buckle is prominently expressed by a long series of ridges known as the Border Hills. The hills rise in places 200 to 300 feet about the adjacent plains or mesas. The strike of the buckle is slightly more irregular than those of the Six Mile and Y-O, and ranges from N. 34 to 53 E. around an over-all principal trend of N. 40 E. The width of the steep part of the buckle is generally 1, 200 to 1, 600 feet in the middle part of its exposed length through T. 10 to 12 S., but in T. 13 S. it narrows to 500 feet or less. The over-all width including all flaring away from the regional dip reaches nearly one mile in places. The southeast limb overrides along the entire length south of U. S. Highway 70, but in a 7-mile stretch from the highway north the overriding side changes four times.

"The finest exposure of any of the buckles is in the north wall where the Border buckle crosses Hondo Canyon. Here the east side, which is down regional dip, overrides the western side although there is practically no upthrow or downthrow of the beds outside the buckled-up area. which here is about three-quarters of a mile wide. The canyon depth on either side of the ridge is about 300 feet. Glorieta and Yeso beds are present on the east side, but neither is in view above the valley bottom on the west side. An auxiliary fault adds to the complication

Kelley (1971, p. 46) continued

"on the west side, where it separates a steep wedge in the core area from gently inclined beds. Three miles to the north the highway cut reveals considerable complication involving breccia, some fragments of which are about 10 feet in diameter. The surface expression, the turning up of the limbs, and the Glorieta exposure on the east side are similar to the Hondo section. However, the 'chaos' in the core area is quite different, and it is difficult to locate the fault precisely in the cut section. It should be at the breccia and the steep beds in the center of the section."

The following table summarizes the views of the several authors:

(Border Hill Structural Zone)

Author	Description	Downthrown side	Displacement
Merritt (1920)	Anticline	-----	-----
Nye (1927, 1928)	Narrow anticlinal fold and fault	West	Moderate
Nye (1933)	Narrow anticlinal fold and thrust fault	West and east	Moderate
McClure (1939)	Narrow anticlinal fold and fault	West	Moderate
Bean (1949)	Narrow faulted anticline nearly vertical fault plane	West and east	Less than 300
Stipp (1956)	Anticline and faulted anticline	-----	Moderate
Mourant (1963)	Very narrow fold combined with thrust fault	-----	50 - 300
Havenor (1968)	Essentially normal fault	East	Less than 200*
Maddox (1968)	-----	East	-----
Kinney et al (1968)	Fault	East	250*
Borton (1969)	Fault	East	150*
Kelley (1971)	Buckle	----	-----

* Estimated from maps.

Sixmile Hill structural zone

Nye (1933, p. 79) wrote,

"The Sixmile Hill fault is also a combination of an anticlinal fold and a fault of slight displacement, but it is shorter and very much less prominent than either the Y-O or the Border Hills fault. The fault is exposed at several places west and northwest of Roswell. The beds on the west side of the fault appear to be upthrown relative to those on the east side. The fracturing and brecciation of the Picaho limestone caused by the fault are most clearly seen where Berrendo Creek crosses it 4 or 5 miles northwest of Roswell. The fault dies out southwestward in Sixmile Hill, 5 or 6 miles due west of Roswell, from which it takes its name. The anticlinal structure of Sixmile Hill is clearly revealed along the road cuts of the main highway due west of Roswell, but the faulting is not. According to information obtained regarding the two Gibson wells drilled for oil on Sixmile Hill in sec. 8, T. 11 S., R. 23, E., the fault probably extends at least that far to the southwest. The first hole drilled was abandoned at a depth of about 600 feet, as it was too crooked, presumably because the drill was deflected along a fault surface. The second hole was drilled a few feet from the first and encountered the same difficulties. Moreover, the depth at which the sandstone near the base of the Picaho was reached in the second hole was notably at variance with the depth at which it was reached in the first. It was also reported that the pyrite crystals were found in the drill cuttings. The displacement along the fault is probably less than 50 feet, although definite data as to the

Nye (1933, p. 79) continued

"amount of displacement were not obtained. The fault appears to die out northeastward in the southwestern part of T. 9 S., R. 24 E., but there is some fragmentary evidence of its continuing still farther to the northeast as a gentle anticline and possibly as a fracture or slight fault. According to Merritt the Sixmile Hill anticline extends southwestward as far as T. 15 S., R. 19 E. The writer found little evidence of anticlinal structure in the canyon of the Rio Hondo in the vicinity of the Hondo reservoir site, nor in the canyon of Rocky Arroyo in the central part of T. 12 S., R. 22 E. It is possible that the anticline trending northeastward from T. 15 S., R. 19 E., may not be continuous with the Sixmile Hill anticline but may be roughly in line with it."

Bean (1949, p. 16 - 17) wrote,

"The Sixmile Hill structure is best known west of Roswell, where it is expressed as a hill whose crest is between 5 and 6 miles from the center of the town. Here the structure is a broad anticline broken by a fault a short distance east of the crest. The structure is at least 60 miles long, and it can be followed southwest from the point where it crosses Highway 285 about 10 miles north of Roswell until it intersects the syncline just east of the Bluewater anticline about 2 miles north of Dunken. It strike along most of its extent is about N. 40° E., but the trend changes in several places north of the Hondo Reservoir so that it averages about N. 31° E. northwest of Roswell. Two faults having a more easterly trend branch off the main structure between Rocky Arroyo and the Rio Felix.

Bean (1949, p. 16 - 17) continued

"The characteristics of the main structure change in several places. Where it crosses South Berrendo Creek two narrow anticlines are exposed. A fault of very small displacement breaks the crest of one of these, but this may not be the major fault. About 2 miles farther south a scarp on the east side of Sixmile Hill evidently lies along the fault, and from just north of Highway 70 nearly to the Hondo Reservoir the fault lies along a nearly straight valley broken in places by low saddles. Good direct evidence for the existence of the fault was found in drilling a well for oil in the bottom of this valley, a mile and a quarter south of the highway. Nye (Fiedler and Nye, 1933, p. 79) reports that two holes were drilled a few feet apart, the second being drilled because the bit was deflected, probably along a fault plane, in the first. The same thing happened in the second hole. The Glorieta (?) sandstone member of the San Andres formation was encountered at two different depths in the two holes, and on the basis of this and other information Nye states that the throw on the fault is 'probably less than 50 feet.' One of the holes is now a water well and was measured in connection with this study.

"The anticlinal nature of the Sixmile Hill structure in this vicinity can be determined by inspection of the cuts along Highway 70, but it is obscured by many variable dips. Some of these are due to collapse, but others are probably expressions of narrower folds on the main anticline. The principal fault does not show in the road cuts, but several smaller faults showing displacements up to 10 feet can be seen. Most of these are probably due to slumping or collapse rather than to the diastrophic forces that formed the main structure.

Bean (1949, p. 16-17) continued

"Two well-defined joint systems occur in the Sixmile Hill area and undoubtedly extend beneath the Hondo Reservoir. One of these parallels the structure and the other trends about N. 65° W., thus intersecting the first set at an angle of about 100 degrees.

"The intake capacity of the limestone of the San Andres in Sixmile Hill is very high because of the numerous sinkholes and the fractured, broken rock caused both by slumping and by deep-seated earth forces.

"The fault valley in Sixmile Hill bifurcates abruptly within a mile of the northeast edge of the Hondo Reservoir, and this probably indicates a bifurcation of the fault. Southwest of the reservoir the river valley lies along the structure for 3 miles, and a short distance to the east shallow valleys and low saddles mark another parallel structural line. The latter almost certainly lies along a fault, and it may be that a parallel fault underlies the river, the two being continuous with the two branches of the fault just north of the reservoir. The structure immediately south of the reservoir shows the same complexities it does to the north -- secondary folds, evidences of collapse, sinkholes (though not as many), and well-developed joints.

"The condition underlying the Hondo Reservoir can be inferred from the condition of the Sixmile Hill structure just north and south of it, remembering that the structure passes directly through the central part of the reservoir. The Sixmile Hill fault underneath the reservoir probably is composed of two subparallel strands less than a mile apart. The strata around and between the strands have been folded and fractured further during formation of the Sixmile Hill structure, and two sets of joints have been developed. Small sinkholes, which are most numerous in the northeastern part of the reservoir, show that solution has been active at the surface, and solution at greater

Bean (1949, p. 16-17) continued

"depths has resulted in much irregular slumping and collapse of the strata. It was in this fractured and broken rock that the reservoir sink was formed under natural conditions by flood waters of the Rio Hondo before the coming of man, and in this silt-covered sink the Hondo Reservoir was built.

"Five miles southwest of the reservoir along the trend of the Sixmile Hill structure, several narrow flexures and minor fractures in a zone 250 yards wide appear along the banks of Rocky Arroyo. No clear indication of a major fault is shown. Continuing southwest, the structure decreases in intensity, but it can be followed easily on aerial photographs, as valleys have developed along the fault almost continuously, low saddles separating the valley heads.

"Faults branch off the main structure in sec. 1, T. 13 S., R. 21 E., and approximately on the line between secs. 7 and 18, T. 15 S., R. 20 E. The branch faults have a more easterly strike than the main structure and can be followed southwestward by their physiographic expression to the eastern limb of the Bluewater anticline, beyond which they do not show clearly on aerial photographs. The more northerly fault apparently lies along the axis of an anticline in part of its extent. The magnitude of the disturbance is not great, however, and the throw at the fault probably nowhere exceeds 20 feet. The vertical throw on the more southerly fault is only 6 feet just south of the Rio Felix, the west side being upthrown, and no anticlinal structure is present.

Bean (1949, p. 16-17) continued

"The anticlinal nature of the main Sixmile Hill structure disappears entirely before it reaches the Rio Felix, and the throw of the fault at the Felix is only 4-1/2 feet, the east side being upthrown. Between the Felix and the Rio Penasco the structure increases in intensity again, and 1 mile north of Highway 83 the width of the disturbance is about 250 yards. The structure here is a complex anticline, and beds can be found dipping at a great many angles, some nearly vertical, on the limbs of several sharp flexures across the structure. A few faults of low displacement are probably present also. The structure is of the same nature here as it is in the vicinity of the Hondo Reservoir, except that sinkholes and collapsed areas are missing. The structure is known to continue to the southwest until it intersects the syncline east of the Bluewater anticline 2 miles north of Dunken and a short distance west of Highway 24.

"The Sixmile Hill structure is thus in most places a broad anticline containing secondary folds and broken by one or more faults of relatively low displacement near the crest. In Sixmile Hill the west limb of the fault is upthrown, but at the Rio Felix the east side is upthrown and it is entirely possible that there are other reversals along its extent. No folding is present at the Felix. In many places the existence of a fault cannot be proven, but the physiographic evidence indicates that it is probably continuously present or nearly so, except north of South Berrendo Creek, where evidence of a fault is lacking and the structure may be simply an anticline."

Mourant (1963, p. 31) describes the Sixmile Hill structural zone as "anticlinal with many minor folds . . ." He says,

> "The structural relief caused by folding is about 300 feet. Escarpments of westward dipping strata on the east side of the structural zone in T. 10 S. mark a fault with the downthrown side on the east. The magnitude of displacement probably was a little less than 100 feet."

Kelley (1971, p. 45-46) wrote,

> "The Six Mile buckle has an exposed or traceable length of about 80 miles from exposures near the Pecos River, about 25 miles northeast of Roswell to a junction with the Dunken syncline in T. 17 S., R. 17 E. The trend is slightly undulated along its over-all strike of N. 41 E. Buckling along the fault is not as evident nor as wide as along the Border and Y-O. In a stretch of more than 20 miles between Monument and Butte Creeks there is essentially no buckling and very little drag, except for a stretch of 3 or 4 miles in T. 15 S., R. 20 E., where thin weak beds high in the Bonney Canyon Member abut the fault. To the north of Butte Canyon, and on through the Fourmile Draw outcrops, buckling is again evident. Buckling along the fault is also common through Ts. 16, 17 S. In the north wall of the Rio Felix there is buckling in the high beds, but not in those in the lower part of the canyon wall. A similar situation is evident in the north side of the Rio Penasco canyon. The upper beds are strongly buckled and the lower ones have no buckling and little or no throw. Strike slip may produce this effect where contrasts of strength exist in successions of beds."

The following table summarizes the views of the various writers:

(Sixmile Hill Structural Zone)

Author	Description	Downthrown side	Displacement (ft)
Merritt (1920)	Anticline	-----	-----
Nye (1927, 1928)	Anticlinal fold and fault	East	Slight
Nye (1933)	Anticlinal fold and fault	East	Less than 50
Bean (1949)	Broad anticline broken by a fault - a complex anticline	East and west	Less than 20
Stipp (1956)	Anticline and faulted anticline	-----	Moderate
Mourant (1963)	Anticlinal fold, faulted	East	100
Havenor (1968)	Essentially normal fault	West	350*
Maddox (1968)	-----	East	100*
Kinney et all (1968)	Fault	East	100*
Borton (1969)	Fault	West	150*
Kelley (1971)	Buckle	-----	-----

* Estimated from maps.

Y-O structural zone

Nye (1933, p. 80-81) wrote,

"A cross section of the Y-O fault is well exposed in the bluffs on the north side of the Rio Penasco at the Y-O crossing, in sec. 2, T. 17 S., R. 19 E. (See pl. 24, A.) At this place it is clearly seen that the beds on the west side have been folded in a narrow anticline, faulted, and thrust against those on the east side. The faulting is also revealed, although much less clearly than at the Y-O crossing, at several places along the Rio Felix, in the southeastern part of T. 15 S., R. 21 E., and in the northwestern part of T. 15 S., R. 22 E. The Rio Felix has closely followed the course of the fault for 5 or 6 miles, although it crosses the fault at many places. The Y-O fault is made prominent by a series of disconnected rounded hills and narrow ridges that stand above the surrounding hills. The fault can be traced northeastward as far as the NW. 1/4 sec. 8, T. 14 S., R. 23 E. Although there is no conclusive evidence of its continuation to the northeast beneath the alluvial deposits and into the Pecos formation east of the Pecos River, there are several lines of evidence indicating either that the Y-O fault extends at least as far as T. 10 S., R. 26 E., or that there are one or more faults of small displacement in line with the Y-O fault which extend to that point. Low hills in the northwestern part of T. 13 S., R. 24 E., appear to be elongated in a northeast-southwest direction, to rise above the Blackdom terrace, and to be in line with a continuation of the Y-O fault. The Shaffer well, drilled for oil in the

Nye (1933, p. 80-81) continued

"NE. 1/4 sec. 30, T. 10 S., R. 26 E., encountered considerable salt water in a sandstone near the base of the Picacho. The New State well, in the NW. 1/4 sec. 27 of the same township and only 2-1/2 miles east of the Shaffer well, was said not to have encountered any water at all in a sandstone that was the same at approximately the same stratigraphic horizon as the one encountered by the Shaffer well. Presumably, therefore, there is a fault between the wells which effectively seals off the salt water in the sandstone encountered by the Shaffer well, for even if the sandstone encountered in the New State well were not precisely the same stratum as the one encountered in the Shaffer well, it does not appear at all probable that the former would be dry if there were no fault between the wells. Furthermore, the peculiar hydrologic conditions existing in the northern part of T. 12 S., R. 25 E., and the southern part of T. 11 S., R. 25 E., suggest a fault or other structural feature roughly in line with the Y-O fault.

"It is not improbable that the Y-O fault, like the Border Hills fault, may reverse itself along a series of fractures closely in line. Some evidence of this was seen in the field, but it was not conclusive. It is equally possible that there may be several lines of faulting extending northeastward, which are roughly in line with one another and with the Y-O fault. The Y-O fault, according to Renick, extends southwestward as far as section 31, T. 18 S., R. 18 E."

In 1927 Nye (p. 184), writing about the geology of the Cactus Flat Reservoir site in T. 17 S., R. 19 E., said,

"The regional eastward dip of the San Andres limestone is interrupted on the south ridge of the reservoir site by a synclinal fold which at first bluffs on the south side of the Rio Penasco, however, show no trace of this syncline. Although the beds on the north side of the reservoir are largely concealed, there is no evidence of the continuation of the pronounced synclinal folding found on the south side. There may be, however, a slight downwarping of the beds in line with the axis of this syncline.

"In the saddle nearest the dam site on the south ridge there is a small irregular fault having a displacement of 2 or 3 feet. It begins at the south edge of the saddle and extends northward for a short distance. As a result of this faulting the beds are sharply buckled and form a conspicuous topographic feature. On the north side of the reservoir there is a wide zone of deformation roughly in line with the fault on the south side.

"There is one prominent irregular ridge caused by a sharp upward buckling of the limestone, that extends down the slope of the hill and seems to be a continuation of the buckling on the opposite slope, although on this side there is no appreciable displacement of the beds. About a hundred feet east of this small ridge, near the top of the hill, there is another irregular line or narrow zone of fracturing and deformation which is roughly parallel to the first. The beds on the west side have slumped down, and close to the fracture, the rocks are tilted upward at a high angle. At the top of the hill there

Nye (1927, p. 184) continued

"are several large open irregular crevices partly filled with large blocks of limestone. The crevices have the same general trend as the faulting and buckling on the south and north slopes. They vary in width up to several feet at the surface and one of the crevices is over 100 feet in length. The largest crevice is open to a depth of at least 8 feet in one place.

"There is evidence of a slight amount of slumping in the second saddle west of the dam site on the south side of the proposed reservoir. Here, however, the beds on the west side of the fractures have dropped only about a foot. The geologic map and sections (Plate 1) accompanying this report, show the structural features described above.

"In view of the localized character and irregularity of all these structural features, the writer believes they are the result not of deep seated earth movements but of the caving in of the roof of a large underground cavern formed by the solution and removal of relatively soluble limestone (or other soluble rocks) by ground water."

Bean (1949, p. 18-19) wrote,

"The Y-O structure is a northeast-trending narrow anticline faulted along the axis. It crosses the Rio Penasco in three places within 2 miles west of the Y-O Crossing, from which it takes its name. Its direction varies only a few degrees from an average of N. 41° E. in the area mapped, and it extends at least from T. 18 S., R. 18 E., to the terrace deposits in T. 14 S., R. 23 E. The structure is marked topographically by a discontinuous line of hills

Bean (1949, p. 18- 19) continued

"along much of its extent, but the Rio Felix also follows it for about 5 miles, swinging back and forth across it.

"The Y-O structure is well exposed in the north wall of the canyon of the Rio Penasco about 0.6 mile west of the Y-O Crossing. The anticlinal structure is well developed here, and the crushed and brecciated fault zone can be seen near the river. The writer was unable to determine the amount and direction of throw at this point, but 0.7 mile southwest, where the structure again crosses the Penasco, the vertical displacement is only 10 feet, the east side being upthrown. The throw is probably greater at the exposure to the northeast. Dips on the flanks of the anticline along the Penasco are generally less than 10°. The structure decreases in intensity south of the southern boundary of T. 17 S., but it continues, according to Renick (1926, pl. 1), to sec. 31, T. 18 S., R. 18 E. To the north it is well exposed along the Rio Felix in several places. In the eastern part of T. 15 S., R. 22 E., the eastern limb of the anticline is well developed, but dips on the western limb are very low. The Y-O structure cannot be followed northeastward across the terraces west of the Pecos River, but Nye (Fiedler and Nye, 1933, p. 80-81) presents evidence from wells that it may extend as far north as T. 10 S., R. 26 E., in the latitude of Roswell."

Renick (1926, p. 123-124) wrote,

"One of the most conspicuous folds in this area is an overthrust that extends in a general northeast-southwest direction and is well exposed in the bluffs of the Penasco

Renick (1926, p. 123-124) continued

> "near the Y-O Crossing. The beds on the west side have been thrust over those on the east side, and in places they have been broken, giving rise to an overthrust fault of slight displacement. Although it is a mere buckle in the rocks it persists for many miles as a conspicuous topographic ridge that is easily recognized either on the ground or from the air."

Havenor (1968, p. 7), discussing the northern Roswell Artesian Basin, wrote,

> "Considerably north of the subject area, geophysical data suggest that a continuation of the Y-O structural zone swings sharply to the east and strata toward the fault zone that forms the southern boundary of the Milnesand Dome of southeast Roosevelt County. In that area it appears, as in this local area also, that the faulting aids, or at least seriously deforms, the Guadalupin rocks."

He also says,

> "The fault displacements appear essentially normal with apparent offsets of from 80 to 650 feet, as mapped on top of the eroded San Andres Limestone. Subsurface data suggest that as much as 1000 feet of stratigraphic throw may have occurred in the Y-O structural zone in the area south of Roswell, although structural contouring on the top of the Glorieta Sandstone does indicate that much displacement. Some minor strata-slip movement is possible along the Y-O zone."

Figure 14 shows Havenor's (1969, p. 17) concept of the Y-O structural zone.

Figure 14 -- Cross section of the Y-O structural zone (after Havenor, 1968)

Kelley (1971, p. 45) wrote,

"The known length of the Y-O buckle is about 72 miles, although through about one half its length it is beneath Pecos Valley fill. It is slightly curved, striking N. 40 to 43 E. Its northernmost exposure is in poorly exposed folds about 18 miles west of Hagerman. As projected northeastward beneath the Pecos Valley, it crosses U. S. Highway 285 about six miles southeast of Roswell, and the Pecos River and U. S. Highway 380 six miles east of Roswell. North of U. S. Highway 380 the buckle is followed by the Pecos River until it ascends the bluffs along a canyon in the northeast corner of T. 10 S., R. 25 E. Northeastward, it is lost on the covered surface. Southwestward, it extends in T. 18 S., R. 18 E., where it dies out in two splay faults about 2 miles north of the northern end of the synclinal bend of the Huapache monocline. The severely compressed part of the buckle is typically only about 500 to 800 feet wide. It is quite disharmonic as a fold and this is well shown in the north bank of the Rio Penasco where at creek level the core is severely compressed compared to beds above. Along the southwestern part, the southeastern block appears lowered in places to as much as 100 feet with respect to the northwest. To the northeast, especially in T. 16, S., R. 20 E., the northwestern side is down on the order of 50 feet locally. However, the buckle follows an older line of deformation, and in Paleozoic time the southeast side appears to have subsided generally. Furthermore, there is subsurface evidence that in the northern part of the fault the southeastern side may have subsided as much as several hundred feet at the end of Permian time.

Kelley (1971, p. 45) continued

"Small drag folds occur in several places on either limb of the buckle. Their axes strike typically N. 15 to 25 E. They are acutely left-branching and indicate right shift along the buckle, i. e. the northwest side moved northeast. If the shift were left, the strike of drag folds would be N. 65 to 75 E., and would be right-branching. Plunges are typically away from the buckle, but occasionally they plunge toward it. Drag folds of this nature occur in secs. 2 and 31, T. 17 S., R, 19 E. In T. 18 S., R. 18 E., just south of the Y-O terminations, there is a fault which is subparallel, but not connected, to the Y-O buckle. It has similar small drag folds on its north side indicating right movement. This fault essentially merges with the north end of the Lewis buckle, which to the south dies out on the western escarpment of the Guadalupe uplift. However, the Y-O buckle does not connect in the outcrop to the Lewis buckle or the northern end of the Guadalupe fault. In this part of the map it may be seen that the Huapache synclinal bend axis is terminated against the Lewis buckle fault. To the north of the buckle, however, there is another synclinal bend associated with a short, closely folded and faulted belt. The geometric relationships at this intersection suggest that the Lewis faulted buckle offsets and is younger than the Huapache monocline. On the other hand, a right offset of the synclinal bend axis by the splay of the Y-O buckle is about 1,800 feet, and this furnishes some evidence of the possible magnitude of strike-slip movement along the Y-O buckle."

The following table summarizes the views of the various authors:

(Y-O Structural Zone)

Author	Description	Downthrown side	Maximum Displacement
Merritt (1920)	Anticline	-----	-----
Renick (1926)	Overthrust	East	Slight
Nye (1927, 1928)	Overthrust	East	-----
Nye (1933)	Anticline faulted (thrust)	East (and west?)	Small
Bean (1949)	Narrow anticline, faulted	West	10
Stipp (1956)	Anticline and faulted anticline	-----	Moderate
Havenor (1968)	Essentially normal fault	West	900*
Maddox (1968)	-----	East	100*
Kinney et all (1968)	Fault	East	200*
Kelley (1971)	Buckle	East	100

* Estimated from maps.

KM structural zone

The KM structural zone is inferred from subsurface data (Maddox, 1968; Havenor, 1968; Kinney et al., 1968), and high altitude aerial photography. The downthrown beds are on the southeast side. The displacement may be as much as 150 feet. Kinney et al. (1968) show no displacement on their structure contour maps.

Kelley (1971, p. 48) wrote,

> ". . . it is about 30 miles long and appears to drop the southeast side as much as 200 feet. Surface support for the existance of this break in the bedrock beneath the Pecos Valley fill lies mostly with a pronounced southwest swing of the Pecos River for about 6 miles east of Lake Arthur. However, just northwest of the river east of Lake Arthur a low inlier escarpment of Queen rocks in valley fill parallels the trace of the fault as projected ..."

Other structural features

High altitude aerial photography, subsurface data, and the known geologic structure in Quay County suggest a structural zone that extends from near Hondo in Lincoln County into central Quay County. This zone roughly parallels the Border Hill structural zone and is 12 to 18 miles northwest of it.

Kelley (1971, p. 48) called this the Serrano buckle and described it as follows:

> "The Serrano buckle is about 26 miles in length and strikes N. 37 E. overall. It extends out of the northern end of the Tinnie anticline and here for several miles beds are buckled and turned from their northerly strikes

Kelley (1971, p. 48) continued

> "to the northeasterly strike of the Serrano buckle. Except for the first five miles of the southern end, where it is obliquely transverse to several fold axes, the surface expression of the buckle through the rest of its course is weak. It exhibits anticlinal buckling in a narrow zone of generally less than 300 feet and the buckling up is alternately greater from side to side. Short left-branching spur folds and short shears together with offsetting and terminating folds and faults around the head of Blackwater Canyon all attest to right movement along the Serrano buckle. Study of some of the offsets lead to an estimate of about 500 feet of horizontal shift along the southern five miles or so. To the northeast this may diminish considerably."

Two other zones have been reported by Kinney et al. (1968). One is between the Y-O and KM structural zones. They call it the S-W fault. Sherman Galloway (personal communication) reports that the zone is exposed in the bed of Cottonwood Creek in the vicinity of the SW1/4 of Sec. 5, T. 16 S., R. 25 E., and that it controls the occurrence of springs there and accounts for the localized abnormally high head on the artesian aquifer there. Kinney et al. show no displacement on their structural contour maps.

Kinney et al. (1968) call the other zone the Major Johnson Fault. It lies about 18 miles southeast of the KM and is parallel to it. Thin structure maps show no displacement comment on structural zones. Several structural zones exist. The exact number is uncertain. They trend about N. 45° E. They have modest displacement and may be the product more of lateral than of vertical movement.

Kelley (1971, p. 47-51) recognizes four faults.

(1) The Bonito fault follows Bonito Creek and extends from the Sierra Blanca to the Capitan Mountains.

(2) The Barrera Fault lies along the base of the Capitan reef escarpment and can be traced for at least 18 miles.

(3) The White Tail Fault extends for 21 miles from the southwest corner of T. 10 S., R. 17 E., southwestward to a termination near the Indian village of White Tail. It is downthrown to the east and has a stratigraphic displacement of 200 - 400 feet.

(4) The Carlsbad Fault is expressed in an outcrop from about 2 miles north of the entrance to Dark Canyon for 5 miles northeasterly toward Carlsbad. It has a stratigraphic displacement of several hundred feet.

Minor structural features

In addition to the features mentioned above, Bean (1949, p. 19-20) mentions a series of minor faults between Arroyo Felix and the Rio Penasco (sec. 36, T. 15 S., R. 18 E.). Mourant (1963, p. 31) mentions an anticlinal area from Salazar Canyon through Ruidoso. Kelley (1971, p. 51-58) discusses in detail a number of other structural features in the southern half of the basin.

Pecos River fault zone

Kinney et al. (1968, p. 13-14) and Maddox (1969) postulated, on the basis of subsurface data, a fault zone that roughly parallels the Pecos River from T. 16 S., almost to T. 8 S. (roughly N. 15° W). They call this the Pecos River Fault zone.

Neither Borton (1969) nor Kelley (1971) mapped it.

The following comments seem justified:

1. In T. 18 S. where abundant data are available from oil wells, they drew no fault. The fault is only postulated in areas where data are comparatively sparse.
2. In T. 12 S., R. 13 S., and in T. 10 S., R. 25 E., the data as given by Maddox are as easily mapped as a syncline as a fault.
3. The structure maps are based primarily upon "electric logs" using such criteria as " * * * a Gamma-ray log feature below the lower most San Andres carbonate * * * " (Kinney et al., p. 10). No attempt was made to relate the "features" observed on the electric logs to the rocks in the outcrops.

In view of these considerations, I feel no compulsion to accept the Pecos River fault zone as an established structural feature of the Pecos River basin.

S T R A T I G R A P H Y

PRECAMBRIAN SYSTEM

The rocks of Precambrian age in the Pecos River basin have been studied by Foster and Stipp (1961), Foster (1959), Fallis (1958), Smith (1957), Flawn (1956), Griggs and Hendrickson (1951), Allison (1950), and several others.

These rocks are the only source of ground water in the small part of the basin in the Pedernal Hills. Elsewhere in the basin they form the basement platform upon which younger, more productive water-bearing rocks rest.

Precambrian rocks crop out in the north and west part of the basin at altitudes higher than 4000 feet and generally higher than 6000 feet. In the southwest part of the basin they are more than 15, 000 feet below sea level.

Figure 15 is a map of the buried surface of the rocks of

Figure 15 -- Map of the buried surface of the rocks of Precambrian age

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Precambrian age, which also shows the areas of outcrop. The total relief on this surface is more than 25, 000 feet.

In the subsurface, granite underlies large areas of Lea and Eddy Counties; rhyolites underlie northern DeBaca and northern Chaves Counties; metamorphic rocks underlie large areas of western San Miguel and eastern Torrance Counties; and sedimentary rocks of Precambrian age underlie parts of Lincoln, Otero, Chaves, and Eddy Counties.

In outcrop the rocks are:

Area	Rock types
Southern Sangre de Cristo Mountains, San Miguel County	granite, schist, quartizite, pegmatite
Pedernal Hills, Torrance County	quartizite, phyllite, schist, greenstone, granite
Chameleon Hills, Torrance County	granite, gneissic granite, schist
Gallinas Mountains, Lincoln and Torrance counties	granite, gneiss
Pajarito Mountain, Otero County	syenite
Sacramento Mountains, Otero County	granodiorite, quartz diorite (?), diorite

S t r a t i g r a p h y

INTRODUCTION

To illustrate stratigraphic relations simple figures are used to show the locations of the formations and their gross lithologic characteristics. Plate 1 is a geologic map that shows the locations of cross sections AA' through HH'. Plates 2 - 9 are straight forward stratigraphic cross sections derived from large scale structure maps. Plates 10 - 14 show the details of lithology as deduced from geological logs of cuttings and drillers' logs. Cross sections BB', GG', and HH' are not included becuase data were insufficient.

PALEOZOIC SYSTEMS

Introduction

Rocks ranging in age from Cambrian to Permian rest directly upon the Precambrian rocks. The rocks of Permian age occur over more than 90 percent of the basin and outcrops of rocks of Permian age occur over about 50 percent of the area.

Rocks older than Permian occur in three areas separated by the Pedernal Uplift.

These areas are (1) the southern Sangre de Cristo Mountains in the northern extremity of the basin, (2) the Sacramento Mountains along the south-central part of the western drainage divide, and (3) the subsurface of the southeastern part of the basin.

The discussion of the rocks of the Sangre de Cristo Mountains is based on the work of Miller, Montgomery, and Southerland (1963), Armstrong and Holcomb (1967), and Griggs and Hendrickson (1951).

The discussion of the rocks of the Sacramento Mountains is based on the work of several authors, principally: Pray (1961), Otte (1959), Lloyd (1949), the Permian Basin Section, Society of Economic Paleontologists and Mineralogists and The Roswell Geological Society (1959), and the Roswell Geological Society (1953, 1956a, and 1958).

The discussion of the pre-Pennsylvanian rocks of the subsurface of the southeastern part of the Pecos River basin is also based on the work of several authors, principally: Lloyd (1949), Meyer (1966), The Roswell Geological Society (1953, 1956a, and 1958), and Haigler (1962).

Pre-Pennsylvanian Systems

Southern Sangre de Cristo Mountains

The rocks of the Arroyo Penasco Formation of Mississippian age that crop out in the southern Sangre de Cristo Mountains are the oldest rocks of Paleozoic age cropping out in the Pecos River basin.

In the Pecos River canyon this formation is more than 100 feet thick. However, its thickness is highly irregular for two reasons: (1) it rests upon the irregular erosion surface of the Precambrian rocks, and (2) it was partially eroded before the overlying Pennsylvanian rocks were deposited upon it. In all probability it occurred over a large part of the Pecos River basin before this erosion began.

This formation consists of three units -- a basal siltstone and shale with thin beds of carbonate, a middle carbonate section, and an upper mixed clastic and carbonate section. Northrup et al. (1946) do not recognize these rocks in their work on San Miguel County.

This formation is not known to have been penetrated by wells. It apparently occurs over only a small part of the basin. Its distribution and thickness are not known.

Sacramento Mountains

Rocks ranging in age from Cambrian to Mississippian crop out on the west side of the Sacramento Mountains, a few miles west of the Pecos River basin divide. At least one well, the Southern Production Company No. 1 Cloudcroft unit, which is in the Pecos River basin, penetrated the same sequence as was observed in the outcrop.

These are the rocks:

	Thickness	
Cambrian (?) System		
Bliss Sandstone	110	Quartz sandstone
Ordovician System		
El Paso Formation	430	minor-- sandy dolomite sandy dolomite; quartz SS
Montoya Formation	190-225	Dolomite & Chty
Valmont Dolomite	179	Dol
Silurian System		
Fusselman Formation	20-100	Chty Dol
Devonian System		
Onate Formation	<60-100	Dol, St St, SS
Sly Gap Formation	0-40	Sh & ls
Percha Shale	20-40	Black Sh
Mississippian System		
Caballero Formation	15-60	ls & sh.
Lake Valley Formation	400	ls & bioherm
Las Cruces Formation (?)		
Rancheria Formation	-300	ls & St St
Helms Formation	60	ls & sh

Subsurface of Southeastern New Mexico

In the subsurface of the southeastern part of the basin, rocks varing in range from Ordovician to Pennsylvanian rest directly upon those of Precambrian age. The pre-Pennsylvanian section includes:

Ordovician System
- Simpson group equivalent
- Montoya Dolomite

Silurian (?) and Devonian System
Devonian and Mississippian System
- Woodford shale equivalent

Mississippian System

The Silurian (?) and Devonian System and the Mississippian System are generally not subdivided into formations or other units except upper and lower Mississippian. In general, these rocks correlate with those observed in outcrop in the Sacramento Mountains.

Figures 16 to 18 show the distribution of these rocks.

Figure 16 -- Ordovician System in southeastern New Mexico

Figure 17 -- Devonian and Silurian Systems in southeastern New Mexico

Figure 18 -- Mississippian System in southeastern New Mexico

Pennsylvanian System

In New Mexico the Pennsylvanian System has been studied extensively. For this report the following sources were consulted:

Kottlowski (1968)

Lloyd (1949)

Smith (1957)

Griggs & Hendrickson (1951)

Pray (1961)

Haigler (1962)

Meyer (1966)

Otte (1959)

Miller, Montgomety and Southerland (1963)

Northrup et al. (1946)

Thompson (1942)

The rocks of the Pennsylvanian system were sediments deposited in a tidal flat-shallow marine sea environment. Clastics interfinger with carbonates. In the deeper basins, like the Delaware, the rocks are relatively thin sequences of black or gray shales. Where there were shallow marine shelves, the rocks are a relatively thick sequence of limestone. Where deltas formed, the rocks include thick clastic sections.

Locally, formation names have been assigned and maps prepared, showing the distribution of these formations. These formations are based on lithology. They do <u>not</u> generally have a geologic time significance.

In general, the rocks of Pennsylvanian age consist of a lower clastic unit, a middle carbonate unit, and an upper carbonate-clastic unit. However, the lower clastic unit of one area may be the time equivalent of the middle carbonate unit of another area.

Using fossils, the rocks of Pennsylvanian age have been divided into five series in New Mexico:

		(Texas equivalent)
Upper Pennsylvanian	Virgil	Cisco
	Missouri	Canyon
Middle	Des Moines	Strahn
	Derry	Bend
Lower	Morrow	Springer

These rocks rest unconformably upon older rocks ranging in age from Precambrian to Mississippian.

In the northern part of the Pecos River basin, the Pennsylvanian rocks are more than 2000 feet thick. They are divided into a lower clastic unit, called the Sandia Formation, and an upper limestone unit called the Madera Formation. The Madera is divided into upper and lower members, with the lower member being dominantly limestone and the upper member the limestone-clastic unit.

In the Sacramento Mountains the Pennsylvanian rocks range from almost 3000 to about 2000 feet in thickness. There the formations are called the Gobbler (which includes the lower clastic and middle carbonate units), the Beeman (an argillaceous limestone and calceous shale), and the Holder.

In the subsurface of southeastern New Mexico, no formation names are recognized and the strata are simply referred to as "Morrowian", "Derryian," etc.

Permian System

Several interrelated problems limit our understanding of the stratigraphy of rocks of Permian age in the Pecos River basin; these include:

1. the Pennsylvanian-Permian transition,
2. lateral differences in the environment of deposition,
3. the relation of reef or lime bank deposits to adjacent deposits,
4. criteria for distinguishing stratigraphic units are not the same throughout the basin (in some cases the difference between surface and subsurface usage is substantial), and
5. the Permian-Triassic transition.

Wolfcampian series

Formations of Wolfcampian age in the Pecos River basin include: (1) the Sangre de Cristo Formation, (2) the Bursum (Laborcita) Formation, (3) the Abo Formation, and (4) the Hueco Limestone.

The relationship between these formations and the underlying older rocks is difficult to assess in some places. Sedimentation was apparently continuous over much of the region between the periods. To complicate interpretation, crustal adjustments that began during Pennsylvanian time came to a conclusion during Wolfcampian time.

Rocks of Wolfcampian age rest upon rocks ranging in age from Precambrian to late Virgilian. Indeed, the lower part of the Sangre de Cristo Formation and possibly the basal Bursum beds are actually Virgilian in age.

The Sangre de Cristo, Bursum, and Abo Formations are continental deposits. The Hueco Limestone was deposited in the marine sea of the Delaware basin. The Hueco Limestone interfingers with the Abo Formation. Figure 19 shows in plan view the relation of the four formations. Figure 20

Figure 19 -- Relationships between the Sangre de Cristo, Bursum, Abo, and Hueco Limestone Formations, Pecos River basin, New Mexico

Figure 20 -- West to east diagrammatic section of Permian units across the Pedernal landmass

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shows their relationship in cross section.

The Sangre de Cristo Formation is composed of thick beds of coarse-grained, conglomeratic, arkosic sandstone; red, green, and gray shales and siltstone; and a few beds of gray or pink, earthy limestone (Baltz and Bachman, 1956, p. 100). In the Pecos River basin the thickness of the Sangre de Cristo Formation ranges from less than 500 feet to about 1000 feet.

During the early stages of Sangre de Cristo deposition the Pedernal Uplift locally supplied a considerable amount of sediments but in later phases the Pedernal Uplift apparently was completely buried by the Sangre de Cristo Formation and most of these sediments are believed to have been derived from highlands to the east, north, and west of the mountains.

The Bursum Formation, of probable Wolfcampian age, unconformably overlies the Pennsylvanian and unconformably underlies the Abo Formations. It outcrops in central New Mexico west of the Pecos River basin. In outcrop, its thickness ranges from 28-234 feet. It consists of dark purplish-red and green shale separated by thinner beds of arkose, arkosic conglomerate, and gray limestone.

The lithology of the Bursum Formation changes abruptly in short distances. Pray (1961, p. 91. 93-95) described a section that changes within a distance of 2 miles from limestone, conglomerate, and olive-gray shale to more than half red beds and in a distance of 3 miles to a section that consists almost exculsively of red mudstone with limestone-pebble and limestone-cobble conglomerate.

In the northernmost Sacramentos, Otte defined the Laborcita Formation as the interval between the Pennsylvanian and Abo Formations, using a quartizite-cobble conglomerate about 200 feet higher than Pray's Bursum-Abo contact for his Laborcita-Abo contact (Pray, 1961, p. 91). The Laborcita varies in thickness and composition. The stated type locality contains 480 feet of gray and red mudstone, gray limestones, sandstones, and conglomerates (Otte, 1959, p. 26).

The Abo Formation rests unconformably on the Bursum and grades into the overlying Yeso. This 200 to 1400 foot unit of dark red-brown shale with local arkoses and conglomerates transgresses time from upper Wolfcamp to lower Leonard (Snyder, 1962, p. 25). Subsurface geologists call the Leonardian age, but Abo-like, rocks the Wichita Formation.

The Hueco Limestone underlies the great Permian reef of the Delaware basin, being the lowest 500 feet of Permian strata in the Sierra Diablo, where it has a basal clastic unit grading upward into limestone (King, 1942, p. 561).

In the Permian basin, Hayes (1964, p. 10) indicated that the Hueco Limestone ranges through 1750 feet of gray to black or brown shale and brown limestone, with some gray sandstone.

The Reef Complex

During Leonardian and Guadalupian time a reef or limebank developed around the margin of the Delaware. As a consequence, many geologists discuss the stratigraphy of the Leonardian and Guadalupian series in terms of Backreef or Northwestern Shelf Facies, Reef or Basin Margin Facies, and Fore Reef or Delaware Basin Facies. For this report we shall not delve into the question of whether the basin margin rocks were produced by a true barrier reef or are merely a lime bank; we shall instead recognize that between the deposits of the basin and those of the shelf there exists a complex transition zone which contains in place rocks that may be referred to conveniently as "reef", and also contains rocks that may be characteristic of either shelf or basin facies.

For the purpose of this report, we shall refer to these rocks as the reef-lime bank complex.

Leonardian Series

Leonardian-age rocks in the Pecos River basin include those of the Wichita, Bone Springs, and Yeso Formations and the "Abo Reef." They also include part of the lower San Andres Limestone.

Overlying the Wolfcampian Abo Formation are red beds and beds of brown, fine-grained anhydritic dolomites. These beds, which look like and are sometimes called "Abo," constitute the Wichita Formation of the subsurface. Southward and eastward, these beds contain green shales and dolomite and then interfinger with a narrow zone of white, coarse-grained dolomite, which Lemay (1960, p. xvii-xxi) called the Abo Reef. In outcrop the Victorio Peak Limestone is stratigraphically equivalent to the Abo Reef. Lloyd (1949, p. 27) considers the overlying 500 to 1000 feet of bedded gray calcitic limestone to be a fossil barrier reef. This part of the formation has been named the Victorio Peak member. These rocks give way in turn to the black siltstones and black massive limestone of the lower Bone Springs Formation.

The Yeso Formation overlies the Wichita Formation. As Figure 21

Figure 21 -- Lithologies of the Yeso Formation

shows, the Yeso Formation includes a variety of rock types. In the northern part of the Pecos River basin it consists almost entirely of red siltstone and sandstone, and north of the basin it interfingers with the Sangre de Cristo Formation and loses its identity.

Through the central part of the Pecos River basin, the Yeso consists of beds: Red shales, siltstones, sandstones, limestone, dolomite and evaporite, including gypsum, anhydrite, and salt. In the western part of the Pecos River basin where the Yeso outcrops or is very near the surface, the salt and perhaps some of the gypsum have probably been removed by solution.

In the southern part of the basin the Yeso consists almost entirely of gypsum, anhydrite, and dolomite. The division between the Bone Springs Dolomite and the Yeso Formation is based on the presence of anhydrite. The Bone Springs contains no anhydrite.

The thickness of the Yeso Formation appears to range from about 1,200 to 1,800 feet in the Sacramento Mountains escarpment; locally, it may be thicker or thinner than this range of thickness. The southern surface section is 1,239 feet thick; the depth interval of the Yeso Formation in the Southern Production Co. test is from 2,180 feet, a thickness of 1,800 feet; and the northern surface section contains 1,200 feet of exposed Yeso Formation. At this latter section, neither the upper nor lower contacts are exposed. The estimated total thickness is 1,300 to 1,400 feet. These three sections afford the best evidence of the Yeso thickness in the area, but all are approximations. Halite is known in the subsurface, and its solution would cause surface sections to be thinned. The data from the subsurface test are too incomplete to ascertain within the Yeso the effect of inclined strata (though the total thicknesses of pre-Yeso units accord with those measured in adjacent surface sections) faulting, or thickening by intrusive rocks. One igneous mass, 20 to 30 feet thick, is known in the subsurface section.

Mapping of the upper and lower contacts of the Yeso Formation is unreliable in providing good estimates of the thickness of the Yeso in much of the Pecos River basin.

According to Hayes (1964, p. 12), the Bone Springs Formation is a limestone, but sample description on file with the New Mexico Bureau of Mines and Mineral Resources indicates that it is predominantly a dolomite.

According to Perhac (1970, p. 9-10), in the Gallinas Mountains the Yeso Formation (1) consists of about 1500 feet of feldspathic sandstones and siltstones of early Leonardian age, (2) conformably overlies the Abo Formation, and (3) has a gradational contact with the Abo Formation.

The Yeso Formation conformably overlies the Wichita, and Hayes (1964, p. 12) says the Bone Springs Formation in the Guadalupe Mountains conformably overlies the Hueco Limestone.

The Cutoff Shale, which consists of thin-bedded limestone interbedded with dark siliceous shale, sandy shale, and soft sandstone, has been considered both as the upper member of the Bone Springs Formation and as a distinct formation. The Cutoff Shale grades laterally into the San Andres Limestone.

For the purpose of this report, the Abo reef, the Victorio Peak Limestone, and the Cutoff Shale are considered to be part of the reef-limebank complex.

In the Sierra Diablo escarpment 2500 feet of Bone Springs beds rest unconformably on the Hueco (King, 1942, p. 561). The lower part consists of black limestones and shales. We believe sedimentation in the Pecos River basin continued from Wolfcampian into Leonardian time without interruption.

Many geologists take the top of the rocks of Leonardian age in the Pecos River basin to be the "top" of the Yeso Formation or the top of the Bone Springs Formation.

However, this approach is a decided oversimplification. Kottlowski et al. (1956) demonstrated that the San Andres Limestone in the San Andres Mountains is of Leonardian age. Hayes (1964, p. 12) in his diagram showing correlation of Permian rock units in the Guadalupe Mountains questions this simple age-lithology relationship.

The Glorieta Sandstone has variously been considered as (1) A discrete formation in the Glorieta Mesa area, (2) A basal sandstone member of the San Andres Limestone and (3) the uppermost member of the Yeso Formation. It apparently interfingers with both the Yeso and the San Andres. Jicha and Balk (1958) in the lexicon of New Mexico geologic names cites the Glorieta as Leonardian.

The evidence indicates that sedimentation was continuous from Leonardian into Guadalupian time and the time plane probably crosses the several lithologies. Until more specific formal evidence has been gathered and studied, the exact top of the rocks of Leonardian age will remain a matter for speculation.

Early workers considered the Glorieta Sandstone to be the upper member of the Yeso Formation. More recent workers have considered it in the area of Glorieta Mesa to be an independent formation and in the remainder of the Pecos River basin to be the lowest member of the San Andres Limestone.

Lloyd (1949, p. 22) considered it gradational with the Yeso. In actuality, the term has probably been applied to sandstone beds that intertongue with both the San Andres Limestone and the Yeso Formation, and to sandstone lenses and beds within the San Andres Limestone.

The name Glorieta was first used by Keyes (1915, p. 2, 7), who appliedit to the main body of the Dakota Sandstone (Cretaceous) around the south end of the Rocky Mountains. Although Keyes gave no type locality, presumably the sandstone was named from Glorieta Mesa in Santa Fe and San Miguel Counties, New Mexico, or for the town of Glorieta at the north end of the mesa. Cretaceous formations do not crop out at either of these places. Common usage had determined the Glorieta to be the prominent sandstone, well developed and exposed on Glorieta Mesa, that separates the Yeso and the San Andres Formations.

The Glorieta was first designated Permian by Hager and Robitaille (1919). Baker (1920, p. 111, 118-119, 126) stated that it was the basal member of the Upper Triassic, but, as pointed out by Rich (1921, p. 295-296), Baker confused the Glorieta with the Santa Rosa Sandstone of Triassic age, of which erosional remnants lie on Glorieta Mesa.

Baltz and Bachman (1956, p. 101) wrote of the Glorieta in the southeastern Sangre de Cristo Mountains as follows:

> "Glorieta sandstone member of the San Andres formation. In the hogback belt along the eastern front of the Sangre de Cristo Mountains the Glorieta sandstone member of the San Andres formation is a prominent cliff-forming unit. It is gray to tan on a fresh surface and usually weathers to tan or light brown. Typically it is composed of sub-round, clear, quartz and scattered grains of magnetite. Individual beds of the Glorieta sandstone member are medium to massive bedded and generally parallel. Well developed cross-lamination is common.

Baltz and Buelman (1956) continued

"South of latitude 36°00' in the Sangre de Cristo Mountains, the Glorieta sandstone rests on the Yeso formation. From latitude 36°00', in the vicinity of Lucero, northward the Glorieta rests on the Sangre de Cristo formation. The basal contact of the Glorieta sandstone member is sharp to gradational. At places the lower few feet of the Glorieta sandstone member contains material reworked from underlying rocks. In the vicinity of Lucero conglomeratic material similar to that in the Sangre de Cristo formation has been observed near the base of the Glorieta sandstone member.

"In the Sangre de Cristo Mountains the Glorieta sandstone member is variable in thickness. At Chapelle it is about 125 feet thick but near Romeroville it is almost 300 feet in thickness. At Kearny's Gap it is 220 feet thick, and in the vicinity at Ocate it varies from 250 to 275 feet in thickness.

"Fossils have not been found in the Glorieta sandstone member. However, its stratigraphic position indicates that it is of Leonard age."

Lang (1939, p. 850) called the Yeso to San Andres Limestone interval in the Roswell area the "Hondo" sandstone. He describes the Hondo as about 50 feet of yellowish to brownish-red streaked sandstone composed of coarse white quartz grains with calcareous iron cement. It shows local cross bedding, and contains abundant iron concretions and nodules in the upper part.

Bean (1949, p. 9) wrote of the Glorieta west of Roswell as follows:

> "The sandstone member at the base of the San Andres is named the Glorieta from its type locality at Glorieta Mesa, where it forms the cap rock. The name "Hondo sandstone," which has sometimes been used in the Roswell Basin, refers to the same rock unit. The Glorieta is typically a white to yellow medium-grained, well-sorted calcareous sandstone. Morgan states that its thickness increases to the north at the expense of the overlying limestone beds, from a thickness of about 12 feet in the southwestern part of the basin to about 300 feet at Glorieta Mesa. The sandstone commonly considered by geologists acquainted with this region to be the Glorieta is exposed in the Rio Hondo water gap through Border Hills. Cross bedding is well developed in its upper part here. Lower zones contain many solution cavities, mostly less than a quarter of an inch in diameter, giving the sandstone a pock-marked appearance. The sandstone here grades downward through about 8 feet of calcareous sand and sandy limestone into silty limestone commonly referred to as the Yeso formation. The upper boundary of the Glorieta (?) is much sharper, the upper 6 inches being fine-grained, very thin-bedded sandstone stained by limonite.
>
> "A similar sandstone occurs at the Hondo water gap 40 feet below the Glorieta (?), and two sandstones separated by 109 feet of limestone are present at the

Bean (1949, p. 9) continued

"Runyan Ranch on the Rio Penasco. It is probable that several sandstones of similar lithologic type occur near the contact of the San Andres and Yeso formations, and at any given place it may well be impossible to prove which, if any, is continuous with the sand capping Glorieta Mesa.

"In the western part of the Roswell Basin the main water body apparently extends through the Glorieta (?) sandstone member and the overlying porous carbonate rocks with little regard for their different character. Morgan reports that farther east, in the artesian area and its vicinity, water in the Glorieta is trapped between overlying beds of the San Andres, which are here impervious, and beds of the Yeso below, and as a result it is almost invariably salty."

Mourant (1963, p. 18) wrote about the Glorieta in the Hondo drainage basin:

"The Hondo Sandstone Member (Leonard Series) of the San Andres Limestone consists of a basal sandstone bed about 20 feet thick, beds of silty limestone, siltstone, gypsum, and anhydrite about 90 feet thick, and an upper bed of sandstone about 40 feet thick. The sandstone is friable, and it consists of well-sorted, medium, subangular, frosted grains of quartz cemented with limonite, which colors the sandstone light tan to dark red. The Hondo, as herein described, has been

Mourant (1963, p. 18) continued

> "previously mapped as a member of the Chupadera Formation (Lang, 1937, p. 850), and is called Glorieta Sandstone by Hood, Mower and Grogin (p. 13). The subangular, frosted, quartz grains and the absence of other minerals make the Hondo Sandstone Member a good marker bed, as it is easily distinguished from other formations in the area."

The Glorieta Sandstone is absent in the central Guadalupe Mountains. Skinner (1946, p. 1863-1864) concluded that the Glorieta Sandstone grades with the Yeso Formation near the basin margin. Hayes (1964, p. 23), however, thought it pinched out north and west of the Guadalupe Mountains.

Harbour (1970) recognized two sandstone units in the Rio Hondo valley. The upper one he equated to the Hondo Sandstone of Lang, the lower one he equated to the Glorieta Sandstone; and he suggested that the two might merge to the north.

Kelley (1971) believes that the Glorieta is one of the two basalt members of the San Andres Limestone. He says that Rio Bonita member of the San Andres which is dominately limestone and dolomite in the south interfinger with the Glorieta member to the north so that in the area between distinctly Glorieta Sandstone and distinctly Rio Bonita Limestone, there is an area in which beds of limestone and dolomite alternate with beds of sandstone.

These writers, as well as several others, make three points consistently:

(1) They believe the Glorieta Sandstone is of Leonardian age, but have no specific evidence to support their contention.

(2) It has a characteristic lithology that is easily recognized.

(3) In the northern part of the Pecos River basin the unit is consistent and thick; in the southern part of the basin it contains beds of other lithologies.

In this report, the Glorieta Sandstone is treated as a discrete formation. The top of the Glorieta Sandstone is taken at the top of the first sandstone with Glorieta lithology, and the base is taken at the top of the first bed with Yeso character. Clearly, top and bottom picks are highly subjective.

Figure 22 is a structure map of the Glorieta Sandstone. It is

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Figure 22 -- Structure contours of the Glorieta Sandstone

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based upon data from a variety of sources. Consequently, it may be altered considerably by any future investigation.

The San Andres Formation outcrops over a significant portion of the Pecos River basin. It is missing entirely from about one-tenth of the basin, (fig. 23). In general it is thin in its exposures in San

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Figure 23. -- Lithologies of the San Andres Formation

Miguel County and in wells where younger permeable rocks overly it, and may be more than 1600 feet thick near the edge of the shelf.

In its type section, the San Andres Formation is Leonardian in age, but in the Pecos River basin (especially in the southern part near the reef-lime bank complex) only the basal part is of Leonardian age. This part of the San Andres Formation is equivalent to the upper part of the Bone Springs Dolomite. The remainder is of Guadalupian age. The exact position of the boundary between Leonardian and Guadalupian age of parts of the San Andres Formation north of the reef-lime bank complex is moot.

Figure 23 shows the distribution of lithologies in the San Andres "limestone."

In the Guadalupe Mountains the San Andres Formation consists of a brown cherty member and an upper member. The bulk of the lower cherty member is dolomite and dolomitic limestone and may contain as much as 25 percent chert. The upper member consists of dolomite and dolomitic limestone and is relatively chert free. It is about 1,200 feet thick. The lower part of the lower cherty member is probably of Leonardian age.

Along the Rio Penasco in sec. 15, T. 17 S., R. 20 E., Bean (1949, p. 11-13) measured 770 feet of limestone with some dolomite and shale. The evaporite and clastic content of the San Andres Limestone increases from west to east and from north to south. Salt is a common San Andres lithology in the eastern part of the Pecos River basin.

The San Andres varies in thickness and lithology. In subsurface near the basin margin it contains 1500 feet of tan to dark brown crystalline and oölitic dolomite (Kinney, 1961, p. 197). In Guadalupe County, it changes from light gray cavernous limestone in the north-western part to an anhydrite-gypsum-salt facies in the east where it dips into the Tucumcari basin. The type section consists of some 600 feet of light to dark gray limestone, sometimes sandy or dolomitic, and contains a large fauna (Kottlowski, 1961, p. 197, 198).

Kelley (1971, p. 7-14) in his comprehensive study of the outcropping San Andres divided it into three members: Rio Bonito-Glorieta (oldest), Bonney Canyon, and Fourmile Draw (youngest). Figure 24 shows the north-south relation of these members as Kelley

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Figure 24 -- North-south stratigraphic diagram of the San Andres Members

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saw them in the outcrop.

The Rio Bonito member interfingers with the Glorieta. It is generally thick-bedded limestone and dolomite. Its thickness ranges from 300 to 650 feet (fig. 24).

The Bonney Canyon member is thin-bedded and is porous limestone and dolomite. Its thickness ranges from less than 60 to 300 feet (fig. 24). The subsurface Slaughter zone of porosity is roughly equivalent to the Bonney Canyon member.

The Fourmile Draw member is typically evaporatic and thin-bedded. Its base is equivalent to the Cherry Canyon Sandstone. In the northern part of the basin it overlies the Glorieta. Its thickness ranges from about 350 to more than 800 feet.

Three interrelated problems complicate a discussion of the upper contact of the San Andres Formation. These are:

1. the regional relationships of lithologic units,
2. the conformability of the younger Guadalupian rocks to the San Andres, and
3. the relationship of the Guadalupian age rocks to overlying rocks of Ochoan and Triassic age.

The consensus of opinion among students of the San Andres-younger rock contact is that the beds are unconformable. However, opinions vary about the nature of the unconformity. For example: Young (1965, p. 283) says there is a slight discordance; Hayes (1964) says the contact is locally unconformable; and Tait et al. (1962, p. 515) mention "a regional unconformity which is apparent over most of southeastern New Mexico." Gratton and LeMay (1969) say the contact is unconformable west of the Cheveroo oil field.

In addition to these differences in opinion, isolated remarks by other authors suggest that perhaps other interpretations are possible. For example, Boyd (1958, p. 27) refers to subaqueous erosional features in the rocks of the San Andres Formation and Hayes (1964, p. 29) included 50 feet of dolomite as San Andres that Moran (1954) mapped as Grayburg.

Kelley (1971, p. 16) noted that the Grayburg on Bonney Canyon north of Capitan Mountains that "suggests post-San Andres uplift south of the Capitan Fault and consequent removal of high San Andres beds before Grayburg time." He also noted,

> "Irregularities in detail, present along the base of the Grayburg, together with considerable solution weathering and collapse breccia in the top of the Fourmile Draw member of the San Andres, suggest at least a discomformity in the Pecos Valley region."

Kinney (1969, p. 4) wrote,

> "Perhaps the base of the Lovington sand should have been considered as the top of the San Andres Formation with the sand and overlying carbonate a part of the Artesia Group. However, present usage is well established."

Thus, we see first that ideas are not fixed about the nature of the conformability relations and, second, that in practice the top of the San Andres is defined arbitrarily.

Where rocks of Triassic age overlie the San Andres the contact is clearly unconformable. Northrop et al. (1946) show that in San Miguel and Mora Counties the Bernal Formation (their upper clastic member of the San Andres Formation) rests in places directly upon the Glorieta Sandstone. Smith (1964) says that in the Little Black Peak Quadrangle (Socorro and Lincoln Counties) west of the Pecos River Basin, "The contact between the San Andres Formation and the overlying Bernal Formation is a disconformity which a Karst topography developed."

Apparently a distinct, well-defined unconformity west and north grades into a slight or ill-defined unconformity east and south. Figure 23 shows the approximate eastern limits of the unconformity. Where the unconformity is well defined, it is a Karstic surface, which some observes believed could have formed in part in the subsurface by the solvent action of circulatory ground waters.

Guadalupian Series

The rocks of Guadalupian age overlying the San Andres Formation have been called (a) the upper clastic member of the San Andres Formation, (b) the Bernal Formation, (c) the Whitehorse Group, (d) Pecos Formation in the Chalk Bluff Formation, and (e) the Artesia Group.

Terms (a) and (b) above are identical; modern users prefer Bernal. Tait et al. (1962) defined the Artesia Group and showed that it merges with the Whitehorse Group of west Texas and Oklahoma and with the Bernal of central and northern New Mexico. They suggest that the terms Pecos Formation and Chalk Bluff Formation are inappropriate.

The Artesia Group consists of five formations: Grayburg (oldest), Queen, Seven Rivers, Yates, and Tansill (youngest). For a short period the term Carlsbad Group and Carlsbad Limestonewere used for the carbonate part of Seven Rivers, Yates, and Tansill.

For convenience in this report we use the Artesia-Bernal for the post-San Andres rocks of Guadalupian age.

Figure 25 shows the distribution, thickness and predominate

Figure 25. -- Lithology and thickness of the Artesia Group

lithologies of the Artesia-Bernal rocks. These rocks probably occurred throughout the Pecos River basin originally, but were eroded from the western third during late Tertiary time. Even though they "outcrop" over a broad area in the central part of the basin, for the most part they are not well exposed, because they are covered by Quaternary alluvium.

The thickness of the Artesia-Bernal rocks ranges from less than 100 feet in outcrops along the western margin of the Pecos River basin to more than 2000 feet near the southern limit.

The rocks of the Artesia-Bernal in the north and west parts of the Pecos River basin are siltstone and sandstone. Laterally, east and south, the rocks grade into and interfinger with evaporites and carbonate. Near the reef limebank complex region at the margin of the Delaware basin, the rocks are predominantly limestone and sandstone.

The Artesia Group contains the Grayburg, Queen, Seven Rivers, Yates and Tansill formations (Tait et al., 1962, p. 504). Contacts within the group are conformable.

The Grayburg Formation contains from 299 feet (Dickey, 1940, p. 47) to 475 feet (Moran, 1954, p. 1288) of buff sandstone, dolomite and anhydrite. North of Roswell Kelley (1971, p. 16) mapped the Grayburg-Queen as a single unit. He describes the Grayburg in outcrop as follows:

> "The southernmost outcrops are in north McKittrick Canyon (T. 26 S., R. 21 E.) where they grade with the lowermost overlying Queen Formation into the reef or bank deposits of the Goat Seep dolomite. Grayburg is also mapped along the east flank of Sierra Blanca basin extending in a band from the Capitan Mountains southward through Fort Stanton to the Ruidoso area. Along this belt the Grayburg rests on Bonney Canyon beds of the San Andres with all the Fourmile Draw Member

Kelley (1971, p. 16) continued

"missing. Tan, brown, medium- to fine-grained sandstone is the principal lithology, and south of Fort Stanton thicknesses appear to reach 400 to 500 feet in a few miles. In several places near the junction of U. S. Highway 380 and the Fort Stanton road, a cherty gray dolomite is found near the top and often just below cherty conglomerate beds of the Santa Rosa Formation.

"In the area of the type locality of the Grayburg, along the Huapache monocline and in the adjoining Guadalupe Mountains, the dominant lithology is very light tan, almost lithographic dolomite and calcareous dolomite with intercalated fine-grained sandstone. Sandstone beds are somewhat more common and thicker bedded in the lower part. Bedding ranges mostly from a few inches to about one foot, although some beds reach 10 feet in sandstone. All bedding thickens noticeably as the reef is approached, where massiveness takes over and carbonate increases.

"Northward of the type locality, sandstone and dolomite give way to reddish, more friable, thinner-bedded sandstone and mudstone, and in T. 22 S., R. 22 E. gypsum first appears. Northward, gypsum is more common, and in the sink holes at Antelope Springs southeast of Hope (T. 18 S., R. 23 E.), red- and white-banded gypsum several tens of feet thick is evident.

"In the northern part of the area, from about Macho Draw and U. S. Highway 285 northward, wide expanses of undivided Grayburg-Queen are seen both west and east of the highway. In this area, red mudstone and

Kelley (1971, p. 16) continued

> "muddy gypsum predominate, but thin dolomite beds are present, especially in the lower part of the sequence."

The Queen Formation encompasses about 420 feet of sandstone, dolomite, and anhydrite in shades of gray, tan, and yellow. Graves measured the "Type Queen" established by W. R. Moran (Graves, 1958, p. 31-3). Kelley (1971, p. 16) describes the Queen as follows:

> "As described by Hayes (1964, p. 30-31), the Queen is lithologically similar to the Grayburg in the near-reef and reef areas, but with almost twice the proportions of clastic beds. Perhaps because of this fact, the outcrops and outcrop soils are slightly darker than the Grayburg and the overlying Seven Rivers Formation.
>
> "As with the Grayburg, Queen lithology of the near reef type changes northward into thinner beds of red sandstone and mudstone with dolomite. North of Rocky Arroyo, gypsum appears and shortly becomes a nearly dominant part of the formation, especially in the upper part. Thin dolomite beds are gray or gray and magenta. The upper contact around Rocky Arroyo is above a prominent sandstone ledge.
>
> "In the Guadalupe Ridge area the Queen appears to be almost 400 feet in thickness (Hayes, 1964, p. 31); however, to the north in the Seven Rivers embayment, the thickness does not appear to exceed 200 feet, although no section was measured."

According to Dickey (1940, p. 48) the Seven Rivers Formation averages 500 feet of anhydrite and brown dolomite. However, Kelley (1971, p. 16-17) points out that in outcrop the Seven Rivers Formation is dominately carbonate near the reef-limebank complex, but in a distance of 7 to 9 miles it transforms into a dominately evaporite facies which can be mapped for 70 miles northward.

The Yates Formation ranges from 200 to 300 feet of sandstone near the shelf margin (Fritz and Fitzgerald, 1940, p. 26) to 50 feet of fine-grained sand with anhydrite in the orginal type locality in Yates Field, Pecos County, Texas (New Mexico Geological Society, 1954, p. 43). In the Guadalupe Mountains, Hayes (1959, p. 59) measured and described 328 feet of dolomite and siltstone.

According to Kelley (1971, p. 17-18) the Yates Formation in outcrop consists of carbonate and evaporite intertongue near the reef-limebank complex. North of Lake McMillan gypsum dominates the Yates outcrop to about Roswell. North of Roswell siltstone and sandstone dominate the lower part of the formation and gypsum and red mudstone dominate the higher part of the formation.

DeFord and Riggs (1941) introduced the Tansill Formation in 1941 as 124 feet of magnesian limestone with stringers of silt and marl.

Figure 25 shows the three areas that we recognize in the eastern part of the Pecos River basin, where younger rocks overlie the Artesia-Bernal. In the southernmost area, the Artesia-Bernal is overlain by the Rustler or Salado Formation and the upper contact is well defined. In the central area the Rustler and Salado Formations are missing. In both the central and northern areas the rocks of the Artesia-Bernal are similar to the rocks of the overlying formation and contacts are difficult to pick. But the surface of the Artesia-Bernal is an unconformity.

In the Delaware basin the Delaware Mountain group of Guadalupian age overlies the Leonardian Bone Springs Formation. From bottom to top, the 3500 feet of buff to black sandstones and limestones divides into the Brushy Canyon, Cherry Canyon, and Bell Canyon Formations (Lang, 1937, p. 873, 874).

The Brushy Canyon Formation begins with up to 50 feet of dark gray to black interbedded shaled sandstone and limestone, overlain by 1000 feet of fine-grained sandstone with coarse-grained lenses, and a few beds of sandy, dolomitic limestone (Hayes, 1964, p. 12).

The Cherry Canyon Formation consists of 1000 feet of fine-grained thin-bedded, laminated sandstone with several limestone members. King (1942, p. 580-581) described these limestones: The black Getaway lies 100 to 200 feet up in the Cherry Canyon and locally attains 200 feet in thickness; the thin, dark, fossiliferous South Wells Limestone occupies 75 feet of section beginning 600 feet above the Cherry Canyon base; just below the top of the formation, the Manzanita member appears as 25 to 100 feet of orange brown weathering buff earthy limestone.

The Bell Canyon Formation contains 700 feet of very fine sandstone to siltstone with persistent interbeds of limestone. Five of these limestones are designated as members of the Bell Canyon: Hegler, Pinery, Rader, McCombs, and Lamar. In the following Bell Canyon Section by King (1948, p. 171-172), the McCombs is called the flaggy limestone bed, since it was not named as a member until 1956.

Positions of the limestone within the formation vary as shown by comparison of the following descriptions with the measured section above.

The base of the Hegler Limestone marks the base of the Bell Canyon Formation. This horizon was chosen because the 15 feet of ledge-forming dark gray platy limestone is the oldest bed grading into the Capitan Limestone (King, 1942, p. 582).

About 30 feet above the formation base lie 150 feet of Pinery Limestone, consisting of straight thin beds of dark gray, slightly cherty limestone with lighter, thicker, more fossiliferous limestone beds near its base. Southward, it thins to 25 feet of dark, thin, straight limestone beds (King, 1942, p. 582-583).

The massive, light gray Rader Limestone member caps the Rader Ridge along the base of the reef escarpment, where its base is 225 feet above the base of Bell Canyon and covers 100 feet of section. There it contains a few thin layers of darker limestone which gain predominance as the member thins away from the reef to 15 feet in the Delaware Mountains (King, 1942, p. 583).

King and Newell (1956, p. 386) briefly describe the McCombs Limestone member asa persistent flaggy limestone bed ten feet thick, "lying about a third of the way up in the 400-foot sandy interval between the Rader and Lamar members."

Lang (1937, p. 874-875) defined the Lamar Limestone member as a black calcareous bed about 25 feet thick, which becomes a pale gray limestone at the reef escarpment. At the base of the reef escarpment, King (1942, p. 583, 586) reports the Lamar as 150 feet of gray, granular fossiliferous well-bedded limestone, which thins to 15 feet of dark, non-fossiliferous limestone in the Delaware Mountains.

Locally, up to 35 feet of Delaware Mountain Sandstone and Limestone overlie the Lamar.

Rocks of Guadalupian age in the reef-limebank complex consist of massive limestone and dolomite plus quartz sandstone, and include the San Andres Formation, the Brushy Canyon and Cherry Canyon Sandstones, the Goat Seep Dolomite, and the Capitan Limestone. Within the complex, the rocks grade from the typical lithology cited below into their basin or shelf equivalents. Consequently, many variants of the litholigies cited occur within the complex.

In the complex, the San Andres Formation is a dense to finely crystalline dolomite with minor amounts of chert in the lower part.

The Brushy Canyon and Cherry Canyon Sandstones -- usually called the Cherry Canyon Sandstone Tongue -- are a fine-grained, well sorted quartz sandstone. It may contain chert nodules or silicified fossils. It may also contain carbonate beds that are similar to the San Andres carbonates.

The Goat Seep Dolomite is as much as 1200 feet thick and ranges from a massive gray limestone to a massive gray dolomite.

The Capitan Limestone overlies the Goat Seep, probably with disconformity (Hayes, 1964, p. 19). King (1942, p. 59) reports 2400 feet of partially recrystallized and dolomitized limestone with a well preserved fauna in the calcitic limestone sections.

Two near-reef facies of the Capitan Limestone exist: a sandy, dolomitic breccia and a thin-bedded limestone (King, 1948, p. 63-64).

Three exposures of the breccia occur, one near the Grisham-Hunter Lodge in South McKittrick Canyon, another near Devil's Hall in Pine Spring Canyon, and the other on the western cliffs of the mountains north of Guadalupe Peak. King (1948, p. 63) describes these outcrops as a rudely bedded breccia with sandy, light-buff or pink dolomitic matrix containing jumbled limestone blocks up to several feet in diameter. Fossil imprints appear in the matrix near the Grisham-Hunter Lodge. Well-bedded, fine-grained calcareous sandstone lenses mark the breccia, which may reach 300 feet in thickness before grading into its normal, massive Capitan surroundings (King, 1948, p. 63).

The thin-bedded limestone represents a gradual transition from the massive Capitan.

Ochoan series

The Ochoan series in the Pecos River basin includes the Castile, Salado, Rustler, and Dewey Lake Formations. The Castile Formation is mostly anhydrite; the Salado mostly salt. The basal clastic beds in the Rustler Formation give way to beds of anhydrite, dolomite, and gypsum in its upper part. The Dewey Lake Formation consists mostly of clastic red beds.

The Castile (by most definitions) occurs only in the Deleware basin, where as the Salado, Rustler, and Dewey Lake Formations extend from the basin over the reef-limebank complex onto the shelf as continuous stratigraphic units. Sedimentary features at the Delaware basin margin apparently did not influence the deposition of these younger rocks.

Although these formations are useful lithologic units, not all geologists agreed that the entire interval is Ochoan. Snider (1966) correlated the Castile with the Seven Rivers and lower Yates Formations and he correlated the Salado of the Delaware basin with the upper Yates, Tansill and Salado Formations in areas beyond.

Cave (1954) and Moore (1959) correlated the Castile Formation with the youngest rocks of Guadalupian age or the shelf margin.

According to Silver and Todd (1969, p. 2248) the basel part of the Castile grades laterally into the youngest part of the reef-limebank complex and Jones (1954) believes the rest of the Castile is coeval with the lower part of the Salado of the shelf.

Most geologists take Hayes(1964, p. 15-16) point of view that present data are inconclusive and therefore relations of the Castile Formation to adjacent formations can only be conjectured.

The principal reasons geologists take this view are: first, the Salado consists mostly of salt and it does not crop out except in isolated places where it consists dominantly of some other rock types because the salt had been removed by solution. So over much of the outcrop Rustler rests directly on Castile and the relation of the Castile to the Salado cannot be seen.

In addition alluvium covers much of the potential outcrop, so geologists cannot see relations between the Castile and the underlying rocks or possible lateral equivalents.

Kelley (1971, p. 20) divides the Castile in outcrop "into a lower laminated member consisting of gray-to-white gypsum and dark limestone, and an upper member consisting of massive, generally white gypsum." He also says, "The Castile appears to overlie the Bell Canyon conformably, and it underlies the Salado and Rustler unconformably."

To further confuse matters geologists are inconsistent in their definition of the formations.

The practice of subsurface geologists who work on the northern part of the Delaware basin (as evidenced by the formation definition on the strip logs of the petroleum section, NMBMMR) is to define the formation of the Ochoan series as follows:

Dewey Lake -----Red clastics to the top of the Rustler

Rustler ---------Top of the first anhydrite below the redbeds to the top of the first salt.

Salado ----------Top of the first salt to the base of the salt.

Castile ---------Base of the salt to the top of the Delaware mountain group.

Following these definitions figure 26 shows the thickness of the salt and figure 27 shows structure contours on "top of the salt."

Figure 26 -- Thickness of the salt

Figure 27 -- Structure contours on "top of the salt"

Contours on these maps extend into areas where the Salado and Rustler Formations are ill-defined on other bases and probably are based upon salt beds of Guadalupian age. Thus the upper and lower limits of each formation and the lithologies included within each formation depend upon the criteria used to define the formation.

Richardson (1904) named the Castile Formation for outcropping evaporites he observed between the Delaware Mountain Group and the Rustler Formation. Later when drill hole information revealed the thick salt sequence, geologists simply referred them to the Castile. As early as 1923 Lang (1935) claims to have divided the interval into the Lower Salt series (Castile) and Upper Salt series (Salado) without making a clear distinction between them. In 1935 Lang named the Salado Formation and distinguished between the Salado and the Castile on the basis of the polyhalite content. The Salado being defined as the part of the salt section in which K_2O is 1 percent or more. He noted (p. 263) that the Castile "lies unconformably on the Delaware Mountain formation" and laminated rocks "are not conspicuous in the Castile, (but) they are by no means confined to it."

In 1939 Lang defined the content between the Castile and Salado arbitrarily at the base of a locally magnesitic, dense, non-banded anhydrite that contains no calcite. This definition confines the Castile to the Delaware basin.

Adams (1944, 1969) used the top of the well laminated anhydrite as the top of the Castile Formation.

The dominant lithology of the Castile Formation is laminated or banded anhydrite.

The banding or lamination consists of alternating thin layers of organic-rich carbonate (generally calcite), and thicker layers of nearly pure gypsum on anhydrite (Anderson, 1967, p. 225). Clearly, the extent of other lithologies in the Castile Formation depends upon how the Castile is defined.

To further complicate description, geologists are divided about the occurrence of unconformities both at the base and at the top of the Castile Formation.

Richardson (1904), Lang (1935, p. 268), and Mear (1963) believe the Castile sediments were deposited unconformably upon the underlying rocks. However, most geologists, including Lang (1939) believe the contact between the Castile and Delaware Mountain Groups is conformable, because the uppermost beds of the Delaware Mountain Group are also laminated and no interruption of sedimentatives can be interpreted from the rocks. Geologists differentiate between these formations by referring all the evaporatives to the Castile.

The upper limit of the Castile is more controversial. Bjorklund and Motts (1959) thought the Castile and Salado Formations intertongued. Lang (1941, p. 155), Cave (1954), and Adams (1969) believe these formations are conformable and that sedimentation was continuous. Mear (1963), Kroenlen (1939), King (1947), and Adams (1944) suggest that the formations are unconformable.

Interpretation of the lithology and distribution of the Castile Formation depends upon how one interprets the presence and magnitudes of this interface. If the formations are conformable, the definition of the formation top is arbitrary and the Castile, Salado can be thought of as a lithologic entity, which consists predominantly of anhydrite and salt -- the upper part being dominantly salt. If however, an erosional unconformity separates the two formations, their thickness, extent, and character depends upon the nature and magnitude of the unconformity. The most extreme case is an erosional unconformity on a tilted surface. The evidence for this case is far from conclusive. The most compelling argument grows out of two observations: (1) there is a regional angular unconformity on the Artesia Group (top of the Guadalupian series) and (2) the Castile Formation was deposited upon the Delaware Mountain Group without interruption.

One would expect then that the regional tilt would have extended over the Delaware basin and not have been limited to the shelf. As a consequence erosion would have occured in the basin as well. Since Delaware Mountain, Castile sedimentation was continuous, we would then expect the erosion surface to be on the Castile. Moreover, Castile equivalents on the shelf would have been the first removed by the subsequent erosion.

Cross section in AA', along the Pecos River, shows salt resting on the Delaware Mountain Group.

Anderson (personal communication, January 28, 1971) challenges this interpretation on the grounds that he sees no evidence for unconformity in his collection of cores of the Castile Formation. Moreover, he has proposed (1967 , p. 6) a type stratigraphic section for the Castile Formation, which includes four anhydrites and three halite beds. These beds he says can be correlated throughout most of the basin. He concedes the possibility of an unconformity at the top of the Anhydrite IV, because of the presence of nodular or brecciated zones that could have been generated when the halite dissolved.

The salts beds in the Castile are composed of practically pure sodium chloride with no potash (Adams, 1944, p. 1607).

According to Snider (1966), a graduate student of Anderson's, the Castile Formation covers an area of about 10, 000 square miles of the Delaware basin in Texas and New Mexico at a thickness between 1300 and 2000 feet. Along the north and east edges of the basin it thins abruptly. In its northern and western reaches the Castile is mostly banded anhydrite with some massive anhydrite, nodular anhydrite, and dolomites, and bituminous limestone. Sulfur occurs in Culberson County, Texas, between depths of 240 and 1250 feet.

During the late 1960's the Castile Formation became an exploration target for native sulfur. According to Davis and Kirkland (1970) bacteria reduced anhydrites and gypsum ($CaSO_4 \cdot nH_2O$) in the presence of carbon and hydrogen derived from petroleum to hydrogen sulfur gas, which was in turn oxidized by oxygenated ground-water to free sulfur and water.

In those areas where sulfur occurs, the Castile Formation is both porous and permeable.

The maximum thickness of the Salado Formation in the Delaware basin is 2400 feet (Kroenlein, 1939, p. 1688). On the shelf the maximum thickness is about 1500 feet.

In the area where the Salado and Rustler Formations are well defined (fig. 27), most geologists take the base of the Salado in New Mexico as the base of the Fletcher Anhydrite member. This anhydrite ranges from 50 to 100 feet in thickness, is dense, and non-banded. On the shelf it rests unconformably upon rocks of the Artesia Group. In the basin it lies upon banded anhydrite. However Kelley (1971, p. 24) points out, "North of about T. 20 S., R. 27 E., the Salado evaporite lies on Tansill evaporites rather than dolomite and the contact becomes difficult to recognize." The top of the Fletcher Anhydrite is the "base of salt" over large areas.

On the shelf the La Huerta Silt member overlies the Fletcher. It cannot be defined in the Delaware Basin Anhydrite. This member is almost 150 feet thick. The bulk of the member consists of thin beds of shale and silt in a silty halite with a few irregular thin beds of strings of anhydrites. Near the base of this member is a bed of halite about 5 feet thick through which red sand is disseminated.

The Cowden Anhydrite member overlies the La Huerta Silty member. On the shelf it is usually 150-200 feet above the "base of salt". It ranges from 15 to 40 feet in thickness, It is a blue-gray, glassy anhydrite with fine patches and stringers of magnesitic, fracture-filling halite and a minute amount of brown shaly material (Lang 1942, p. 71). The Cowden Anhydrite extends well into the basin where it blends with other anhydrite beds and loses its identity.

Except for Vace Triste Sand member the rocks overlying the Cowden Anhydrite have not been named. At the top of the Salado Formation is an erosional unconformity, and geologists generally take the top of the massive salt as the top of the formation.

Most of the rock overlying the Cowden Anhydrite is salt, but 40 or more thin anhydrite beds have been indentified. According to Kroenlein (1939, p. 1689) each anhydrite bed has an inch thick bed of gray-green clay at its base. Dolomite and magnesite are common in the Salado Formation in the southern and western parts of the Permian basin. Thin beds of sandstone and siltstone are common.

The halite beds include not only halite but polyhalite, sylvite, carnallite, and langbeinite, plus disseminated anhydrite and red, green, and gray clay. Native sulfur has also been found.

Jones (1959, p. 13) gives the relative abundance of the principal rock types in the Salado Formation in the Carlsbad district as:

Halite	38.6 percent
Argillaceous Halite	45.0 percent
Sulfate	12.5 percent
Clastic	3.9 percent

Near the outcrop the upper part of the Salado is characterized by a leached zone that consists largely of unconsolidated reddish-gray to brown salt and clay with varying amounts of brecciated gray or red gypsum. The thickness of the leached zone is one-third to one-tenth the thickness of the original rock present. Most subsurface geologists include the leached zone with the Rustler Formation. This zone is of variable thickness and lithology.

The outcrops that have been labeled Salado are mostly gypsum and clay. They probably consist of the Fletcher and Cowden Anhydrites plus the residue from the dissolved halites.

As figure 25 shows the Salado Formation loses its identity northward. Two reasons for this are:

(1) The Salado underwent erosion before the Rustler was deposited upon it. So northward the Salado salts have not only been eroded more but have been thinned by solution in Permian time as well as late Cenozoic time.

(2) The underlying rocks of Permian age all show a clastic facies north and west interfingering with carbonate-evaporite facies south and east. The clastic facies, having essentially the same source areas and made of deposition, are very much alike. In those areas where the clastic facies of the several formations is the dominant one, differentiation and identification of the individual units is difficult to impossible. If the Salado has a clastic facies, as the thin sandstones and siltstones suggest, they would be difficult to distinguish from the underlying clastics of Guadalupian age or those of the overlying Rustler Formation.

The following discussion of the Rustler Formation is taken from Adams (1944, p. 1612-1615) with modifications as noted:

Deposition of the Rustler was preceded by a period of uplift and erosion in the area along the west edge of the Delaware basin. This erosion stripped off all the western Salado and may have truncated the entire Castile Formation as well. The lowest Rustler outcrops observed are about 100 feet above the top of the Delaware Mountain Group. As a result of uplifts beyond the limits of the Delaware basin, the oldest deposit of the Rustler Formation, in its western outcrops is a clastic member. Included are coarse, siliceous conglomerates with well- rounded pebbles up to 2 or 3 inches in diameter, coarse gray sandstones, traces of red and yellow shale, coarse dolomite conglomerates, and bedded gray and buff dolomite. Many of the siliceous pebbles are etched in a peculiar manner with all the broken crystals of the original surface spalled out, leaving well-rounded pebbles covered with unmarred crystal faces. The bedding in all these deposits seems to be distorted. Toward the east the conglomerates grade into sandstones.

Where the basal sandstones of the Rustler rest on the beveled surfaces of the Salado, as in the area south and east of Carlsbad, they are characterized by abrupt irregularities in thickness. Apparently these variations are due to the filling of salt solution valleys in the surface of the Salado. Above the basal clastic phase, the Rustler is largely an evaporite formation and marks the final stage of evaporite deposition in the southern Permian basin.

In the subsurface where the complete Rustler section is preserved, it can be divided into two main parts, an upper 150-to-175 foot bed of anhydrite or gypsum; and a lower group of dolomite, anhydrite, sand, and shale members. Along the south and west limits of the Rustler area the anhydrites of the lower group grade into dolomites and the dolomites into limestones. Toward the north and east the dolomite stringers, in turn, decrease in prominence, and at the northeast edge of the Delaware basin part of the upper anhydrite and the anhydrites of the lower group grade into salt.

Where the Rustler carbonates crop out in the Rustler Hills of eastern Culberson County, Texas, the section consists of dense, brecciated limestones and dolomites with rough, pitted, weathered surfaces, interbedded with sandstones and limestone conglomerates. Much of the pitting is due to the solution of gypsum inclusions. Many of the gray and green shales of the subsurface take on a purple cast after weathering on the surface. The maximum thickness here is about 375 feet and none of the upper anhydrite is exposed.

Unlike the Salado, the Rustler Formation crops out over widely scattered areas both east and west of the Pecos River. Outcrop distribution is controlled by erosion, solution subsidence, and burial under Triassic and Quaternary cover. The western outcrops are limited to the basal carbonate and clastic section, with the upper anhydrites suggested by a gypsite plain east of the Rustler Hills. As the only resistant member in the thick series of softer beds, the limestones from low scarps and floor many of the gentler slopes.

East of the Pecos River, in central Eddy County, New Mexico, is a small area in which the upper as well as the lower part of the Rustler is exposed. Here, where the upper Rustler stratigraphy is similar to that of the north-central part of the Delaware basin, Lang (1939, p. 8384) measured the following section:

1. 30 feet gypsum
2. 30 feet grysiferous dolomite
3. 100 feet gypsum
4. 30 feet redbeds
5. 20 feet gypsum
6. 35 feet dolomite
7. 3 feet redbeds
8. 70 feet gray sandstone
9. 35 feet redbeds
10. 130 feet gypsum
11. 5 feet redbeds

The first five members in the foregoing section belong to the upper Rustler, the others to the lower part of the formation. The 30-foot gypsiferous dolomite, No. 2 in the sequence, is persistent marker in the north half of the Delaware basin. Vine (1963) divided the Rustler Formation in this same area, the vicinity of Laguna Grande de la Sal (T. 23 S., R. 29 E.) into five members: an unnamed lower member, Culebra Dolomite member, Tamarisk member, and Magenta member, and the Forty-niner member.

The unnamed member, the lower sandstone of Jones (1959), consists of 120 feet of siltstone, gypsum, and very fine-grained gray sandstone.

The Culebra Dolomite member consists of 30 feet of light gray, silty, thin bedded to massive, locally oölitic, microcrystalline (with spherical vugs 1-10 mm in diameter) dolomite.

The Tamarisk member, the middle gypsum of Jones (1959), consists of 115 feet of white, massive gypsum and siltstone.

The Magenta member consists of 20 feet of dolomite interlaminated with pale green anhydrite.

The Forty-niner member, upper gypsum of Jones (1959) consists on 40-65 feet of white, massive gypsum and siltstone.

According to Hale (1947, p. 238-241) the base of the Rustler in the Frontier Hills, southwestern Eddy County consists of 80-100 feet of fine grained dolomitic limestone that grades into gypsum eastward. This dolomite is probably equivalent to the Culebra member. The underlying equivalent of the unnamed member and the Tamarisk member are not exposed or are so poorly exposed that their stratigraphic position is uncertain.

The unnamed member is characteristic of the extreme northwest part of the Delaware basin and is limited to the area of pre-Rustler solution troughs.

Local features include a zone of euhedral quartz crystals in the Tamarish member between the Magenta and Culebra dolomites, and oölites in one or the other of the two main dolomite members. The oölites are most common in that part of the Rustler overlying the reef-limebank complex and shelf areas.

The contact of the Rustler and overlying Dewey Lake Formations appears to be conformable. In the central part of the Permian basin the same can be said of the Rustler and Salado, but along the west and north margins of the Delaware basin the Rustler unconformably truncates the entire Salado section. The sharpest angular unconformity is in the western Delaware basin where the Rustler rests on the basal members of the Castile Formation.

The Dewey Lake redbeds, which outcrop east of the Pecos River in eastern Eddy County, have been called "Pierce Canyon" and "Upper redbeds". They probably correlate with the Quartmaster Formation of northeastern New Mexico and northwestern Texas. They consist of as much as 600 feet of very fine grained, red to orange-red sandstone and siltstone. Gypsum and anhydrite are common as cement, secondary crystals, and veins. These beds probably served as a protective cap over the evaporites of the Rustler and the Salado Formations during the period between their deposition and deposition of the overlying upper Triassic rocks.

MESOZOIC SYSTEMS

Triassic system

The Dockum Group, of Triassic age, are the only rocks that occur in the Pecos River basin. These rocks make up the bulk of the so called "redbeds" of eastern New Mexico. As Figure 28 shows they

Figure 28 -- The Dockum Group of Triassic age.

underlie about one quarter of the basin and crop out along a continuous north-south belt, which lies east of the Pecos River south of T. 1 S. and north of Anton Chico. Between T. 1 S. and Anton Chico the river roughly bisects the outcrop. The rocks dip to the east.

Westward dipping beds of Triassic rocks occur near the basin divide on the west side south of Glorieta Mesa and east of Sierra Blanca.

Within the Pecos River basin the Dockum Group includes the Tecovas, Santa Rosa, and Chinle Formations.

The Tecovas Formation which occurs only in southeastern Lea County, consists of as much as 270 feet of red shale, siltstone, and very fine-grained sandstone. These sediments were derived from the underlying Dewey Lake Formation upon which the Tecovas rests unconformably.

The Santa Rosa Sandstone lies unconformably upon the older rocks except where the Tecovas was deposited first. It consists of as much as 450 feet of medium to coarse grained sandstone with thin beds of shale, claystone, or siltstone. In many places it is conglomeratic sandstone or a conglomerate.

In the western part of the Pecos River basin it contains limestone and quartz pebbles. In the southeastern part of the basin it is arkosic and micaceous. In outcrop it is cross-bedded and friable. Individual beds range from thick to massive. Although the Santa Rosa Sandstone is dominantly red to reddish-brown, some beds are gray to white.

As figure 28 shows, in the east-central part of the Pecos River basin this unit cannot be defined with confidence. The "redbeds" above the uppermost anhydrite contain sandstones like those called the Santa Rosa elsewhere, but these occur as relatively thin (50 to 150 feet) beds with gray, green, and red shale. Moreover these beds occur as much as 1600 feet above the top of the uppermost anhydrite. Kelley (1971, p. 26) assigns the rocks that outcrop in this area to the Santa Rosa Formation.

The Chinle Formation consists of red shale, siltstone, and fine-grained sandstone. Its maximum thickness is more than 1200 feet, but because erosion preceded deposition of overlying rocks, its thickness varies markedly in short distances. In Lea County the Chinle is 325 feet thick, yet in Winkler County, Texas, only a few miles away, its thickness is 1000 feet. In Quay County 1230 feet have been reported, but in De Baca County, a few miles west, where it is covered only by alluvium, the maximum thickness is about 850 feet.

Jurassic System

Rocks of Jurassic age occur only in the northern part of the Pecos River basin near the divide in San Miguel County (fig. 29). Only two

Figure 29. -- Rocks of the Jurassic and Cretaceous ages in Pecos River basin, New Mexico

formations of the San Raphael Group are present -- the Entrada Sandstone and the Morison Formation.

The Entrada Sandstone is a fine- to medium-grained poorly cemented sandstone. In the western part of its exposure area it is white to light buff; in the central part it is pink; and in the eastern part it is pink and has a buff zone at the top. It is essentially a single massive bed about 50 to 65 feet thick, which commonly shows sweeping cross-bedding. A thin horizontal bed is separable from the massive bed at both the top and bottom of the Entrada.

The Morrison Formation is composed of sandstone and shale and a thin limestone, the Todilto Limestone member, present at the base of the formation in places.

The Todilto Limestone member of the Morrison Formation, is a fine-grained gray limestone, about 15 feet thick. The thin laminations are crumpled and broken, apparently as a result of sliding while the limestone was in the semiplastic state.

In the lower third to lower half of the Morrison Formation sandstone and shale are present in about equal amounts, but locally either sandstone or shale may predominate. The sandstone is light gray, weathering buff or pinkish, is moderately cemented, fine- to medium-grained, and is interbedded with shale. The shale of this lower part of the formation is dark red somewhat mottled with grayish-green.

The upper part of the formation is largely shale and subordinately thin-bedded sandstone. The shale is grayish-green, weathering to an olive-drab color. The sandstone is fine-grained and highly quartzitic. It is gray in color and weathers to a dark gray which is commonly mottled with green.

The thickness of the Morrison Formation ranges from about 250 feet to more than 400 feet.

Cretaceous System

As figure 29 shows, rocks of Cretaceous age occur (1) along the northeastern divide of the Pecos River basin in San Miguel County, (2) as isolated outliers resting on the Chinle Formation in the eastern part of the basin, and (3) around Sierra Blanca on the western divide.

The rocks of Cretaceous age consist mostly of shales and sandstones with thin beds of limestone.

East and northeast of the Pecos River these rocks include the Purgatoire, Dakota, Graneros, Greenhorn, Carlile, and Niobrara Formations. In the Sierra Blanca area they include the Dakota, Mancos, and Mesaverde Formations.

Lower Cretaceous Formations

The Purgatorie Formation has two members: the Lytle Sandstone (lower) and the Tucumcari Formation (or Glecairn Shale). In the northeast the Lytle Sandstone member rest unconformably upon the Morrison Sandstone. The Cretaceous outliers in eastern New Mexico are Tucumcari Formation resting upon the Chinle Formation.

The Lytle Sandstone consists of two units. The lower unit consists of 25-50 feet of white to light buff sandstone interbedded with bluish-gray shale. The upper unit consists of as much as 75 feet of massive cross-bedded white sandstone and thin lenses of conglomerate containing quartz pebbles. The thickness of the Lytle Sandstone member depends upon the topography at the time of deposition. It is probably thickest in the former valleysand thinnest in the uplands.

The Tucumcari Formation consists of about 50 feet of slightly quartzitic brown sandstone interbedded with bluish-gray shale, sandy shale containing abundant marine fossils, and thin beds of calcareous sandstone.

Upper Cretaceous Formations

The Dakota Sandstone (Mesa Rica of Scott, 1970) is a fine- to coarse-grained quartzitic sandstone that commonly contains pebbles of quartz and chalcedonic silica. It is white to buff on fresh surface but weathers to brown or reddish-brown. Cross-bedding and ripple marks are common. Its thickness ranges from 90 to 130 feet. It is gradational with the underlying Tucumcari Formation. In the Sierra Blanca area the Dakota Sandstone may include elements of the Purgatorie Formation in its base and it grades into the overlying Mancos Shale.

In the northeast part of the Pecos River basin the Pajarito Shale overlies the Dakota and grades into the overlying Graneros Shale. The Pajarito Shale consists of as much as 80 feet of gray fossiliforous shale and soft brown sandstone.

The Grancros Shale, Greenhorn Limestone, and Carlile Shale are formations of the Benton Group. The Graneros Shale conformably overlies the Dakota Sandstone. It is a black fissle shale that contains thin beds of bentonite at the top. It also contains thin beds of limestone and shale. It is as much as 215 feet thick.

The Greenhorn Limestone consists of 30 to 50 feet of thin beds of fine-grained, argillaceous limestone and interbedded calcareous shale. It is gradational with the underlying Graneros Shale.

The Carlile Shale occurs over a relatively small part of the Pecos River basin north and east of Las Vegas. It conformably overlies the Greenhorn Limestone. It is a dark gray shale containing large calcarean concretions, as much as 3 feet in diameter, near the top. It also contains a highly fossiliforous zone. Its thickness in the Pecos River is not known, but is 200 feet in Union County.

In the Sierra Blanca area the equivalent of the Pajarito Shale and the Benton Group are the Mancos Shale and the Mesaverde Formation.

The Mancos Shale consists of as much as 400 feet of black fissle shale and thin bedded or fissle limestone with beds of sandstone.

The Mesaverde Formation consists of quartzose sandstone, thin beds of limestone, siltstone, shale, and coal. The sandstone is thin bedded to massive and partly cross-bedded. It is generally coarse-grained, although in part it is poorly sorted. The grains are angular to well-rounded. The shale is fissle, dark colored, and carbonaceous. Bituminam coal is common, but the beds are thin. The thickness of the MesaverdeFormation is as much as 490 feet.

The NiobraraFormation occurs in a very small part of the Pecos River .basin north of Las Vegas and only the 15 foot thick Fort Hays Limestone member is present.

CENOZOIC SYSTEMS

Tertiary System

Eocene (?) series

In the Pecos River basin the Cub Mountain Formation occurs only in the vicinity of Sierra Blanca. It rests unconformably upon the Mesaverde Formation, and igneous rocks dates as Oligocene occur within it. Consequently, Weber's (1964, p. 105) assignment of an Eocene age to the Cub Mountain Formation is tentative.

The maximum thickness of the Cub Mountain Formation has not been established. It is at least 500 feet and may be more than 2000 feet. It is a chert pebble conglomerate overlain by a series of poorly indurated beds of sandstone, siltstone, and varigated shale.

Oligocene series

The igneous rocks of the Pecos River basin (fig. 30) consist of

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Figure 30. -- Igneous rocks of the Pecos River basin

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(1) a relatively old volcanic sequence at Sierra Blanca, (2) a later dike "swarm" in the Capitan-Sierra Blanca region, that is roughly contemporaneous with, (3) massive but shallow plutons scattered through eastern Lincoln and Torrence Counties, plus (4) isolated dikes scattered through the basin.

The bulk of Sierra Blanca consists of as much as 4000 feet of basaltic andesite flows, breccia and agglomerate, into which subsilicic stocks and dikes have intruded.

Elston and Snider (1964) studied the dike swarms in some detail. The following is a condensation of their work:

> The prominent dike swarm between the village of Capitan and Nogal extends from the vicinity of Sierra Blanca some 40 miles to the north-northeast, into the Jacarilla Mountain area. The longest individual dikes are tens of feet wide and about 3 miles long, but the majority are much smaller.
>
> Air photos of the outcrop belts of the Mancos Shale, Mesaverde Formation and Cub Mountain Formation show hundreds of low NNE-trending ridges marked by prominent tree lines. On the ground, each ri·dge turns out to be composite dike, make up of many individual dikes with complex cross-cutting relationships. The ridges are covered by innumerable dark boulders formed by spheroidal weathering of various types of diabase. Outcrops are poor except in cuts along U. S. Highway 380 and the abondoned railroad between Carrizozo and Capitan.
>
> The dikes fall into at least seven types, which are in order of age:
>
> Type 1 - Labradorite-olivine diabase porphyry
> Type 2 - Olivine diabase porphyry
> Type 3 - Diabase
> Type 4 - Hornblende-biotite diabase
> Type 5 - Rhyolite
> Type 6 - Latite grading into trachyte
> Type 7 - Phonolite

According to Perhac (1970, p. 28-30) the magmas that formed the plutons were implanted beneath a sedimentary cover that was 2500 to 3700 feet thick. The plutons consist of masses of alkalic to subalkalic, silicic to subsilicic rocks including rhyolite, trachyte, monzonite, syenite, and diorite.

Elston and Snider (1964) believe the intrusion of the felsitic shallow plutons was probably contemporaneous with the intrusion of the rhyolite dikes.

East of the Pecos River northeast of Roswell are two nearly parallel dikes which are locally known as the Railroad Mountain dike and the Devil's Race Track dike (Semmes, 1920, p. 421-426). Two other horseshoe-shaped sills are known. One, the Dunlap Sill, is in Ts. 3 and 4 S., R. 23 E.; the other is in T. 7 S., R. 19 E. (Semmes, 1920, p. 425-426).

Pratt (1954, p. 143) and Hayes (1964, p. 39-40) describe three igneous dikes in the Castile Formation in secs. 11, 14, and 15, T. 26 S., R. 24 E.

Pratt (1954, p. 146-147) describes the occurrence of (1) possible dikes in the outcrop of Culberton County, Texas, and (2) a sill, 410 feet thick, penetrated by a test hole also in Culberton County, Texas.

Three isolated dikes shown is figure 30 are subsilicic and range from gabbro at Railroad Mountain to trachyte in T. 26 S., R. 24 E.

Thus, with few exceptions the igneous rocks that are of post-Permian age are deficient in silica and could be derived from a common source. Ages determined by radioactive isotopes (Weber, 1971; Kottlowski et al., 1969; and Perhac, 1970) range from 27 to 34 m. y. for Sierra Blanca volcanics and a Gallinas Mountain traychite. We, therefore, treat <u>all</u> post-Permian igneous rocks as Oligocene, recognizing that new data may alter this interpretation considerably.

Late Tertiary and Quaternary Systems

All the post-Oligocene sediments shown in figure 31 consist of

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Figure 31 -- The Ogallala Formation

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clay, silt, sand, gravel, and caliche deposited by conventional sedimentary processes plus sediments associated with collapse structures. Although most of the sediments are the product of aggrading streams, a few deposits -- caliche, lake and playa deposits, and dune sands, etc. -- came about through other processes, some of which still operate.

The aggredation of alluvium has been going on since mid-Miocene. Some of the alluvium material has been deposited and eroded many times. Consequently, the deposits are difficult to distinguish by age. Young alluvial deposits overlie old ones. Mappers attitudes vary. One school maps the age of the alluvium according to the relative abundance of the material present; the other maps only the surfical deposits. Thus, subsequent compilers will show major departures from the age relations shown in figure 31.

Late Miocene and Pliocene series

The only lithologic unit of Late Miocene and Pliocene age recognized in the Pecos River basin is the Ogallala Formation.

Frye (1970, p. 7) wrote,

"The character of the Ogallala deposits demonstrates that they are primarily the product of stream action, probably locally supplemented by eolian activity and periodically interrupted by widespread soil development. Futhermore, the basal part of the formation consists of a series of fills in separate valleys that, in general, trended from west to east. Coalescence of the alluvial fills from one valley to another gradually took place as the individual divides were buried in the progressively thickening alluvial fills. The final integration of the extensive plain of alluviation, permitting an essentially unrestricted lateral migration of stream channels, occurred during the late phase of Ogallala deposition. Some

Frye (1970, p. 7) continued

"elements of the former bedrock topography (particularly in west-central Texas) were probably never buried by Ogallala deposits. The resultant coalescent plain, marked only by depositional constructional topographic features, maintained an equilibrium sufficiently long to permit the strong development of the "Ogallala-climax" soil."

He further commented,

"Although it seems clear that the Ogallala Formation is predominantly a stream deposit and that the sediments were derived from a source in the mountains to the west, there is far less certainty about the mechanism that initiated and terminated the episode of deposition. Smith (1940) has reviewed the several hypotheses and points out that they all involve the relative importance of tectonic factors and climatic change. He also reviewed the relation of Ogallala deposition to several interpretations of Rocky Mountain erosional history. Although agreeing that the subject is controversial, he found the weight of evidence in favor of the interpretation given by Fenneman in 1931. Fenneman (1931, p. 107) summarized his view as follows:

'It may be assumed that at the close of the later cycle the greater part of the province and others adjacent were covered by a continuous graded plain, made by degradation of the mountains and aggradation of the Great Plains. The peneplain (Rocky Mountain peneplain) in the mountain province is believed

Frye (1970, p. 7) quoating Fenneman (1931, p. 107) continued

> 'to correspond in geologic date with the surface date with the surface of the Pliocene sediments that now cover the High Plains.... The country then rose to about its present height, not this time as a mountain range but as a gentle arch ....' "

In the Pecos River basin the Ogallala Formation consists of as much as 350 feet of poorly sorted, stratified, semi-consolidated gravel, sand, silt, and clay (in order of diminishing importance). It is capped by a layer of caliche, which may be as much as 40 feet thick. Where the caliche cap is missing either because it was removed by erosion or because it was never deposited, similar lithologic units are shown as Tertiary-Quaternary or Quaternary age deposits in figure 31. On the cross sections (Plate 2 to 9) no distinction was made. Figure 31 shows the distribution of the Ogallala west of the Pecos as mapped by Bretz and Horberg (1949).

Pleistocene and Holocene series

Although surficial deposits of Pleistocene and Holocene age mantle much of the surface of the Pecos River basin, we shall consider only the Gatuna Formation, alluvium in the drainageways, dunes, caliche, and playa deposits (fig. 32). The upland alluvial deposits and

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Figure 32 -- Pleistocene and Holocene rocks

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the surficial gravels on pediments are so much like the Ogallala Formation that they need no additional discussion.

The Gatuna Formation (Pleistocene?) was first described by Robinson and Lang (1938). They wrote (p. 84-85),

> "The name Gatuna is here given to an assemblage of rocks of various kinds that were laid down in the Pecos Valley in post-High Plains time and apparently

Robinson and Lang (1938, p. 84-85) continued

"after the completion of the maximum cycle of erosion in this valley. The deposits are of terrestrial origin and with them began the process of refilling the Pecos Valley. The dominant material of which they are composed is fine red sand. However the material is largely of local derivation and therefore the character of the source of the material has had a controlling influence on the composition and color of the resulting deposits. Conglomerates, stream gravels, gypsum, and limestone, as well as bedded and unconsolidated sands and silts, comprise this formation. They are gray, purplish, and yellow as well as red. The inclusion of caliche wash has in most places contributed to this formation a slightly paler reddish color than that of the Pierce Canyon redbeds. The name is derived from Gatuna Canyon in northeastern Eddy County, New Mexico. The formation is of Quaternary age.

"The Gatuna formation mantles many places to a depth of only a few feet. In Pierce Canyon it is more than 100 feet thick and it may exceed 300 feet at the head of Cedar Canyon."

Vine (1963, B27-B31), writing about the geology of the Nash Draw Quadrangle, Eddy County, noted the following about the Gatuna Formation:

(1) It is generally thin, 3-5 feet, and is directly overlain by Recent caliche.

(2) It consists of friable sandstone, siltstone, and conglomerate, but locally included gypsum, gray shale, and claystone.

(3) Its thickness may exceed 100 feet.

(4) In some areas where the exposures are small or partly covered, it is difficult to distinguish from the Pierce Canyon redbeds and the Santa Rosa sandstones.

(5) Its deposition followed immediately after, or in part accompanied, a period of active solution in the Rustler and Salado Formations.

(6) It may be equivalent in part to the Ogallala Formation.

Hendrickson and Jones (1952, p. 25) mention that potash test holes have penetrated as much as 200 feet of clay and sand attributed to this formation.

Numerous playa deposits occur within the basin.

In the 1942 Pecos River joint investigation report Morgan and Sayre (p. 34) wrote,

> "In New Mexico, most of the area east of the Pecos River drains into small closed depressions forming innumerable playas and occasional lakes. The material washed into and deposited in these basins for the most part consists of silts and clays. Some of the lake deposits consist largely of gypsite deposited from lakes containing high concentrations of calcium sulphate. Flat Lake, northeast of Artesia, and Laguna Grande de la Sal, east of Loving, are examples of this type of lake. Both lakes contain thick deposits of gypsum and in both, salt is being precipitated from the lake water."

Vine (1963, p. B35) wrote,

> "Playa deposits consist of alluvium and eolian sands reworked by shallow-lake waters. Normally, lakes form in depressions after periods of heavy runoff and

Vine (1963, p. B 35) continued

> "evaporate soon thereafter. Parts of some depressions are occupied by more or less perrenial lakes, of which the largest is Salt Lake (also called Laguna Grande de la Sal on many maps). The level of some of the lakes is maintained, at least in part, by the discharge into them of water and brine from potash refineries in the area."

Robinson and Lang (1938, p. 85) wrote,

> "Laguna Grande de la Sal is a playa. It has been filled in to a depth of 55 feet or more (about 15 feet above the present lake level) with fine crystalline gypsum, that may in part be inwash of detrital material from the upper Rustler gypsum beds but the greater amount is more likely the result of precipitation of gypsum from gypsiferous waters from Nash Draw and the springs that discharge into the playa or perhaps from other sources. These gypsum deposits are sightly calcareous, but near the top of the deposit there is a 6-foot bed of soft pure white caliche overlain by 3 feet of white crystalline gypsum. On the surface of the lowest swales of the playa there is a thin black mud layer which is now mantled by a heavy crust of salt in some places as much as 2 feet thick."

The following description of the Pinos Wells and Encino basins was adapted from Titus (1969, p. 91-92): Pinos Wells basin has a drainage area of about 180 square miles, and in the center of the basin playas occupy two shallow depressions. Dunes composed of material derived from the playas have formed to the east. The basin contains no lacustrine sediment, and no shorelines are evident around the sides of the basin (Smith, 1957, p. 84-86, and Meinzer, 1911, p. 82-84). The sediment of the basin floor and the low divide to the northeast is mostly thinly-bedded silt, sand, and clay, but layers of granule to pebble gravel are interbedded with the finer-grained clastics. Wind erosion tends to leave a pebble pavement that locally protects the surface, a phenomenon also noted by Meinzer (p. 83). The sediment, which is very similar in appearance to flood-plain deposits in the present Rio Grande and Pecos Rivers, is thought to be alluvium deposited by an ancient river.

Encino basin, slightly larger than Pinos Wells basin, was filled by a lake in which more than 20 feet of lacustrine sediment was deposited (Meinzer, 1911, p. 75-82; Smith, 1957, p. 80-84). A single playa depression occupies the center of the valley floor, and dunes of gypsum and clay lie immediately east of the depression. Shorelines were described by Meinzer (p. 77-78). Meinzer (p. 76) found four feet of laminated lacustrine sediment resting on "yellow sand and gravel" in a dug well less than a mile south of the town of Encino. A probable correlative of the sand and gravel, found in exposures about a mile to the southwest, is thinly bedded and silty, and these are thought to be river alluvium.

Dune sand occurs over extensive areas of the Pecos River basin. Morgan and Sayre (1942, p. 34-35) wrote,

> "From the vicinity of Crane, Texas, north to Fort Sumner there is an almost continuous blanket of fine wind-deposited sand spread over an area extending westward from the western escarpment of the High Plains to a line 6 to 12 miles east of the Pecos River. The thickness of the sand mantle ranges from a few feet to 60 feet but the average is about 10 to 15 feet. Darton referred to the sands as the Mescalero Sands."

Nicholson and Clebsch (1961, p. 42) amplified this description when they wrote,

> "Probably much of it has been derived from the Permian and Triassic rocks of the Pecos Valley. The sand is generally fine- to medium-grained and uniformly reddish-brown, but near the base of Mescalero Ridge and in some parts of the San Simon Swale it is white. The difference in color probably indicates that this light-colored sand was derived from the Ogallala Formation. The dunes are stable or semistable over most of the area but are actively drifting in some places. The thickness of the dunes ranges from a few inches to 30 feet, but generally the sand forms a veneer 5 to 10 feet thick. In areas where it is thickest, the lower part of the sand section is semiconsolidated. The cementing agent is probably iron oxide that has been leached from the upper part and reprecipitated below by downward percolating water. The semiconsolidated lower part of the Mescalero sands is observable in blow-outs where the unconsolidated upper portion has been removed by wind erosion."

In De Baca County, where dune sand occurs west of the Pecos River, Mourant and Shoemaker (1970, p. 20) noted that most of the sand grains are quartz, but some are composed of calcium carbonate derived from nearby caliche.

Melton (1940) showed that the dunes of the high plains started forming about 15,000 years ago in response to a wind that blew initially toward S 70° E and gradually shifted to the present N 20° E.

Caliche occurs extensively through the Pecos River basin. These deposits and especially those capping the Ogallala Formation have been studied extensively, most recently by Reeves (1970) and Aristarian (1970). The caliche ranges in thickness from only a few inches to more than 40 feet. It is primarily calcium carbonate, but may include substantial amounts of silica. The variability of the caliche was perhaps best illustrated by Reeves (1970, p. 355), when he wrote,

> "Caliche on the southern High Plains, Texas and eastern New Mexico, may be of Pliocene, Pleistocene, or Holocene age, may have formed on eolian, lacustrine, or fluvial sediments of Pliocene, Pleistocene, or Holocene age, and may range in thickness from only a few inches to several tens of feet. Studies show that all such profiles have formed as part of a pedogenic process.
>
> "Field studies of massive caliche profiles in Mexico, New Mexico, and Texas indicate that all can be classified on the basis of progressive development into young, mature, and old types.
>
> "Considerable overlap may occur, and all types need not be present in any one profile; the parent material, depth and amount of infiltrating surface water and to some extent chronological age, determine the thickness and zonal development of the profile. Relative age is not necessarily correlative with chronological age, but no old-type caliche of Holocene age was found in the investigated areas."

Within the Pecos River basin alluvium occurs in three places:

1. from Fort Sumner to Lake Avalon (the Roswell area),

2. the Black River valley and the lower Pecos River valley (the Carlsbad area), and

3. local drainageways that are remote from the main valley of the Pecos River.

In the Roswell area the maximum thickness of the alluvium is more than 300 feet; in the Carlsbad area it is more than 200 feet thick and may be as much as 300 feet; in the local drainageways the alluvium may be as much as 100 feet thick as at Tarbin (Mourant and Sho maker, 1970, p. 20) but generally is much thinner (10-15 feet) except where talus and colluvium impinge upon the drainageways.

Most discussions of alluvium in the Pecos River basin distinguish between "the older alluvium" and the younger alluvium. In the Roswell area Nye (1933) mapped terraces and distinguished the deposits on these terraces in his text, but mapped them together with a quartzose conglomerate, a limestone conglomerate, high-level gravel deposits, and caliche as undifferentiated deposits of Pleistocene series.

According to Nye (p. 38-39) the limestone conglomerate capping the high mesas near Melena, along Eagle Draw north of Hope and near the heads of Cottonwood Creek and the high-level gravel deposits occurring 15 to 20 miles west of the alluvium basin near the Rio Hondo and the Rio Penasco are of the same general age.

In the area from Lake McMillan to Lake Avalon Meinzer, Remick, and Bryan (1927) and Cox (1967) showed that the limestone conglomerate overlies the quartzose conglomerate. Meinzer, Remick, and Bryan (p. 10) thought the contact between them was unconformable, but Cox (p. 19) says unconditionally, "The contact between the two conglomerates is gradational."

Morgan (1938, p. 170) believed, "that the limestone and quart- conglomerates and associated deposits are remnants of material h made up a single extensive alluvial plain * * * ."

In both the Roswell area and the Carlsbad area the older alluvium consists of quartzose conglomerate plus beds of clay, silt, and sand. It contains caliche.

Accordinging to Cox (1967, p. 19),

> "The quartzose conglomerate consists of pebbles of chert, quartzose, limestone, and igneous rocks with a siliceous sand matrix cemented with calcium carbonate. The pebbles are subangular to well rounded and are as much as 3 inches in diameter. Generally, the siliceous pebbles are more abundant that the calcareous pebbles, and the siliceous pebbles are more rounded. The quartzose conglomerate is well indurated, and the rock in some places fractures across the pebbles. Lenses of calcareous-cemented sandstone occur in the conglomerate. The lenses are as much as 3 feet thick and probably consist of beds of pure matrix and cement.
>
> "The overlying limestone conglomerate contains more limestone pebbles than the quartz conglomerate, and it contains abundant subangular to subrounded limestone cobbles. Generally, the limestone conglomerate contains siliceous pebbles, abundant limestone pebbles and cobbles, and calcareous matrix and is cemented by calcium carbonate. Although well indurated, it is not as resistant to erosion as the underlying quartzose conglomerate."

The principal difference between the two conglomerates is that the quartzose conglomerate in both the Roswell and Carlsbad areas is deformed slumping caused by the removal of soluble material from the underlying Permian rocks.

The deposits of the Blackdom terrace and the Orchard Park terrace consist of up to 20 feet of beds of silt and beds of pebbles imbedded in a matrix of silt and fine sand. The older Blackdom terrace, where undissected, is underlain by dense compact caliche as much as 4 feet thick.

The deposits of the Lakewood terrace consist chiefly of brown silt with interbedded lenses of gravel and sand. Morgan (1938, p. 167) says the maximum thickness of these deposits is unknown, but probably is more than 50 feet.

The alluvial deposits in the remote drainageways consist of silt, sand, gravel, and cobble deposits. The alluvium commonly rests against the bedrock from which it is derived and may grade into, or intertongue with, playa deposits.

Solution and Collapse features

Collapse features are surficial structural phenomena created when the underlying rocks are removed by solution. Thus, solution and collapse features are conveniently discussed together.

For the Pecos River basin these features include:

1. those associated with rocks of the Yeso and San Andres Formations and the Artesia Group; and

2. those associated with the Salado Formation and the Castile Formation.

San Andres-Artesia features

At least 13 published works refer to solution and collapse features associated with the San Andres Formation and the Artesia Group. The earliest mention is by Renick (1926, p. 123), in which he attributes some of the structural features as far west as 6 miles west of Hope to the removal by circulating ground water of beds of salt and gypsum and "certain of the limestones."

In 1933, Nye (p. 83-84) attributed the sink holes northwest and west of Roswell and south of Hope to the removal of gypsum and anhydrite beds by circulating groundwater.

Morgan (1938, 1941, and 1942) concerned himself with the role of solution and collapse in the development of the present Pecos River Valley.

Gorman and Robeck (1946) believe the karst topography of north central Guadalupe County is due to solution of rocks in the San Andres "formation."

Morgan and Sayre (1942, p. 36) discuss briefly the mechanics of solution and the topographic effects of solution in the Pecos valley. Bean (1949, p. 20) attributes the solution and collapse features in the eastern Rio Hondo area to the removal of gypsum and anhydrite and some limestone in the San Andres Formation; those features in the western part of the basin he attributes to solution of gypsum beds in the Yeso Formation.

Hendrickson and Jones (1952, p. 27) paraphrase Morgan. Clebsch (1958, p. 1723) writing about the effect of solution and collapse on ground water movement in western Guadalupe County said,

> "Solution and collapse have profoundly affected the topography and hydrology of western Guadalupe County. Limestone and gypsum in Permian rocks have been removed by subsurface solutional processes that have been intermittently active from Late Permian

Clebsch (1958, p. 1723) continued

"or Triassic time to the present. Where the soluble rocks are exposed, a typical karst topography has resulted; where they are overlain by insoluble clastic rocks, a karstlike topography had developed on sandstone, exhibiting vertical-walled collapse holes, most of which range from a few feet in diameter and less than 10 feet in depth to several hundred feet in diameter and 150 to 200 feet in depth. The largest such feature is a subsidence depression about 6 miles in diameter.

"Principal water-bearing units are limestone of the San Andres formation of Permian age and the Santa Rosa sandstone of Triassic age. The process of solution has created a highly permeable limestone aquifer. The combined processes of solution and collapse or subsidence have served to facilitate recharge in the outcrop area of the limestone and where water in the limestone is under water-table conditions. In one area, rupture of the impermeable bed supporting a high-level perched water body has permitted the perched water to leak to the main zone of saturation. Near the Pecos River, rupture of the confining bed overlying the aquifer is the San Andres formation permits artesian water to discharge to the surface."

Bjorklund and Motts (1959, p. 74-76) extended the work of Morgan (1938) into southern Eddy County and to the development of the valleys of streams tributary to the Pecos River.

Motts and Cushman (1964) discuss the sink holes in the Roswell basin -- an area lying roughly west of the Pecos River to the western divide and between T. 4 N. and T. 22 S. -- in considerable detail. They say (p. 27) the sinkholes and closed depressions are formed

> "by ground water moving upward under pressure through zones of structural weakness and dissolving the soluble rocks, by surface water percolating downward and laterally and dissolving the soluble rocks, and by a combination of these two processes."

Dinwiddie (1967, p. 44) paraphrased Clebsch (1958).

Rustler-Salado-Castile features

Lee (1925) did not distinguish between (1) structural features caused by the solution of gypsum and anhydrite and (2) the structural features caused by solution of salt beds.

Morgan (1942, p. 32) recognized collapse features in the overlying rocks due to the solution and removal of salt from the Sadado Formation.

Moley and Huffington (1953) attribute extensive accumulation of Cenozoic fill in the Permian basin of west Texas and southeastern New Mexico to the solution and removal by circulating groundwater of the underlying salt deposits.

Describing conditions in the vicinity of Rattlesnake Springs, Eddy County, Hale (1955, p. 17-18) wrote,

> "Solution and other erosion probably have removed much of the Castile Formation in this area. The depth to which the anhydrite has been altered to gypsum in the area seems to be between 100 and 200 feet. Many sinkholes and small solution passages exist, the presence of which is revealed by a hollow ring given out as one walks across many of the gypsum beds."

Bjorklund and Motts (1959, p. 74-76) recognize the role of solution and fill in the area south of Carlsbad.

Olive (1957) recognized straight narrow depressions ranging in width from a few hundred feet to 1 mile and in length from about half a mile to 10 miles. He called these features solution-subsidence troughs and attributed them to subsidence to near-surface earth blocks to fill voids dissolved by underground water moving along subjacent drainage channels parallel to the troughs.

Vine called attention to recent domal structures in southeastern New Mexico in which salt solution caused collapse of overlying strata to form a breccia core over which later sediments were draped.

Nicholson and Clebsch (1961, p. 46-47) not only recognize solution and collapse features in Lea County, but also point out that the process is a dynamic one. They point out that the San Simon Swale last collapsed about 1936 and was filling at a rate of about 1 foot every 5 years in 1961.

Leve (1962) wrote, "The surface of the Red Bluff area is modified by Karst features, a result of solution in the underlying Castile and Salado Formations."

Reddy (1961) concluded that the Queen Lake domes near Malaga, "... probably were not formed as a result of differential solution...." He attributed the domes to, "salt intrusion produced by a combination of differential load and tectonic stress."

Vine (1963, p. 38-39) recognized solution and collapse features in the Nash Draw area of Eddy County.

Titus (1969, p. 93) wrote,

> "Pinos Wells and Encino Basins, as well as the previously described circular depression in T. 3 N., R. 11 E. and somewhat smaller depressions in the Yeso terrane to the north, were apparently formed

Titus (1969, p. 93) continued

"by collapse following solution of gypsum in the underlying Yeso Formation. The floors of Pinos Wells and Encino Basins are nearly 200 feet below the levels of their divides. Encino Basin collapsed early enough to have contained a lake ***, but the collapse of Pinos Wells Basin postdates the time the lakes occupied other basins."

The Pecos Trough

Solution and collapse features cause the very high permeabilities that have been observed in rocks of the Pecos River basin. Solution and collapse are also responsible for the present course of the Pecos River. While stream piracy has occurred the primary reason for the presence of thick alluvium and for the relatively straight north-south alignment of the valley is that the river follows a long collapse zone, the Pecos Trough. The so-called alluvium in this trough is really Ogallala Formation that has been preserved. The lithologic cross sections EE' and FF' (Plates 13 and 14) suggest that some Triassic rocks may also have been preserved. A similar argument can be made for the alluvium of the Black River Valley.

The evidence for this conclusion is:

(1) The path the river follows is not the path of the highest gradient after piracy. One would expect that once piracy occurred the river would follow a course dominated by the most precipitative and highest gradient, such as the Rio Penasco. Yet several more favorable courses were apparently ineffectual in altering the river's path.

(2) The sediments referred to as alluvium are contorted, lithified, and are lithologically similar to the Ogallala.

(3) Cross section AA' shows that a sill occurs at the reef-lime bank complex. Efforts to locate a breach in that sill, although data are abundant, failed. Thus, one would expect to find lake or lacustrine

sediments along the sill if the sediments were due to the alluvial mechanics of the river. There is no significant difference in lithology.

(4) Sediment deposits that are the product of Pecos River alluvial processes are totally unlike those of the underlying "alluvium."

Fluid Dynamic Properties of the Rocks

CONCEPTS AND DEFINITIONS

In many ground water studies the emphasis is on specific aspects of water supply. The authors of reports about these studies usually use the terms water-bearing and water-yielding as synonyms. In this report the terms are not synonymous. All rocks in the zone of saturation (below the water-table) are presumed to be water bearing. Only those that yield water to wells are considered to be water yielding.

Three factors determine the occurrence and behavior of subsurface fluids (including ground water). These factors are (1) the dynamic properties of the solid matrix, (2) the chemical and physical properties of the fluid, and (3) the sources and distribution of energy that act upon the fluid. The properties of the rock that affect (1) the rate and direction of ground-water movement or (2) the volume of water that the rock contains at any instant include the porosity, permeability, capillary characteristics, elastic characteristics of the rock, and mineralogy and particle size of the matrix.

Porosity is the ratio of the volume of voids to a given volume of the porous medium.

Permeability is a measure of the capacity of a porous medium to transmit a fluid through the interconnected void space.

The capillary properties of a rock are those that control the capillary pressures. These properties include the size and shape of interconnected pores, the composition of the solid forming the pore surface, and the energy of that surface.

The elastic properties of a rock, especially the bulk modulus of compression, influence the rate of release of a fluid from a rock under transient pressure changes.

The mineralogy and particle size of the matrix determine the size and distribution of the pores and voids, the composition of the pore surface, and the elastic properties of the rock. A change in any of these properties can be induced by chemical reaction of the rock with the circulating fluids or by compaction brought on by overburden loading or by decompression of the fluid system causing irreversible subsidence.

Clearly, if the volume of rock used to measure these properties were sufficiently small, it could be taken entirely from voids or entirely from solids. These definitions presume a sufficient rock volume to insure that the ratio of voids to solids is a constant and that the chemistry-mineralogy is statistically homogeneous. Under these assumptions, the fluid dynamic properties of a rock are presumed to be intensive, i.e., independent of the volume or mass measured.

In practice, however, the properties of rocks are seldom uniform throughout a lithologic or stratigraphic unit. Other factors such as microfacies, bedding features, structural influences (faults, joints, and fractures), solution phenomena, secondary mineralization, and differential weathering -- affect the values one might measure at any point within a lithologic or stratigraphic unit.

Moreover, these primary dynamic characteristics of a rock are not easily measured. In the laboratory we have no guarantee that the measurements are made on specimens of sufficient size to insure the intensive nature of the observation. Field methods generally produce averages of rock volumes so large that they are at best engineering estimates of the dynamic parameters.

Both field and laboratory measurements of the dynamic properties of rocks may be reported in terms of a joint rock-fluid property. For example, data on permeability are often lacking and the values reported as permeability are in fact the hydraulic conductivity of the rock. Petroleum engineers record the permeability of cores in units (L^2) that suggest that this measurement depends only upon the properties of the rock, but many studies have shown that the permeability measured in the laboratory does depend upon the fluid used (Amys, Bass, and Whiting, 1960, p. 91-100; Muskat, 1949, p. 138-142).

In this report permeability data will be converted to either hydraulic conductivity vel expressed in feet per day (ft/d), or to transmissivity area expressed in square feet per day (ft^2/d). Darcies have been converted to ft/d by multiplying by 2.74. Meinzers have been converted to ft/d by dividing by 7.48.

? why not use Darcies or meinzers. ? stupid units, that's why!

In the Pecos River basin information about the dynamic properties of rocks comes from measurements made of cores (tables 3, 4, and 5), from pumping tests and drill-stem tests (table 6), from the lithologic characteristics of the rocks, from the relative yields and specific capacities of wells that draw water from the rocks, and from discharge-gradient relationships.

Pumping tests, drill-stem tests, and discharge-gradient relationships produce values for the coefficient of transmissivity or transmissibility -- the product of the average conductivity and the thickness of the interval tested. From pumping-test data ground-water hydrologists also calculate the coefficient of storage and the specific storage. The quantities are measures of the elastic properties of the rock, from which water discharges. ?

The dynamic characteristic of the rocks that can be inferred from the lithology are at best generalizations: Shales have smaller permeabilities than sandstones. Limestones are denser than evaporites. Dense limestones generally are more rigid than sandstones. Etc.

The yield of wells or springs that penetrate the various rocks is a guide to their dynamic properties. Sustained large yields indicate large permeability. Although low yields can be produced by poor well-construction properties, uniformly low yields from wells tapping the same lithologic unit indicate that the rock has relatively low permeability.

The specific capacity of a well is the ratio of discharge to drawdown. It is a function not only of the hydraulic characteristics of the rocks, but also of the length of time the well has been pumped, external boundary condition, and well efficiency. No truly reliable method has been devised to relate specific capacity to rock properties, but in general we find that wells in rocks with relatively low hydraulic conductivity (0.1 to 1.0 ft/d) have low specific capacities (.01 to 10 gpm/ft), whereas wells in rocks with large hydraulic conductivity ($>$ 10 ft/d) have large specific capacities (100 to 1000 gpm/ft).

In the Pecos River basin, as in most other basins, data on the dynamic properties of the rocks are irregularly distributed. Core data have been obtained for the oil-producing formations and for cores taken from a few exploration tests for water. Drill-stem tests have been limited to the oil-producing formations. Pumping tests have been made on wells tapping only a few of the water-bearing formations and for the most part these tests were made only on those wells with large yields.

Therefore, the paragraphs that follow, being summaries of available information, contain only very general statements about the water-bearing and water-yielding characteristics of the rocks of the Pecos River basin.

PRECAMBRIAN ROCKS

Wells that produce water from the Precambrain rocks have low yields. Smith (1957, p. 19, 23-24, 69-76, 93) found that in the Pedernal Hills the Precambrian rock served as a low-yield aquifer, supplying sufficient water for stock or domestic purposes. One well (6 N. 13 E. 33.414, about 3 miles north of Negra) had a yield of 100 gpm with 60 feet of drawdown while pumping. The quality of the water was less than ideal, but generally was satisfactory for most uses.

Griggs and Hendrickson (1951, p. 38) report that the Precambrian rocks of San Miguel County have not been tapped as aquifers and that only a few seeps and wet weather springs emerge from these rocks. The only well that was drilled (17 N. 14 E. 12.3101) was abandoned after the rocks were penetrated 60 feet. This well pumped about one gallon per minute.

Montezuma Hot Springs (17 N. 13 E. 36.440) discharges more than 300 gpm at a temperature of as much as 131°F from fractures in granites of Precambrian age. The discharge occurs in an area 30 yards wide and 100 yards long on the south bank of the Gallinas River, a tributary of the Pecos River.

PALEOZOIC ROCKS

Pre-Permian rocks

Very little is known about the pre-Pennsylvanian rocks as water-bearing units. Hood (1959, p. 240) says "* * * (they) are not major aquifers in the drainage area of the Tularosa Basin." Judging from their lithology, they ought to yield small quantities of water to wells, where they are saturated. In the subsurface of southeastern New Mexico, they yield oil and gas.

Some information is available on the water-bearing, water-yielding characteristics of the Sandia and Madera Formations in San Miguel County. They yield water of useful quality to wells, but in these formations wells rarely produce more than 100 gpm. However, many springs issue from the limestone, some of them having substantial flow, the maximum being 400 gpm.

Hood (1959, p. 240) wrote, "Little is known of the hydrology of Pennsylvanian rocks in the Sacramento escarpment except that they yield water only to a few small springs and possibly to a few wells."

The subsurface Pennsylvanian rocks yield oil and gas.

As tables 3 and 4 show, the permeability of cores of oil and gas producing rocks of pre-Permian rocks ranges from .00014 to 9.0 ft/d and the porosity ranges from 1.0 to 29.0 percent.

The permeability estimates from 8 drill-stem tests of rocks of Pennsylvanian age (table 6) range from .0002 to .010 ft/d.

Permian rocks

Wolfcampian rocks

Yields to wells tapping the Sangre de Cristo, Bursum, and Abo Formations are notably low. Rarely do water wells in these formations yield as much as 50 gpm. The average yield is less than 10 gpm.

Specific capacities are available for only a few wells in the Pecos River basin. However, these specific capacities. like those elsewhere in the state, are generally less than 1.0 gpm/ft and most are less than 0.5 gpm/ft.

As tables 3 and 4 show, the permeability of the Abo Formation observed in cores from oil fields ranges from .00055 to .40 ft/d, and its porosity ranges from 2.6 to 12.8 percent. Whereas the permeability of Wolfcampian rocks in general ranges from .0027 to 1 ft/d and their porosity ranges from 4.5 to 13.0 percent. The permeability of the Abo Formation obtained from six drill-stem tests (table 6) ranges from .0001 to .005 ft/d.

No wells yield potable water for the Hueco Limestone in New Mexico. Since data are generally lacking, I presume the permeability of this lithologic unit is very low.

Leonardian rocks

The Yeso Formation yields potable water to wells only along the western part of the Pecos River basin. Wells in the Rio Hondo basin and in Guadalupe and San Miguel Counties generally have yields of less than 10 gpm. A well (9 N. 11 E. 6.311) about 10 miles west of Clines Corner in Torrence County was test pumped at 90 gpm for 24 hours with a drawdown of about 30 feet.

In the central and eastern parts of the Pecos River basin the Yeso Formation yields water that ranges from brackish to true brine. In the southeastern part of the basin oil and gas occur in the Yeso Formation. There the permeability of cores ranges from 0.0000 to .37 ft/d (table 3). The porosity of cores ranges from 2.5 to 14.8 percent (table 4). The only drill-stem estimate of the permeability of the Yeso Formation is .0005 ft/d (table 6).

No wells tapping the Bone Springs Limestone yield potable water. No drill-stem test data were available, and only porosity measurements were available for cores (table 5). These measurements ranged from 3 to 12 percent.

The permeability of cores from the "Abo reef" range from .00027 to 5.4 ft/d and their porosity ranges from 1.5 to 18.3 percent (tables 3 and 5).

West of the Pecos River basin in Torrance County, one well in the Glorieta Sandstone has been pumped as much as 2,000 gallons with only 6 feet of drawdown (Smith, 1957, p. 34). However, within the basin wells in the Glorieta Sandstone generally have low yields (2 - 10 gpm). Fritz Spring (Sec. 29. T. 10. S., R. 17 E.) discharges about 400 gpm from the Glorieta Sandstone.

Meager core data suggest that the permeability of the Glorieta Sandstone is relatively uniform, ranging from 0.0011 to 0.61 ft/day (tables 3 and 4). Its porosity ranges from 5.2 to 20.9 percent.

Permeability and porosity in the San Andres Formation range from barely perceptible to virtually infinite. Cores from oil tests indicate that the porosity ranges from 3.2 to 16.0 percent; the horizontal permeability of these cores ranges from 0.00027 to 1.3 ft/day; and the vertical permeability of the cores ranges from 0.00027 to 0.882 ft/day.

In contrast, Havenor (1968) reported the following ranges of porosity at horizontal and vertical permeability from 291 core from a test well which was drilled as part of a program to define the water resources of the Roswell area;

porosity	0.5 to 38.7 percent
horizontal permeability	.0001 to 11.0 ft/d
vertical permeability	.0001 to 11.0 ft/d

Figure 33 is a histogram of porosity frequency of occurrence. It shows

Figure 33 -- Histogram of porosity in cores from San Andres Formation (data from Havenor, 1968)

that the bulk of the measurements were less than 10 percent. The measurements of permeability (fig. 34) distributed as follows;

Figure 34 -- Histograms of permeability in cores from San Andres Formation (data from Havenor, 1968)

ft/day		K_h	K_v
<0.0001		58	88
0.001	to 0.0099	139	133
0.01	to 0.099	53	36
0.1	to 0.99	33	28
1.0	to 9.9	5	5
	>10.0	3	1

The driller reported that during the drilling of this well a cavern was encountered where the bit dropped 16 feet (fig. 35). Throughout the

Figure 35 -- Core recovery in San Andres test (data from Havenor, 1968)

region of the so-called Roswell Artesian Basin drillers report cavernous conditions. We may thus assume that only rarely does the measurement of permeability or porosity in a San Andres core represent an intensive measurement. Moreover, as figure 35 shows. the solution permeability is in the upper 250 feet of the San Andres.

The occurrence of numerous solution and collapse features in the outcropping San Andres together with the occurrence of numerous sinkholes suggests that solution phenomena generally modify the permeability and porosity of the formation throughout its area of outcrop. Geologic cross-sections suggest that over extensive areas rocksalt has been dissolved from the San Andres Formation. Sink-hole development appears to be due more to the solution of gypsum and anhydrite than to be due to the solution of limestone or dolomite. Where overlying formations have protected it, the San Andres Formation is intact and its porosity and permeability are more due to the primary features of lithology and the secondary features caused by fracture than to solution phenomena.

A great many pumping tests have been conducted for water wells tapping the San Andres, but only a few of these have been under carefully controlled conditions. The great majority of tests were initial development tests or were made to determine the pump size.

To utilize these data we ran a series of controlled step tests on wells tapping the San Andres Formation (Summers, 1972). The relation

$$S = AQ + BQ^n$$

describes the drawdown(s) in the pumped well after pumping at a rate Q for some fixed period of time. A is a constant determined by the hydraulic properties of the aquifer and B is a constant determined by the hydraulic properties of the well. For practical purposes n is equal to 2.

By assuming $n = 2$, we can write

$$s/Q = BQ + A.$$

Then s/Q and Q become the dependent and independent variables respectively, and we can use step test data by plotting s/Q versus Q for each step and fitting a straight line through the points. The constant B is determined by the slope and the constant A by the s/Q-intercept of the line. The plot of A versus transmissibility for the controlled test provides a basis for estimating transmissivity from the value of A calculated from the uncontrolled test. The resulting values of transmissivity contain a great deal of noise (Saleem and Jacob, 1971). By using their pattern (rather than specific individual values) in conjunction with transmissivity data obtained from controlled tests and by integrating this data with our knowledge of the geology of the San Andres Formation, figure 36 emerges.

Figure 36 -- Maximum intrinsic permeability and transmissivity of the San Andres Formation

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This figure shows an area approximately 50 miles long and 12 to 20 miles wide in which the transmissivity is greater than 100,000 ft^2/d. This region should be interpreted as one in which cavernous and solution porosity events are a maximum. It should not be assumed that every pumping test in the region will generate a transmissivity of 100,000 ft^2/d or larger. However, the inverse is true; such large transmissivities are very unlikely outside the area delimited. Thus figure 36 shows that the San Andres divides into three units -- high, medium, and low. The permeabilities observed in cores from oil tests more closely reflect the permeability in the "low" region. But even these values are misleading for just as the permeability of the cores from the water test reflects the effects of solution phenomena (fig. 34), Yedlowsky and McNeal (1969) have demonstrated that solution phenomena are evident in the Cato Field (T. 8 S., R. 30 E.), Chaves County. They stated the maximum "interwell permeability" (transmissivity) is about 441 darcy-feet in a zone which is about 50 feet thick. This represents an average permeability of about 0.8 darcies. The maximum permeability indicated in figure 5 of their paper is about 0.3 darcies. Thus wherever solution phenomena occur, the average permeability is much larger than that measured in cores.

Guadalupian rock

The hydrologic properties of rocks of the Artesia Group are in some respects subdued replicas of the San Andres Formation. Where the rocks crop out and are mainly evaporites, solution phenomena are evident and porosity, permeability, and hydraulic conductivities are relatively large. Where the rocks have been protected by overlying rocks, solution phenomena are less evident and porosity, permeability, and hydraulic conductivity are relatively small.

Measurements of cores from oil tests (tables 3, 4, and 5) reveal porosity ranging from 2.4 to 28.9 percent, horizontal permeability of 0.0005 to 11.0 ft/d and vertical permeability of 0.005 to 1.0 ft/d. The only drill-stem test data available indicate permeability of the given formation is 0.0001 ft/d (table 6).

Over most of the Roswell Artesian basin the Grayburg, Queen, and Seven Rivers Formations of the Artesia Group are the aquitard to the San Andres Formation. However, in the southern part of the Roswell Artesian basin these formations seem to contain the solution features that produce the high permeability. For example, Cox (1967, p. 22) estimates the transmissivity of an evaporite facies of the Seven River Formation between Lake McMillan and Major Johnson Springs at 6.7×10^6 ft^2/d. In all probability the zone of high transmissivity in the San Andres continues through the Grayburg and Queen Formations and joins with that of the Seven Rivers in the Lake McMillan area. Unfortunately, semantic difficulties arise because this high permeability zone is frequently correlated with the San Andres Formation. Yields of wells in the Artesia-Bernal decrease northeast and east, and according to Saleem and Jacob (1971, p. 9) about 8 percent of the water that discharges from the Roswell Artesian basin discharges from rocks of the Artesia Group. This estimate is probably too low because Saleem and Jacob equated the high yields with the San Andres. In DeBaca County wells in these rocks generally yield less than 10 gpm (Mourant and Shomaker, 1970, p. 15). Dinwiddie (1967, p. 28) reports yields of 90 gpm in central Guadalupe County. East of the Pecos River where these rocks are capped by rocks of Ochoan age, they produce oil and the permeability is relatively low.

Rocks of the reef-lime bank complex are relatively permeable throughout. These rocks are the source of supply for the city of Carlsbad and several wells yield 1,000 gpm. Hale (1945 a, p. 43, and 1945 b, p. 229) reported a transmissivity of 5.5×10^4 ft^2/d for the area of the Carlsbad supply wells. Specific capacities greater than 100 gpm/ft are not uncommon in water wells. East of the river where the reef-lime bank complex is deeply buried, Brackbill and Gaines (1964, p. 1353) suggest that the permeability is on the order of 16 ft/d. White (1971) reported the specific capacities of 8 wells in the reef in Texas range from 2.5 - 13 gpm/ft.

Rocks of the Delaware Mountain Group have generally low permeabilities. Tables 3 and 5 give the range of core permeability as 0.027 to 0.22 ft/d and a porosity range of 22.5 to 25.2 percent. These values are consistent with the lithology. No potable water wells are completed in these rocks in New Mexico. However, oil tests in Texas, a few miles south, have flowed as much as 835 gpm.

Ochoan rocks

Information about the porosity and permeability of rocks of Ochoan age is remarkably sparse. No data are available for the Dewey Lake beds. Presumeably their permeability is so low that these beds do not easily yield water to wells.

In its outcrop area the Castile Formation yields water to wells, but yields and specific capacities are small. Hendrickson and Jones (1952, p. 64) describe two wells that yield 2 and 3 gpm with specific capacities of .4 and 1. gpm/ ft respectively. In most water resources studies the Castile Formation is considered to be a barrier to the movement of water and is called impermeable (Cox, 1967, p. 17; Bjorklund and Motts, 1959, p. 122). In practice the permeability and porosity of the Castile Formation are probably very low over large areas.

By most definitions the Salado Formation consists of salt and anhydrite, which most investigators simple accept as impermeable (Hendrickson and Jones, 1952, p. 73; Cooper and Glanzman, 1971, p. A6). According to Vine (1963, p. 3, 7-8) the upper leached zone of the Salado may be saturated with brine and locally a prolific aquifer. Robinson and Lang (1938) report that water enters deep wells occasionally and cite as an example a well drilled to a depth of 1725 feet which had an exceptionally large yield of sodium chloride brine for a zone 60 to 90 feet thick.

The diverse lithologies of the Rustler Formation generates a full range of water-bearing, water-yielding properties. Tests on the Culebra member give transmissivity values of 429 ft^2/d at the Project Gnome site (Cooper and Glanzman,1971) and 5.2×10^4 ft^2/day at the Queen's Lake depression (Cox and Havens, 1961). A few miles south of the state line White (1971) says the Rustler Formation has a transmissivity of 2.9×10^3 ft^2/day. Permeability values are on the order of 15 to 90 ft/day.

The coefficient of storage at the Project Gnome site is 2×10^{-5} (Cooper and Glanzman).

Specific capacities of wells range from 1.7 to 20 gpm/ft.

The Dewey Lake redbeds are generally not considered as a source of potable water, brine, or oil. so no data are available on their water-bearing, water-yielding characteristics.

MESOZOIC ROCKS

Triassic rocks

Although the rocks of Triassic age yield as much as 1000 gpm in T. 4N., R. 26 E. (Mourant and Shomaker, 1970, p. 16) and some wells in Guadalupe and San Miguel Counties yield more than 75 gpm. The permeability of the Santa Rosa and Chinle Formations in the northeastern part of the basin is generally considered to be low, thus accounting for the low specific capacities of wells (less than 0.5 gpm/ft) in that area.

In the east central part of the basin, overlying rocks provide sufficient water so that wells virtually never tap the underlying redbeds. However, no data on their water-bearing characteristics are available.

About one-third of southern Lea County depends upon wells that tap the Dockum Group for water supply. Although the yield of these wells may be as much as 100 gpm, the average well yields much less, 25 to 30 gpm, and their specific capacities are probably less than 0.2 gpm. Wells in the area generally penetrate more than 200 feet of water-bearing rock. The permeability appears to be quite low. However tests on wells in Ward and Winkler Counties, Texas, indicate transmissivity greater than 1.5×10^3 ft^2/d and a permeability of at least 25 ft/d. In the Rio Hondo basin wells in the Dockum Group yield 5 to 10 gpm.

Jurassic Rocks

Wells in Entrada and Morrison Formations have low yields of less than 100 gpm and specific capacities less than 0.5 gpm/ft. In Quay County, east of the Pecos River basin, wells in the Entrada have yields of as much as 250 gpm.

Cretaceous Rocks

Although only a small part of the Pecos River basin is underlain by rocks of Cretaceous age, those in Lea County and nearby areas in Texas have transmissivity in the range of 350 to 600 ft^2/d. Wells in these rocks have specific capacities of less than 2.0 gpm/ft.

In San Miguel County wells tapping rocks of Cretaceous age have specific capacities ranging from .005 - 1. gpm/ft.

In the Rio Hondo basin the Dakota Sandstone yields 5 to 125 gpm; the Mancos Shale yields 6 to 75 gpm; and the Mesa Verde Formation yields 5 to 20 gpm.

CENOZOIC ROCKS

Tertiary Rocks

Eocene rocks

According to Mourant (1963) the Cub Mountain Formation yields 5 to 50 gpm to wells.

Oligocene rocks

In general only small yield domestic wells have been completed in the igneous rocks of Oligocene age. However many small springs discharge ground water from igneous rocks in the Sacramento and Capitan Mountains.

Late Tertiary and Quaternary rocks

Late Miocene and Pliocene rocks

The Ogallala Formation yields as much as 2,000 gpm to wells -- the yield being determined by such factors as the saturated thickness of the formation; the amount of sand and gravel in the saturated part of the formation; and the depth, diameter, and mode of construction of the well.

Numerous tests have been made in New Mexico and west Texas to determine the hydraulic characteristics of the Ogallala Formation. Havens (1966) summarized these tests. The coefficient of transmissivity ranges from 800 ft^2/d to 4.35×10^4 ft^2/d; hydraulic conductivity ranges from 2. to 37 ft/d; porosity is thought to range from 30-45 percent. In southern Lea County the state engineer uses values of 1.34×10^4 ft^2/d for transmissivity and 40 percent for porosity.

Pleistocene and Holocene rocks

The water-bearing, water-yielding properties of the Pleistocene and Holocene rocks have a wide range. depending largely on their grain size, distribution , and their thickness. The hydraulic conductivity of playa sediment ranges from 1×10^{-2} to 7.5×10 ft/day and that of sink hole sediment ranges from 1×10^{-4} to 1×10^{-1} ft/day. Sand and gravel have larger permeabilities, as much as 66 ft/d.

The coefficient of transmissivity of the "alluvium" of the Pecos River above Lake McMillan averages about 1.3×10^4 ft/day, that of the Delaware River Valley is about 8×10^3, but wells in both areas have similar yields (up to 1,500 gpm).

Havens (1971) found that the laboratory permeabilities for the surficial deposits overlying the Ogallala Formation ranged from 10^{-5} to 1 ft/day and that their porosity was 43 to 49 percent.

DISCUSSION

The hydraulic conductivity of the consolidated rocks in the Pecos River basin and adjacent areas is determined more by fracture frequency and solution phenomena than by particle size characteristics. Thus pumping tests and drill-stem tests give larger values than those determined on cores or samples in the laboratory. Moreover data on only one formation -- the San Andres -- is sufficient to permit regional mapping of the hydraulic conductivity. However, by combining knowledge of well yields, specific capacities, coefficients of transmissivity, and hydraulic conductivity, crude estimates of the regional distribution of hydraulic conductivity can be inferred. These inferences are presented on Plates 15 through 19. Again cross-sections BB', GG', and HH' have been omitted because of a lack of data.

HYDROLOGY

CONCEPTS

Subsurface flow system in the hydrologic cycle

The basin concept of ground-water dynamics is this: In response to a hydraulic gradient meteoric water infiltrates from the land surface through unsaturated porous media to the water table; at the water table it enters the zone of saturation where it moves in response to a hydraulic gradient until it discharges at the land surface.

Figure 37 illustrates the role of ground water in the hydrologic

Figure 37 -- Ground water in the hydrologic cycle (after Freeze, 1971)

cycle in a relatively simple hydrologic system. Of the precipitation that reaches the land surface most returns almost immediately to the atmosphere as evaporation or transpiration. Some runs off and a relatively small portion infiltrates. Only a portion of the infiltrating water reaches the water table. Under natural undistrubed conditions this water moves from this recharge area to a discharge area.

In the discharge area ground water may return to the unsaturated zone and eventually discharge by evapotranspiration (evaporation plus transpiration). Phreatophytes may convey water directly from the ground-water reservoir to the atmosphere. The ground water may discharge to springs, streams or lakes. It may also discharge through the works of man -- such as wells, galleries, drains, mines, and tunnels -- which change the natural flow system.

Over a long period of time in a natural flow system (without any works of man) recharge balances discharge and the system is at equilibrium despite variations in precipitation. The average annual discharge equals the average annual recharge.

The simplest subsurface system consists of (1) an area of infiltration called the recharge area, (2) an area in which water leaves the ground-water reservoir called the discharge area, and (3) the porous media through which the water moves. The porous media consist of two parts -- the unsaturated zone and the zone of saturation (also called the ground-water reservoir). The water table separates the two zones. By definition the water at the water table is under a pressure of one atmosphere. In the unsaturated zone the pressure on the water is less than one atmosphere. In the zone of saturation the water is under a pressure greater than one atmosphere.

Only water in the zone of saturation is properly called ground water and only the surface where water is at exactly one atmosphere is properly called the water table. Water-bearing rocks extend downward to a depth where the weight of the overlying rocks closes the available void space to the flow of water.

Figure 37 illustrates another important aspect of natural subsurface flow systems: They are three dimensional. Because flow lines are continuous curves in three dimensional space, they are difficult to illustrate. Throughout this discussion flow lines are projected onto two dimensions either as maps or cross sections. The reader should be continuously aware that the maps and cross sections presented in this report represent only the projection of the specified flow lines onto a plane or more precisely represent the two components that operate in the plane.

Complex Flow Systems

Figure 38 illustrates a complex flow system. The flow field

Figure 38 -- Examples of subsurface flow systems (after Toth, 1962)

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divides into three parts (Toth, 1962): (1) the Local flow system where recharge moves a relatively short distance and to the nearest discharge area; (2) the Intermediate flow system where water moves a relatively longer distance to reach its discharge area, moves beneath a local flow to reach its discharge area, and reaches an intermediate depth and; (3) the Regional flow system that has the longest flow lines, underflows both local and intermediate flow systems, and circulates to the greatest depth.

In figure 38 flow lines of a local (or intermediate) flow system may show movement in directly opposite direction to flow in the more extensive underlying intermediate (or regional) system. This reflects the inability of cross sections to show the third component of movement. Figure 39 illustrates the cross sectional and plan view of apparently

Figure 39. -- Plan and cross section of counter current flow lines.

counter current flow lines in an intermediate system. Because figures 38 and 39 show movement in more than one system, the lines (surfaces) that separate systems, called divides, are lines along which no flow occurs in the plane of the section or map. In most cases the flow, if any, is perpendicular to the plane of the map or cross section.

Hydraulic potential, hydraulic head, and pressure

The energy available to move a unit mass of water through the subsurface from land surface until it reappears at the land surface is equal to the energy required to move that mass of water through the vertical distance represented by the elevation difference between the end points.

The work (W) required to move water through this distance (figure 40) is

$$W = m\,g\,H \tag{1}$$

where m = the mass of this water

g = the graviational constant, and

H = the elevation difference.

Figure 40 -- Diagram showing the division of a subsurface flow system and the relation of hydraulic head to flow-line altitude.

Hubbert (1940) demonstrated that the hydraulic potential at any point along the flow path can be represented as a generalization of the Bernouli theorem which relates the elevation, pressure, and velocity along a flow line of a fluid in frictionless flow. In subsurface flow systems, the velocity term is negligible, so the hydraulic potential is the sum of the gravitional and pressure potential, and for liquids is expressed thusly,

$$\Phi = g\,z + \frac{p - p_o}{\rho} \tag{2}$$

where:

Φ = hydraulic potential at any point on a flow line or head for any point in the flow system

g = acceleration due to gravity

z = elevation of the point above sea level

p = pressure at the point

p_o = atmosphere pressure

ρ = density of the liquid.

If a piezometer is placed at any point on a flow line, the pressure at the point will be

$$p = \rho\,g\,(h - z) + p_o \tag{3}$$

h being the elevation to which the liquid would rise in the piezometer. Substitution of eq. (3) into eq. (2) gives

$$\Phi = g\,z + \frac{[\rho\, g\,(h - z) + p_o] - p_o}{\rho} = g\,h. \quad (4)$$

Thus for pure water the magnitude of the potential is equal to the elevation of the water surface in the piezometer times the acceleration due to gravity. The potential Φ is the work required to transmit a unit mass of water from the point of the piezometer to a sea level discharge area.

The quantity $h = \Phi/g$ is called the hydraulic head. It too is a potential quantity and obeys all the laws of potential theory. Since h is an elevation above sea level, it is expresses in conventional units of length (feet, meters, etc.). However we shall follow Freeze's (1964) notation and use

$$\phi = h \quad (5)$$

where:

ϕ (the Greek leter phi commonly used for potential functions) is the hydraulic head as a point in the flow system, and

h = the elevation above sea level of pure water in a piezometer at that point.

For non-fresh water systems liquid altitudes in piezometers must take into account the density difference between the liquid and pure water and as a crude approximation

$$\phi = (h_1 - z)\,\frac{\rho_1 g}{\rho_w g} + z \quad (6)$$

where:

h_1 = elevation to which a fluid rises in the piezometer

ρ_1 = density of the fluid

ρ_w = density of water

g = acceleration due to gravity .

Note: Bottom hole pressure $= (h_1 - z)\rho_1 g$.

In the unsaturated zone a similar argument can be made. However, in the unsaturated zone a tensiometer would replace the piezometer and the pressure would be thought of as a suction, since it is less than atmospheric. Nonetheless the pressure observed is a positive quantity and must be added to the elevation to obtain the hydraulic potential. Thus, the concept of diminishing potential applies over the full length of a flow line -- from land surface in the recharge area to land surface in the discharge area -- in saturated and unsaturated media. The rate of change of potential along the flow line $\left(\frac{-\Delta \phi}{\Delta l}\right)$ is the hydraulic gradient.

In three dimensional space all the points having the same hydraulic head form a surface which we shall call an equipotential surface and which on a cross section or map becomes an equipotential line. No flow can occur from one point on an equipotential surface to another, because flow requires a change in potential. Therefore flow must be across equipotential surfaces and it must be from higher to lower potentials. Flow may be from LOW to HIGH pressure, as shown in figure 40. Water at the water table is at a pressure of one atmosphere. Therefore water moving from point a to point b must be moving toward higher pressure. However water moving from point c to point d moves toward lower pressure. We conclude, therefore, that on a general flow line, ground water moves from low (atmospheric) pressure to a maximum higher pressure and then to low pressure (figure 41).

Figure 41 -- Relation of pressure to position on a flow line.

Figure 42 shows the equipotentials in a cross section through a

Figure 42 -- Relation of water levels in piezometers and wells to potential distribution in a simple flow system

simple flow system and the water levels we would observe in piezometers at points A and B. The water level in piezometer A_1 has elevation h_1 and the water level in piezometer A_2 has elevation h_2. The water level in a well cased to A_1 and open (or screened) to A_2 is

$$\frac{\int_{A_1}^{A_2} h\,dz}{\int_{A_1}^{A_2} dz}$$

which becomes in many cases simply $\left(\frac{h_{A_1} + h_{A_2}}{2}\right)$, that is the average for the interval.

Similarly, the water levels in piezometers B_1 and B_2 have elevations of h_{B_1} and h_{B_2} and the water level in a well open (or screened) in the interval $B_1 B_2$ will have a water level of $\left(\frac{h_{B_1} + h_{B_2}}{2}\right)$.

In both cases the water level does not correspond with the water table. Clearly the only cases where water-level elevations would correspond to the water table are (1) where the piezometer are placed at the water table, and (2) where the equipotential surface is vertical at the water table. In general the water table is a flow line only where it is horizontal and equipotentials are vertical.

Fluid levels in wells are at best only an average of the hydraulic potential in the subsurface interval penetrated. Conversely fluid level and pressure data, whether from water, oil, or gas wells, converted to fresh water potential must be data points from a dynamic flow system.

Streamflow

Streamflow derives from two sources -- ground-water discharge and surface runoff during periods when precipitation exceeds the infiltration or evaporation rate. For individual storm events hydrologists recognize two additional components: (1) channel storage and (2) bank storage. However, these components simply take into account short term storage of water that was derived originally from surface runoff or ground water discharge.

Water is imported to some basins and in these basins the streamflow may include that imported water. This is a special case and will be excluded from the following discussion.

Surface runoff component of streamflow

The surface runoff component of streamflow consists of runoff during storms and snow melt. Figure 43 illustrates the relation of

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Figure 43 -- Diagram of a simple stream basin showing area contributing surface runoff to successive gaging stations

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surface area in an ideal stream basin to runoff in a stream. Because surface runoff derives from the entire drainage area above a streamflow measuring station the volume of stormflow passing successive downstream stations (all other factors being equal) increases with increased drainage area.

Ground-water component of streamflow

In an ideal basin the ground-water component of streamflow is only a small portion of the total runoff, but is considerably more difficult to describe than the surface runoff. Figures 40 and 42 show an inflection point on the water table. Figure 44 illustrates this feature with even

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Figure 44 -- Cross section through the inflection point on the water table

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greater exaggeration. On the recharge side of this point the vertical component of the hydraulic gradient is downward. On the discharge side it is upward. Because this is so, we see that no natural recharge occurs in the discharge area and no natural discharge occurs in the recharge area. Moreover, assuming homogeneity, the rate of recharge is determined by the vertical component of the hydraulic gradient, which is zero at the inflection point and a maximum at the divide. Therefore the recharge rate, all other conditions being equal, will increase from none at the inflection point to a maximum at the divide.

To determine the source of the ground-water component of streamflow we must first define the recharge and discharge areas, as in figure 45. This is fairly easily accomplished through the use of a

Figure 45 -- Recharge and discharge areas in a basin with a local flow system

water-table map. The inflection point of a cross section becomes a line on the map where the water-table contours show a maximum rate of slope change. In many texts the assertion in made that the direction of ground water flow can be determined from the water-table map by drawing continuous lines that cross the contour at right angles. This is true only as an approximation and then only when the streams fully penetrate the ground water reservoirs. In general, streams do not fully penetrate the ground water reservoirs. At best they usually penetrate a very small percent. Consequently, as figure 46 shows the flowlines inferred from

Figure 46 -- Diagram showing the relation of various ground water "flowlines" in plan view

cross sections and from the water table map do not reflect the actual flow path. More importantly (1) as in figure 47 shows the area of recharge

Figure 47 -- Diagrammatic plan view of a river basin showing the relation of recharge area to stream gaged ground water discharge

that contributes to the ground-water component of streamflow has a significantly different shape than the drainage area for the surface runoff component and (2) the ground water component of streamflow increases at a rate which is larger than the rate of increase of recharge area (because the average recharge rate on progressively larger recharge areas in a basin is progressively larger).

In practice streamflow is depleted by two factors - diversion of water for use and evapotranspiration.

In addition to diversion and evapotranspiration, streams in desert and semiarid regions frequently become influent in their lower reaches and instead of receiving a component from the ground water, contribute part of their flow to the ground-water reservoir. Some drainageways never receive a ground-water component and flow only during times of storm or snow melt. Some of these are influent over their entire reach, some over only a part of their reach, and some apparently contribute nothing to the ground-water reservoir.

PRECIPITATION

For the purpose of this report only the precipitation data available through 1966 were used. These data derive from 90 gaging stations in the basin and 91 in the immediately adjacent area. The length of record for these stations ranges from one year for a few stations to 87 years at Fort Stanton. The period of record for Santa Fe, only a few miles from the northern end of the basin, is 101 years.

Unfortunately, since the periods of record for most stations do not overlap in time and vary remarkably in length, simple isohyetal maps are not very satisfying. Stations with short periods of record must be excluded, thereby not only eliminating part of the data, but also reducing the reliability of the resulting map.

Efforts to improve map quality by relating precipitation to elevation, latitude, and longitude proved fruitless as the following data show

Number of stations	Parameters	Correlation Coefficient
181	latitude	-.122
90	"	.330
181	longitude	-.146
90	"	.443
181	altitude	-.111
90	"	.757

Since the best correlation was between the 90 stations in the basin and altitude, the following procedure was used to obtain an estimate of precipitation. (This procedure involved the use of a computer, IBM 360 model 44SE).

(1) The data were sorted according to the altitude of the station. (2) The precipitation for all years of record for all stations in a specified range was summed and then divided by the number of observations. This generated a mean annual precipitation for the altitude range. (3) The mean annual precipitation for each altitude range was multiplied by the area of that range and converted to cfs (cubic feet per second) -- a number which is both a volume and a rate and which is used throughout this report as the measure of average annual water quantities.

The result of this procedure is given in table 7 and figure 48. Thus

Figure 48 -- Relation of precipitation to altitude

the mean annual precipitation on the Pecos River basin is 27,449 cfs. This table also reveals that although the highest rainfall rate in inches/year is at the highest altitudes, the bulk of the precipitation falls below an altitude of 6,000 feet, because most of the surface area of the basin occurs below an altitude of 6,000 feet.

GROUND-WATER DYNAMICS

Water-table

Plate 20 is a water table map of the Pecos River basin and adjacent areas. This map is based upon data from many sources, but mostly those of the U. S. Geological Survey contained in published reports. However it is also based upon unpublished data in the files of the U. S. Geological Survey and the New Mexico State Engineer's Office, U. S. Geological Survey topographic and river survey maps, and data obtained from the Pecos Valley Artesian Conservancy District.

Flow systems

In addition to the water-table map a series of fresh-water potential maps were prepared for elevation slices or slabs 500 and 1000 feet thick. These maps were based on water levels in wells, bottom hole pressures from drill-stem tests made in wells drilled in search for oil and gas, and fluid level reports in drillers' logs.

Water level and pressure data were converted to fresh-water head. For each slice head data were plotted only for wells that bottomed in that slice or for drill-stem tests conducted in the slice. Isopleths drawn through points of equal values produced a contour map of the average potential in each slice.

These maps were then used to draw cross sections. Each slice became a very long thin rectangle in the cross section. The average potential of the slice was taken to be at the midplane of the slab or the horizontal center line of the cross-sectional rectangle. The value of each contour crossing the plane of the cross section was plotted on the center line of its slice. Points of equal value were connected with each other and to the points of equal value at the water table. This procedure produced the line of equal fresh-water potential on cross-sections AA', CC', DD', EE', FF', GG', and HH' (Plates 21 to 27).

These cross sections were then used to delineate both the subsurface flow pattern in the plane of the cross sections and the divides between flow systems. Using these cross sections, the outer limit of the area contributing recharge to the Pecos River in the plane of the section was defined. These points plotted on a map and connected determined the area that is properly called the ground-water basin of the Pecos River. Figure 49 shows the recharge and discharge areas of

Figure 49. -- Recharge and discharge areas of the Pecos River ground-water basin.

the ground water portion of the Pecos River basin in New Mexico. Recharge falling outside this area does not move to the Pecos River in New Mexico.

This procedure identified an area, also shows in the figure, which strongly suggests that ground water in the northern part of the basin discharges to the Canadian River and not to the Pecos. Moreover the configuration of the water table, although not definitive with a 500 foot contour interval supports this suggestion. Additional evidence for the phenomena derive from the observation that the Pecos and its two principle tributaries in the area become influent in the southern part of this area. Streamflow measurements, which will be discussed later, also support the suggestion.

Perhaps of even greater importance the cross sections reveal that meteoric water circulates to great depths. These waters do not discharge to the Pecos River in New Mexico. In all probability they discharge to the rivers of west and central Texas. The amount and rate of movement of the very deeply circulating water is very small.

In the area of the Pecos River drainage basin two distinct ground-water regions coexist.

(1) A local-intermediate flow system that involves the lower Pecos River.

(2) A regional flow system that transports ground water from the Pecos River basin to the Canadian and other rivers of west Texas (including the Rio Grande).

Part of the recharge area that contributes water to the local-intermediate flow system of the lower Pecos drainage basin lies outside the basin.

The following table summerizes the areas involved:

		Area (mi^2)
I. Pecos River drainage basin		26,103
II. A. Lower Pecos River local and intermediate ground water system		15,646
1. Recharge area	10,001	
area west of drainage basin	14	
area east of drainage basin	371	
2. Discharge area	5,645	
B. Area of Upper Pecos River basin (recharge to Canadian River)		3,699
C. Area of recharge to regional ground water system		7,143

Relation to Lithology

Considerations of cross sections showing detailed lithology, permeability, and fresh-water potential suggest that the movement of water through the evaporite and carbonate section has resulted in the removal of the more soluable evaporites. All the chlorides are missing and most but not all of the sulphates. In general the solubility of sulphate (gypsum and anhydrite) decreases with increasing temperature and pressure and increases with increasing salinity. Thus the sulphates tend to remain at depths where pressures and temperatures are greater. The highly permeable zones of the local-intermediate flow systems are the product of solution and collapse phenomena, which in turn are due to the solution first of chlorides, and second of anhydrites. In all probability the solution of carbonates has gone on at a relatively steady rate and is only now beginning to affect the gross permeability of the system.

Roswell Region

In previously published reports (Feidler and Nye, 1933; Hantush, 1957; Saleem, 1971) the discussion of ground water in the "Roswell artesian basin" have been divided into three parts -- the artesian aquifer, the aquitard or aquiclude, and the shallow or alluvial aquifer. The basis for this division lies in the following observed facts:

(1) Deep wells flowed at the land surface; shallow wells did not.

(2) Deep wells were cased through the alluvium and discharged water from Permian age rocks, predominately limestone, which were called the San Andres. Shallow wells were screened in the alluvium. Intermediate depth wells produced water in relatively few cases.

Consideration of the cross sections AA', DD', EE', FF', and GG' (Plates 21-28) shows that

(1) the flow region is continuous

(2) the area of recharge lies both east and west of the area of alluvium (except for an element of recharge which well be considered later)

is this a joke Ha Ha

(3) flow to wells can be segregated from the flow to the streams.

Figures 50 and 51 diagrammatically summarize the flow systems

Figure 50 -- Diagrammatic cross section through the Roswell region before pumping showing the flow system

Figure 51 -- Diagrammatic cross section through the Roswell region in 1972 showing the flow systems due to pumping

before pumping began and as they are now. These figures are based on the cross sections. Figure 50 shows that before pumping began ground water moved from recharge areas on both sides of the river to the discharge area with a relatively shallow divide in the San Andres Formation. It also shows flow in the San Andres underflowing the river and moving in the regional flow system that discharges eastward. Figure 51 shows that three ground-water systems now exist: (1) The remnant of the initial system that recharges east of the river and provides ground-water flow to the river and which sustains the water level of the Bottomless Lakes and Bitter Lake wildlife area, which is here called the East basin system. (2) The "shallow" system which receives recharge from the nearest part of the recharge area to the west (figure 51). (3) The "artesian" system which receives recharge from the central part of the western recharge area. Figure 51 also shows that part of the water which was once underflow is now captured by the "artesian" wells.

Cross section AA' (Plate 21) shows that the ground water which is not intercepted by wells moves to the south and the majority of it discharges at Major Johnson Springs south of Lake McMillian. South of Major Johnson Springs the depth to the divide between the ground water moving to the Pecos River and the ground water moving in the regional system is relatively shallow, less than 1000 feet at the river. Cross section AA' (Plate 21) shows that the Pecos River should be influent south of Fort Sumner. This condition was intimated by Mourant and Shomaker (1970, p. 28), who wrote, "Below the mouth of Taiban Creek to the Chaves County line, the inter-relationship of surface flow, underflow, bank storage, ground-water inflow, and evaporation and transpiration losses is poorly understood." This reach of the river is influent because of the heavy ground-water pumpage in the Roswell area. It was not influent beforehand. Moreover inspection of the equipotential of cross section FF' (Plate 25) suggests that a portion of this water reaches the San Andres and discharges through the "artesian" system.

The argument for this system lies in the observation that (1) no water stages changes have occurred in the Bottomless Lakes, and (2) water level change maps of the shallow aquifer (Ballance et al., 1962, p. 58-59; Hudson, 1971, p. 22-23) show no water level decline at the river. If water were diverted to the west as underflow -- water level change would occur, because the profile is at equilibrium and diversion of water would disturb that equilibrium. That there is no diversion to the "artesian" system is clearly indicated by the failure of any potentiometric map or cross section to show a continuous potential decline from the east to the system. Some recharge from the river has been induced and is discussed under the heading "induced recharge."

The reef-lime-bank complex

Figure 52 is a diagrammatic cross section along the strike of the

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Figure 52 -- Diagrammatic cross section along the strike of the reef-lime-bank complex

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reef-lime-bank complex from the state line in Range 21 East to the Lea-Hobbs County line in Township 19 North. This diagram shows the relationship of the ground-water flow systems to the reef-lime-bank complex. It shows (1) the complex is part of the Pecos River ground water system only on the west side of the river. For the most part the complex is in a much larger regional system. (2) Over its outcrop the complex is in the recharge area. (3) Equipotential lines on cross section CC' (Plate 4) suggest that ground water is discharged from the reef in its lower reaches.

Streamflow data

The U. S. Geological Survey maintains (or has maintained) continuous recording gages at a number of stations on the Pecos River Drainageways. Figure 53 shows the location of gaging stations or

Figure 53 -- Locations of streamflow gaging stations recording the flow of surface runoff only

drainageways which discharge surface runoff only. Figure 54 shows the

Figure 54 -- Locations of streamflow gaging stations on the Pecos River basin

locations of gages on the Pecos River proper. The discharge at these stations is made up of both surface runoff and ground water components.

For these gaging stations a procedure was devised by Dr. Allan Gutjahr, statistician, and myself (which will be published in detail later) which takes advantage of the flow duration data to determine the average annual contribution for each component. When the logarithm of flow in cfs is plotted against cumulative frequency, a smooth curve usually results that appears to be the union of two straight lines. Moreover if both the surface runoff and ground water contributions are log-normally distributed, their individual distribution would be straight lines on probability paper. Thus if surface runoff makes up n percent of the flow, then ground water must make up (100 - n) percent, and the value of the frequency of a particular flow must be made up of n times the surface runoff plus (100 - n) times the ground water. By taking advantage of the fact that at low flows streamflow consists mostly of the ground water component and at large flows it is made up mostly of surface run-off, the flow duration curve was divided into two components which were log-normal and which when summed generated an approximation to the observed curves. Although the fit of the approximation and observed curve wasn't always ideal, the mean calculated using the mean of the computed components were within 10 percent of the long term mean reported by the U. S. Geological Survey in the annual reports or the mean computed in conventional fashion using the flow duration data. Thus we believe that the segregation prodecure provides a reliable basis for calculating the average annual surface runoff and the average annual ground water discharge passing a gage for which sufficient data are available. These separations form the basis for the discussion of the hydrologic budget.

Areas contributing to surface runoff

Surface runoff in the Pecos River basin is to drainageways that are continuous with the main channels, to drainageways that terminate in sink holes, and to drainageways that terminate in large closed depressions. Figure 55 distinguishes the area of the surface water basin that contributes

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Figure 55 -- Area contributing surface runoff to the Pecos River

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to surface runoff from the area that is non-contributing. Table 8 gives the areas of the drainage basin as delineated by planimeter measurements on a map having a scale of 1:500000.

Summarized these areas are:

		Area (mi.^{2})
I. Pecos River drainage basin		26,103
II. Area above gage (4075)		
A. Contributing	18,405	
in Texas	-32	18,373
B. Non-contributing		
east	3,167	
west	2,843	6,010
II. Area in New Mexico below gage	1,720	1,720

Perennial streams at high altitudes

Several perennial streams (such as the Rio Hondo, Rio Bonito, Tecoleta Creek and the Gallinas River) are the product of local ground water flow systems at relatively high altitudes. These streams become influent in their lower reaches. They contribute only surface runoff to the main channels of the Pecos River. The infiltrating stream flow becomes ground-water recharge.

Hydrologic budgeting

To account for all the ground water we must recognize that ground water discharges to wells and to the streams. However water is diverted from the streams to irrigate corps and part of the diverted water comes from the ground-water component of the streamflow. In part of the discharge area water discharges at the maximum potential rate, because water is continuingly available. Again however part of that water derives from surface runoff and part from ground-water discharge. Therefore the mean annual streamflow at a gaging station can be thought of as

$$Q_t = Q_o + Q_u$$

where:

Q_o = the observed mean annual discharge

Q_t = the discharge that would have passed the gage if diversion and evapotranspiration were zero

Q_u = the ground water and surface runoff that are used up or returned to the atmosphere either by evapotransipation from the discharge area or through irrigation and subsequent evapotranspiration through crops.

This equation also can be written

$$Q_t = S_t + G_t = S_o + G_o + S_u + G_u$$

where S and G are the surface runoff and ground water components of streamflow.

$$S_t = S_o + S_d + S_{et} - S_p$$

$$G_t = G_o + G_d + G_{et} - G_p$$

where

G_t and S_t	=	total component
G_o and S_o	=	observed component
G_d and S_d	=	portion of surface runoff component diverted for irrigation
G_{et} and S_{et}	=	portion of surface runoff component returned to the atmosphere by evapotranspiration
G_p	=	portion of the pumped ground water derived from ground-water storage
S_p	=	surface runoff due to pumping more water than the crops used in life processes.

To apply these equations to the Pecos River gaging stations requires that we make the following assumptions:

1. The maximum evapotranspiration rate is the mean potential evaporation determined by Hantush (1959, p. 25) (table 9) and it applies to 1.7 percent of the discharge area.

2. The diversion of water uses up 2.5 acre feet of water per irrigated acre.

3. The ratio of G_d/S_d and G_{et}/S_{et} is generally the same as the ratio of G_o/S_o determined from the flow duration data.

The assumption that 1.7 percent of the discharge area operates at a maximum evapotranspiration rate is based on the recognition that the length of the river through the discharge area shown in figure 49 is about 280 miles. Therefore, recognizing that within this reach are 4.8 square miles of reservoirs, 150 square miles of salt cedar, plus many perennial lakes and ponds, the effective discharge area was taken to be a strip of land 1/3-mile wide straddling the river. This strip represents 1.7 percent of the discharge area or 93 square miles. If the entire discharge area evapotranspires runoff or ground water at 1 percent efficiency of the potential, the resulting discharge would be 150 cfs; whereas assigning all the discharge to 1.7 percent of the area at maximum efficiency gives 151.6 cfs. Saleem and Jacob (1971, p. 42) estimated the consumptive salt cedars' use for 1937 to 1968 in the Middle basin (above Lake McMillan). Their average is about 134 cfs. The area of salt cedars had evapotranspiration losses of about the same magnitude before the salt cedar became effective. Salt cedar losses would account for about half the average evapotranspiration loss. I believe the estimate based maximum potential applying to 1.7 percent of the discharge area gives a conservative estimate of the mean annual loss for any reach of the Pecos River.

The justification for choosing 2.5 acre feet/acre (.00414 cfs) lies in two facts. First the potential evapotranspiration estimated by Hantush and reported in table 9 averages 2.82 feet per year. Since the growing season is somewhat less one would expect the actual use by plants to be somewhat less. In practice U. S. Geological Survey data for station 3850, Fort Sumner main canal, show that for 1960 to 1968 the average delivery rate was 34398 acre feet. This water was used to irrigate 6600 acres. A low flow station (3855.20) on the Pecos River monitors ground-water discharge and the return flow from the Fort Sumner main canal. It provided data on 60 months over a period of 10 years. Using these data to obtain an average month and multiplying by 8.7 (number of months the drain operates) we obtain the average low flow for an average year (19068 acre feet). Of this amount approximately 8000 acre feet was ground-water flow estimated to have passed gaging station 3845. Therefore 23330 acre feet or 3.5 acre feet/acre of the diversion are not accounted for. Allowing 1.0 acre feet for seepage gives 2.5 acre feet/acre as a reasonable value to use in estimating G_d and S_d. Saleem and Jacob's (1971) data suggest a rate of 1.7 acre feet/acre.

The procedure for estimating S_t was to obtain from the flow duration data n and the mean, S_m, for surface runoff normal distribution; for each gaging station

$$S_o = nS_m.$$

These values are given in table 10. To determine S_d, the acres irrigated by diversions of streamflow above each gage was determined from the U. S. Geological Survey publication "Water Resources Data for New Mexico, Part 1, Surface Water Records, 1961 to 1969," modified by information from other sources. The increment of area between successive gages was determined and the rate of application of the surface runoff component for that area is then

$$\Delta S_d = 2.5\ n\ \Delta A_I$$

where A_I is the irrigated area between successive gages.

For each gaging station $S_d = \Sigma \Delta S_d$ as shown in table 11.

To determine S_{et} the area of the discharge area between successive gaging stations, ΔA_d was determined.

$$\Delta S_{et} = .017 \times \text{Potential Evapotranspiration} \times \Delta A_d.$$

For each gaging station

$$S_{et} = \Sigma \Delta S_{et}$$

as shown in table 12.

Table 13 contains the estimated values for S_t obtained by summing S_o, S_d, and S_{et}. Table 13 also contains S_p -- that portion of surface runoff derived from pumping wells in excess of the volume required for irrigation; this value was assumed to be 0.7 acre feet/acre. This estimate was based on the difference between average annual pumping (3.2 acre feet/acre) estimated from Saleem and Jacob's (1971, p. 55) data and the estimated water consumption (2.5 acre feet/acre). The 3.2 acre feet/acre estimate also seemed reasonable in the light of Mower's (1959, p. 127) data which generate an average of 2.8 acre feet/acre for the period 1938 to 1954, but which show a distinct trend toward increasing pumpage for irrigation (1.7 acre feet / acre in 1938 to 3.7 acre feet/acre in 1954).

Unlike S_{et} and S_d, S_p is taken to be a term applied only to the gaging station above which the irrigation took place. This term represents a local ground-water input to the surface water runoff. I believe that since the water would have discharged naturally downstream, the effect needs to be compensated for only in the area where it actually occurs. The effect on the flow duration data for the next station downstream is small.

Tables 10, 11, and 12 give the computation of G_o, G_d, and G_{et}. Table 14 gives the computation of G_t. It includes a term G_p, which represents the ground water pumped from storage.

To approximate this quantity, Saleem and Jacob's estimate of the water level decline (p. 56) for the period 1926 to 1969 (40 feet in the "shallow" aquifer) was applied to the area of the alluvium (682 mi^2) and divided by 44 years to give an annual rate of release from storage (porosity of 10 percent) of about 54.8 cfs for the alluvium.

Their water level change in the "confined-artesian" wells (52 feet) applied to the total discharge area (2556 mi^2) with a coefficient of storage of .00005 produced an annual release from storage of .13 cfs -- a negligible quantity.

The net change of water level in the non-alluvium segment of the discharge area can only be postulated.

Water level change data for wells west of the alluvium and in the discharge area are remarkably sparse. Limited data suggest that the water level decline due to pumpage at 10 S. 20 W. 16.444 began in 1961 and changed about 4 feet in 7 years. If the average water level change at the center of pumpage is 52 feet over 44 years and 4 feet during 7 years, then the average water level over the area is approximately

$$WL = \frac{52 - 7}{\ln 52 - \ln 7} = 22.4 \text{ feet.}$$

The area of decline is 1874 mi^2. The porosity is 1 percent. Therefore the ground water released from storage in the limestone terrane is 6.1 cfs and the total release from storage in the discharge area is 54.8 + 6.1 or 60.9 cfs.

For the purpose of a long term average no water was derived from storage in the recharge area. Water level data for 18 wells in the recharge area are available for various periods of time beginning about 1956. In these wells water levels fluctuate over a range of 3 to 10 feet. In 1969 water levels in 6 of these wells were at or near their all time high. Consequently I assume that these water levels are responding to climatic variations in recharge rather than to pumpage in the discharge area.

The depletion from storage in the Carlsbad area is estimated from the estimated water level decline reported by the state engineer, using a porosity of 10 percent.

Discharge-drainage area relationships

When the G_t, S_t, and Q_t are plotted against the cumulative areas of table 15, figure 56 results. This figure shows that the discharge from

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Figure 56 -- Total streamflow, total surface runoff component, and total ground-water component versus drainage area above gage

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the upper 2000 - 4000 square miles of the Pecos River basin does not relate well to the lower part of the basin. By subtracting the area and discharge observed at station 3830 from down stream stations (table 16) and plotting the results, figure 57 results. This figure shows a nearly ideal

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Figure 57 -- Total streamflow, total surface runoff component, and total ground-water component versus drainage area of the lower Pecos River basin

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linear relation of discharge with increasing area and passing through zero for both coordinates. Had the area been chosen somewhat larger the fit would have been still better.

The relationship of the flow components of station 3860 to its neighbors demonstrates the effect of influent seepage that returns to the stream from which it was originally derived. The perturbation is local and has little influence on the downstream discharge-drainage relationship.

Stations 3955, 3965, and 3995 show anomalously high total and surface runoff. This anomaly is probably the result of pumpage in excess of the 3.2 acre feet assumed and for which the 0.7 acre foot correction was made. To bring these values into full accord a greater unused discharge rate somewhat differently distributed would be necessary. However, the complete record of the downstream stations suggests that the pumped water would have actually discharged downstream, so again we have a clear indication that locally anomalies do not adversely affect the cumulative discharge-area relationships. Moreover, the general accord of the data supports the contention that the basic assumptions are essentially correct. Efforts to produce consistent results using values other than 2.5 acre feet/acre for irrigation consumptive use produced much less consistent plots and data distributions that could not be rationalized without calling upon conditions that contravene those supported by available data.

Induced recharge

Figure 58 is a map of the Pecos River basin showing the recharge

Figure 58 -- Map of the Pecos River basin showing the recharge and discharge areas of the lower Pecos River basin

and discharge areas of the lower Pecos River basin, and the areas of sink holes and infiltration in the western half of the drainage basin. In the discharge areas pumpage has reversed the natural hydraulic gradient and recharge occurs now where it did not under non-pumping conditions.

Figure 57 suggests that infiltration from the Pecos near Acme (station 3860) is about 180 cfs, most of which is ground water that discharged or would have discharged to the river upstream from the gage.

Another source of induced recharge is the storm runoff that crosses the discharge areas. In years past this water would not have become influent. In fact for 7 of the 11 stations reporting storm discharge only, there appears to be no infiltration loss. As figure 59 shows, these 7

Figure 59 -- Relation of surface runoff areas for stations that do not discharge ground water

stations show a clearly linear relation between drainage area and mean discharge. However, 4 flows which cross the discharge area where infiltration is common show a combined loss of 44 cfs. Arguing that (1) 4 of 6 of the arroyos are in the discharge area, (2) these are representative, and (3) approximately 18 arroyos cross the discharge area, the total estimated induced recharge becomes

$$\frac{4}{6} = \frac{x}{18}, \quad x = 12,$$

the number of infiltrating arroyos. Therefore if the mean annual infiltration rate is 11 cfs per arroyo, the induced recharge to 12 arroyos is 132 cfs.

Natural recharge

Tables 10 through 16 deal with discharge phenomena. However, these data, combined with our knowledge of the location and extent of the recharge area, provide the information required to estimate recharge volumes and rates.

Because the recharge rate increases from 0 at the inflection point to a maximum at the divide, our most accurate determination is at best an average rate. Furthermore, since only the recharge area nearest the discharge area contributes to the discharge in the upper reaches of the stream, only the lower recharge rate contributes to the discharge. In the middle reaches of the stream, large recharge areas -- including areas near the divide with higher recharge rates contribute to the discharge. In the lower reaches nearly the entire recharge region contributes at the highest average rate. We should expect, therefore, that dividing the total ground-water discharge component, G_t, by the apparent recharge area for an upstream gage would produce a number which is too small, because

(1) The area is the apparent area and is larger than the actual area that provides recharge for the stream to discharge.

(2) The average recharge rate on the actual area is smaller than the average for the apparent area.

As progressive downstream stations are considered, the calculated recharge rate will approach the actual average as the actual area approaches the apparent area. When the actual area and the apparent area become identical, further increases in area will produce no increase in the calculated average. Table 17 gives the areas in square miles of the recharge areas and discharge areas in the Pecos River basin. Table 18 gives the apparent average recharge rate calculated by dividing the total ground-water component (G_t - 68.9) observed at a gage by the apparent recharge area. The large value of .089 cfs/mi^2 suggests that the recharge area delineated is too small by about 500 square miles. A small change in the eastern boundary of the recharge area where data are scanty would provide the additional area, but would not change the other results presented here appreciably.

Except for the Acme station the relation seems to remain constant (0.06 cfs/mi^2) for gaging stations 4020 to 4075. This rate, however, is misleading, because recharge has been induced in the discharge area as a consequence of pumping ground water. The natural recharge estimated must be reduced by the amount of induced recharge. For the contribution of the Pecos River in the vicinity of Acme (3860) no correction need be made. This water would have appeared as ground water in our computation in any event. However the affect of induced surface runoff from arroyos must be discounted. Therefore, applying the correction to the most downstream station (4075), we get an average annual recharge rate on the recharge area of .0465 cfs/mi^2 or .63 inches. If we allow for an additional 500 square miles of contributing recharge area the rate would be .0443 cfs/mi^2 or 0.6 inches per year. Thus no significant error will be introduced if we take 0.6 inches per year to be the natural recharge rate in the recharge area.

Artificial recharge

Cushman and Motts (1964) studied the possibility of enhancing recharge by diverting runoff to sink holes. As figure 58 shows, sink holes occur in both the recharge and discharge areas. According to Cushman and Motts' observation the recharge occurs almost immediately in some sink holes, but in those with a clay build-up in their bottoms recharge occurs rapidly only when the water level is above the clay bed. For sink holes with clay the recharge rate is very slow (on the order of 9.1×10^{-3} ft/day). On the assumption that the total area of sink holes is about 40 square miles in the western half of the basin, the total recharge through the clay is only about 3.9 cfs. Any effort that will increase this rate would be beneficial, for as Cushman and Motts point out, 30 to 70 percent of the water that stands in these holes is lost to evaporation.

Two factors determine the actual recharge rate in a sink hole, (1) the surface runoff, and (2) the infiltration rate. For example, suppose that a hypothetical sink hole has a drainage area of about 20 square miles. The annual average discharge into this sink hole could be, therefore, as large as 0.5 cfs (from figure 59). Suppose too that storage in the sink hole is about 87 acre feet (the same as San Juan sink hole), which is equivalent to .13 cfs. We would expect if runoff occurred once each year about .37 cfs to infiltrate after ponding and about .06 cfs to infiltrate from the pond.

In practice runoff occurs sporadically and sinks seldom fill to capacity. Therefore, evaporation losses are larger and infiltration volumes are smaller. To increase the recharge rate, either the infiltration rate must be increased or drainage from a larger area must be diverted to the sink hole.

In most cases neither technique is practical, moreover the cost to achieve recharge by treating each hole individually would be very large per cfs added.

A more convenient method to increase recharge would be to keep water flowing over the infiltrating reach near Acme, which is dry about 15 percent of the time. This would increase the induced recharge about 20 cfs at no additional cost.

Total Pecos River Budget

Table 19 accounts for the water derived from precipitation above the lowest gage (4075). The underflow was estimated using the recharge area and a recharge rate of 0.0440 cfs/mi^2. The underflow estimate is probably too low, because the recharge rate should be somewhat higher in the areas of recharge that contribute to underflow.

Thus, of the total precipitation in the basin 5.82 percent is accounted for. The remainder must be lost almost immediately to evaporation and transpiration.

The term Q_t at station 4075 (1078.5 cfs) is therefore the total water that will be available in the Pecos River basin above gage 4075 -- without evaporation, transpiration, or diversion.

Roswell area ground-water budget

The area west of the river and north of station 4020 constitutes the Roswell basin. Its area includes 75 percent of the area above the gage and the recharge area receives 75 percent of the precipitation (Table 20). The recharge area has an area of 7310 mi^2 and the recharge rate is .0465 cfs/mi^2. The discharge area is about 3468 mi^2. The total area is 10778 mi^2.

The rest of the drainage area above the gage and east of the river is here called the East basin. The recharge area of the East basin is 2112 mi^2; the discharge area is 1132 mi^2; the total area is 3244 mi^2.

The following table gives the ground-water budget in cfs for the "shallow," "artesian," and East basin flow systems of the Roswell area.

	Ground water system (cfs)				
	Shallow	Artesian	Roswell basin total	East basin	Total
Recharge					
natural	19.6	320.3	339.9	98.2	438.1
induced	174.1	136.9	311.0	---	311.0
	193.7	457.2	650.9	98.2	749.1
Discharge to					
Consumptive irrigation	157.7	285.6	443.3	---	443.3
ET	36.0	---	36.0	12.0	48.0
Stream flow	---	---	---	61.8	61.8
Pumped to runoff	54.8	90.7	145.5	---	145.5
Storage	-54.8	-6.1	-60.9	---	-60.9
	193.7	370.2	563.9	73.8	637.7
Underflow	0	87.0	87.0	24.4	111.4

This table is deduced from the data previously presented. It is based on the conclusion that since water is being pumped from storage in the shallow system, no streamflow discharge occurs. A second assumption is that no streamflow discharge of the East basin flow system becomes induced recharge to the shallow flow system. In practice this assumption probably is not true, but allowing for induced recharge would change the figures in various columns, but would not alter the conclusion that underflow is about 111 cfs. However, increasing the estimated volume of water pumped to runoff would decrease the amount of underflow significantly. If, for example, the volume of ground water pumped to surface runoff is twice as large, no underflow would occur.

Fiedler and Nye (1933, p. 250-253) report that the average groundwater discharge before pumping consisted of

	cfs
Benendo Springs	65
North Spring	85
South Spring	60
Rio Felix, Rio Penasco, and Seven Rivers	20
Unaccounted gain in Pecos River from Acme to Rio Penasco	50
Major Johnson Springs	40
Other springs	5
total	325.

Allowing 101 cfs for underflow and 48 cfs for evapotranspiration, the estimated natural discharge (which should equal the natural recharge) of the basin would have been at least 473 cfs. This compares with the present estimate of 438 cfs. This is excellent agreement and the difference could easily be accounted for by the over-pumpage.

Using a different procedure, Hantush (1957, p. 52) estimated annual recharge in the Roswell artesian basin (the area west of the river above gaging station 4020 in this report) for the years 1941 to 1953. His average of 354 cfs compares favorably with the 339.9 cfs estimated here.

According to D. Rabinowitz (personal communication, 1972), his analysis of tritium isotope budget suggests a normal natural recharge of 270,000 ± 30,000 acre feet per year (373 ± 41 cfs). This compares with 339 cfs estimated here.

Saleem and Jacob (1971) estimated the average annual recharge in the "principal confined aquifer" as 240,000 acre feet and the "shallow aquifer" as 28,000 acre feet. The sum is equivalent to an average annual recharge rate of 370 cfs, 30 cfs more than is estimated here.

Thus the recharge determined here agrees with others as follows

	percent
Fiedler and Nye	92.6
Hantush	96.0
Rabinowitz	91.1
Saleem and Jacob	91.9.

Ground-water budget of the Carlsbad basin

The Carlsbad basin is the name used here to designate the basin area between gaging stations 4020 and 4075. The following table gives the ground-water budget for this basin (assuming a recharge area of 580 square miles and a recharge rate of .0465 cfs/mi^2).

	cfs
Input	
Underflow	111.4
Natural Recharge	27.0
Induced Recharge	82.9
	221.3
Discharge	
Pumpage consumed	73.5
ET	41.0
Streamflow	-32.9
Pumped to runoff	12.5
Storage	-19.0
	75.1

table (continued).

	cfs
Underflow	146.2

This budget is also based upon data previously presented. If the underflow from the Roswell-Artesian area is indeed negligible and if the volume of ground water pumped to recharge is also underestimated, then the underflow from Carlsbad basin is substantially less than the 146.2 cfs cited. However, I believe that for the long-term average we are dealing with in this report, the estimations presented are substantially correct. The 146.2 cfs is underflow that discharges to Red Bluff Reservoir or to the Pecos River downstream from the reservoir.

The Upper Pecos ground-water budget

The Upper Pecos ground-water basin consists of an area of about 3300 square miles above Alamogordo Reservoir, but for the purpose of this report is considered to consist of the 2870 square miles above gaging station 3830, of which 1641 square miles are recharge area and 1229 square miles are discharge area. In the following budget natural recharge is estimated at the same rate (0.044 cfs/mi^2) as for the lower basin. This rate is probably too low. The induced recharge is estimated from figure 56, using the following argument. A straight line through the origin and the total flow points for the lower basin should pass through the total flow points for stations 3785 and 3795, or the total flow points should all be on the same straight line which does not pass through the origin. We expect this latter case because all the flow has been accounted for and therefore the cumulative flow at downstream stations should increase systematically. Any station which fails to show an increase must either be influent or receive no discharge from either the drainage area or the recharge area that is added between the gages. This is truly unlikely. Any influent loss should reappear downstream and the data for the station below an influent reach should fall below the straight line drawn through the origin, because influent losses are only apparent losses. They reappear downstream. The influent loss depresses the curve in the influent reach.

Station 3795, however, has a total flow that is about 120 cfs larger than we would predict using downstream data. This 120 cfs must become underflow. Of the 196 cfs of recharge above station 3795 we account for the entire portion at gage 3830. We conclude therefore that no underflow occurs between the upper and lower basins.

	cfs
Recharge	
natural	76
induced	120
	196
Discharge	
Streamflow	112
ET	48
Consumptive Irrigation	41
	201

Figure 60 compares the total discharge-area relationship of the Lower Pecos and the Canadian computed in identical fashion. The Canadian appears to have discharge that is 80-90 cfs larger than the Lower Pecos. This difference is most probably due to recharge in the Upper Pecos in excess of that predicted by the average recharge rate. The fact that the estimated discharge at station 3830 is slightly larger than the estimated recharge suggests that the recharge estimate is too low. Moreover, estimating the recharge rate for the area above station 3785 by simply dividing G_t (4.4) by the recharge area (126. mi^2) gives an apparent recharge rate of 0.035 cfs/mi^2. If to this we add .005 cfs/mi^2 (obtained by dividing the 90 cfs excess of the Canadian by the 1641 square miles of recharge area in the Upper Pecos basin) we get an average recharge rate of .09 cfs/mi^2 (1.2 in/year) which is consistent with the topography and the precipitation. I conclude, therefore, that the difference in the discharge-area relationship between the Pecos and Canadian Rivers is due to recharge in the Upper Pecos drainage area.

Figure 60 -- Relation of Q_t to drainage area for the Pecos and the Canadian Rivers, New Mexico

INFERENCES ABOUT WATER CHEMISTRY

The "artesian" system

Figure 51 shows that in the artesian system wells along the eastern edge of the system discharge water that has traveled from the western edge of the recharge area along the deeper and longer flow lines. This water has circulated through evaporites (including salt) that occur in the Yeso Formation. We expect, therefore, that when the water mixes with water that has moved primarily in the San Andres Formation that the result will be a water richer in chloride and sulphate.

Similarly, the induced recharge moves through a lithologic domain that was formerly part of the underflowing regional system. These rocks contain a few remnant salt beds and extensive beds of anhydrite. Consequently, the induced recharge to the artesian system can be expected to bring with it larger sulphate than chloride content.

The shallow system

Because a relatively large proportion of the water discharged from the shallow system is derived from induced recharge, the sulphate content can be expected to show a sizeable range depending upon whether the water discharged by a well circulates only in the alluvium or whether it circulates into the underlying Grayburg-Queen Formation.

East basin

Water in the East basin circulates through extensive beds of gypsum, anhydrite, and salt, so the dissolved solids content can be expected to be much larger than for water of a similar sized system but in much less soluble rocks. Because the East basin contributes much of the ground water to the Pecos River, the quality of the ground water discharged to the river should approach the quality of the water in the Bottomless Lakes.

CONCLUSION

The hydrologic picture presented here is based largely on 1926-1969 data. It assumes dynamic equilibrium during that period. However, since the internal consistency is excellent and since the agreement between the results presented here and those obtained by others is also very good, I believe that the techniques used and the results presented are reliable.

COMMENTS AND RECOMMENDATIONS

A great furor has been raised over the assertion that the Roswell basin is overdrawn. This study indicates that an underflow of more than 100 cfs occurs annually. The assertion of overdevelopment is based primarily on the observation that water levels in wells are declining. I believe this study shows clearly that water levels are declining not because the amount of available water is too small, but because the wells are concentrated over a relatively small area, causing excessive interference between wells. Consequently, I recommend that an engineering feasibility study be made to consider the economics of designing and installing a well field to optimize yields and minimize water-level decline. This implies that existing wells be utilized whenever possible, but would undoubtedly call for many of the wells to be abandoned.

To make such a feasibility study will require a great deal of additional data. I recommend that one test hole be drilled in each 150 square miles (approximately 1000 test holes). These test holes should be drilled to a minimum of 4000 feet and should be drill-stem tested at least every 250 feet. From drill-stem tests the following information will be obtained: 12 mi squares

(1) head in each interval tested,

(2) average permeability and transmissitivity of each interval tested,

(3) water samples for complete chemical analyses of water (In the field and as soon as water samples can be obtained E_h, pH, HCO_3^-, $CO_3^=$, and Cl^- should be determined), and

(4) temperature of the water in the interval tested.

In addition cuttings should be sampled and complete sets of electric logs should be obtained. One well in ten should be utilized as an observation well to monitor water-level changes as a function of depth.

The estimated cost of such a program if carried out over 10 years is as follows:

	millions of dollars
Drilling costs	40
Drill-stem tests	20
Chemical analyses	2
Electric logs	10
Salaries of scientists, engineers, and administrators	10
Overhead and miscellaneous expenses	40
Total	122

The program would cost about $12.2 million per year to execute, plus about 20 million in the two year period following the completion of the drilling to interpret the data and to prepare an engineeringly sound program for recovering the available water.

Hernandez (1971, p. 80) estimates that the value added ranges from 17.50 to 61.40 dollars per acre foot pumped per acre (6.9 to 24.5 million dollars annually). The gross value of irrigated crops in the Pecos River basin in New Mexico in 1966 was 22.7 million dollars (Hansen, 1968, p. 144), of which more than 17.0 million dollars came from the lower Pecos River basin.

The 142-million-dollar cost of a short term project dedicated to the preservation of the water resource based economy is entirely justifiable. From this program other benefits would be derived, for the program would provide data extremely useful to the petroleum and mineral industries. The data would provide the first truly regional analysis of ground-water systems and would serve as a guide for other similar studies.

Details in several parts of the flow system are lacking. These details should be provided as soon as possible. Detailed studies should include the following:

(1) the ground-water conditions in the East basin,

(2) the induced recharge area in the vicinity of the Acme gage, and

(3) the chemistry of the flow system using existing data.

In addition observation wells should be established so as to monitor the water table fluctuation over the entire recharge area. Observation wells are especially needed in the East basin.

Redistributing the discharging wells would produce the following benefits:

(1) by increasing the distance between wells the water level change would be minimized, thereby reducing the amount of water derived from storage,

(2) with less drawdown the long flow lines through the Yeso would be eliminated, thereby decreasing the salt water degradation problem, and

(3) induced recharge could be controlled since water that leaves the water surface is no longer subject to evaporation processes and less water would be used up in evapotranspiration.

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Table 1. -- Geologic time scale for the Pecos River basin, New Mexico.

Era	System	Epoch	Age of base (m. y.)
Cenozoic			
	Quaternary		
		Holocene	
		Pleistocene	3
	Tertiary		
		Pliocene	11
		Miocene	25
		Oligocene	40
		Eocene	60
Mesozoic			
	Cretaceous		130
	Jurassic		180
	Triassic		225
Paleozoic			
	Permian		270
		Ochoa	
		Guadalupe	
		Leonard	
		Wolfcamp	
	Pennsylvanian		305
		Virgil	
		Missouri	
		Des Moines	
		Derry	
		Morrow	
	Mississippian		350
	Devonian		400
	Silurian		440
	Ordovician		500
	Cambrian		570
Precambrian			
	Precambrian		---

Table 2. Data for Hypsometric Curve, Pecos River basin, New Mexico.

Contour Inverval From	to	Area	Percent %	Cumulative percent
-	3000	213	.81	.81
3000	4000	7660	29.34	30.15
4000	5000	7668	29.37	59.52
5000	6000	5341	20.45	79.98
6000	7000	3527	13.51	93.49
7000	8000	993	3.80	97.29
8000	9000	454	1.73	99.02
9000	10000	119	.45	99.47
10000	11000	70	.26	99.73
11000	12000	52	.19	99.92
12000	-	6	.03	99.95
Total		26103	99.95	

Table 3. Permeability of cores from oil and gas fields in New Mexico (after Roswell Geological Society, 1956, 1960, and 1967).

Lithologic Unit	Permeability (ft/d)					
	Horizontal			Vertical		
	Number of Observations	Minimum	Maximum	Number of Observations	Minimum	Maximum
Ordovician rocks	4	.0055	.21	2	.00082	.0014
Silurian rocks	1	.00082		1	.00055	
Siluro-Devonian rocks	5	.00027	1.4	3	.00027	.78
Devonian rocks	26+	.00016	3.2	13	.00027	.82
Mississippian rocks	---	---	---	---	---	---
Pennsylvanian rocks	23	.00027	4.9	4	.0012	.34
Permian rocks						
Wolfcampian rocks	13	.0027	1.0	8	.0014	.46
Leonardian rocks						
Abo (reef)	9	.00027	5.4	1	.00082	
Bone Springs Limestone	---	---	---	---	---	---
Yeso Formation	6	.0000	.055	2	.0016	.0082
Glorieta Formation	2	.022	.036	1	.0247	
San Andres Formation	27	.00027	.411	10	.00027	.822
Guadalupian rocks						
Grayburg - San Andres	7	.0055	1.1	2	.0055	1.0
Grayburg	4	.0040	.41	---	---	---
Queen - Grayburg	3	.0014	.052	---	---	---
Queen	13	.010	.69	1	.41	
Seven Rivers	2	.047	.10	---	---	---
Yates - Seven Rivers	4	.0049	.16	---	---	---
Yates	7	.0030	.16	1	.019	
Delaware Mountain Group	10	.027	.22	1	.082	

Table 4. Core permeabilities for oil and gas producing rocks in southeastern New Mexico (Core Laboratories, Inc., 1961, p. 3).

		Permeability (ft/d)		Porosity (%)	
		from	to	from	to
Granite wash		.014	9.0	3.5	26.1
Ordovician (Ellenburger)		.00027	6.2	1.3	13.8
Silurian (Fusselmar)		.00014	.71	1.4	10.7
Devonian		.0027	7.8	1.8	25.2
Pennsylvanian	- Derryian	.0044	.85	4.0	15.7
	- Des Moinesian	.00055	2.0	1.0	29.0
Permian	(Abo)	.00055	.40	2.6	12.8
	(Yeso)	.00027	.37	2.5	14.8
	(Glorieta)	.0011	.61	5.2	20.9
	(San Andres)	.00082	1.3	3.2	14.0
	(Grayburg)	.004	.44	7.0	20.0
	(Queen)	.00055	11.0	5.7	27.0
	(Seven Rivers)	.0011	1.2	5.9	28.9
	(Yates)	.00055	11.0	2.4	27.4

Table 5. Porosity of cores from oil and gas fields in New Mexico (after Roswell Geological Society, 1956, 1960, and 1967).

Lithologic Unit	Porosity: Number of Observations	Porosity: Minimum	Porosity: Maximum
Ordovician rocks	4	2.5	16
Silurian rocks	1	5	
Siluro - Devonian rocks	6	1.9	10
Devonian rocks	29	.6	14
Mississippian rocks	1	7.1	
Pennsylvanian rocks	27	3	17
Permian rocks			
Wolfcampian rocks	10	4.5	13
Leonardian rocks			
Abo (reef)	1	1.5	18.3
Bone Springs Limestone	3	3	12
Yeso Formation	6	5	11.6
Glorieta Formation	2	11.4	12
San Andres Formation	30	4	16.3
Guadalupian rocks			
Grayburg - San Andres	7	8.75	21
Grayburg	4	11.1	28.6
Queen - Grayburg	3	2,7	13
Queen	12	10.8	25.4
Seven Rivers	2	7	11
Yates - Seven Rivers	3	14.1	17.7
Yates	7	8.3	22.5
Delaware Mountain Group	11	22.5	25.2

Table 6. Permeabilities estimates from reported drill-stem test data using a formula developed by Dolan et al. (1957).

Lithologic Unit	Number of tests	Estimated Permeability (ft/d) Minimum	Maximum
Pennsylvanian rocks	8	.0002	.010
Abo Formation	6	.0001	.005
Yeso Formation	1	.0005	
San Andres Formation	1	.003	
Queen Formation	1	.0001	

Table 7. -- Mean annual precipitation by altitude range and total percipitation of the Pecos River basin, New Mexico.

Altitude interval (feet)	Arithematic mean precipitation (inches/year)	Total annual precipitation on the area (cfs)
less than 3500	11.72	3491
3501 to 4000	12.13	3432
4001 to 4500	13.64	3853
4501 to 5000	13.51	3814
5001 to 5500	14.85	2923
5501 to 6000	14.36	2825
6001 to 6500	15.45	2049
6501 to 7000	16.73	2129
7001 to 7500	19.84	731
7501 to 8000	22.06	801
8001 to 8500	25.44	469
8501 to 9000	26.47	398
more than 9000	29.88	543
	Total	27,449

Table 8. -- Areas in the Pecos River drainage basin above selected gaging stations in New Mexico.

Gaging Station	Area above gage in drainage basin (mi.^{2}) Non-contributing east	west	Contributing
3779			53
3785			135
3795			852
3830			1830
3835			849
3845			759
3860	1211	2843	5292
3955	624		3535
3965			767
3995			1020
4010			658
4020			1003
4040	496		216
4050			32
4065	776		1119
4070	46		77
4075	14		208
	3167	2843	18405
Area in New Mexico below gage			1720
Gaged area in Texas			-32
Total area of drainage basin			26107

Table 9. -- Potential evapotranspiration in areas along the Pecos River (after Hantush, 1959).

Gaging Station	County	Elev. (ft)	Lat.	Long.	Arithmetic mean PE in ft
Terro	San Miguel	7,500	35° 46'	105° 40'	1.7
Dilia	Guadalupe	5,200	35° 11'	105° 03'	2.40
Santa Rosa	Guadalupe	4,610	34° 56'	104° 41'	2.75
Alamogordo Dam	De Baca	4,306	34° 36'	104° 23'	2.84
Ft. Sumner	De Baca	4,028	34° 28'	104° 15'	2.89
Bitter Lakes Wild Life Refuge	Chaves	3,670	33° 29'	104° 24'	2.79
Roswell W. B.	Chaves	3,571	33° 19'	104° 26'	2.94
Hagerman	Chaves	3,419	33° 07'	104° 20'	2.79
Artesia	Eddy	3,350	32° 51'	104° 24'	3.12
Lake Avalon	Eddy	3,208	32° 29'	104° 15'	3.24
Carlsbad	Eddy	3,120	32° 25'	104° 14'	3.11
Carlsbad CAA Ap.	Eddy	3,249	32° 20'	104° 16'	3.28
					2.82

Table 10. -- Observed components of surface runoff and ground water discharge from flow duration data.

Gaging Station	Period of record	n	S_m (cfs)	S_o (cfs)	100-n	G_m (cfs)	G_o (cfs)	S_o+G_o
3785	1920, 1924 1931-1969	54	167	90.2	46	8.1	3.7	93.9
3795	1904-1914 1929-1969	75	189	141.8	25	6.4	1.6	143.4
3830	1913-1914 1929-1969	27	349	94.2	73	24.6	18.0	112.2
3835	1939-1969	20	534	106.8	80	106.0	84.8	191.6
3845	1938-1969	60	245	147.0	40	170.	68.0	215.0
3860	1938-1969	51*	403	205.5	34*	12.0	4.1	209.6
3955	1938-1969	66	409	269.9	34	11.0	3.7	273.6
3965	1939-1969	75	358	268.5	25	13.7	3.4	271.9
3995	1961-1969	73	363	265.0	27	.5	.1	265.1
4010	1961-1969	39	233	90.9	61	.5	.3	91.2
4020	1945-1969	31	299	92.7	69	94.	65.9	157.6
4050	1939-1969	59	105	62.0	41	101.	41.4	103.4
4065	1939-1969	26	263	68.4	74	62.8	46.5	114.9
4070	1952-1969	58	88.6	51.4	42	29.5	12.3	63.7
4075	1939-1969	61	159	97.0	39	84.6	33.0	130.0

* river only flows 85 per cent of time.

Table 11. -- Estimated consumption of diverted water by crops.

Gaging Station	ΔA (Acres)	T_D (cfs)	n	ΔS_D (cfs)	S_D (cfs)	100-n	ΔG_D (cfs)	G_D (cfs)
3785	75	.3	54	.2	.2	46	.1	.1
3795	4825	16.6	75	12.5	12.7	25	4.1	4.2
3830	7100	24.5	27	6.6	19.3	73	17.8	22.0
3835	500	1.7	20	.3	19.6	80	1.4	23.4
3845	---	---	60	---	19.6	40	---	23.4
3860	3000++ 6600	33.1	60	13.7	33.3	40	19.4	42.8
3955	104000	358.8+	66	28.7	62.0	34	330.1	372.9
3965	30000	103.5+	75	8.3	70.3	25	95.2	468.1
3995	16000	55.2	73	40.3	110.6	27	14.9	483.0
4010	1000	3.5	39	1.4	112.0	61	2.1	485.1
4020	2000	6.9	31	2.1	114.1	69	4.8	489.9
4050	13000++ 13000	89.7	59	26.5	140.6	41	63.2	553.1
4065	4000	13.8	26	3.5	144.1	74	10.3	563.4
4070	---	---	58	---	144.1	42	---	563.4
4075	---	---	61	---	144.1	39	---	563.4

++ irrigated by wells.
+ 92 per cent pumped from wells.

Table 12. -- Estimated evapotranspiration of stream flow in the Pecos River basin, New Mexico.

Gaging Station	PE (in)	ΔA_D (mi^2)	ΔT_{ET} (cfs)	n	ΔS_{ET} (cfs)	S_{ET} (cfs)	100-n	ΔG_{ET} (cfs)	G_{ET} (cfs)
3785	1.7	56	1.4	54	.8	.8	46	.6	.6
3795	2.4	312	11.2	75	8.4	9.2	25	2.8	3.4
3830	2.7	861	34.9	27	9.4	18.6	73	25.5	28.9
3835	2.8	100	4.2	20	.8	19.4	80	3.4	32.3
3845	2.8	44	1.8	60	1.1	20.5	40	.7	33.0
3860	2.8	1579	66.4	60	39.8	60.3	40	26.6	59.6
3955	2.9	1639	71.4	66	47.1	107.4	34	24.3	84.9
3965	2.9	415	18.1	75	13.6	121.0	25	4.5	88.4
3995	3.1	409	19.0	73	13.8	134.8	27	5.2	93.6
4010	3.2	372	17.9	39	7.0	141.8	61	10.9	104.5
4020	3.2	93	4.5	31	1.4	143.2	69	3.1	107.6
4050	3.1	552	25.7	59	15.2	158.4	41	10.5	118.1
4065	3.1	804	37.4	26	9.7	168.1	74	27.6	145.7
4070	3.1	39	1.8	58	1.1	169.2	42	.7	146.4
4075	3.1	116	5.4	61	3.2	172.4	39	2.2	148.6

Table 13. -- Estimated surface runoff component of stream flow for Pecos River, New Mexico.

Gaging Station	cfs				
	S_o	S_D	S_{ET}	S_P	S_T
3785	90.2	.2	.8	---	91.2
3795	141.8	12.7	9.2	---	163.7
3830	94.2	19.3	18.6	---	132.1
3835	106.8	19.6	19.4	---	145.8
3845	147.0	19.6	20.5	---	187.1
3860	205.5	33.3	60.3	2.9	296.2
3955	269.9	62.0	107.4	100.5	338.8
3965	268.5	70.3	121.0	29.0	430.8
3995	265.0	110.6	134.8	15.5	494.9
4010	90.9	112.0	141.8	---	344.7
4020	92.7	114.1	143.2	---	350.0
4050	62.0	140.6	158.4	12.5	348.5
4065	68.4	144.1	168.1	---	380.6
4070	51.4	144.1	169.2	---	364.7
4075	97.0	144.1	172.4	---	413.5

Table 14. -- Estimated ground water component of stream flow for Pecos River, New Mexico.

Gaging Station	cfs				
	G_O	G_D	G_{ET}	G_P	G_T
3785	3.7	.1	.6	---	4.4
3795	1.6	4.2	3.4	---	9.2
3830	18.0	22.0	28.9	---	68.9
3835	84.8	23.4	32.3	---	140.5
3845	68.0	23.4	33.0	---	124.4
3860	4.1	42.8	59.6	---	106.5
3955	3.7	372.9	84.9	46	415.5
3965	3.4	468.1	88.4	55	504.9
3995	.1	483.0	93.6	55	521.7
4010	.3	485.1	104.5	61	528.9
4020	65.9	489.9	107.6	61	602.4
4050	41.4	553.1	118.1	80	632.6
4065	46.5	563.4	145.7	80	675.6
4070	12.3	563.4	146.4	80	642.1
4075	33.0	563.4	148.6	80	665.0

Table 15. -- Estimated total discharge of Pecos River, New Mexico.

Gaging Station	G_T	S_T	Q_T	Drainage area (mi^2) Total	non-contributing	contributing
3785	4.4	91.2	95.6	188		188
3795	9.2	163.7	172.9	1040		1040
3830	68.9	132.1	201.0	2870		2870
3835	140.5	145.8	296.3	3719		3719
3845	124.4	187.1	311.5	4478		4478
3860	106.5	296.2	402.7	13824	4054	9770
3955	415.5	338.8	754.3	17983	4678	13305
3965	504.9	430.8	935.7	18750	4678	14072
3995	521.7	494.9	1016.6	19770	4678	15092
4010	528.9	344.7	873.6	20428	4678	15750
4020	602.4	350.0	952.4	21431	4678	16753
4050	632.6	348.5	981.1	22175	5174	17001
4065	675.6	380.6	1056.2	24070	5950	18120
4070	642.1	364.7	1007.8	24193	5996	18197
4075	665.0	413.5	1078.5	24415	6010	18405

Table 16. -- Discharge and area attributed to the Pecos River drainage area below gaging station 3830.

Gaging Station	Area-2870 (mi^2)	G_T-68.9 (cfs)	S_T-132.1 (cfs)	Q_T-201.0 (cfs)
3835	912	72.0	13.7	95.2
3845	1608	55.6	55.0	10.5
3860	6900	37.6	164.1	201.7
3955	10435	346.6	206.7	553.3
3965	11202	436.0	298.7	734.7
3995	12222	452.8	362.8	815.6
4010	12880	460.0	212.6	672.6
4020	13883	533.5	217.9	751.4
4050	14131	563.7	216.4	780.1
4065	15250	606.7	248.5	855.2
4070	15327	573.2	232.6	806.8
4075	15535	596.1	281.4	877.5

Table 17. -- Summary of recharge and discharge areas of the Pecos River basin, New Mexico.

Gaging Station	Area Recharge (mi^2) West	East	ΔA	$\Sigma \Delta A$	Area Discharge (mi^2) ΔA	$\Sigma \Delta A$
3835	132	31	163	163	50	50
3845	396	67	463	626	44	94
3860	3838	523	4361	4987	1579	1673
3955	1101	801	1902	6889	1639	3312
3965	801	164	965	7854	415	3727
3995	476	128	604	8458	400	4135
4010	453	318	771	9229	372	4507
4020	113	80	192	9422	93	4600
4035	790	204	994	9452	479	4614
4040	790	204	994	9452	3	4617
4050	40	20	60	9512	70	4687
4065	162	207	369	9981	804	5491
4070	---	---	---	9981	39	5530
4075	3	17	20	10001	116	5645
	7739	2162	10001		5645	

Area of Ground Water Basin		15646		
Recharge	10001			
Discharge	5645			
Ground Water recharge outside of Drainage Basin				
East	371			
West	14	-385	15261	
Recharge to Canadian			3699	
Recharge to underflow			7143	
Total Drainage Area				26103

Table 18. -- Calculated apparent average annual recharge, Lower Pecos River basin, New Mexico.

Gaging Station	Apparent Recharge Area (mi^2)	G_T-68.9 (cfs)	Apparent Recharge Rate (cfs/mi^2)
3835	163	72.0	.44
3845	626	55.6	.089
3860	4987	37.6	.0075
3955	6889	346.2	.050
3965	7854	436.0	.056
3995	8458	452.8	.054
4010	9229	460.0	.050
4020	9421	533.5	.057
4050	9512	563.7	.059
4065	9981	606.7	.061
4070	9981	573.2	.057
4075	10001	596.1	.060

Table 19. -- Budget for the entire Pecos Basin.

	cfs
I. Total Precipitation on Basin (26,135 mi^2)	27449
Less Precipitation on area below gage 4075	-1512
Less Precipitation on area above gage but in Texas	-28
II. Total New Mexico Precipitation above gage 4075	25908
III. Surface runoff	
Surface runoff at gage S_o+G_o	-130.0
Evapotranspiration of stream flow above gage $S_{ET}+G_{ET}$	-321.0
Total consumption + diversion $S_o+G_o-G_P$	-627.5
IV. Underflow	
to Pecos-Rio Grande	-317.9
to Canadian	-110.2
V. Total Precipitation accounted for	1506.6
VI. Total Precipitation not accounted for and presumed lost to evapotranspiration almost immediately	24401.4
Percent accounted for in Pecos River Basin above gage	5.82%

Table 20. -- Precipitation in the recharge area of the lower Pecos Basin, above gaging station 4075.

Altitude	Interval	Mean Precipitation (in)	Recharge Area (mi^2)	cfs	Total
3500	4000	12.13	1733	1547	
4000	5000	13.58	4176	4178	
5000	6000	14.61	3227	3473	
6000	7000	16.09	760	901	
7000		20.95	104	161	
					10260
		East Basin			
3500	4000	12.13	1460	1305	
4000	5000	13.58	1292	1293	
					2598
		Roswell Area only			
					7662

Pecos River ms by W.K. Summers

Figs. 1-60

Figure 1
Pecos River basin in New Mexico

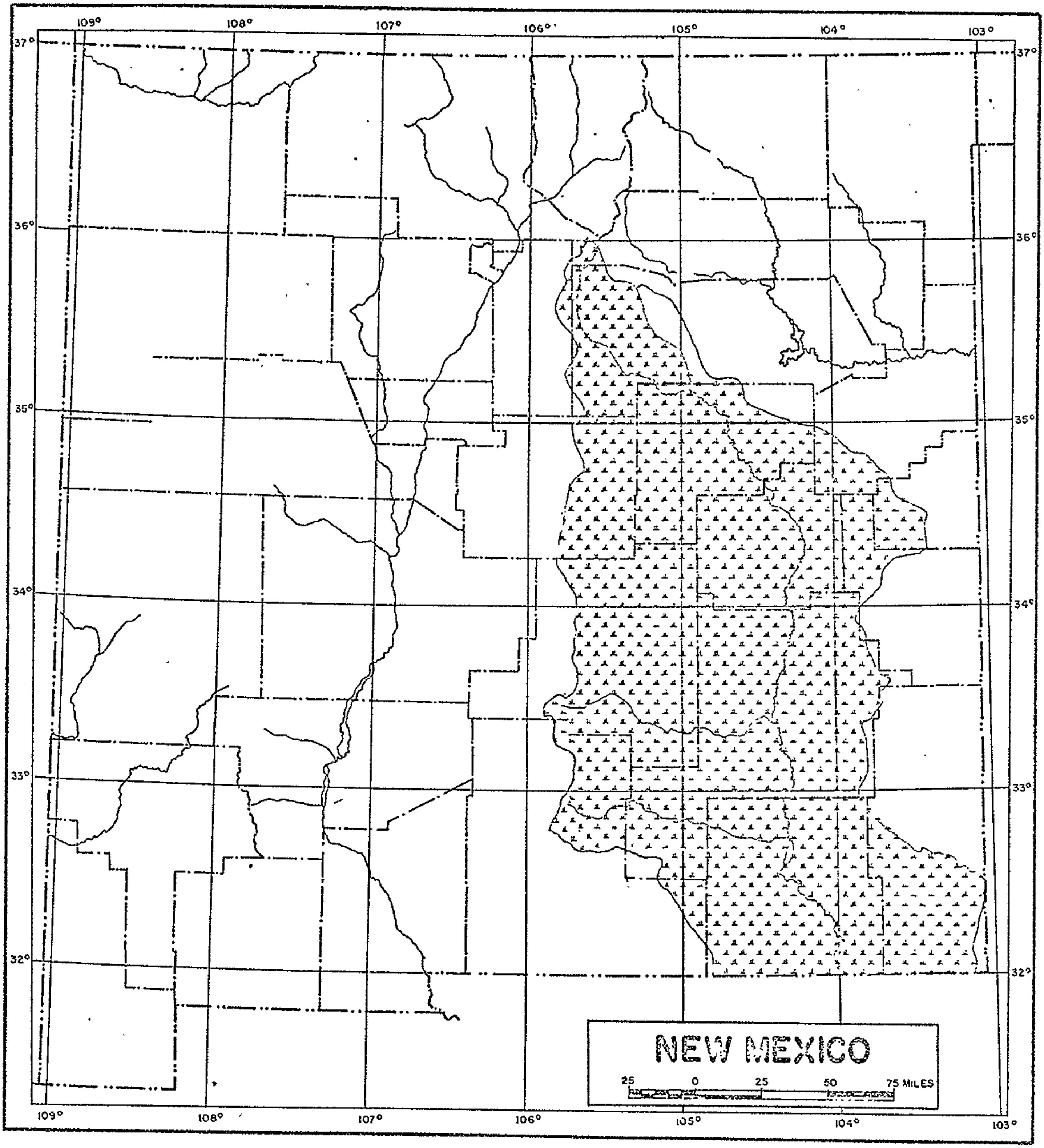
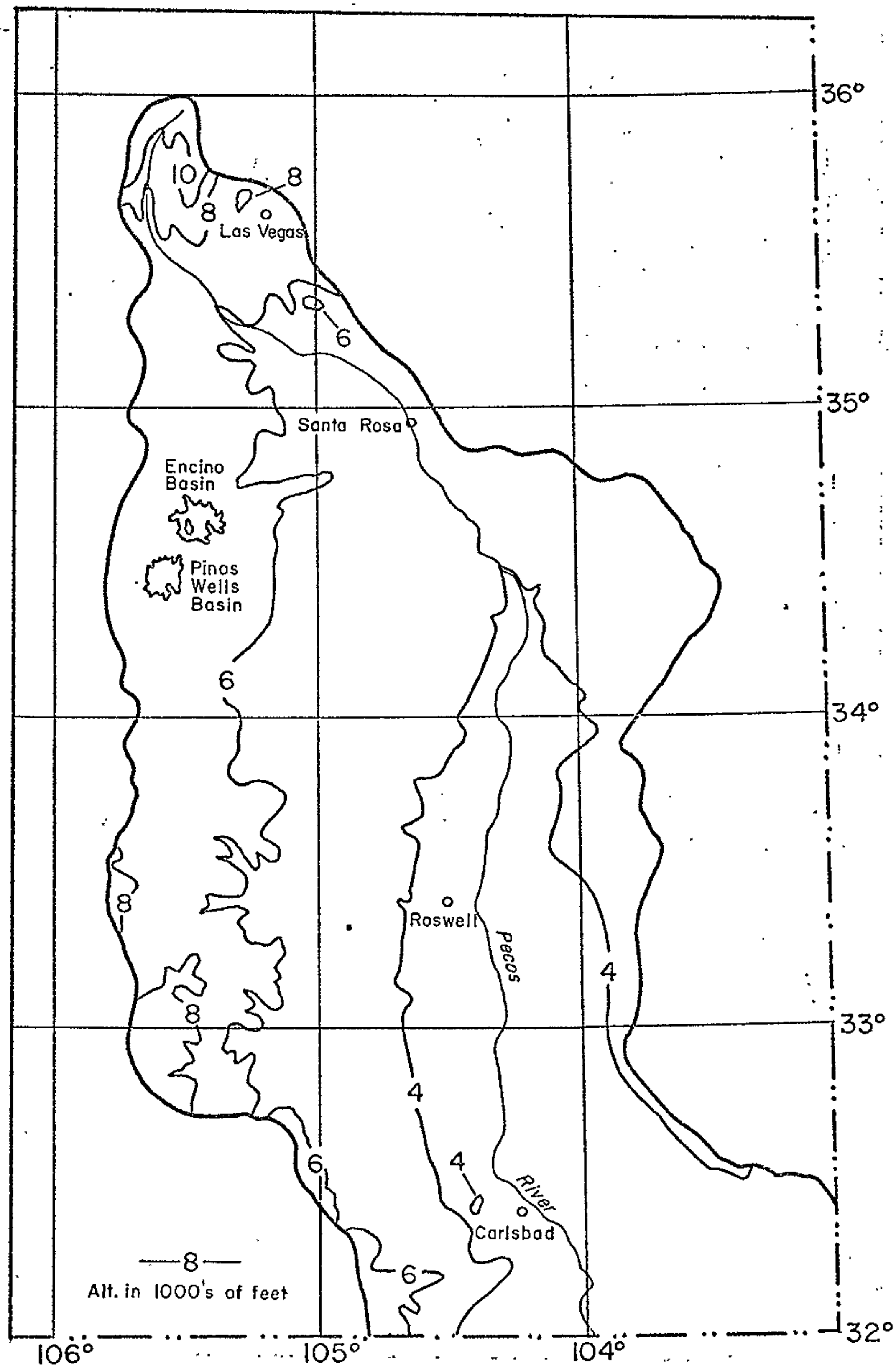

NEW MEXICO
25 0 25 50 75 MILES
109°
108°
107°
106°
105°
104°
103°
37°
36°
35°
34°
33°
32°

Figure 1

Figure 2
Topographic map of the Pecos River basin, New Mexico

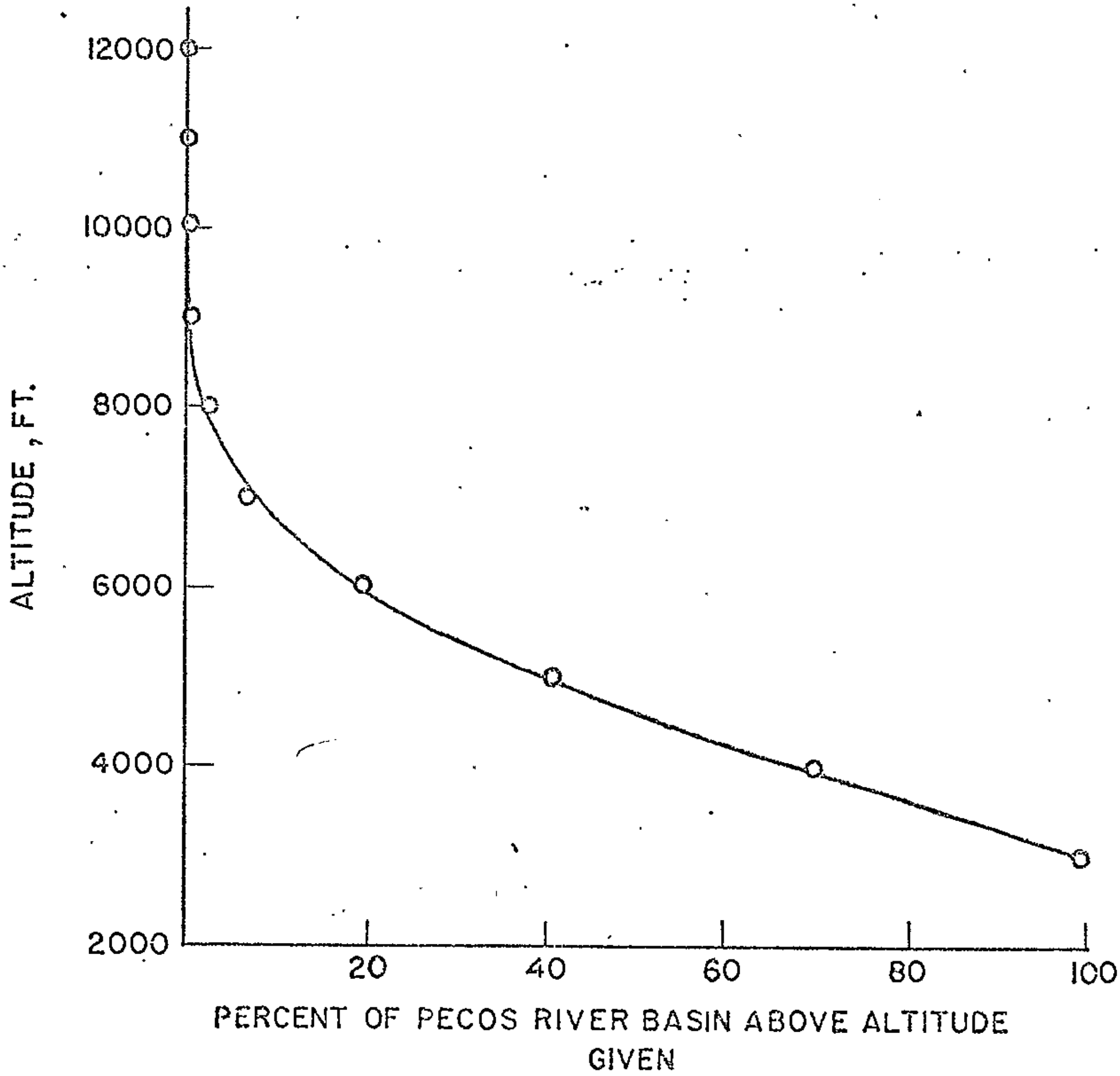


36°
35°
34°
33°
32°
106°
105°
104°
10
8
8
Las Vegas
6
Santa Rosa
Encino
Basin
Pinos
Wells
Basin
6
4
8
8
Roswell
Pecos
River
4
6
4
4
Carlsbad
6
8
Alt. in 1000's of feet

4

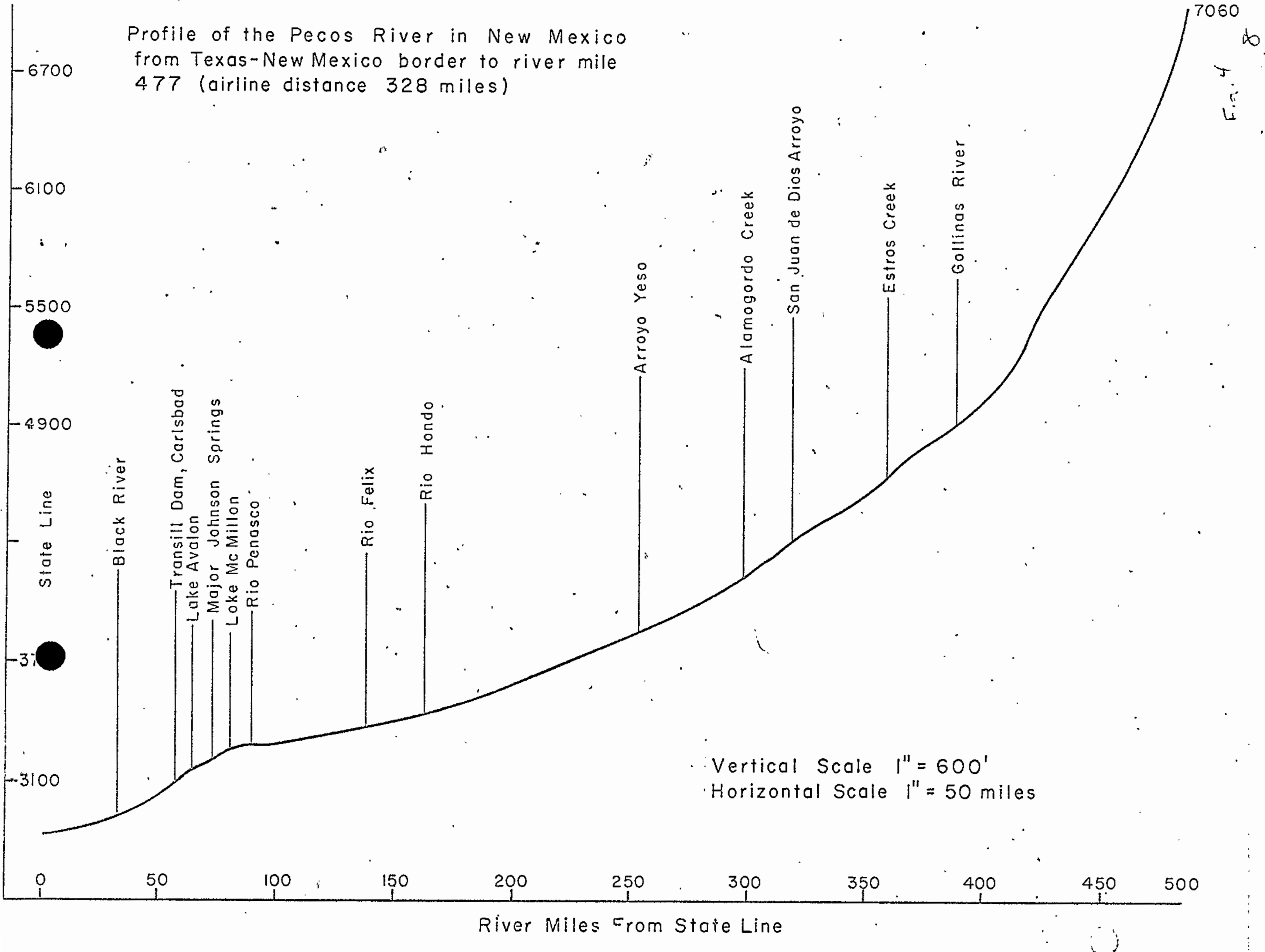
Figure 3

Hypsometric curve, Pecos River basin, New Mexico



12000
10000
8000
6000
4000
2000
ALTITUDE , FT.
20
40
60
80
100
PERCENT OF PECOS RIVER BASIN ABOVE ALTITUDE GIVEN

Figure 4
Profile of the Pecos River



Profile of the Pecos River in New Mexico from Texas-New Mexico border to river mile 477 (airline distance 328 miles)
7060
6700
6100
5500
4900
3100
State Line
Black River
Transill Dam, Carlsbad
Lake Avalon
Major Johnson Springs
Lake Mc Millon
Rio Penasco
Rio Felix
Rio Hondo
Arroyo Yeso
Alamogordo Creek
San Juan de Dios Arroyo
Estros Creek
Gollinas River
Vertical Scale 1" = 600'
Horizontal Scale 1" = 50 miles
0
50
100
150
200
250
300
350
400
450
500
River Miles From State Line

Figure 5
Profile of the Rio Penasco

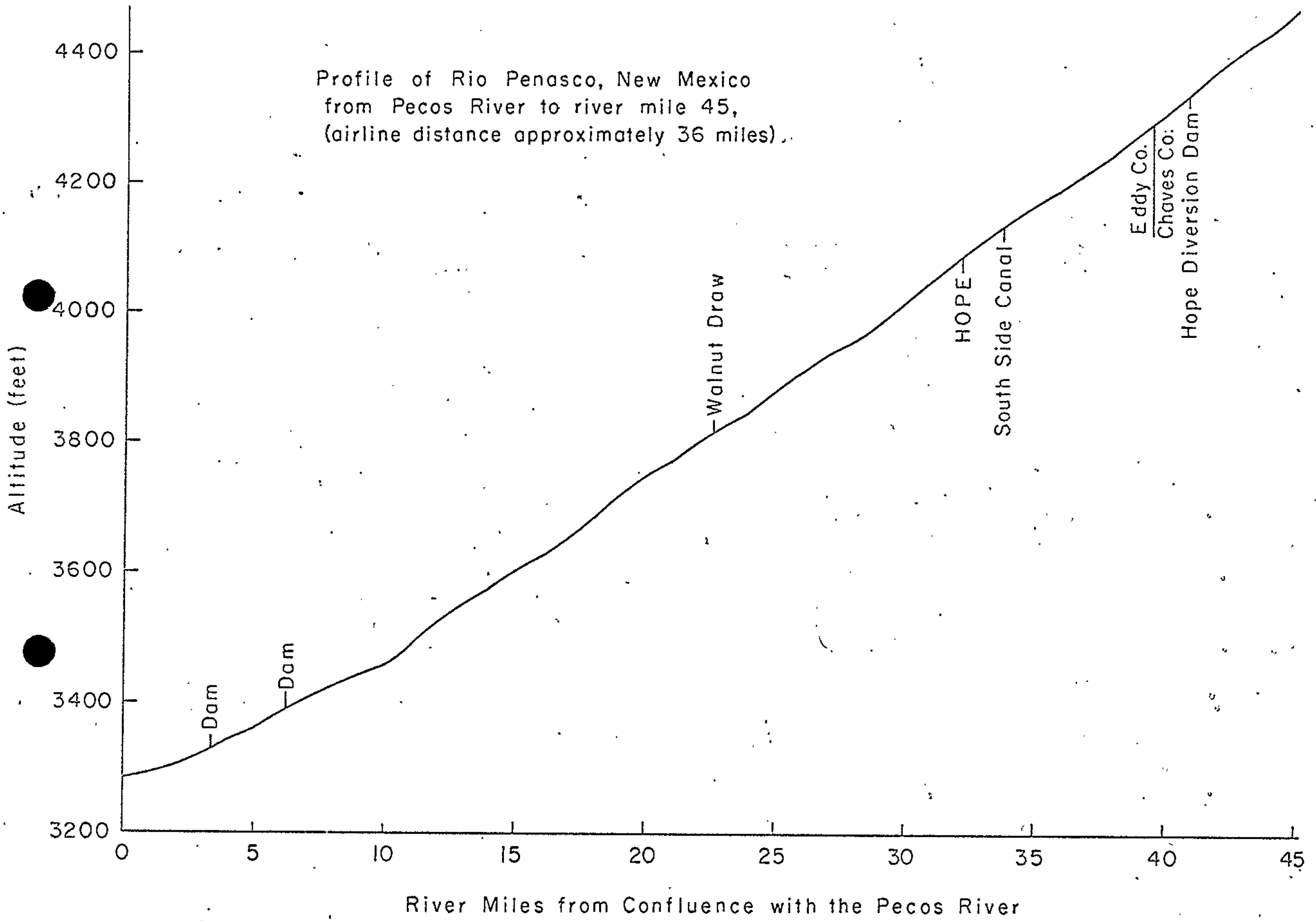
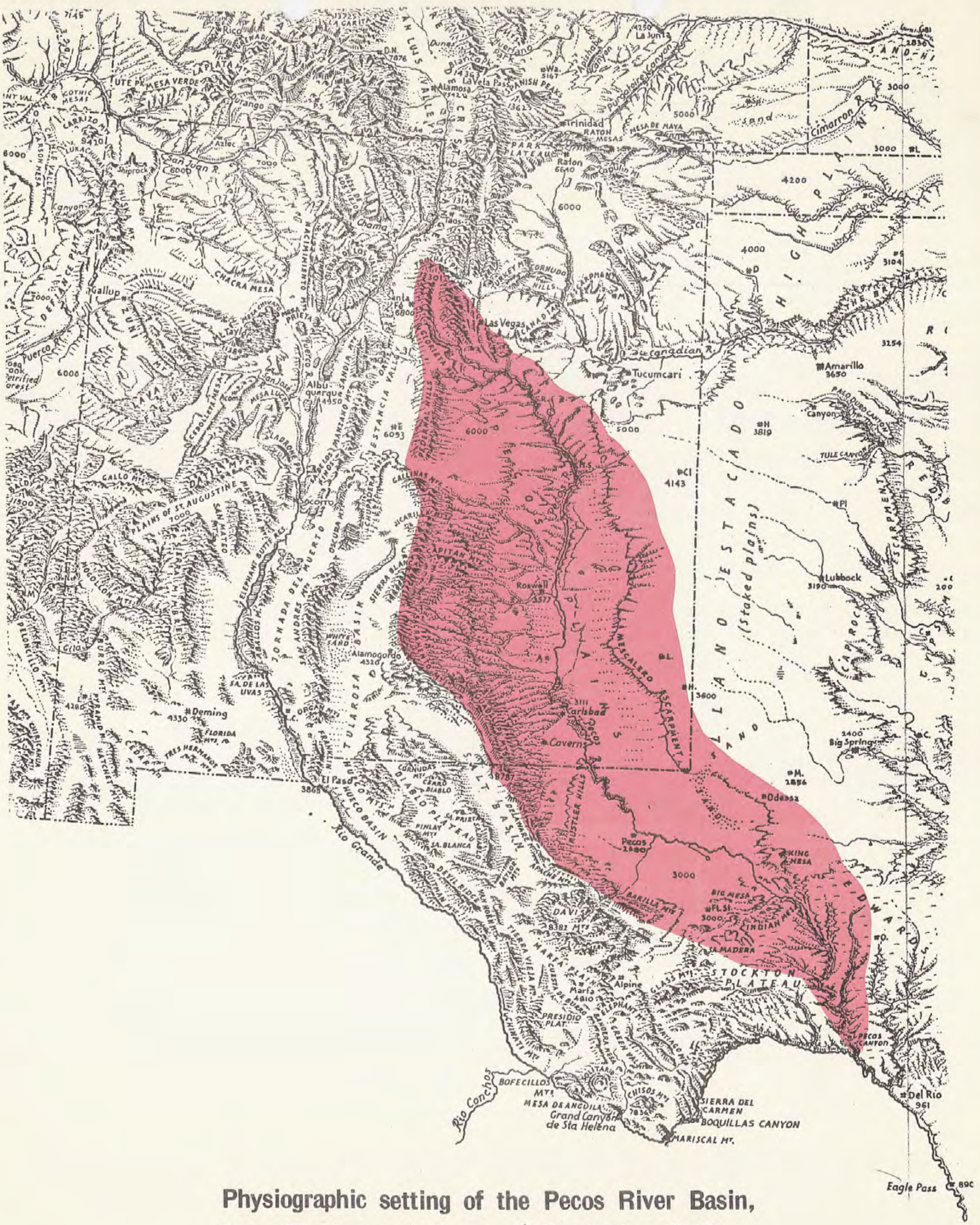

Profile of Rio Penasco, New Mexico
from Pecos River to river mile 45,
(airline distance approximately 36 miles).
Altitude (feet)
4400
4200
4000
3800
3600
3400
3200
0
5
10
15
20
25
30
35
40
45
River Miles from Confluence with the Pecos River
Dam
Dam
Walnut Draw
HOPE
South Side Canal
Eddy Co.
Chaves Co.
Hope Diversion Dam

Figure 6
Physiographic setting of the Pecos River basin



Physiographic setting of the Pecos River Basin, New Mexico and Texas (after Raisz, 1939)

Figure 7

Profiles of erosion surfaces in the Pecos River basin (after Hor~~g~~erg, 1948, p. 465, and Thornbury, 1965, p. 316)

b

Figure 8

A. Probable drainage pattern of Southern High Plains before development of Pecos River

B. Present drainage pattern of Southern High Plains (after Plummer, 1932, p. 770)

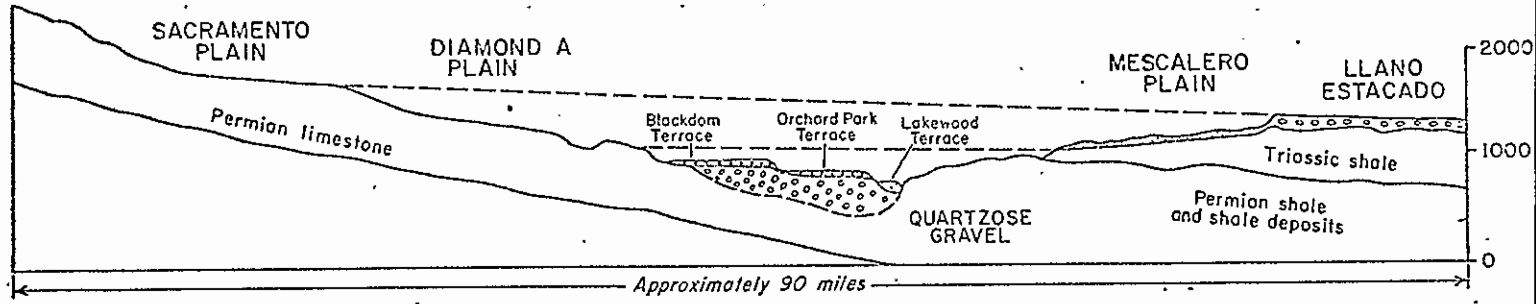


FIG. F. 17

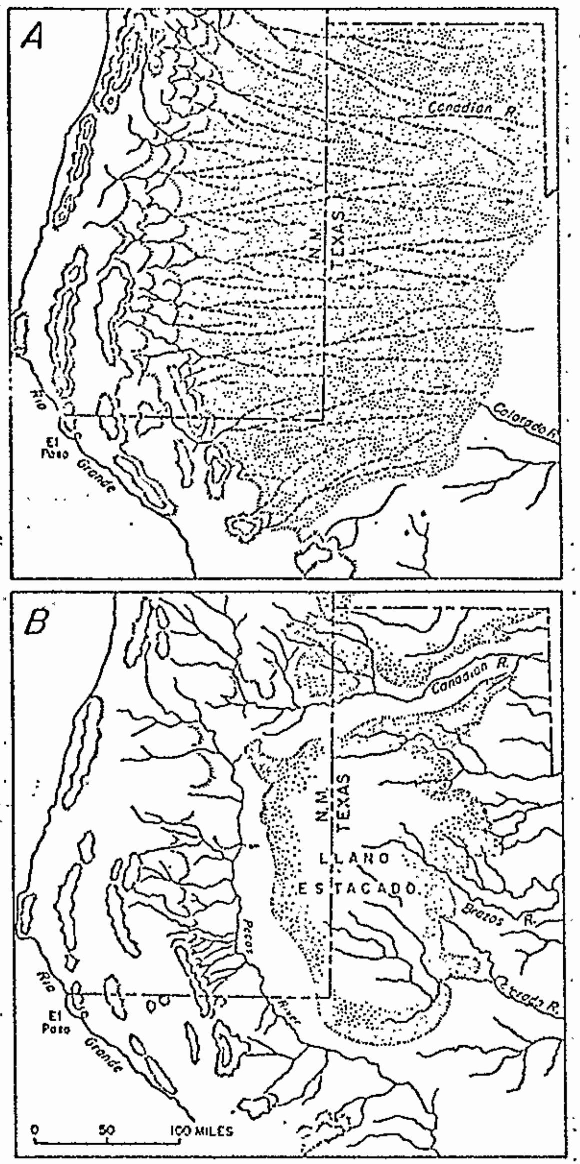


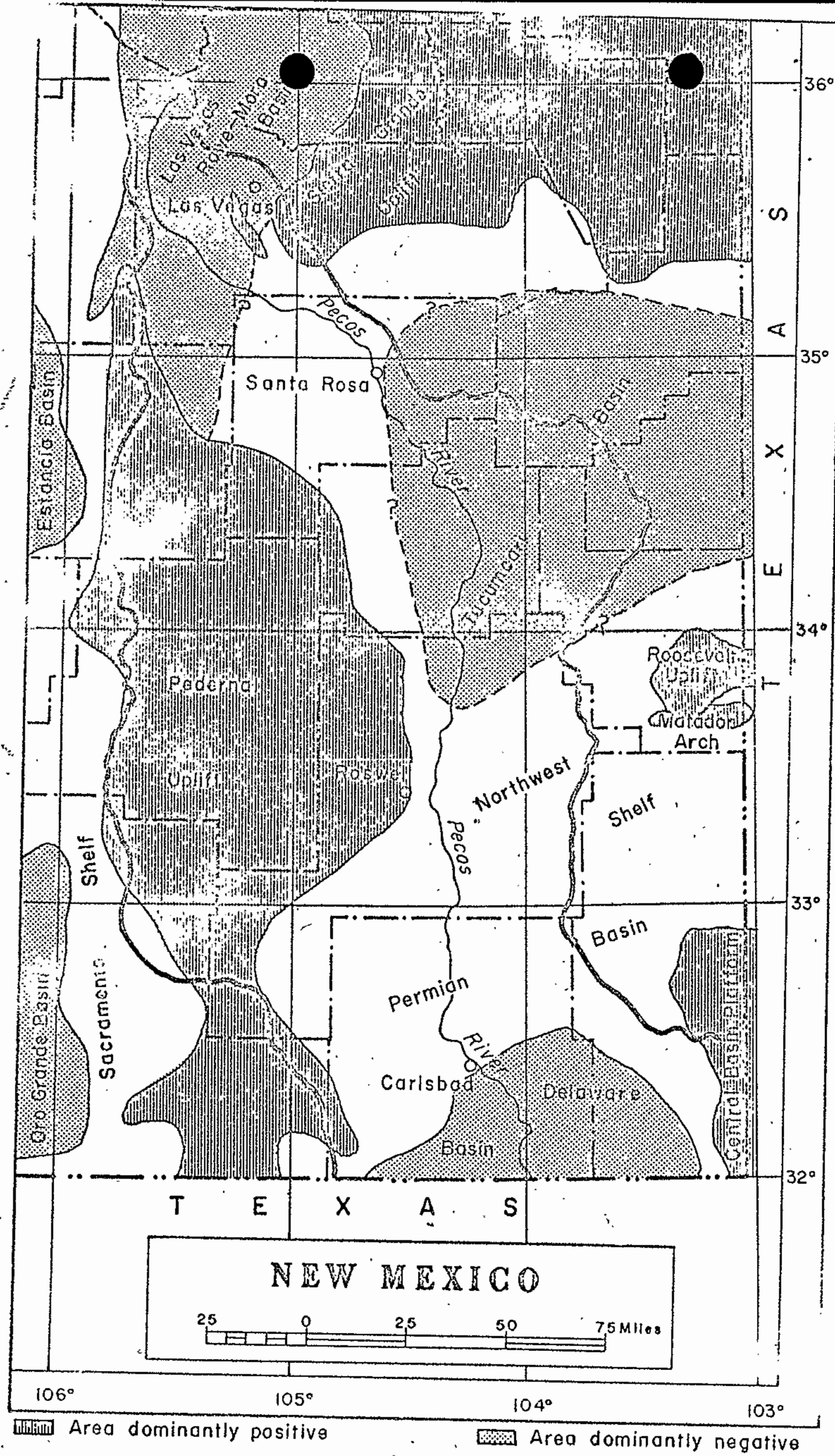
FIG. 8.

8

4

Figure 9

Tectonic Features during late Paleozoic time in Southern New Mexico

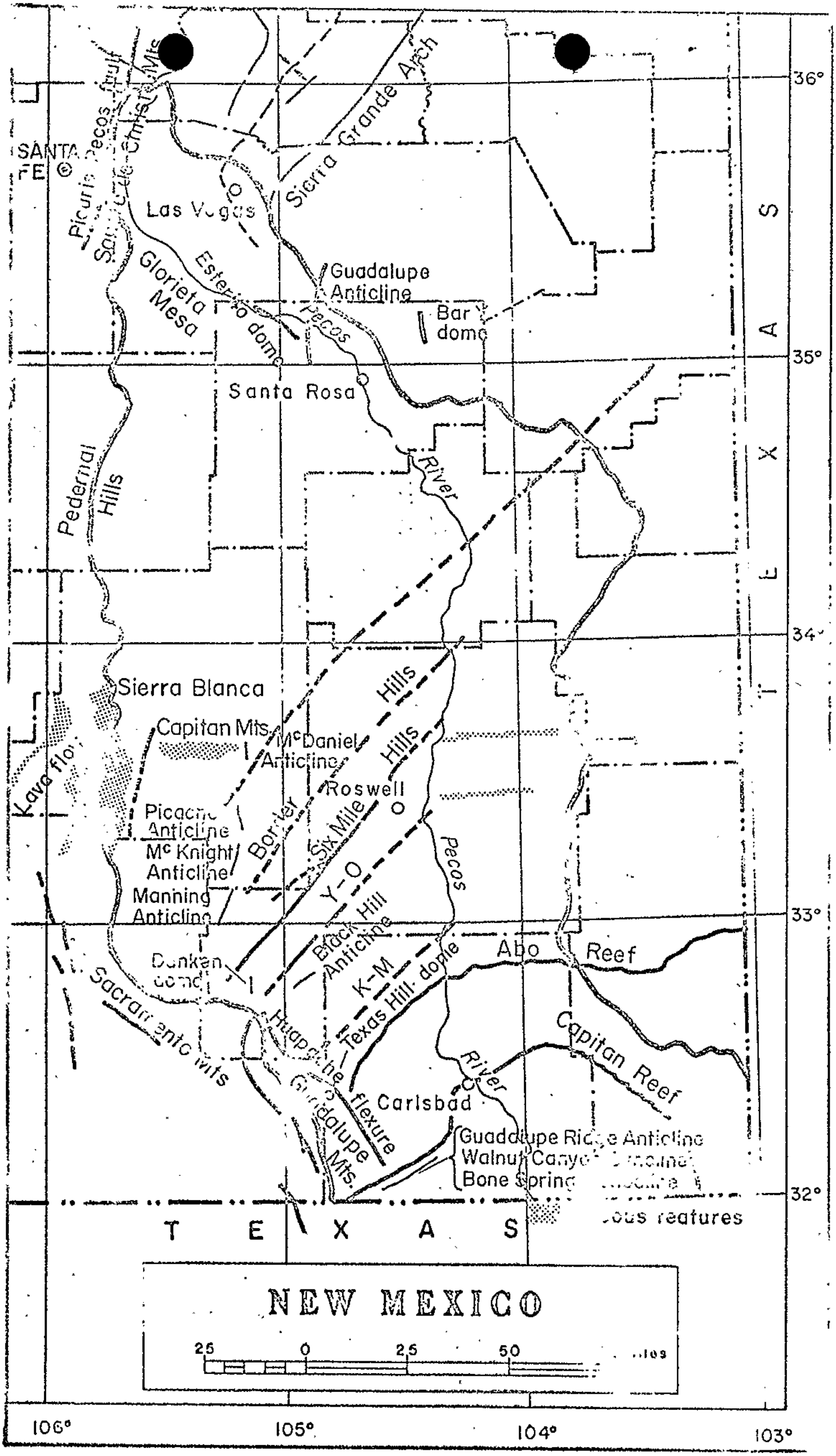


36°
35°
34°
33°
32°
106°
105°
104°
103°
Las Vegas
Rayado-Mora Basin
Las Vegas
Sierra Grande Uplift
Pecos
Santa Rosa
Estancia Basin
River
Tucumcari Basin
Pederna
Uplift
Roswell
Roosevelt Uplift
Matador Arch
Northwest
Shelf
Pecos
Shelf
Basin
Permian
Oro Grande Basin
Sacramento
River
Carlsbad
Delaware
Basin
Central Basin Platform
T E X A S
T E X A S
NEW MEXICO
25
0
25
50
75 Miles
Area dominantly positive
Area dominantly negative

Figure 9 16

Figure 10

Location of principle structural features in the Pecos River basin, New Mexico

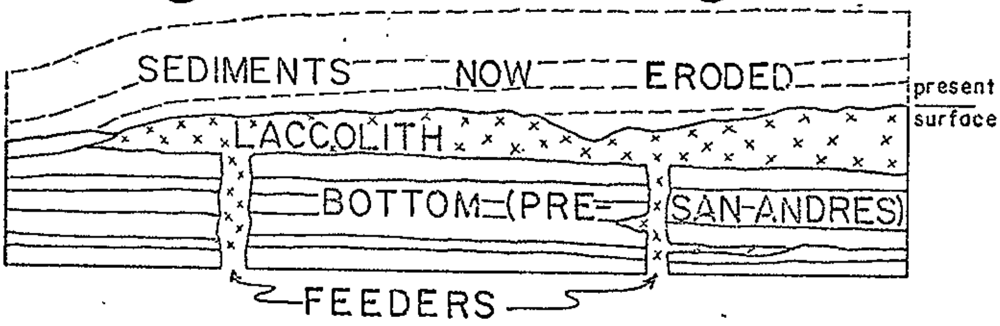


36°
35°
34°
33°
32°
106°
105°
104°
103°
SANTA FE
Picuris Pecos fault
Sangre de Cristo Mts
Sierra Grande Arch
Las Vegas
Glorieta Mesa
Guadalupe Anticline
Bar dome
Pecos
River
Santa Rosa
Pedernal Hills
Sierra Blanca
Capitan Mts.
McDaniel Anticline
Lava flow
Roswell
Hills
Picacho Anticline
McKnight Anticline
Manning Anticline
Border
Six Mile
Y-O
Black Hill Anticline
Dunken dome
K-M
Texas Hill dome
Abo
Reef
Sacramento Mts
Huapache flexure
Guadalupe Mts.
Capitan Reef
Carlsbad
Walnut Canyo
Bone Spring
T E X A S
NEW MEXICO
25
0
25
50

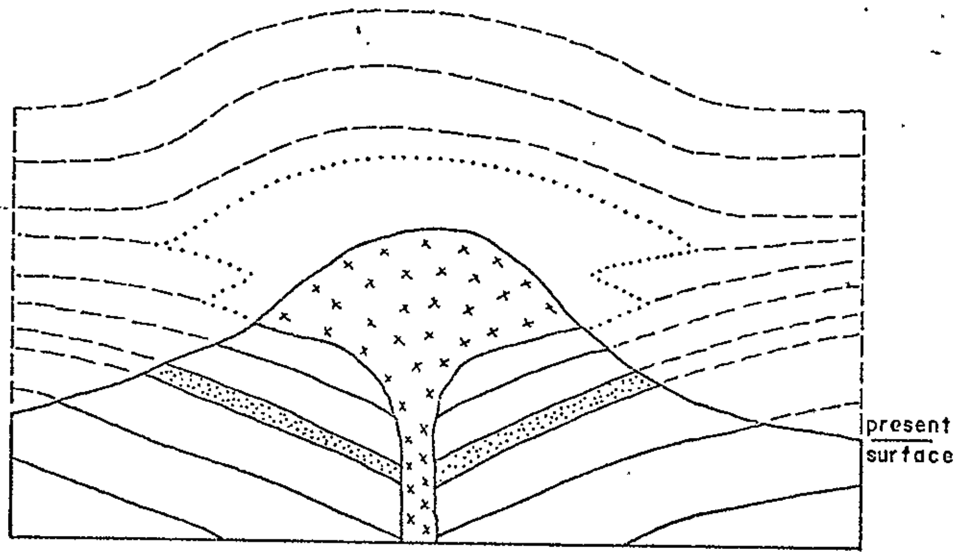
Figure 10 18

Figure 11

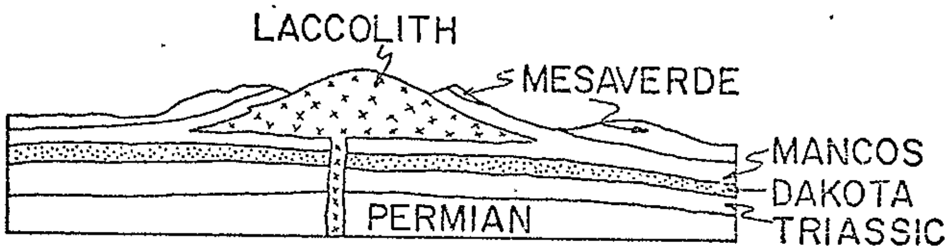
Diagrammatic cross-sections through the Capitan, Carrizo, and Vera Cruz Mountains



a, CAPITAN MOUNTAIN

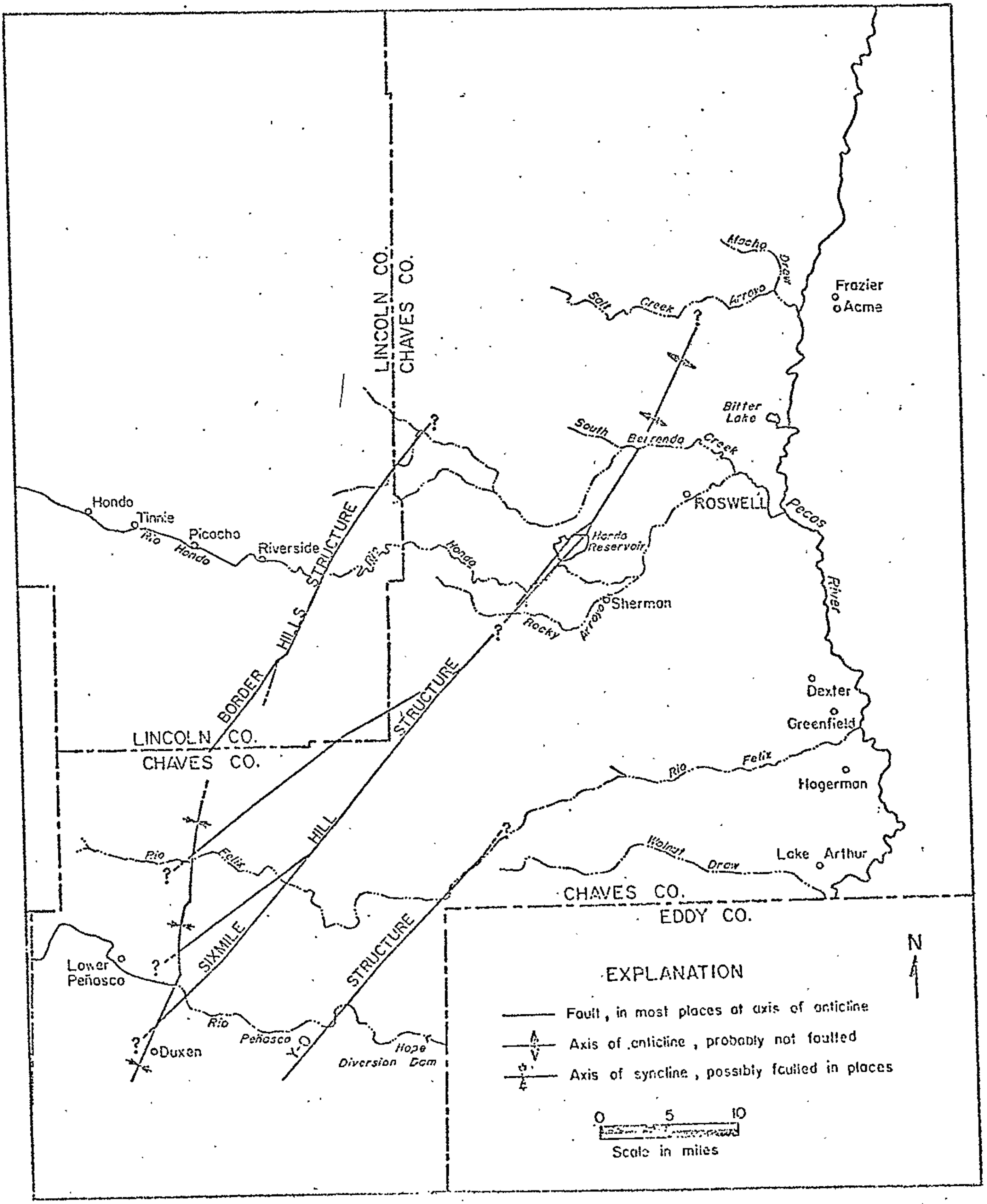


b, CARRIZO MOUNTAIN LACCOLITH



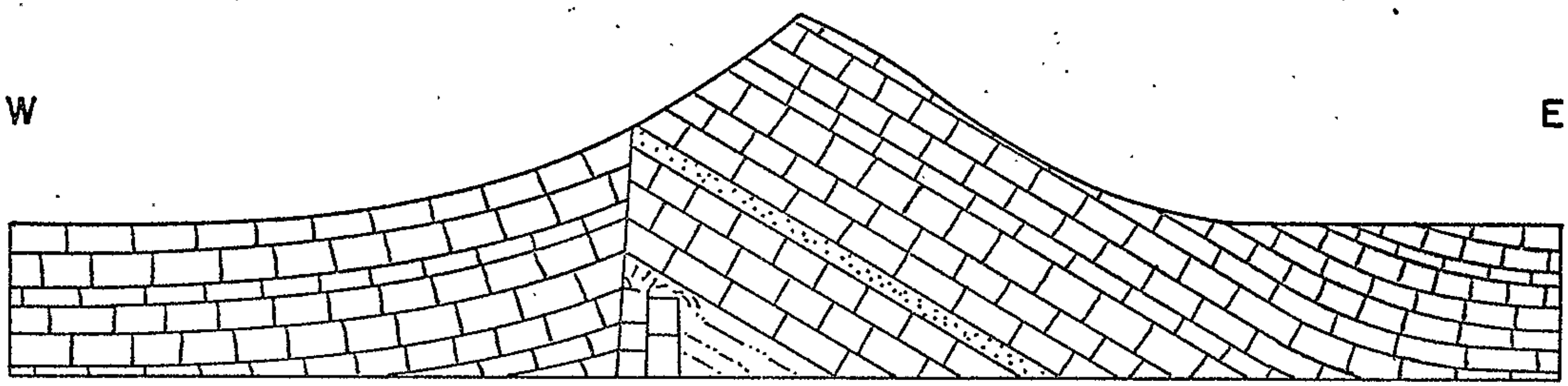
c, VERA CRUZ MOUNTAIN

Figure 12
Plan view of structural zones (after Bean, 1949)

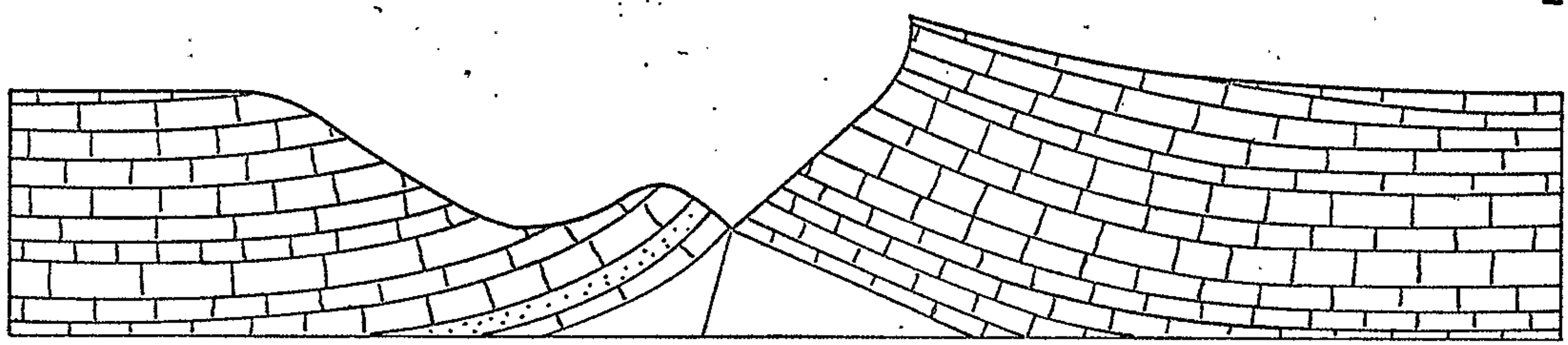


LINCOLN CO.
CHAVES CO.
Macho Draw
Salt Creek Arroyo
Frazier
Acme
Bitter Lake
South Berrenda Creek
ROSWELL
Pecos River
Hondo
Tinnie
Picacho
Riverside
Rio Hondo
Hondo Reservoir
Shermon
Rocky Arroyo
BORDER HILLS STRUCTURE
SIXMILE HILL STRUCTURE
Y-O STRUCTURE
Dexter
Greenfield
Rio Felix
Hagerman
Walnut Draw
Lake Arthur
LINCOLN CO.
CHAVES CO.
CHAVES CO.
EDDY CO.
Lower Peñasco
Rio Peñasco
Duxen
Hope Diversion Dam
N
EXPLANATION
Fault, in most places at axis of anticline
Axis of anticline, probably not faulted
Axis of syncline, possibly faulted in places
0 5 10
Scale in miles

Figure 13
Diagrammatic sections across the Border Hills



a



b

Figure 14
Cross section of the Y-O structural zone (after Havenor, 1968)

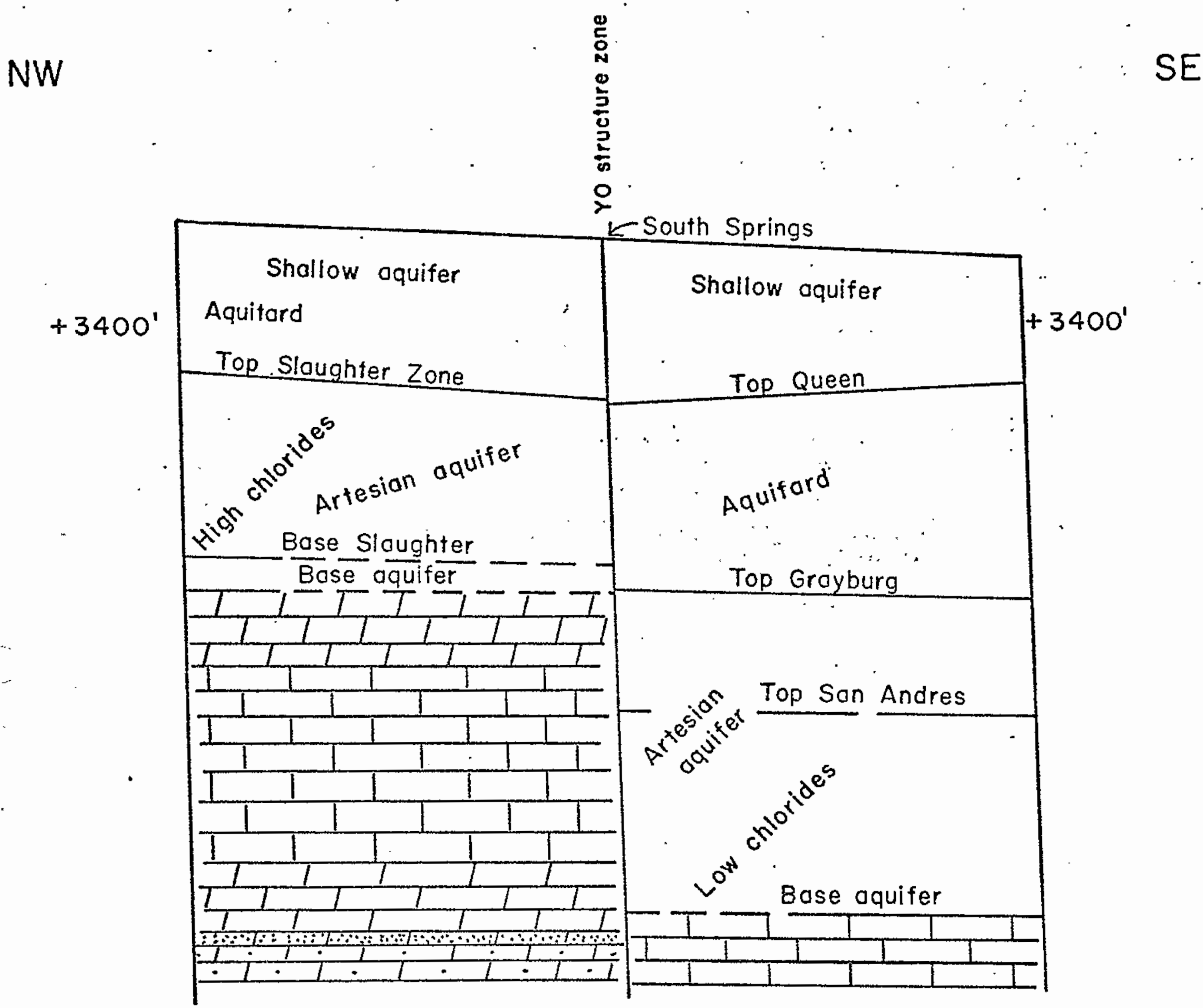

NW
SE
YO structure zone
South Springs
+3400'
+3400'
Shallow aquifer
Aquitard
Top Slaughter Zone
High chlorides
Artesian aquifer
Base Slaughter
Base aquifer
Shallow aquifer
Top Queen
Aquitard
Top Grayburg
Artesian aquifer
Top San Andres
Low chlorides
Base aquifer

Figure 15

Map of the buried surface of the rocks of Precambrian age

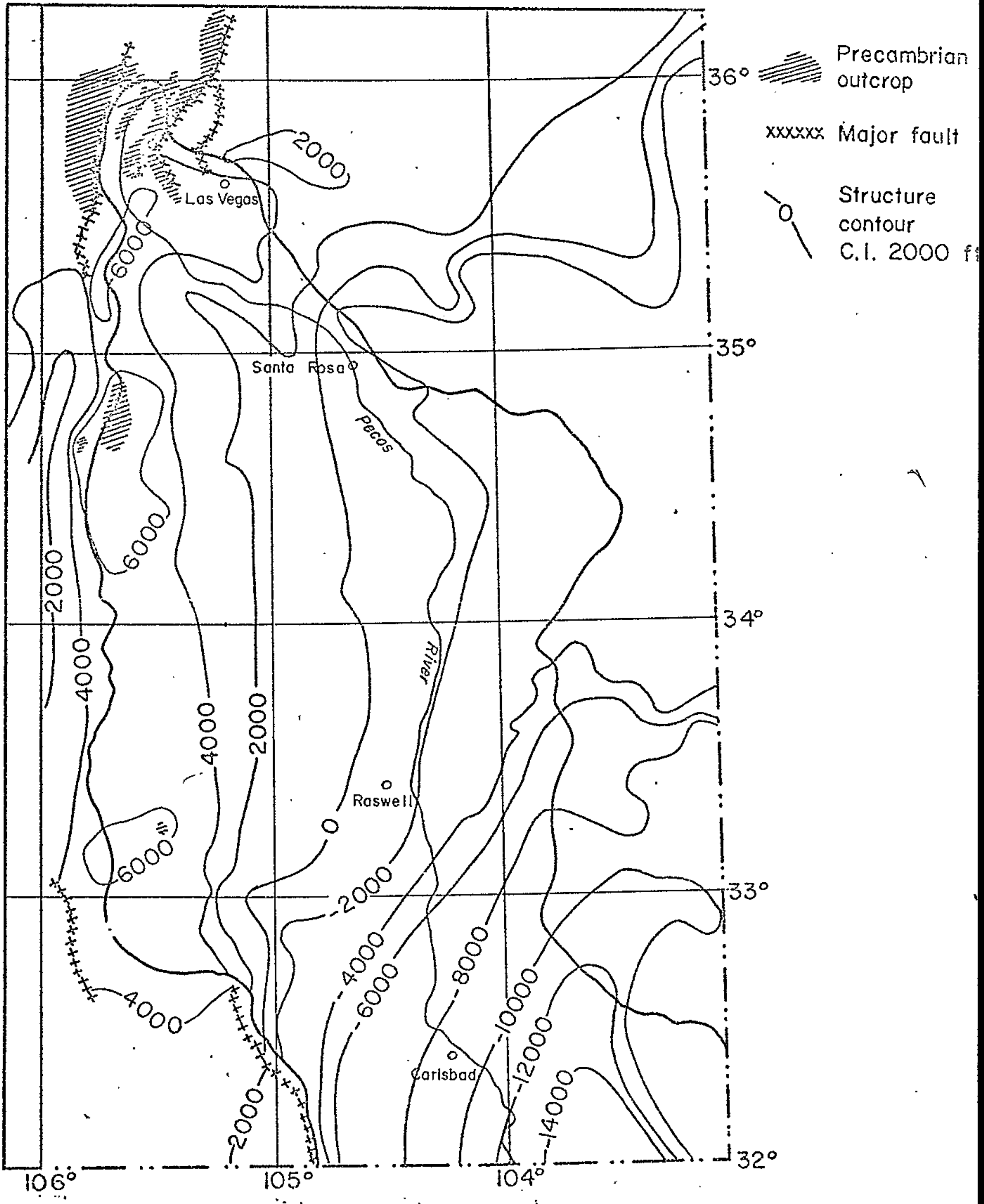

Precambrian outcrop
xxxxxx Major fault
Structure contour C.I. 2000 ft
36°
35°
34°
33°
32°
106°
105°
104°
Las Vegas
Santa Rosa
Pecos River
Roswell
Carlsbad
2000
4000
6000
0
8000
10000
12000
14000

Figure 16

Ordovician System in southeastern New Mexico (after Lloyd, 1949)

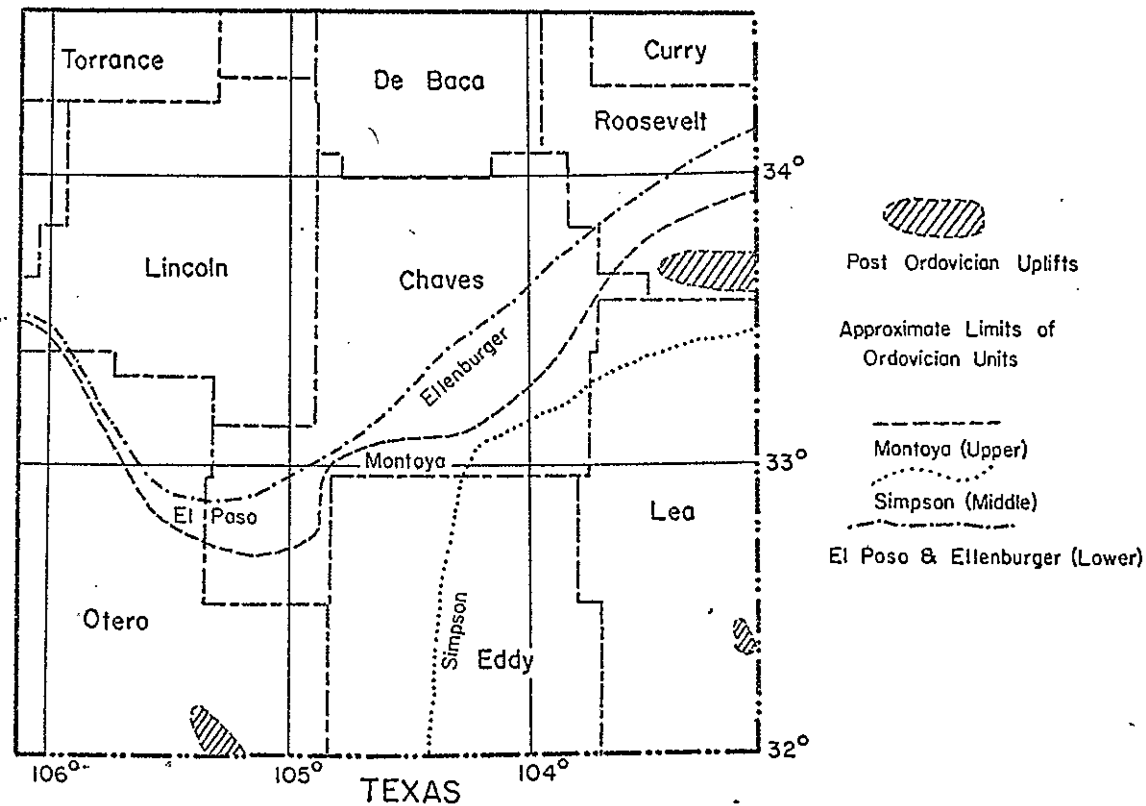

Torrance
De Baca
Curry
Roosevelt
Lincoln
Chaves
Ellenburger
Montoya
El Paso
Otero
Simpson
Eddy
Lea
34°
33°
32°
106°
105°
104°
TEXAS
Post Ordovician Uplifts
Approximate Limits of Ordovician Units
Montoya (Upper)
Simpson (Middle)
El Paso & Ellenburger (Lower)

Figure 17

Devonian and Silurian Systems in southeastern New Mexico (after Lloyd, 1949)

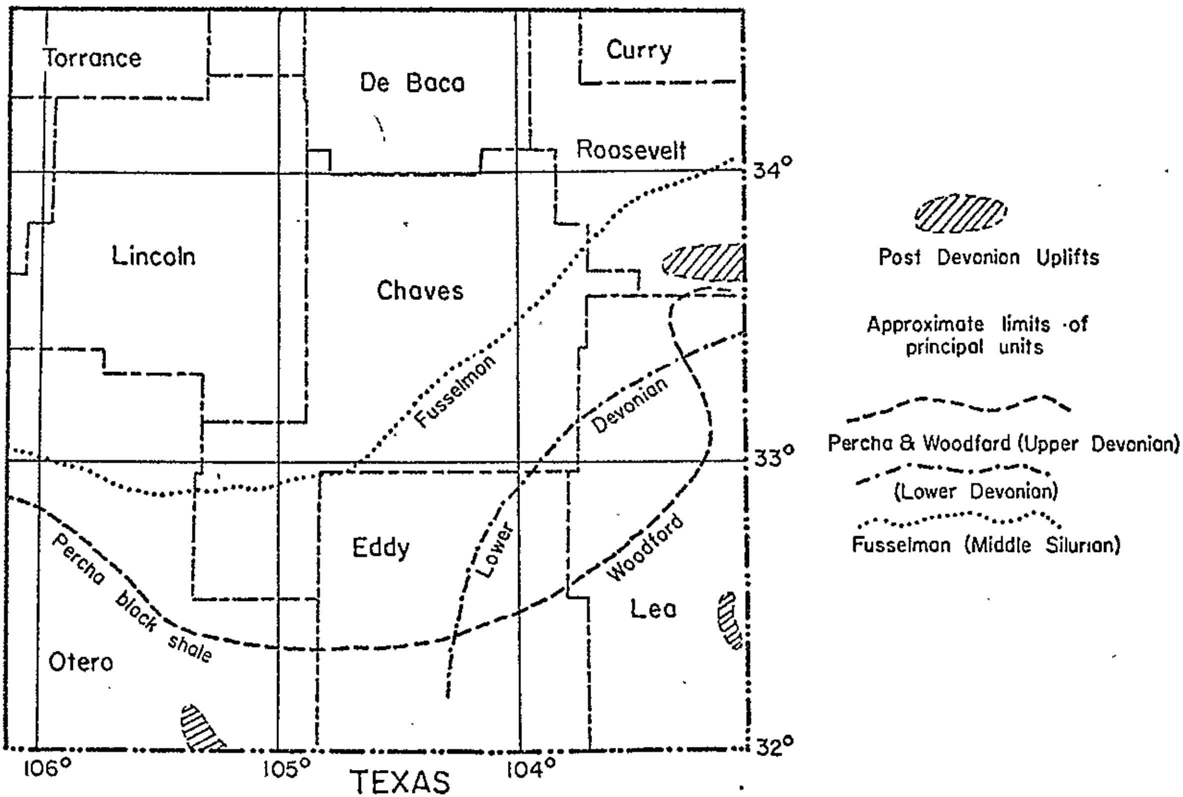

Torrance
Curry
De Baca
Roosevelt
Lincoln
Chaves
Eddy
Lea
Otero
Fusselman
Devonian
Lower
Woodford
Percha black shale
34°
33°
32°
106°
105°
104°
TEXAS
Post Devonian Uplifts
Approximate limits of principal units
Percha & Woodford (Upper Devonian)
(Lower Devonian)
Fusselman (Middle Silurian)

Figure 18

Mississippian System in southeastern New Mexico (after Lloyd, 1949)

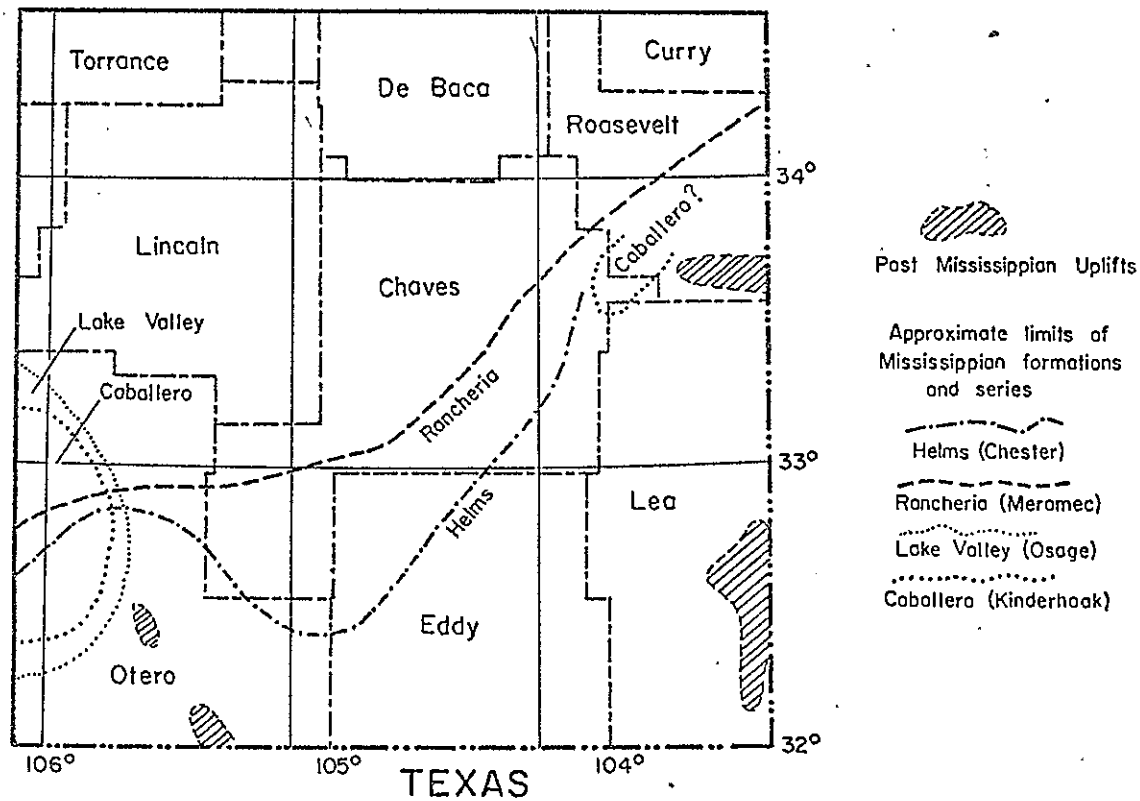
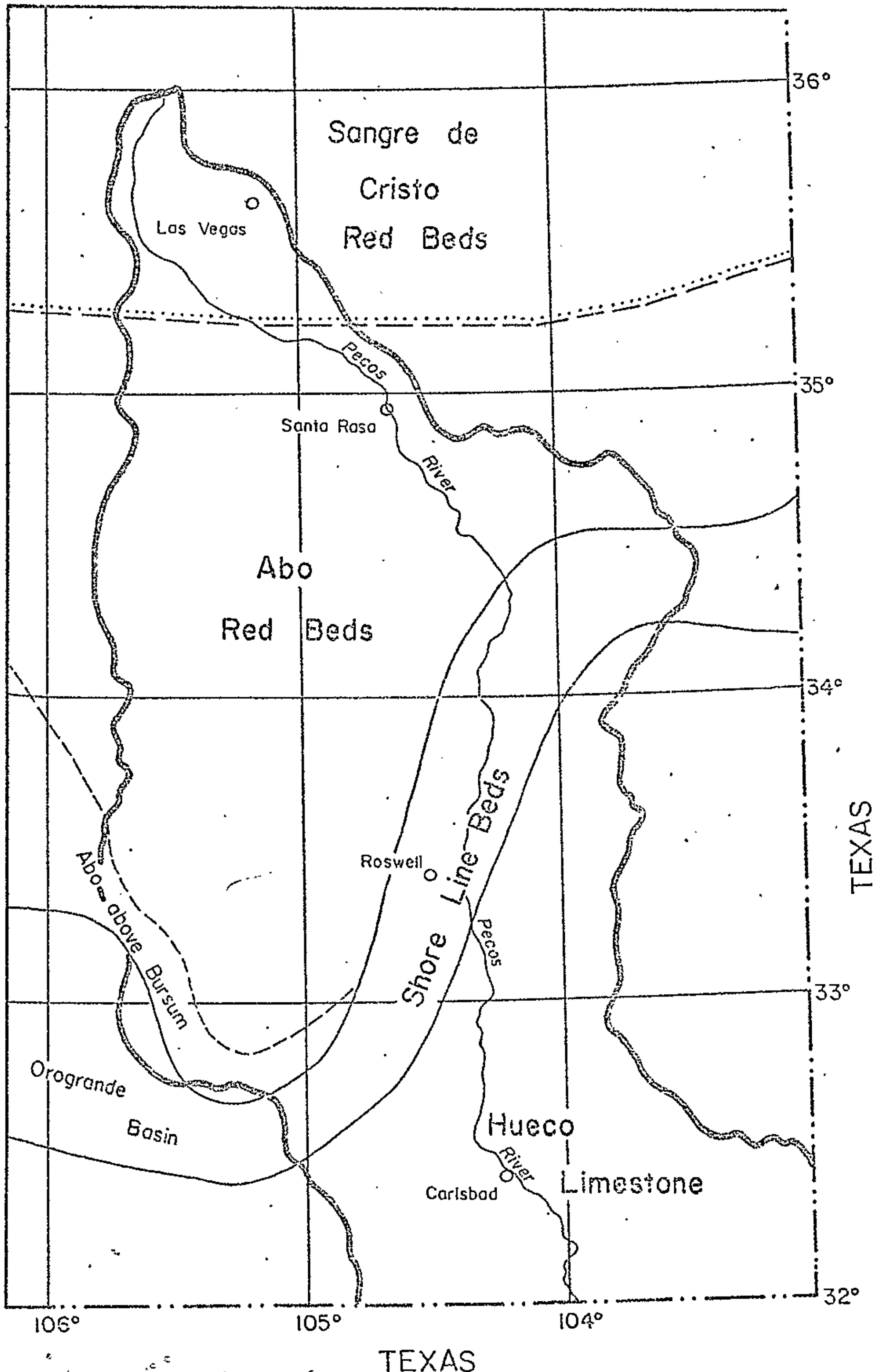

Torrance
De Baca
Curry
Roosevelt
34°
Lincoln
Chaves
Caballero?
Lake Valley
Caballero
Rancheria
33°
Helms
Lea
Eddy
Otero
32°
106°
105°
104°
TEXAS
Post Mississippian Uplifts
Approximate limits of Mississippian formations and series
Helms (Chester)
Rancheria (Meramec)
Lake Valley (Osage)
Caballero (Kinderhook)

Figure 19

Relationships between the Sangre de Cristo, Bursum, Abo, and Hueco Limestone Formations, Pecos River basin, New Mexico



36°
Sangre de
Cristo
Red Beds
Las Vegas
Pecos
35°
Santa Rosa
River
Abo
Red Beds
34°
Shore Line Beds
Roswell
Abo above Bursum
Pecos
33°
Orogrande
Basin
Hueco
Limestone
River
Carlsbad
32°
106°
105°
104°
TEXAS
TEXAS

Figure 20

West to east diagrammatic section of Permian units across the Pedernal landmass (after Kottlowski, 1963, p. 55)

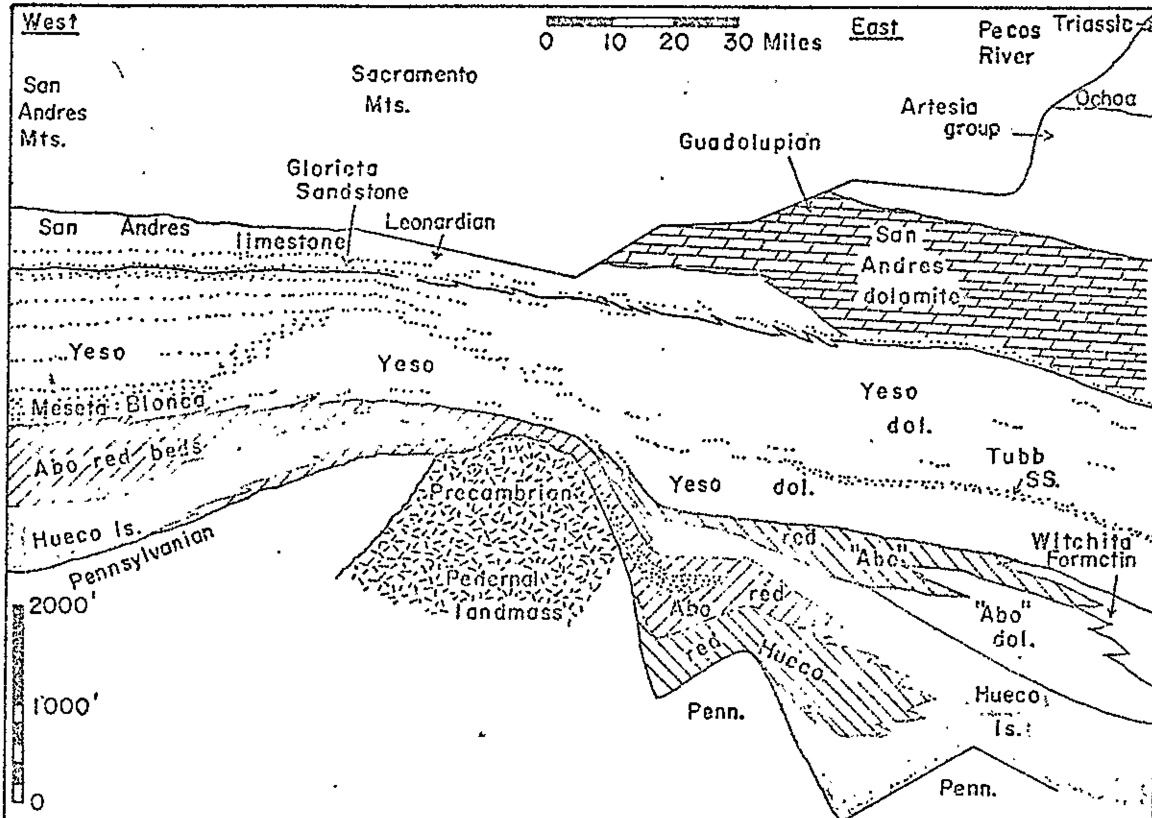

West
0 10 20 30 Miles
East
Pecos River
Triassic
San Andres Mts.
Sacramento Mts.
Ochoa
Artesia group
Guadolupian
Glorieta Sandstone
Leonardian
San Andres limestone
San Andres dolomite
Yeso
Yeso
Meseta Blanca
Yeso dol.
Tubb SS.
Abo red beds
Precambrian
Yeso dol.
Hueco ls.
Pennsylvanian
red "Abo"
Witchita Formation
Pedernal landmass
Abo red
red Hueco
"Abo" dol.
2000'
1000'
0
Penn.
Hueco ls.
Penn.

Figure 21

Lithologies of the Yeso Formation

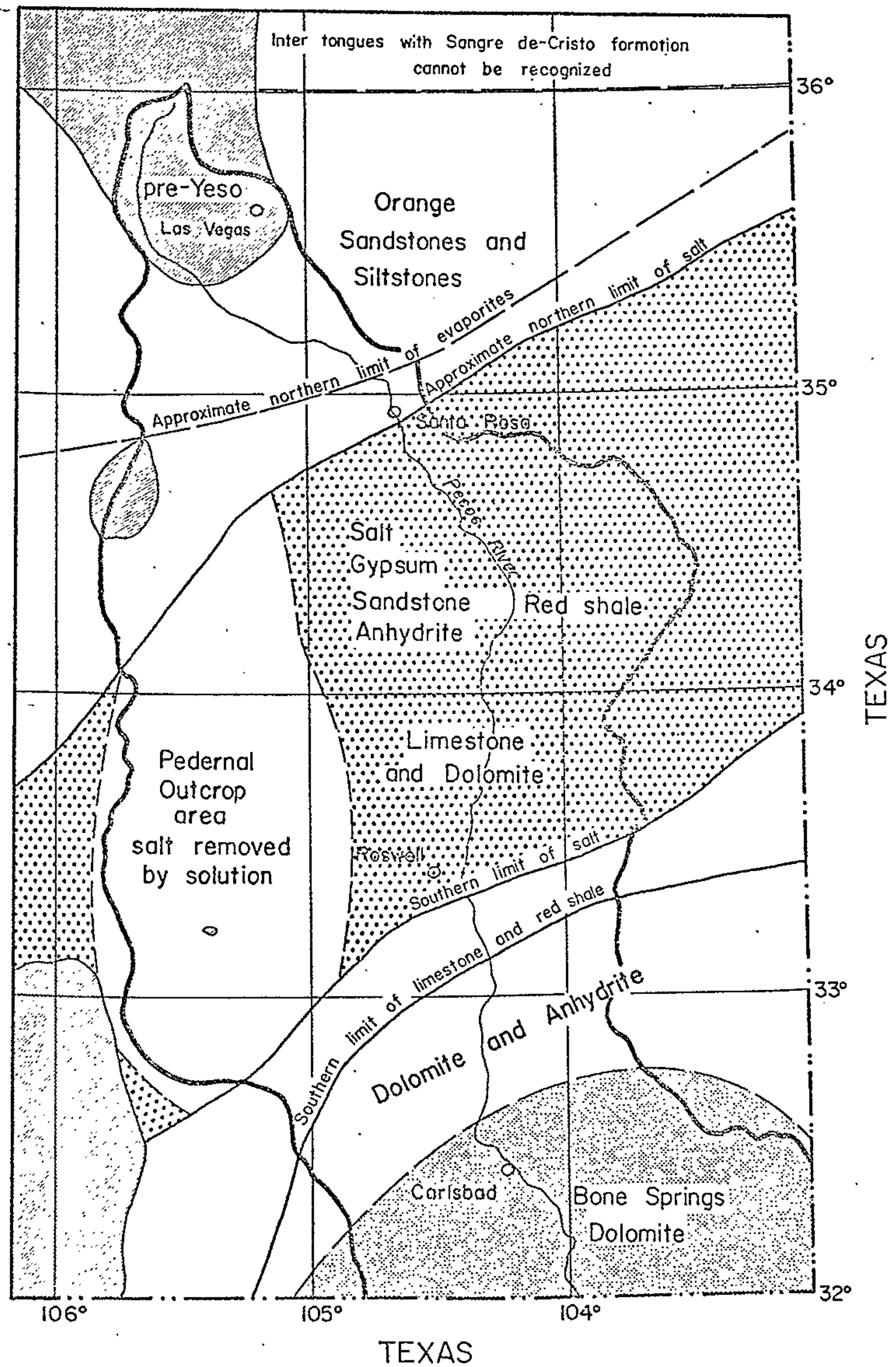
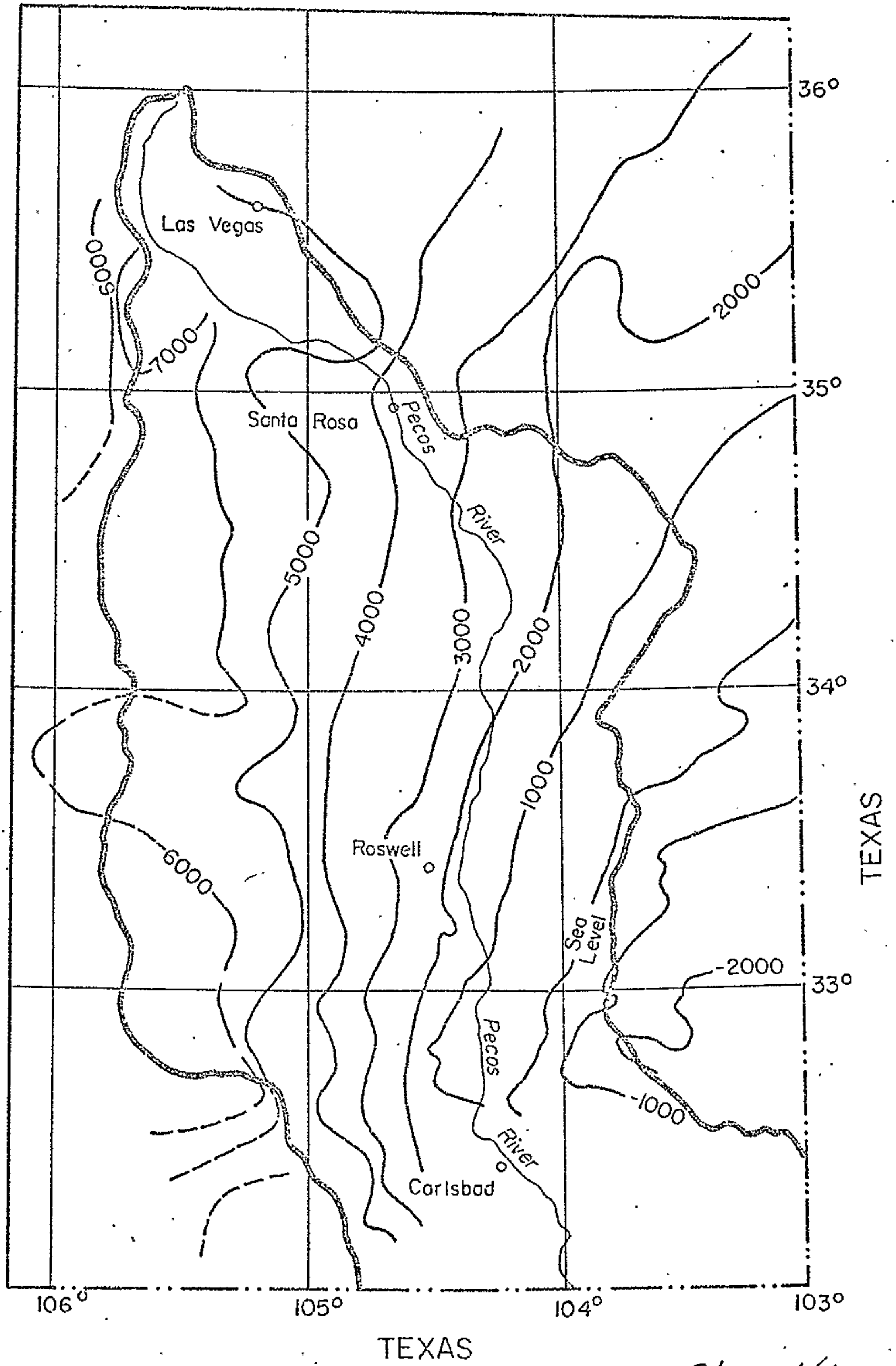

Inter tongues with Sangre de-Cristo formotion
cannot be recognized
36°
pre-Yeso
Las Vegas
Orange
Sandstones and
Siltstones
Approximate northern limit of evaporites
Approximate northern limit of salt
35°
Santa Rosa
Pecos River
Salt
Gypsum
Sandstone
Anhydrite
Red shale
34°
Limestone
and Dolomite
Pedernal
Outcrop
area
salt removed
by solution
Roswell
Southern limit of salt
Southern limit of limestone and red shale
Dolomite and Anhydrite
33°
Carlsbad
Bone Springs
Dolomite
32°
106°
105°
104°
TEXAS
TEXAS

Figure 22

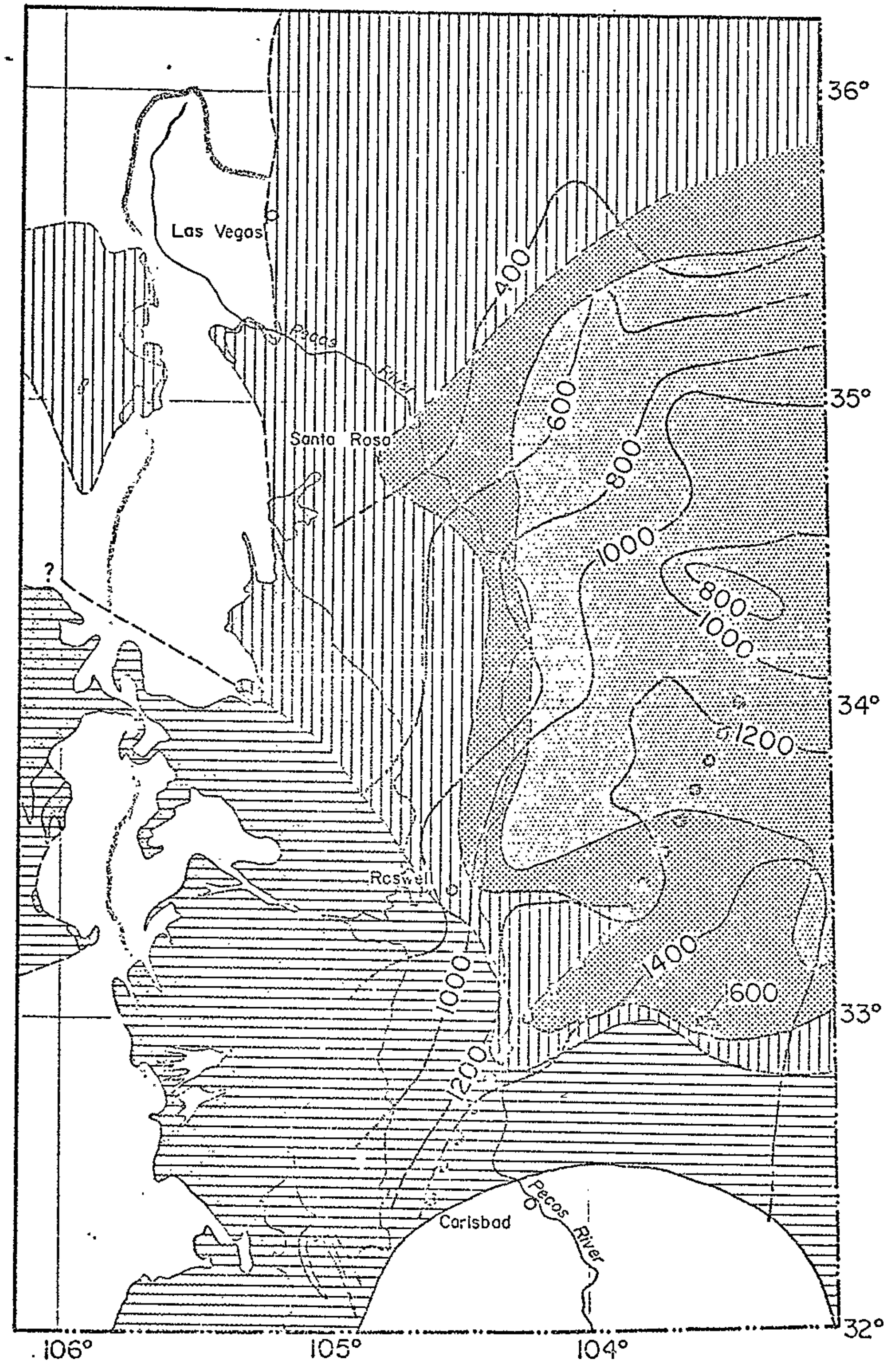
Structure contours on the Glorieta Sandstone


36°
35°
34°
33°
Las Vegas
Santa Rosa
Pecos
River
Roswell
Carlsbad
Pecos
River
Sea Level
7000
6000
5000
4000
3000
2000
2000
1000
6000
-2000
-1000
TEXAS
106°
105°
104°
103°
TEXAS

Glorieta

Figure 23

Lithologies of the San Andres Formation



36°
35°
34°
33°
32°
106°
105°
104°
Las Vegas
Pecos River
Santa Rosa
Roswell
Carlsbad
Pecos River
?
400
600
800
1000
800
1000
1200
1000
1200
1400
1600

EXPLANATION

Pre-San Andres or Basin Equivalents

San Andres Outcrop

Limestone and Dolomite

Limestone, Dolomite, Anhydrite and Gypsum

Limestone, Dolomite, Anhydrite, Gypsum and Red Shale

Limestone, Dolomite, Anhydrite, Gypsum, Red Shale and Salt

Approximate Eastern Limit of Erosional Unconformity on Top of San Andres

200 Isopach Contours (Feet)

Approximate Lithologic Boundaries

Figure 24

North-south stratigraphic diagram of the San Andres Members
(after Kelley, 1971, p. 11)

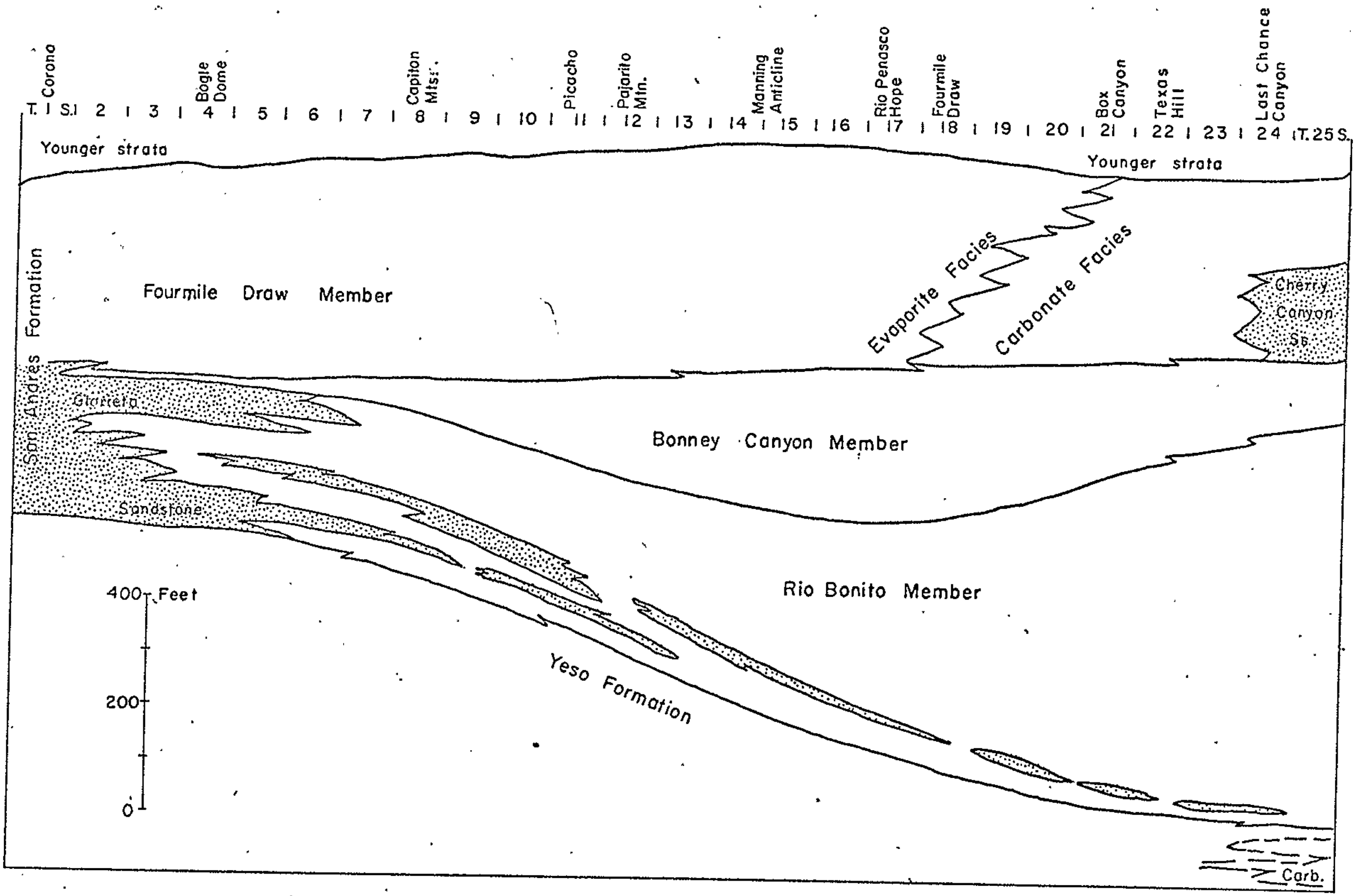
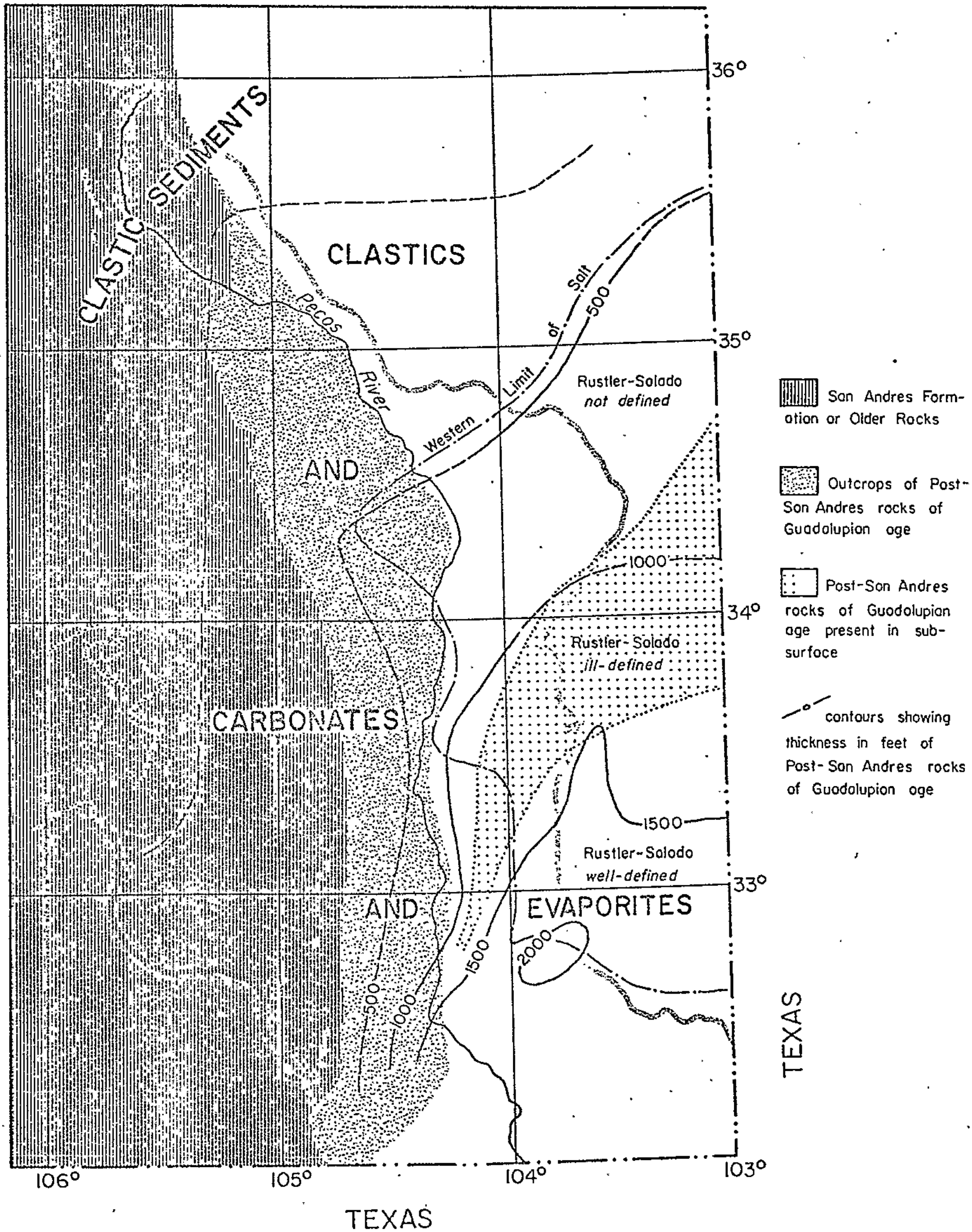

Corona
Bogle Dome
Capitan Mts.
Picacho
Pajarito Mtn.
Manning Anticline
Rio Penasco Hope
Fourmile Draw
Box Canyon
Texas Hill
Last Chance Canyon
T. 1 S. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 T. 25 S.
Younger strata
Younger strata
San Andres Formation
Fourmile Draw Member
Evaporite Facies
Carbonate Facies
Cherry Canyon Ss.
Glorieta Sandstone
Bonney Canyon Member
Rio Bonito Member
400 Feet
200
0
Yeso Formation
Carb.

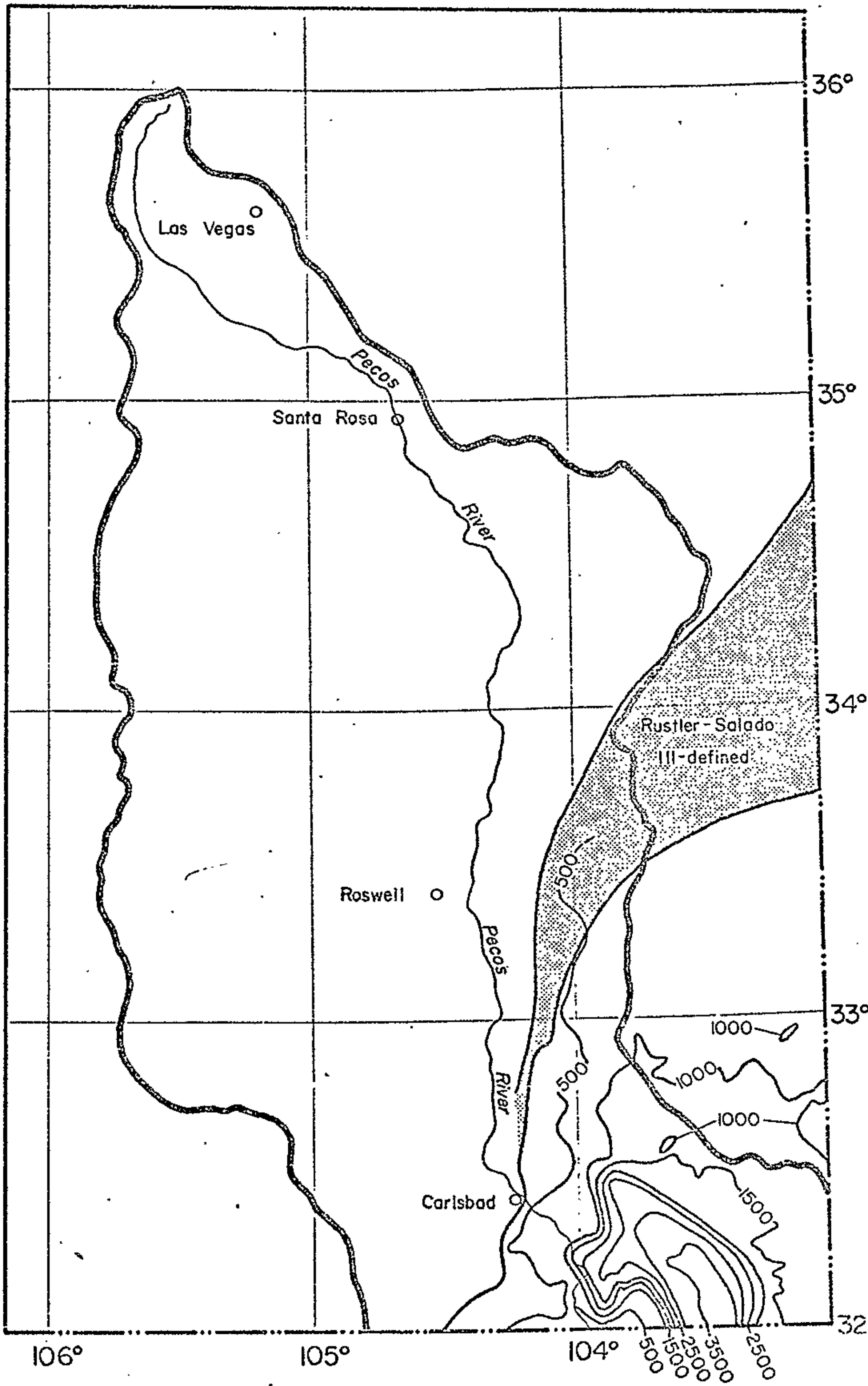
Figure 25

Lithology and thickness of the Artesia Group



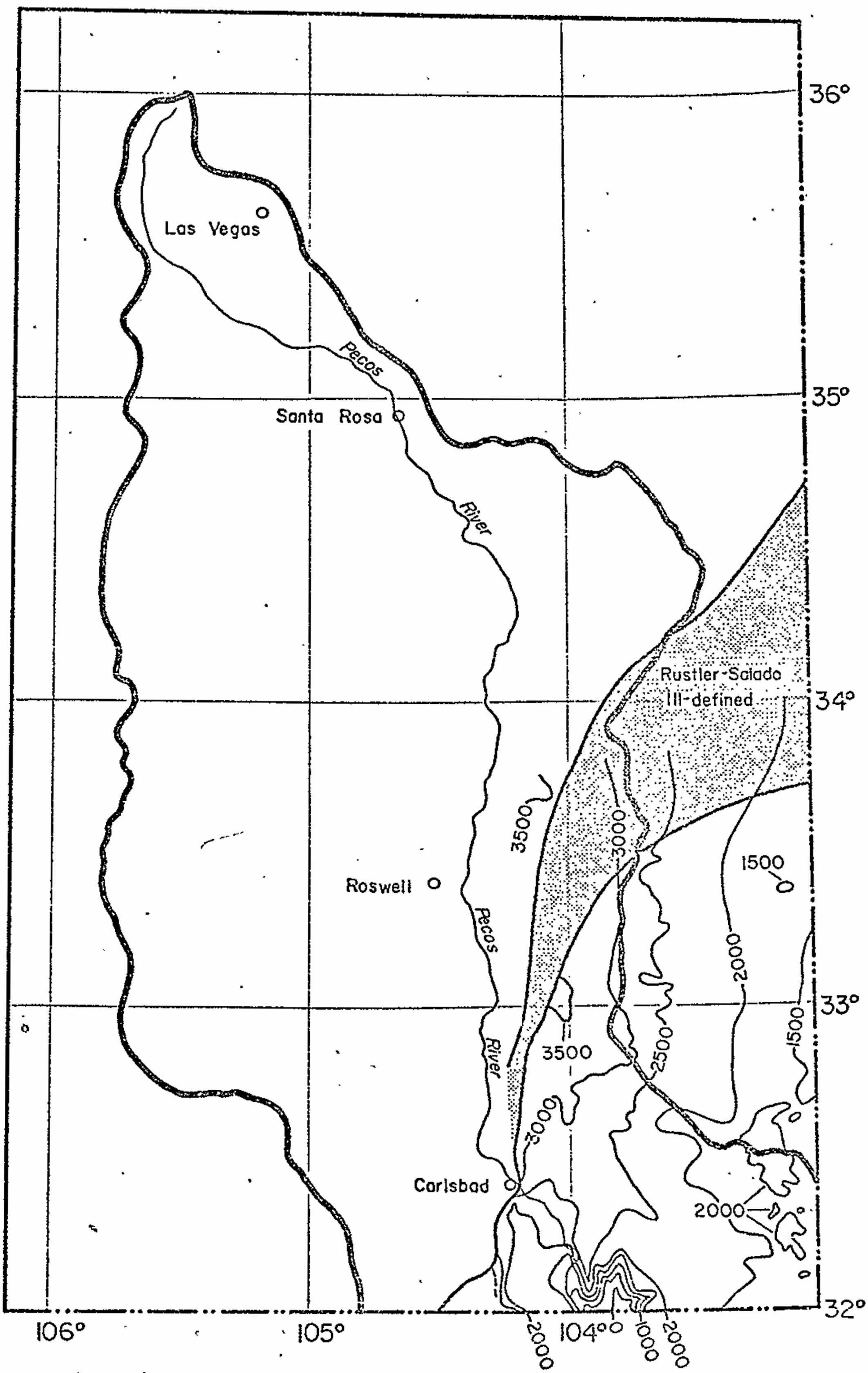
CLASTIC SEDIMENTS
CLASTICS
Pecos River
Western Limit of Salt
500
Rustler-Solado not defined
AND
1000
Rustler-Solado ill-defined
CARBONATES
1500
Rustler-Solado well-defined
AND
EVAPORITES
2000
1500
1000
500
36°
35°
34°
33°
106°
105°
104°
103°
TEXAS
TEXAS
San Andres Formation or Older Rocks
Outcrops of Post-San Andres rocks of Guadalupian age
Post-San Andres rocks of Guadalupian age present in subsurface
contours showing thickness in feet of Post-San Andres rocks of Guadalupian age

Figure 26
Thickness of the salt



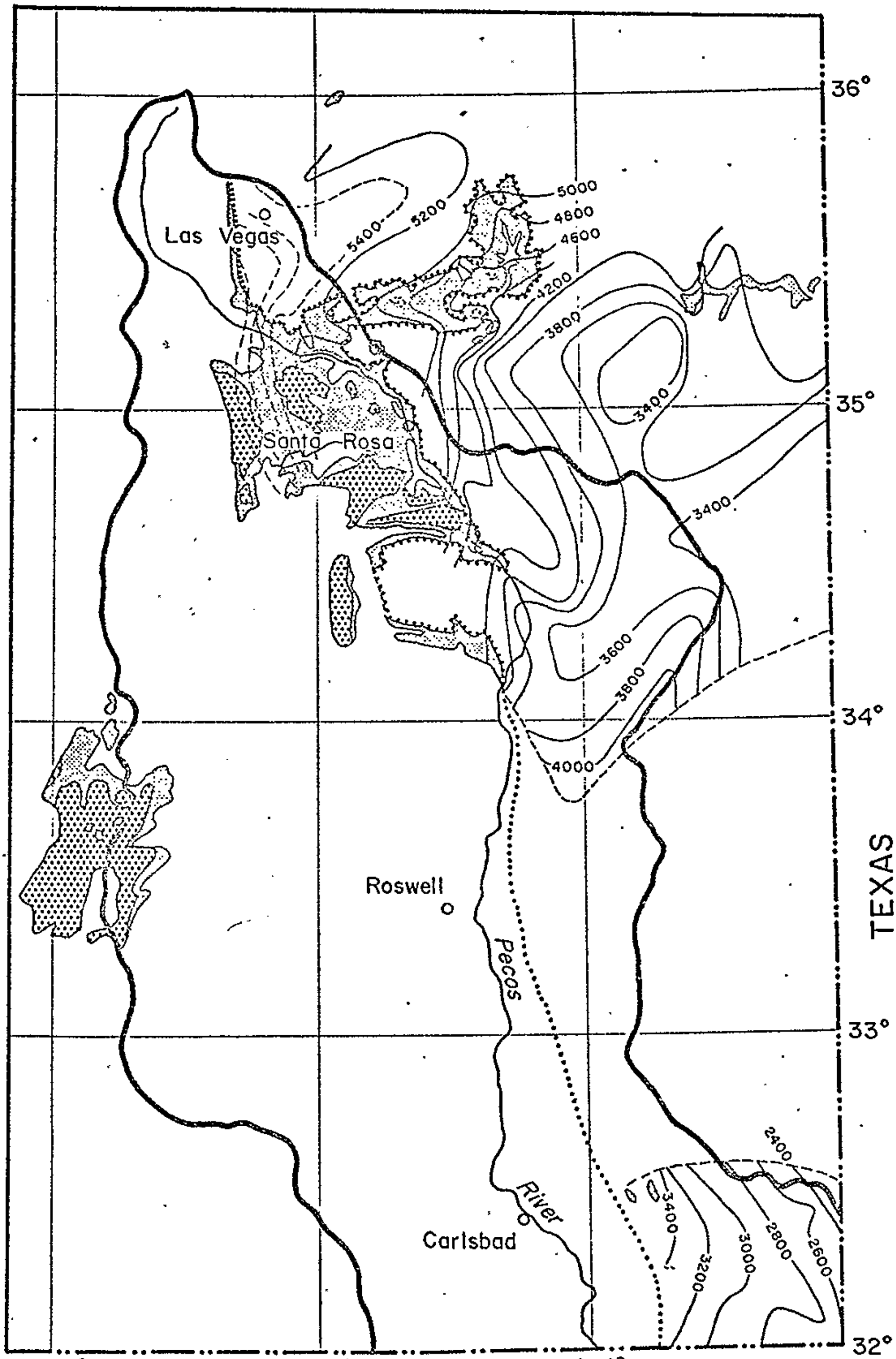
36°
35°
34°
33°
32°
106°
105°
104°
Las Vegas
Pecos
Santa Rosa
River
Roswell
Pecos
River
Carlsbad
Rustler - Salado
Ill-defined
500
500
1000
1000
1000
1500
500
1500
2500
3500
2500

Figure 27
Structure contours on "top of the salt"



36°
35°
34°
33°
32°
106°
105°
104°
Las Vegas
Pecos
Santa Rosa
River
Rustler-Salado
Ill-defined
3500
3000
1500
Roswell
Pecos
2000
River
3500
2500
1500
3000
Carlsbad
2000
2000
1000
2000

Figure 28
The Dockum Group of Triassic age

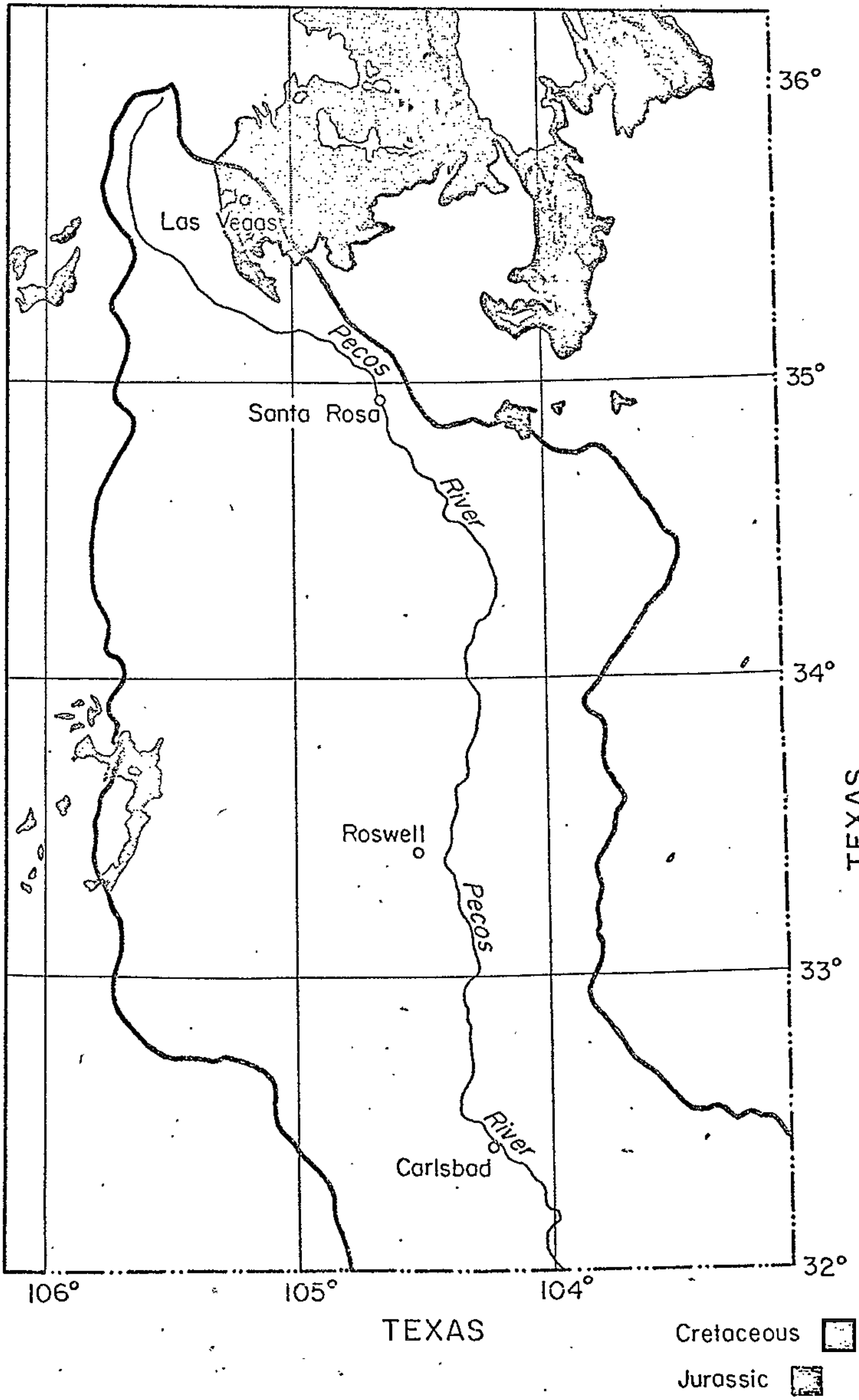


Outcrop Subcrop Outcrop of older rocks

200 foot contour interval on Santa Rosa

.... western limit of continous subcrop

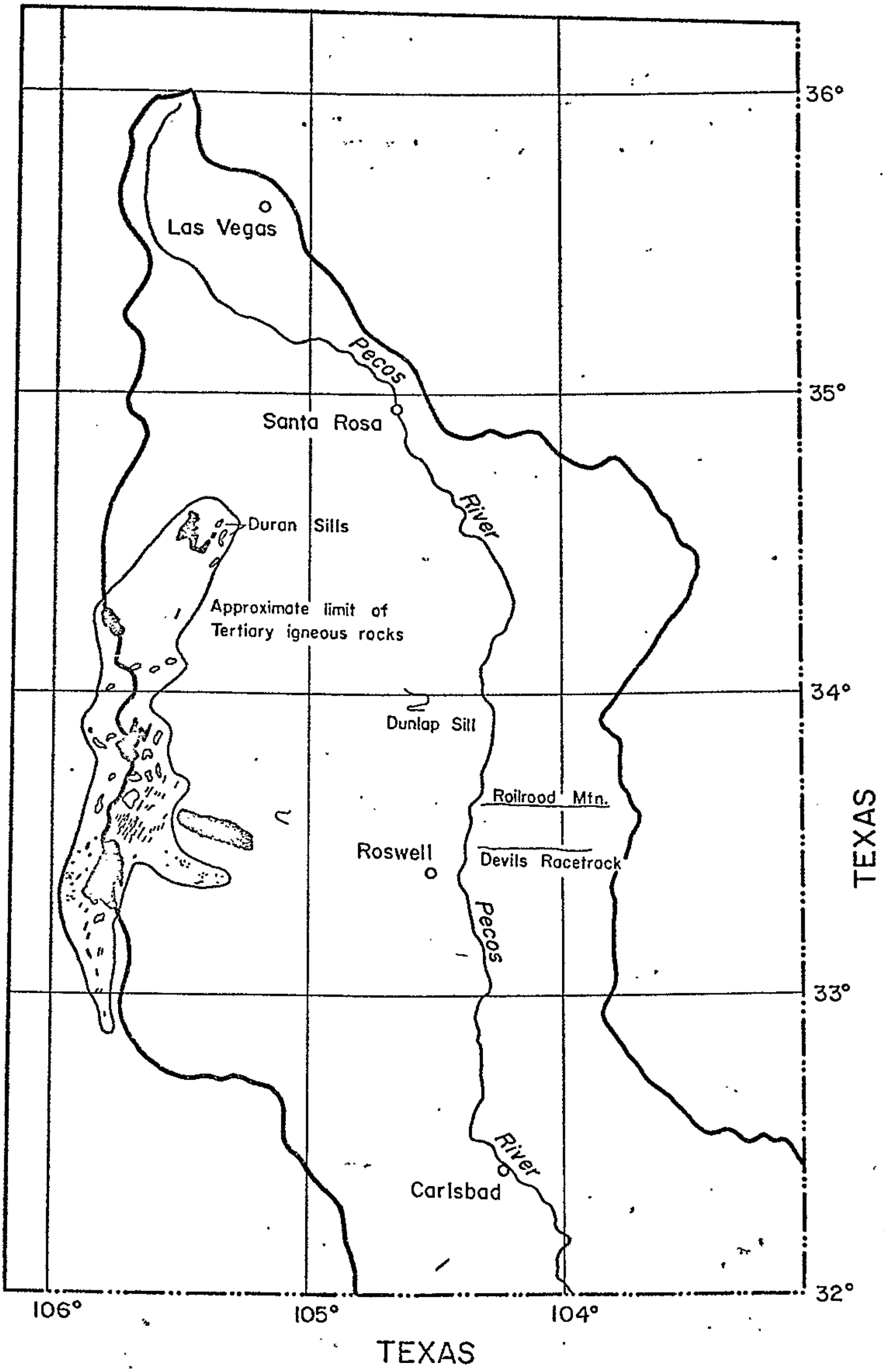
Figure 29
Rocks of the Jurassic and Cretaceous ages in Pecos River basin, New Mexico



36°
35°
34°
33°
32°
Las Vegas
Pecos
Santa Rosa
River
Roswell
Pecos
River
Carlsbad
106°
105°
104°
TEXAS
TEXAS
Cretaceous
Jurassic

Figure 30

Igneous rocks of the Pecos River basin



36°
35°
34°
33°
32°
106°
105°
104°
Las Vegas
Pecos
Santa Rosa
River
Duran Sills
Approximate limit of
Tertiary igneous rocks
Dunlap Sill
Railroad Mtn.
Roswell
Devils Racetrack
Pecos
River
Carlsbad
TEXAS
TEXAS

Figure 31

The Ogallala Formation

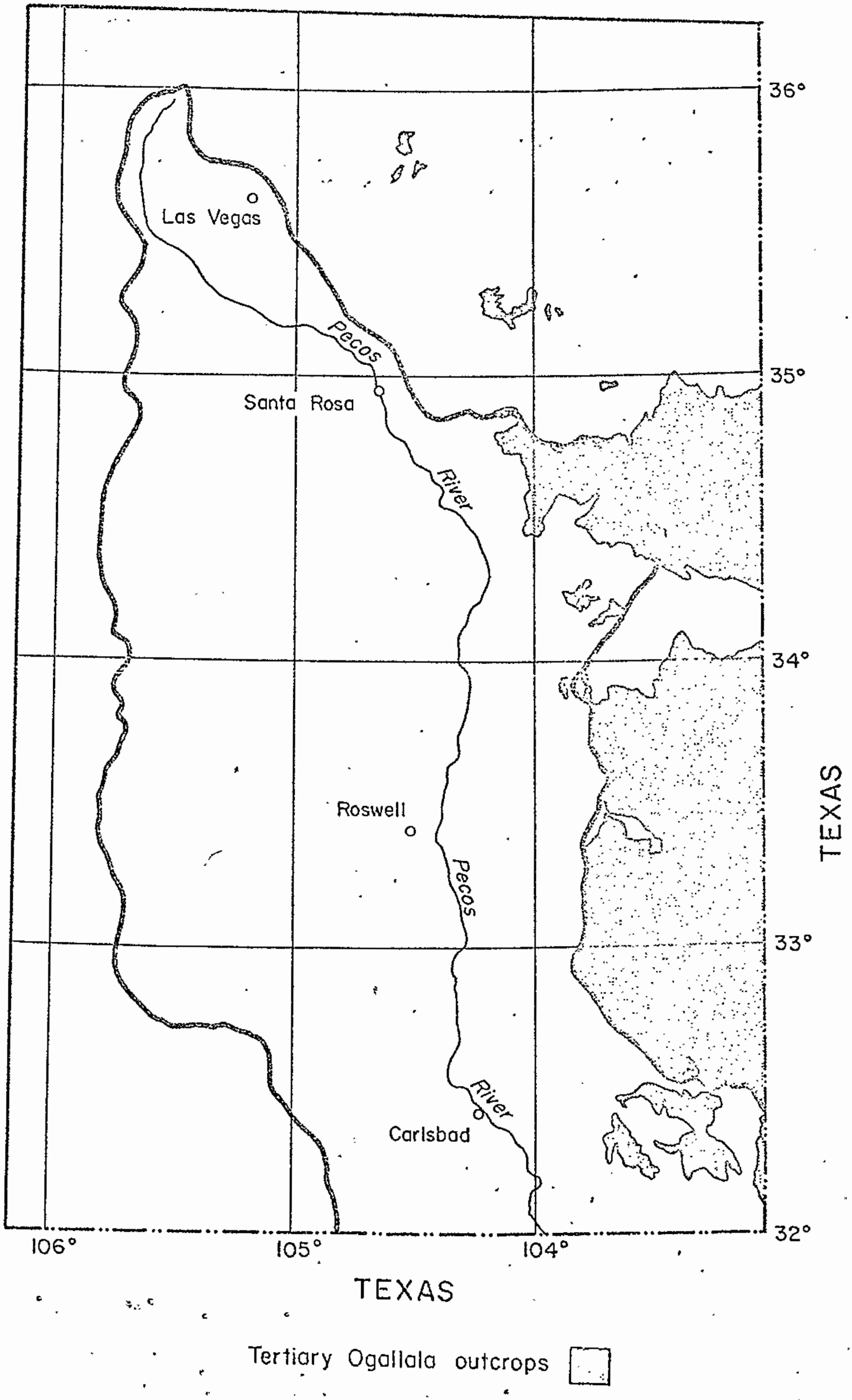
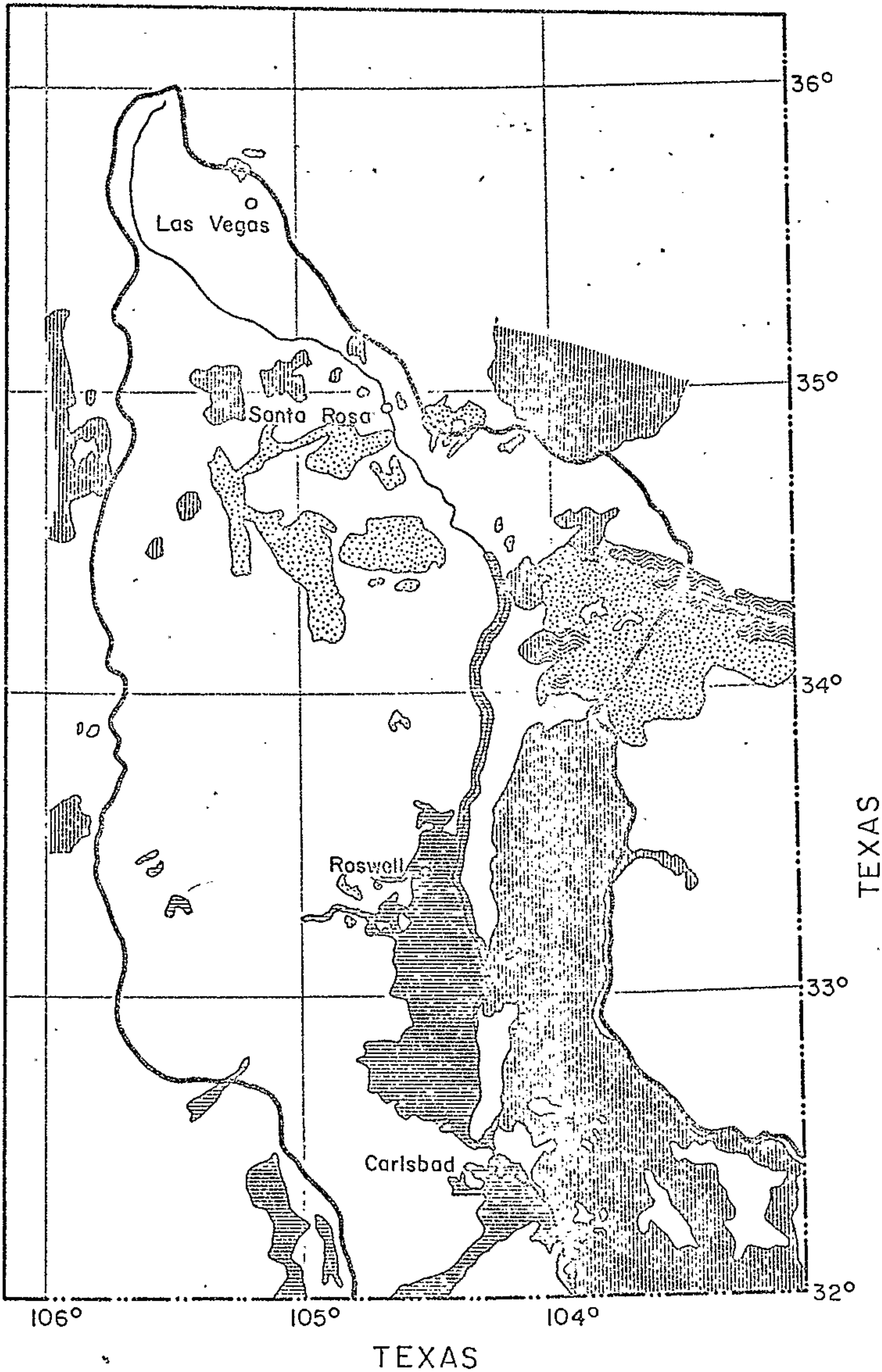

36°
35°
34°
33°
32°
106°
105°
104°
Las Vegas
Pecos
Santa Rosa
River
Roswell
Pecos
River
Carlsbad
TEXAS
TEXAS
Tertiary Ogallala outcrops

Figure 32

Pleistocene and Holocene rocks


36°
35°
34°
33°
32°
106°
105°
104°
Las Vegas
Santa Rosa
Roswell
Carlsbad
TEXAS
TEXAS

EXPLANATION

Dune sand

Alluvial clay, silt, sand, and gravel

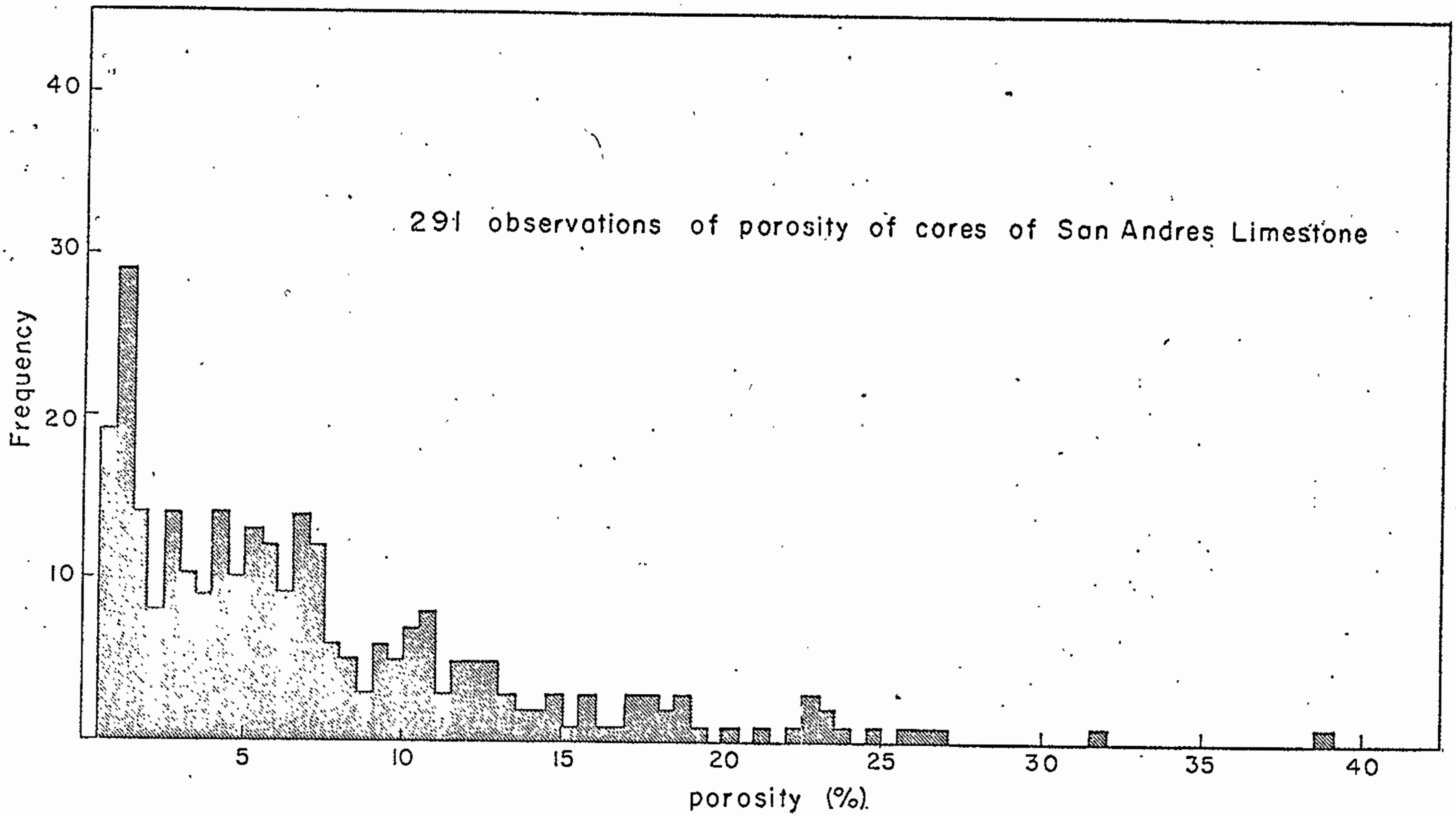
on
Bolsum deposits maybe Ogallala Formation without caliche cap in part

Gatuna Formation

Unconsolidated sediments on pediment

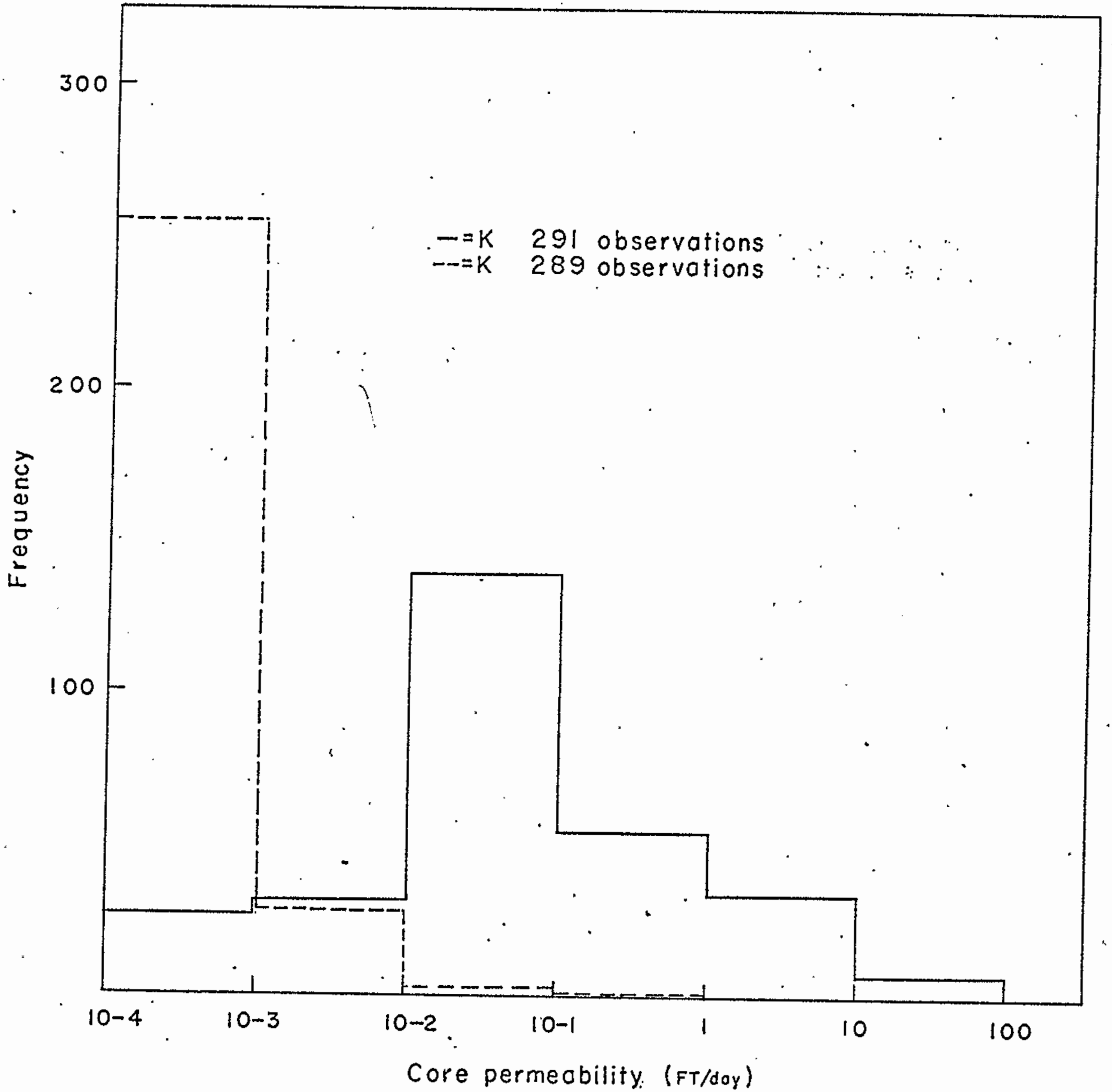
Approximate lithologic boundary

Figure 33
Histogram of porosity in cores from San Andres Formation



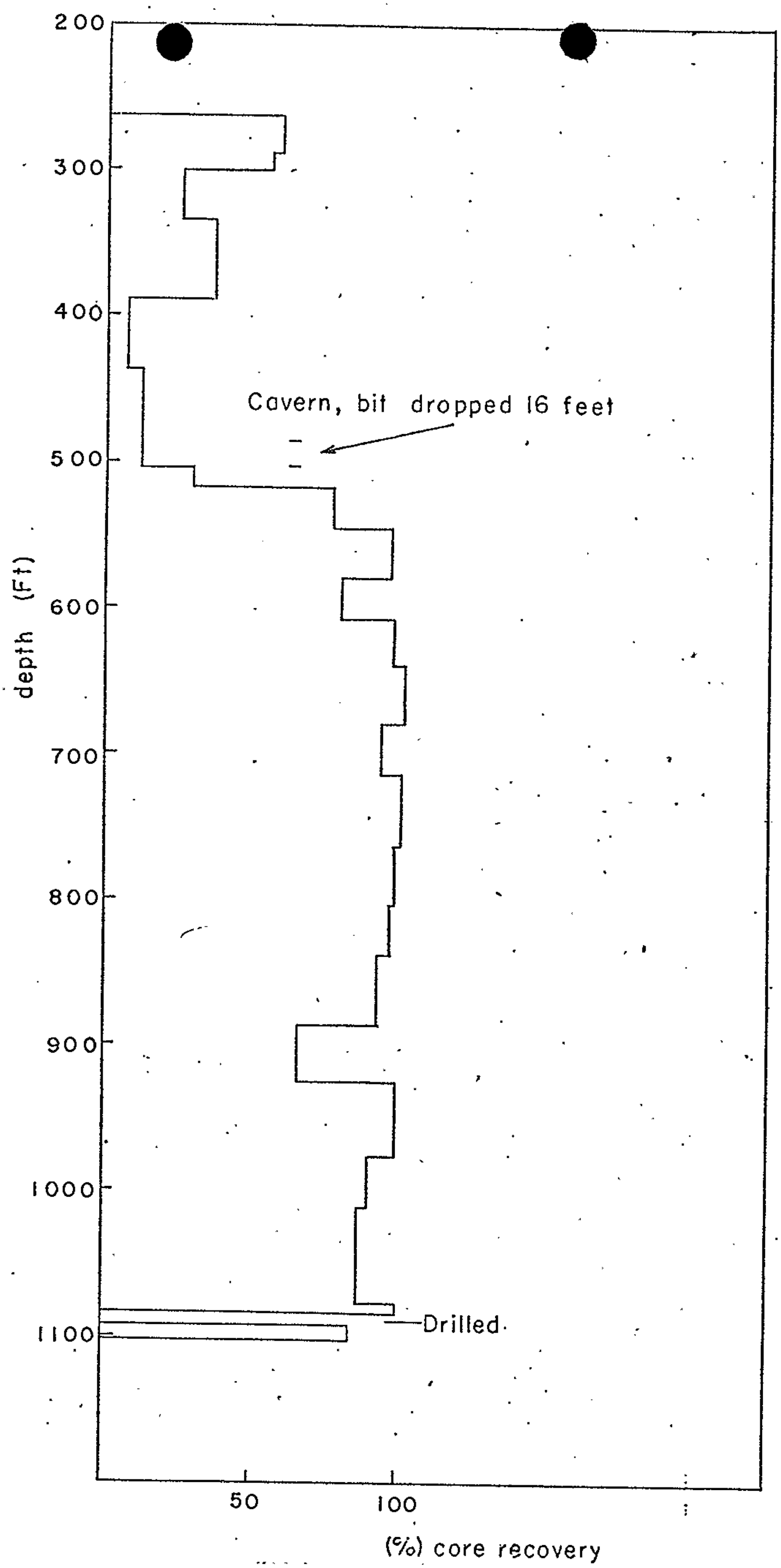
291 observations of porosity of cores of San Andres Limestone
Frequency
40
30
20
10
5
10
15
20
25
30
35
40
porosity (%)

Figure 34
Histograms of permeability in cores from the San Andres Formation



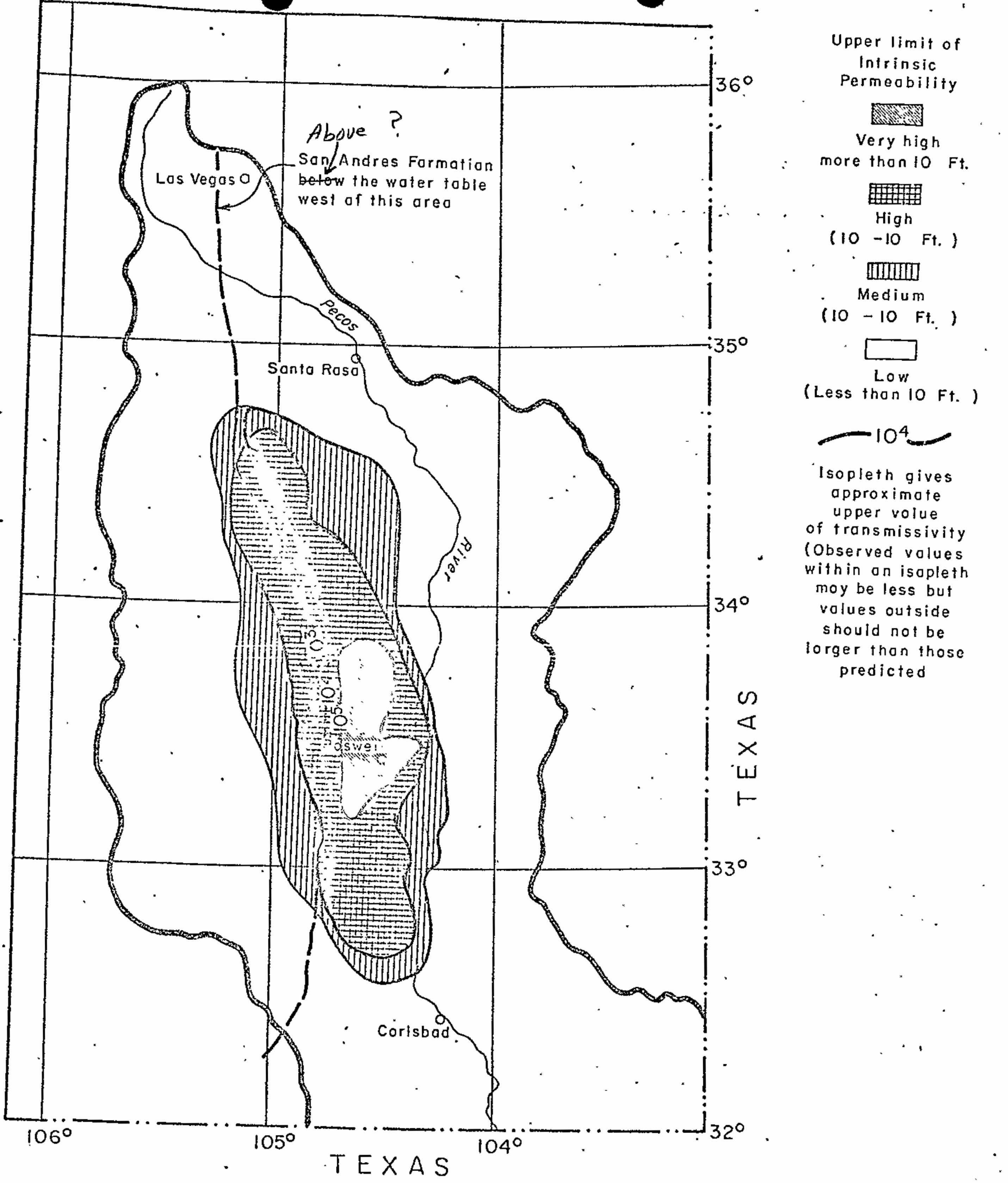
300
200
100
Frequency
—=K 291 observations
--=K 289 observations
10-4
10-3
10-2
10-1
1
10
100
Core permeability (FT/day)

Figure 35
Core recovery in San Andres test



200
300
400
500
600
700
800
900
1000
1100
depth (Ft)
Cavern, bit dropped 16 feet
Drilled
50
100
(%) core recovery

Figure 36
Maximum intrinsic permeability and transmissivity of the San Andres Formation



Above ?
San Andres Formation ~~below~~ the water table west of this area
Las Vegas
Pecos River
Santa Rosa
Carlsbad
oswel
10^3
10^4
10^5
36°
35°
34°
33°
32°
106°
105°
104°
TEXAS
TEXAS
Upper limit of Intrinsic Permeability
Very high more than 10 Ft.
High (10 -10 Ft.)
Medium (10 - 10 Ft.)
Low (Less than 10 Ft.)
10^4
Isopleth gives approximate upper value of transmissivity (Observed values within an isopleth may be less but values outside should not be larger than those predicted)

Figure 37
Ground water in the hydrologic cycle
(after Freeze, 1971)

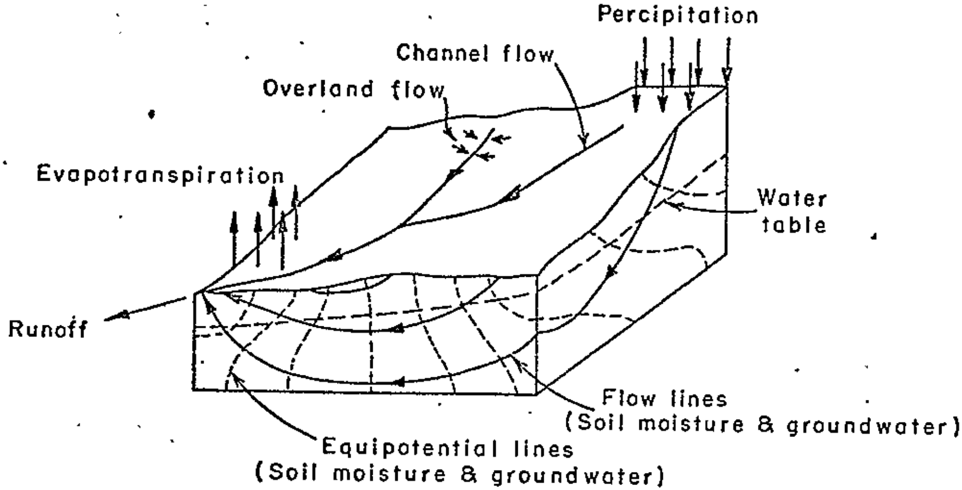
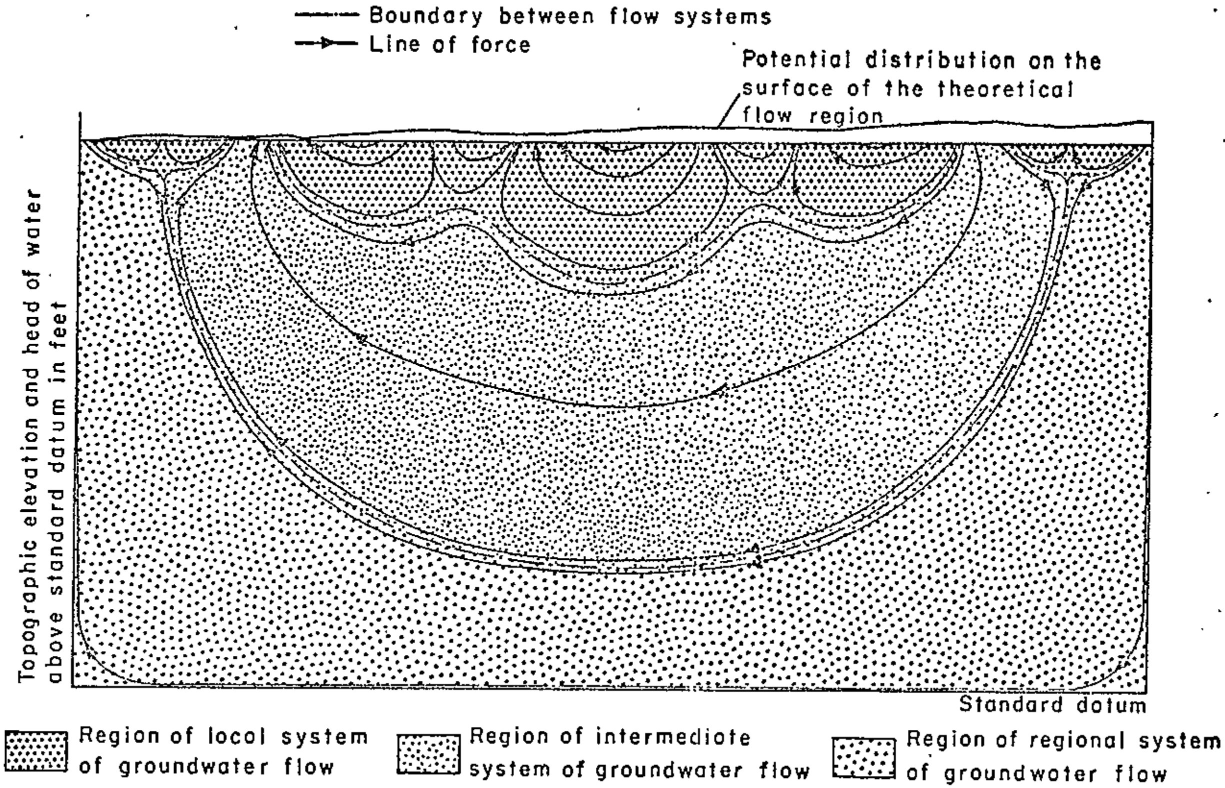

Percipitation
Channel flow
Overland flow
Evapotranspiration
Water
table
Runoff
Flow lines
(Soil moisture & groundwater)
Equipotential lines
(Soil moisture & groundwater)

Figure 38
Examples of subsurface flow systems
(after Toth, 1962)



Boundary between flow systems
Line of force
Potential distribution on the surface of the theoretical flow region
Topographic elevation and head of water above standard datum in feet
Standard datum
Region of local system of groundwater flow
Region of intermediate system of groundwater flow
Region of regional system of groundwater flow

Figure 39
Plan and cross section of counter current flow lines

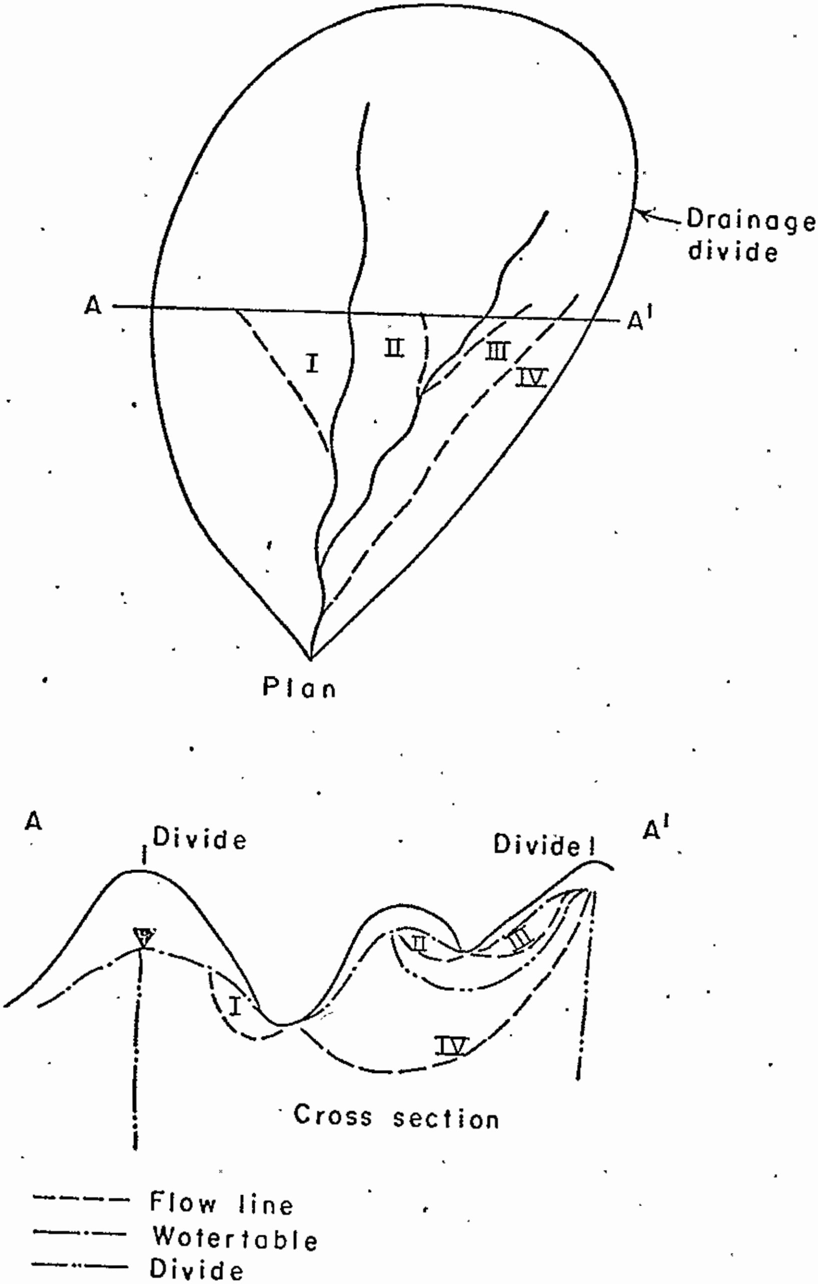
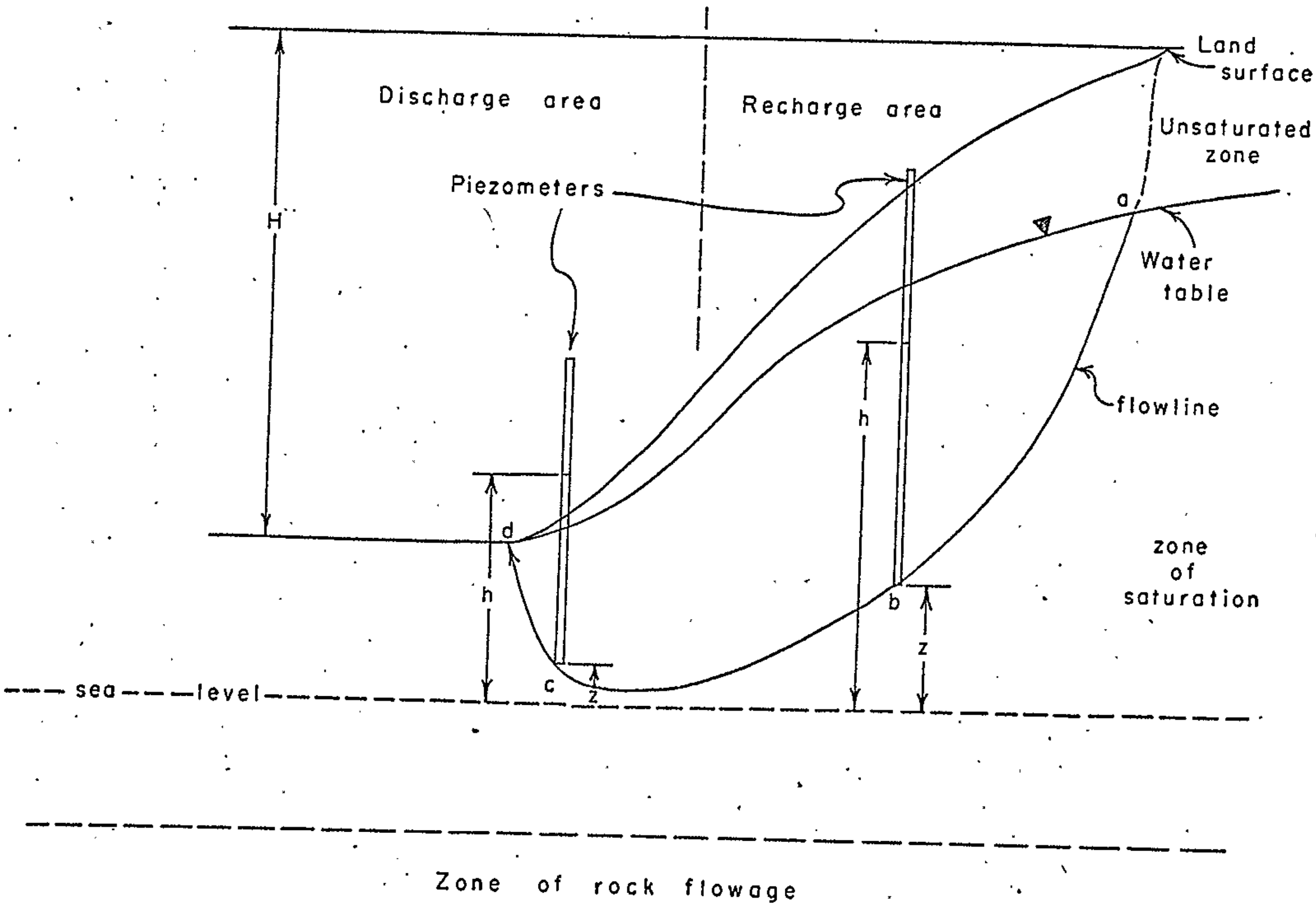

Drainage divide
A
A'
I
II
III
IV
Plan
A
Divide
Divide
A'
I
II
III
IV
Cross section
Flow line
Watertable
Divide

Figure 40

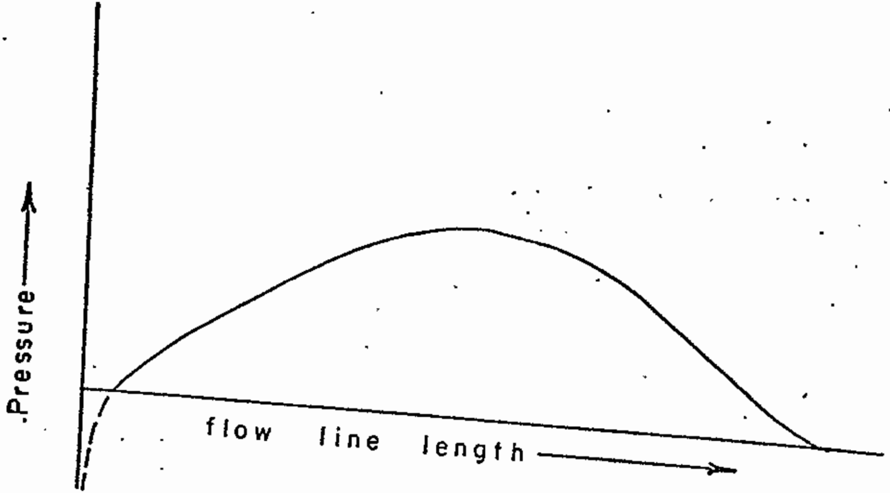
Diagram showing the division of a subsurface flow system and the relation of hydraulic head to flow-line altitude.



Land surface
Discharge area
Recharge area
Unsaturated zone
Piezometers
H
a
Water table
h
flowline
d
zone of saturation
h
b
z
c
z
sea level
Zone of rock flowage

Figure 41

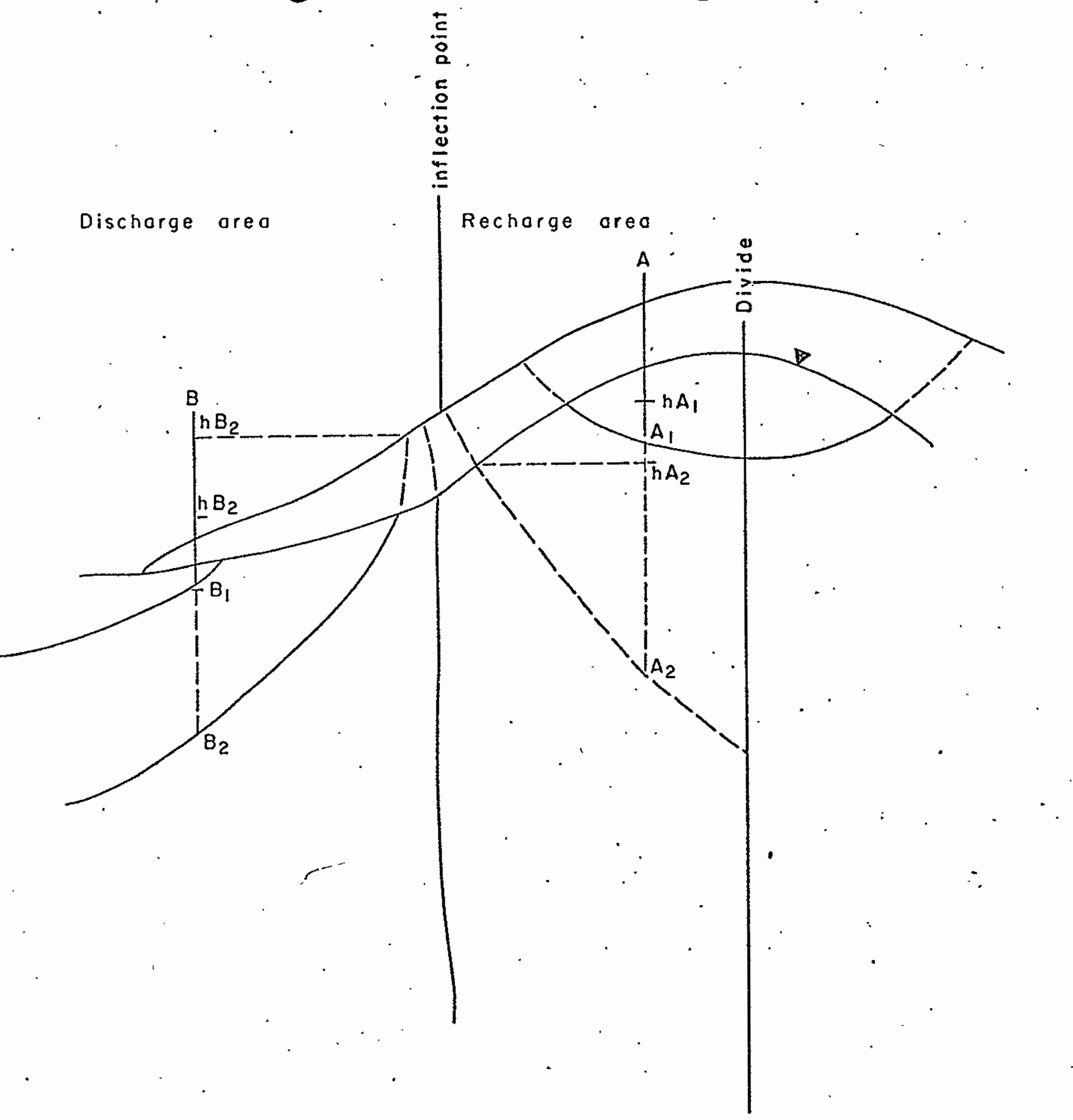
Relation of pressure to position on a flow line



Pressure
flow line length

Figure 42

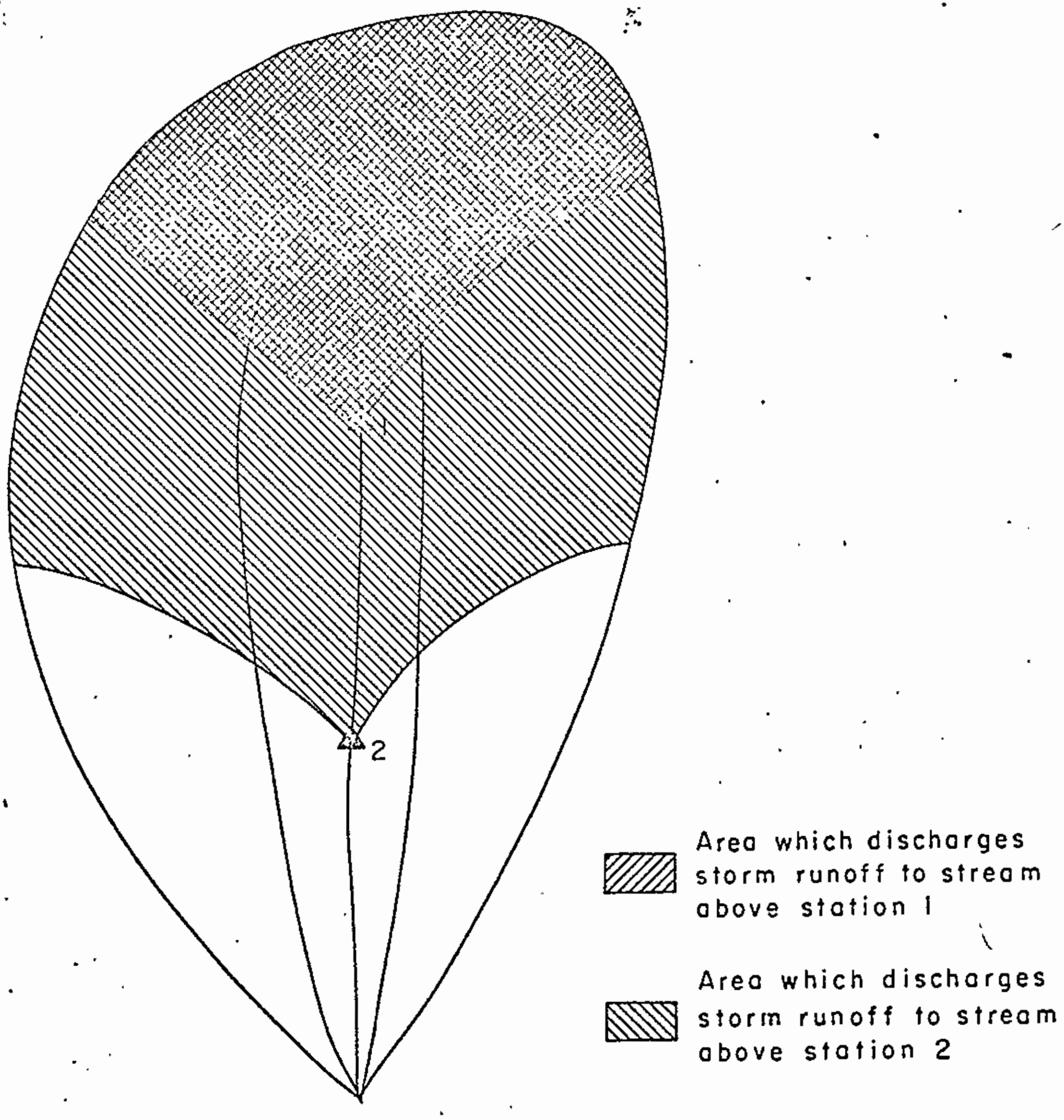
Relation of water level in piezometers and wells to potential distribution in a simple flow system



inflection point
Discharge area
Recharge area
Divide
A
B
hB2
hB2
B1
B2
hA1
A1
hA2
A2

Figure 43

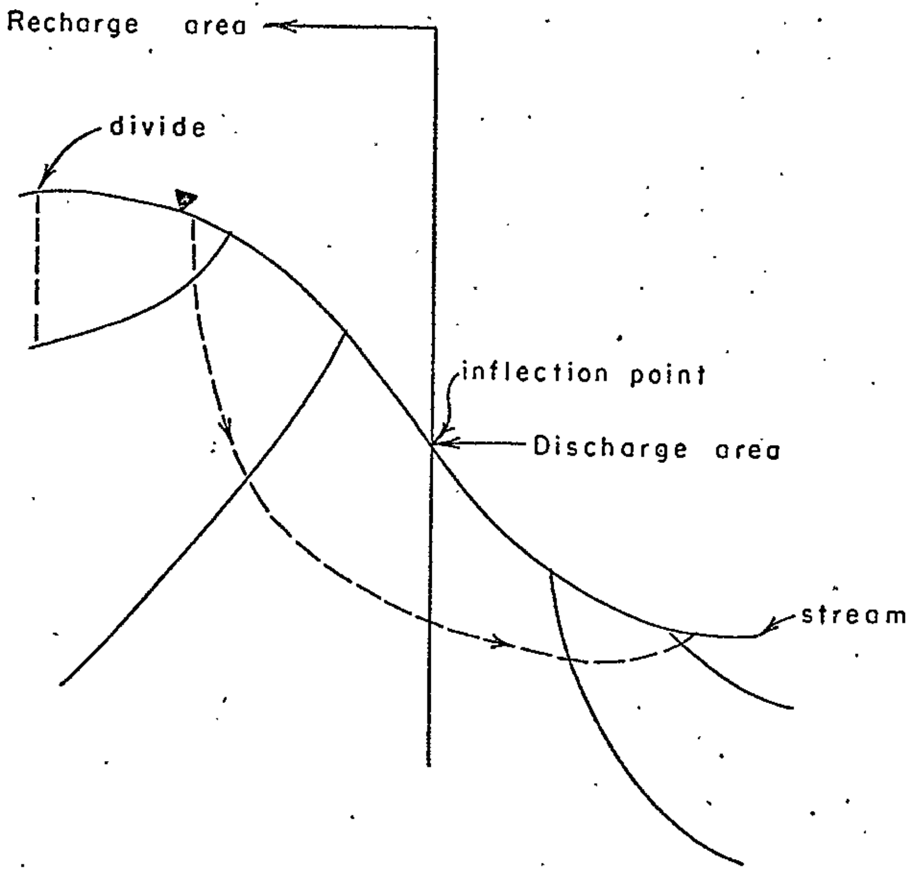
Diagram of a simple stream basin showing area contributing surface runoff to successive gaging stations



2
Area which discharges storm runoff to stream above station 1
Area which discharges storm runoff to stream above station 2

Figure 44

Cross section through the inflection point on the water table



Recharge area
divide
inflection point
Discharge area
stream

Figure 45

Recharge and discharge areas in a basin with a local flow system

Figure 46

Diagram showing the relation of various ground water "flowlines" in plan view

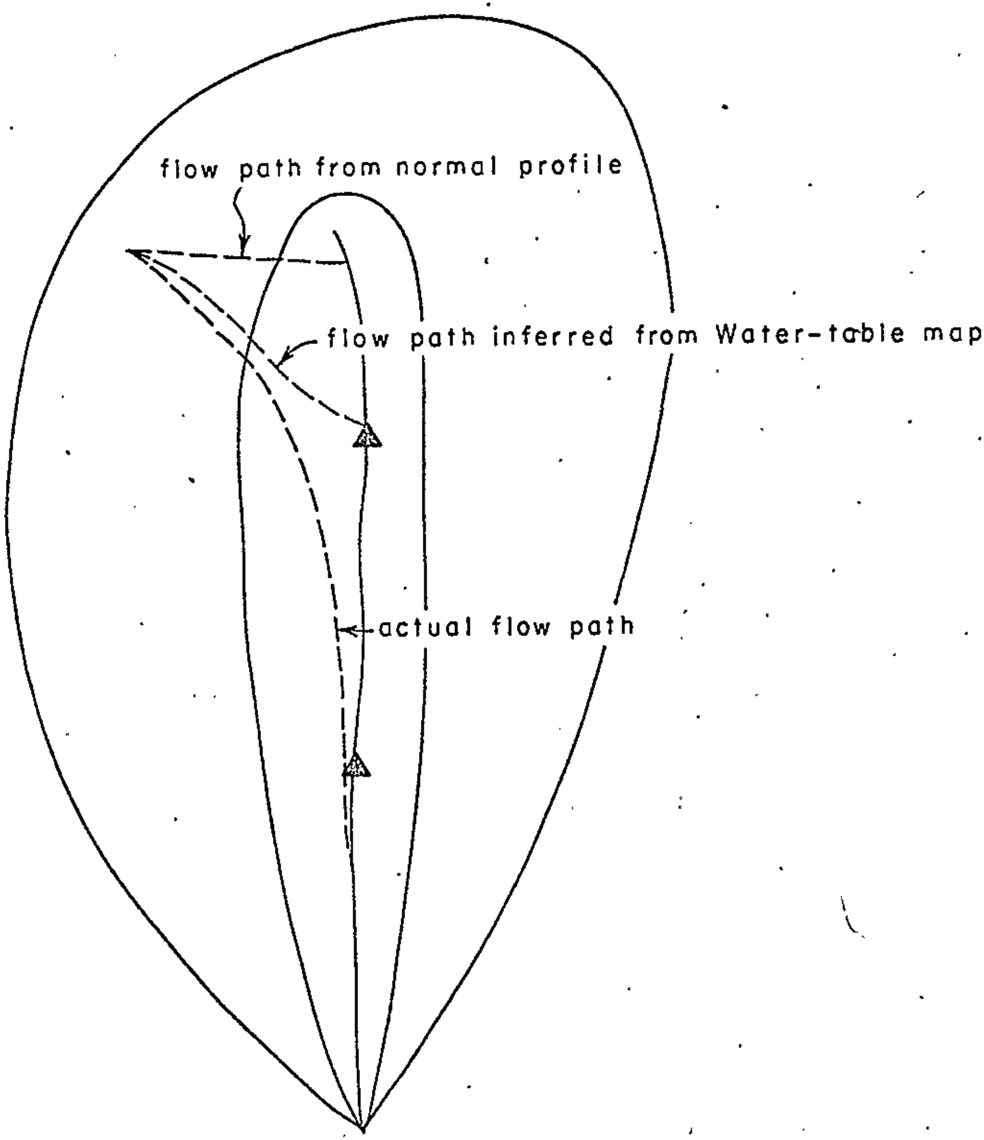

flow path from normal profile
flow path inferred from Water-table map
actual flow path

Figure 47

Diagrammatic plan view of a river basin showing the relation of recharge area to stream gaged ground water discharge

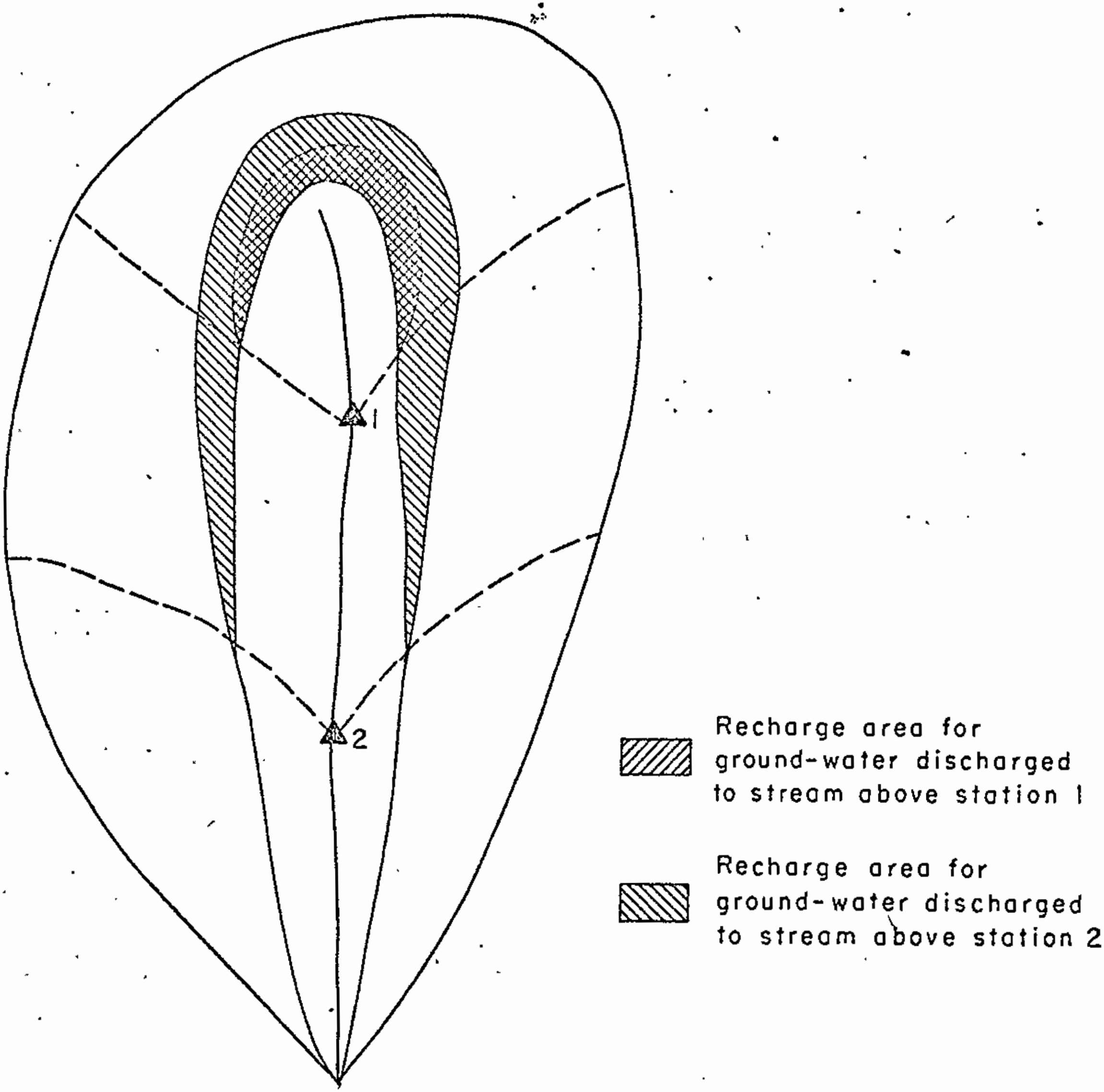

1
2
Recharge area for ground-water discharged to stream above station 1
Recharge area for ground-water discharged to stream above station 2

Figure 48

Relation of precipitation to altitude

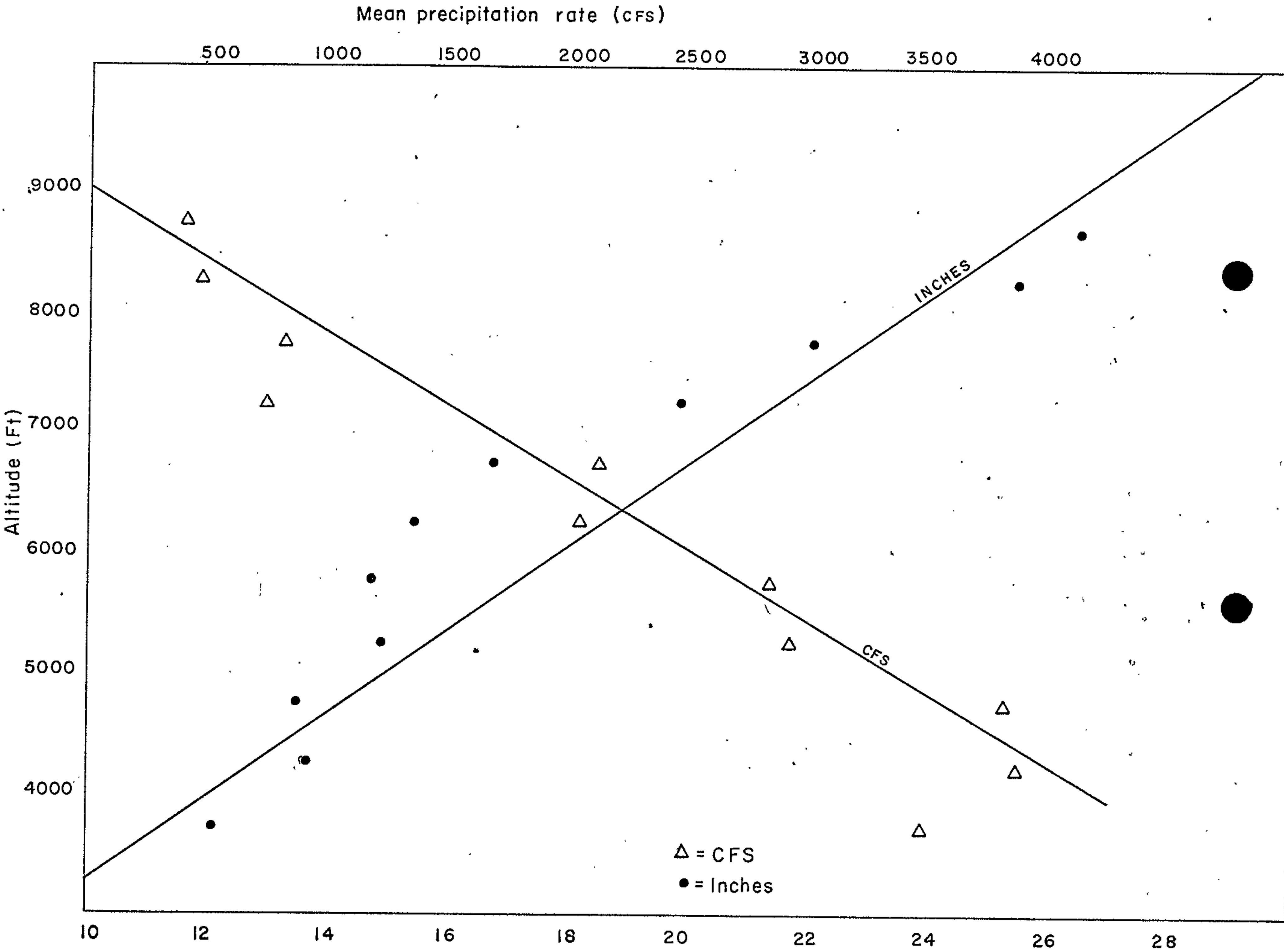
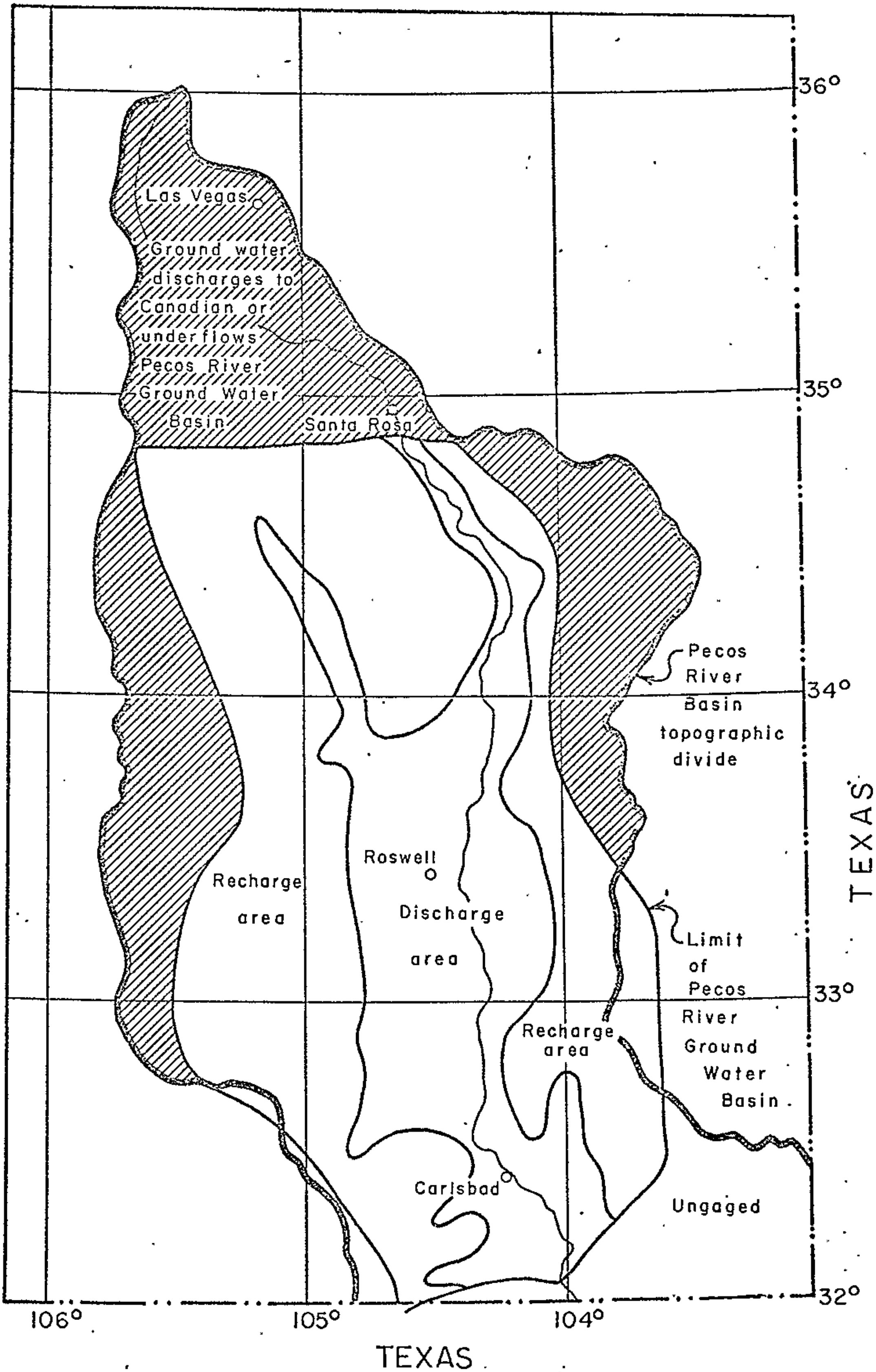

Mean precipitation rate (CFS)
500
1000
1500
2000
2500
3000
3500
4000
Altitude (Ft)
9000
8000
7000
6000
5000
4000
INCHES
CFS
Δ = CFS
• = Inches
10
12
14
16
18
20
22
24
26
28
95

Figure 49

Recharge and discharge areas of the Pecos River ground-water basin.



36°
35°
34°
33°
32°
106°
105°
104°
Las Vegas
Ground water discharges to Canadian or underflows Pecos River Ground Water Basin
Santa Rosa
Pecos River Basin topographic divide
TEXAS
Roswell
Recharge area
Discharge area
Limit of Pecos River Ground Water Basin
Recharge area
Carlsbad
Ungaged
TEXAS

Figure 50

Diagrammatic cross section through the Roswell region before pumping showing the flow system.

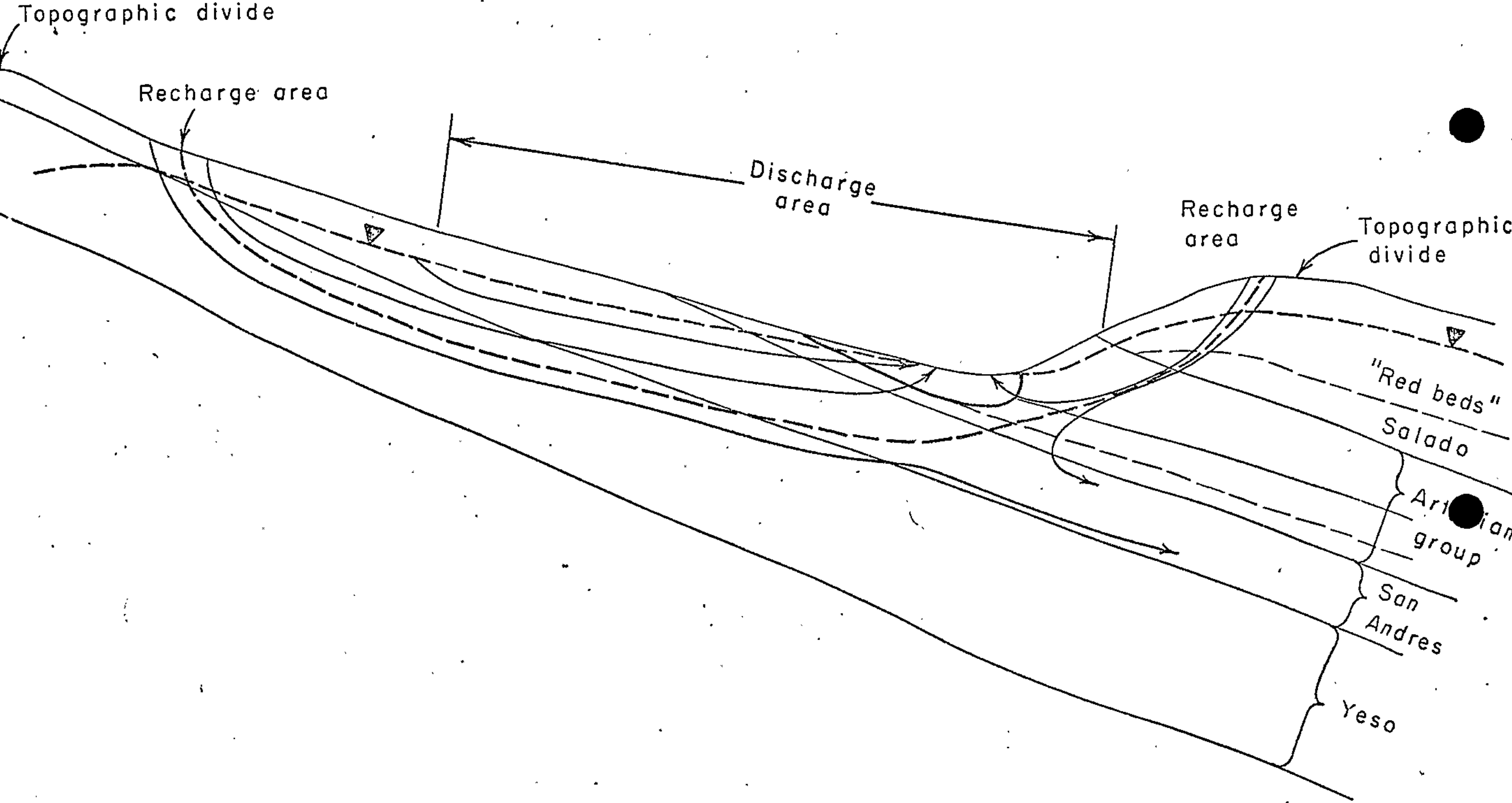

Topographic divide
Recharge area
Discharge area
Recharge area
Topographic divide
"Red beds"
Salado
Artesian group
San Andres
Yeso

Figure 51

Diagrammatic cross section through the Roswell region in 1972 showing the flow systems due to pumping

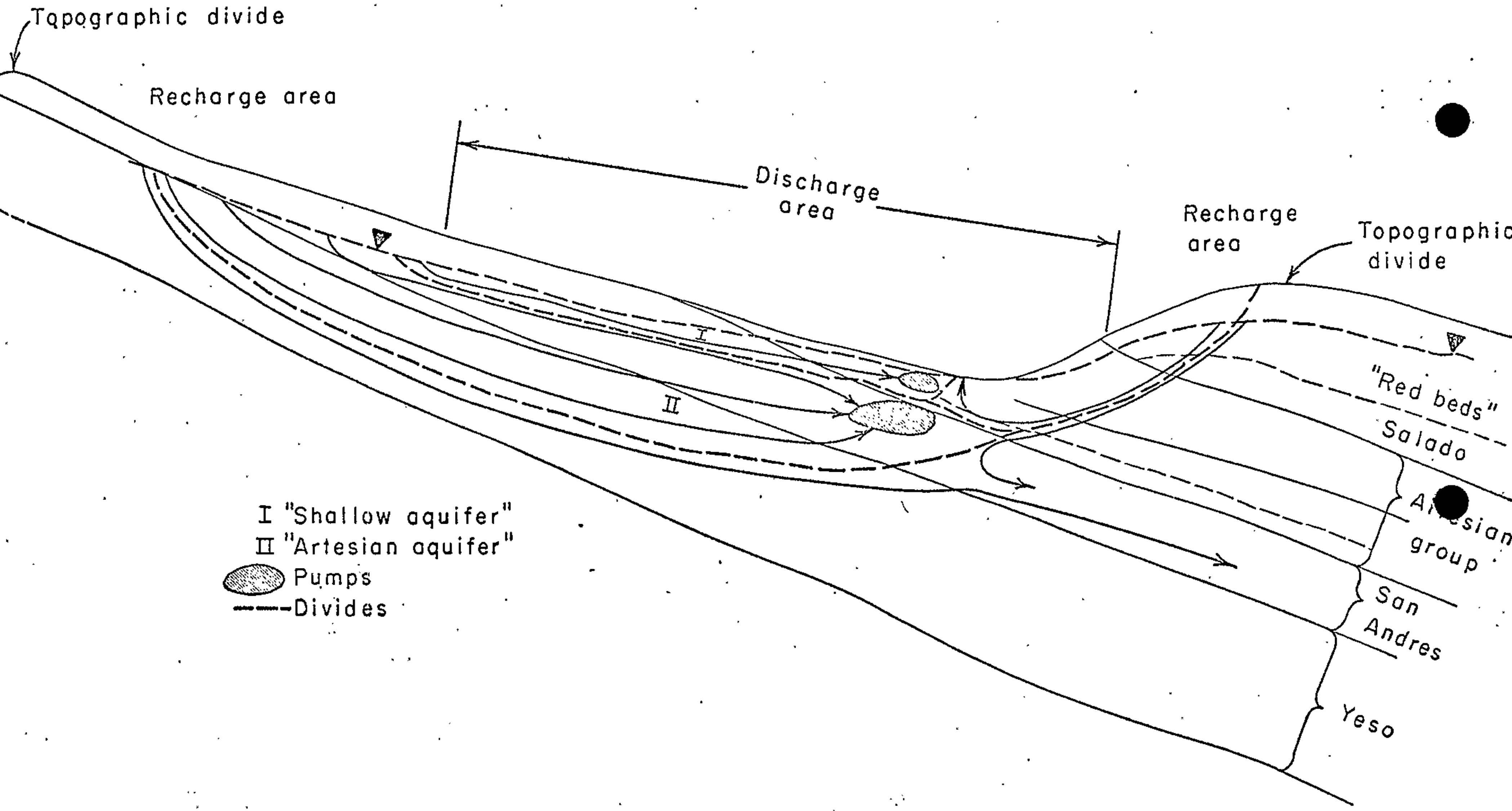

Topographic divide
Recharge area
Discharge area
Recharge area
Topographic divide
I
II
"Red beds"
Salado
Artesian group
San Andres
Yeso
I "Shallow aquifer"
II "Artesian aquifer"
Pumps
Divides

Figure 52
Diagrammatic cross section along the strike of the reef-lime-bank complex

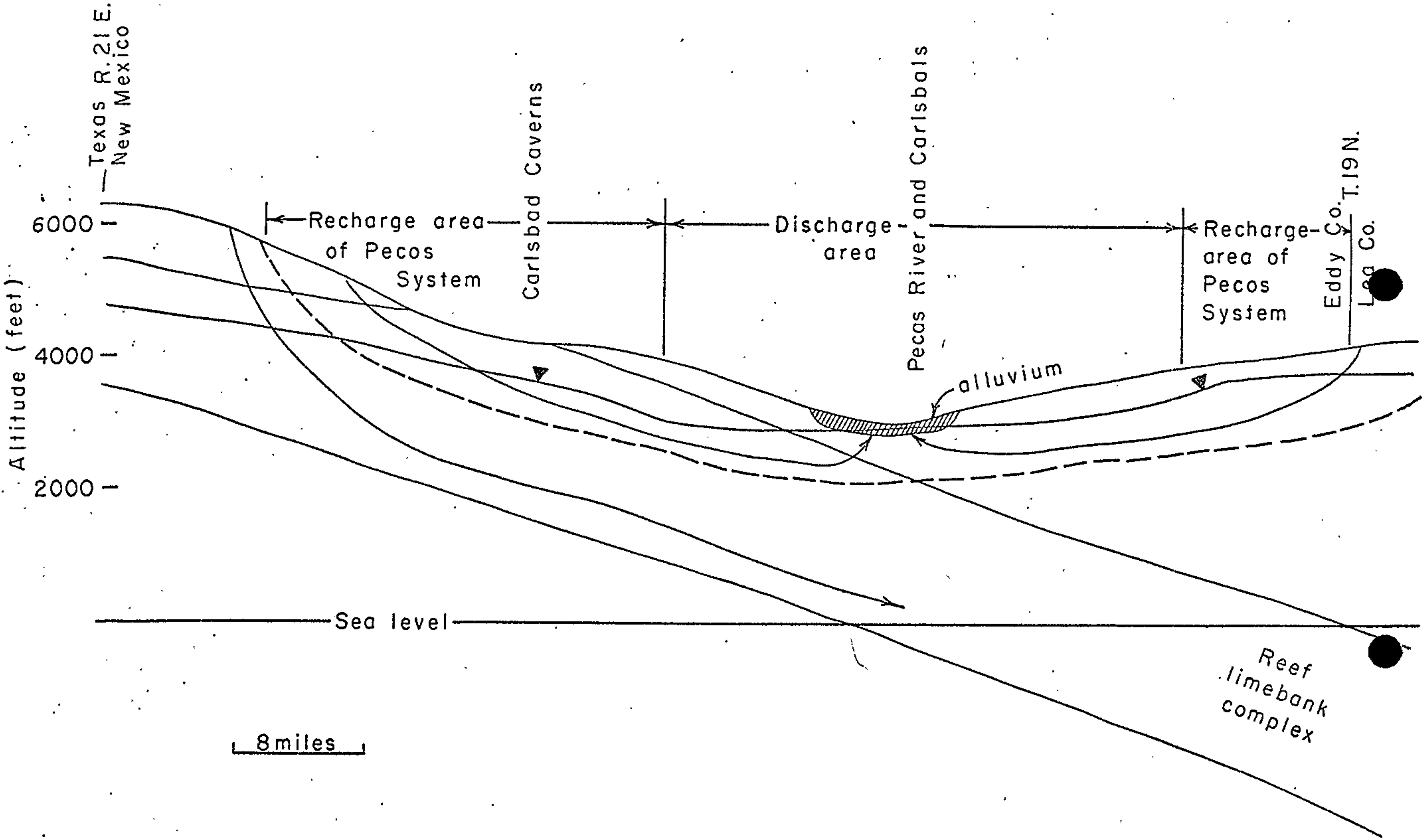

Texas R. 21 E.
New Mexico
Carlsbad Caverns
Pecos River and Carlsbals
T. 19 N.
Eddy Co.
Lea Co.
6000
4000
2000
Altitude (feet)
Recharge area of Pecos System
Discharge area
Recharge area of Pecos System
alluvium
Sea level
Reef limebank complex
8 miles

Figure 53

Locations of streamflow gaging stations recording the flow of surface runoff only

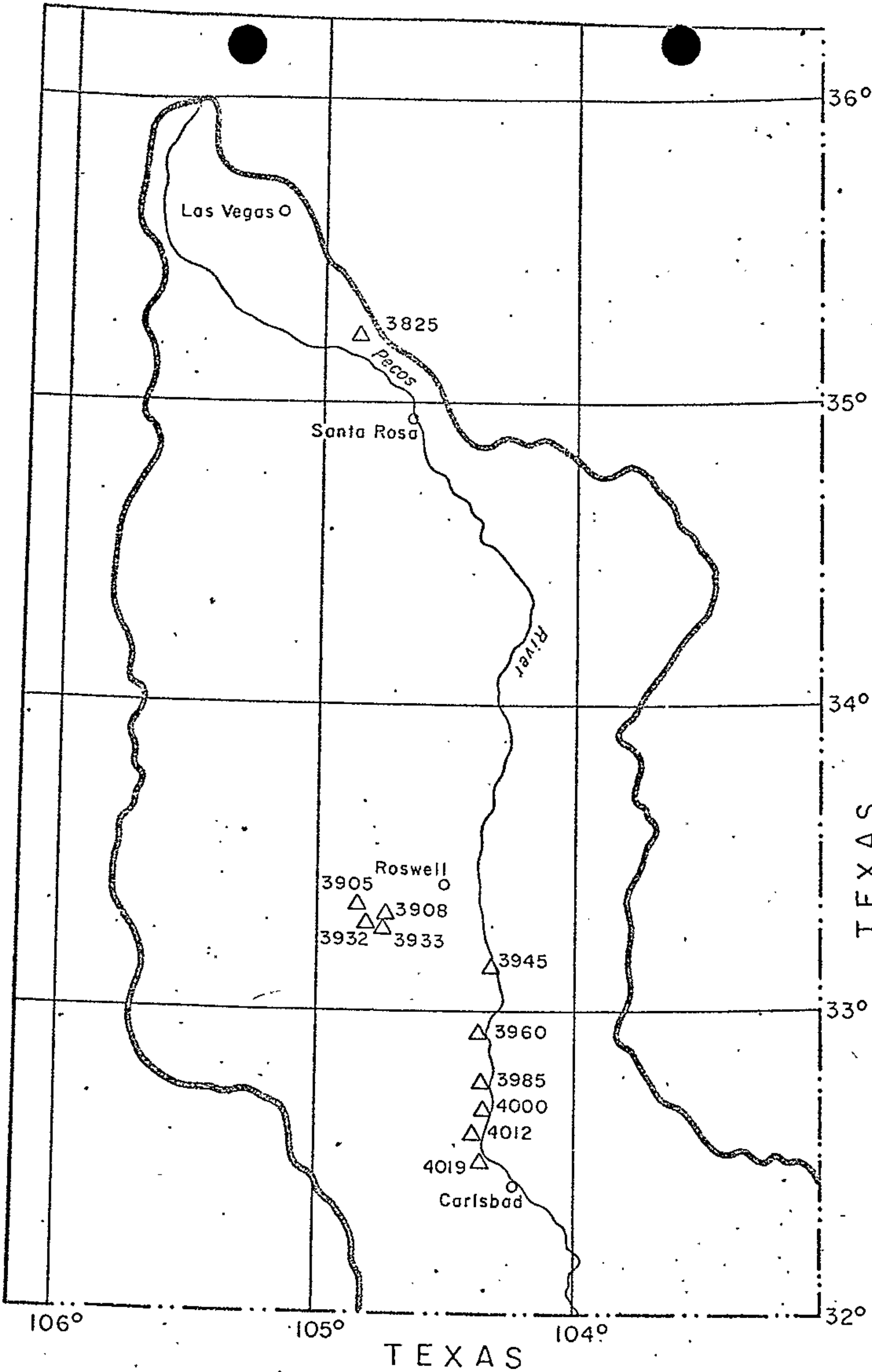

36°
35°
34°
33°
32°
106°
105°
104°
Las Vegas
3825
Pecos
Santa Rosa
River
Roswell
3905
3908
3932
3933
3945
3960
3985
4000
4012
4019
Carlsbad
TEXAS
TEXAS

Figure 54

Locations of streamflow gaging stations on the Pecos River basin.

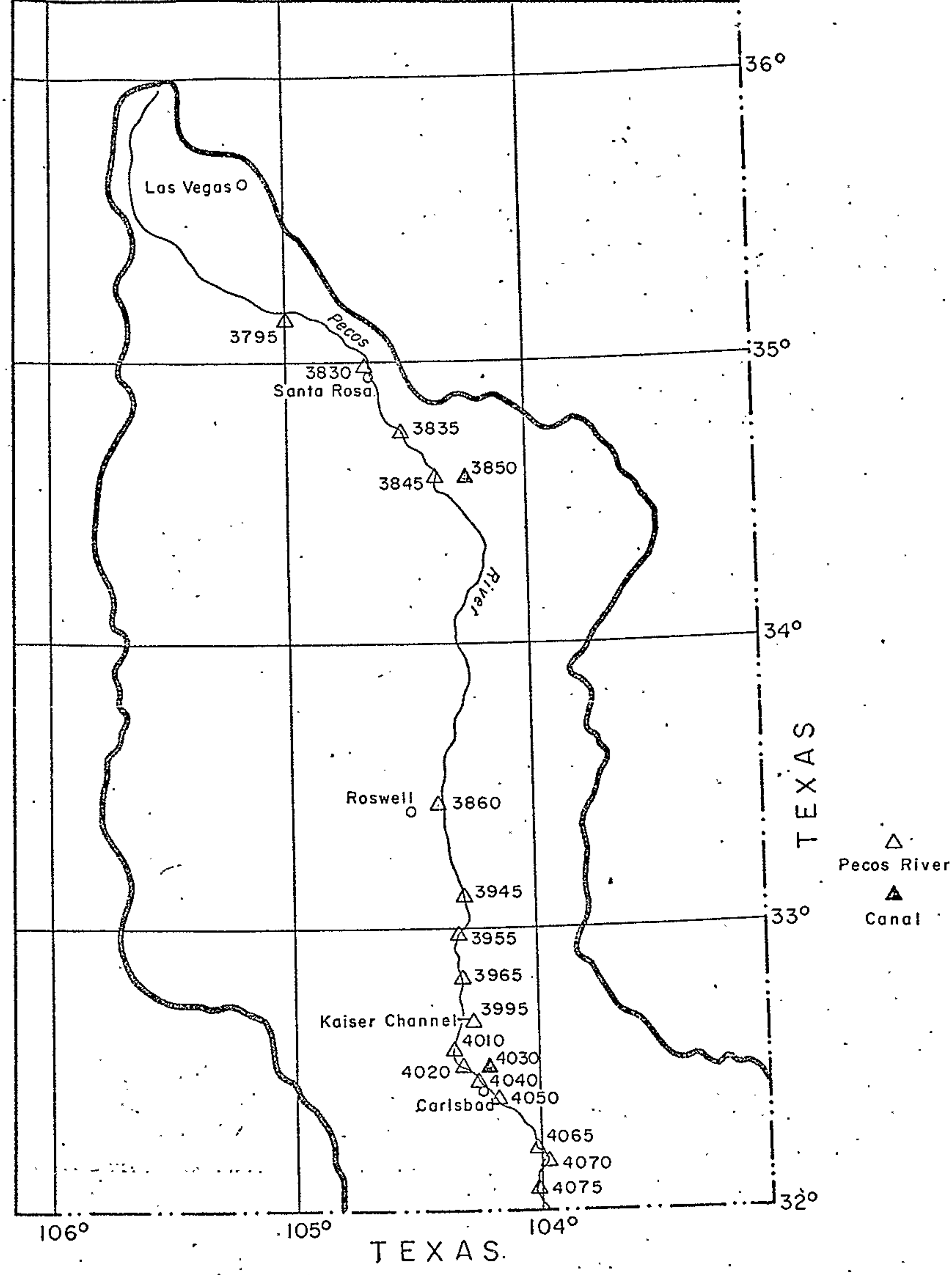
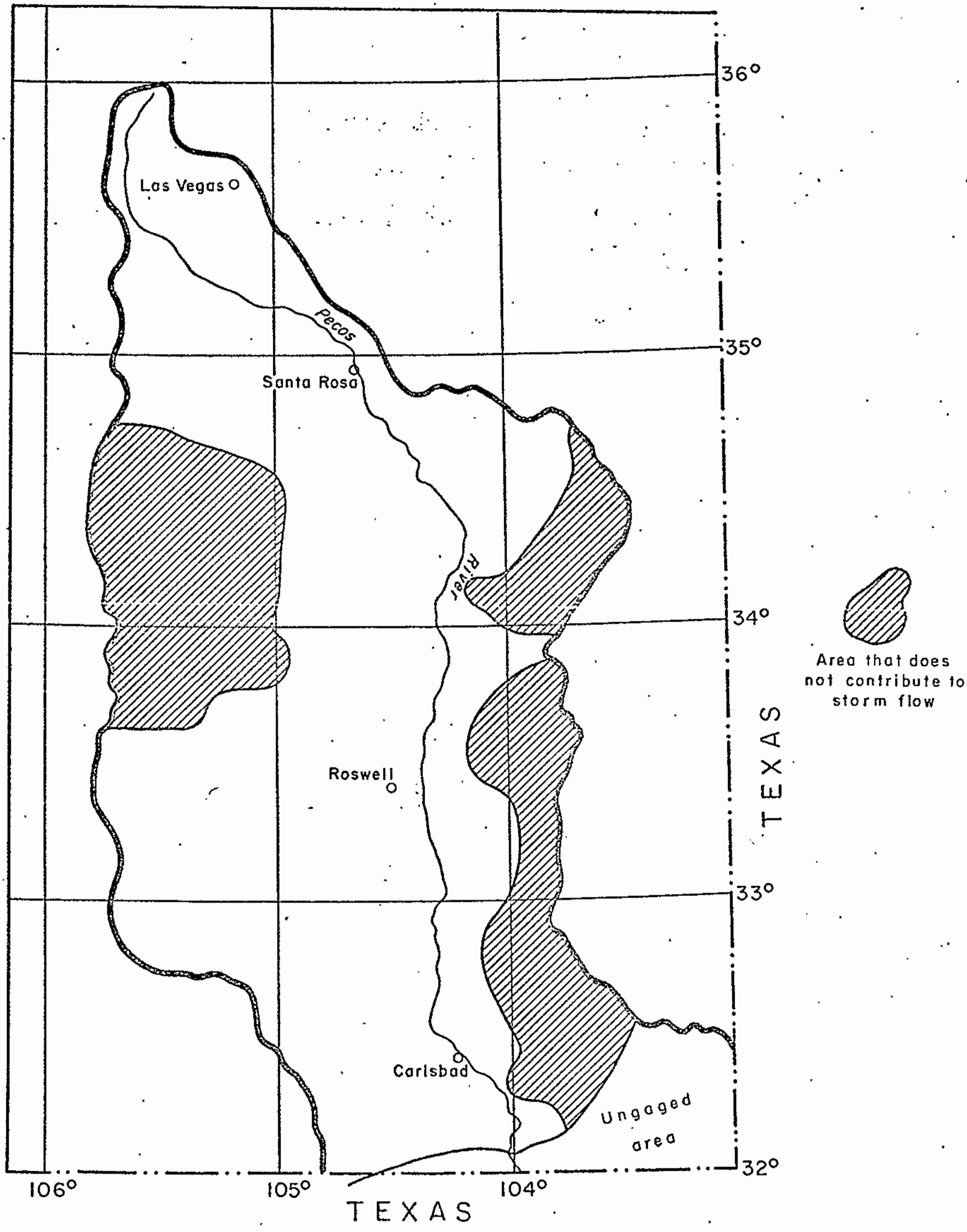

36°
35°
34°
33°
32°
106°
105°
104°
TEXAS
TEXAS
Las Vegas
Pecos
River
3795
3830
Santa Rosa
3835
3845
3850
Roswell
3860
3945
3955
3965
3995
Kaiser Channel
4010
4020
4030
4040
Carlsbad
4050
4065
4070
4075
Pecos River
Canal

Figure 55

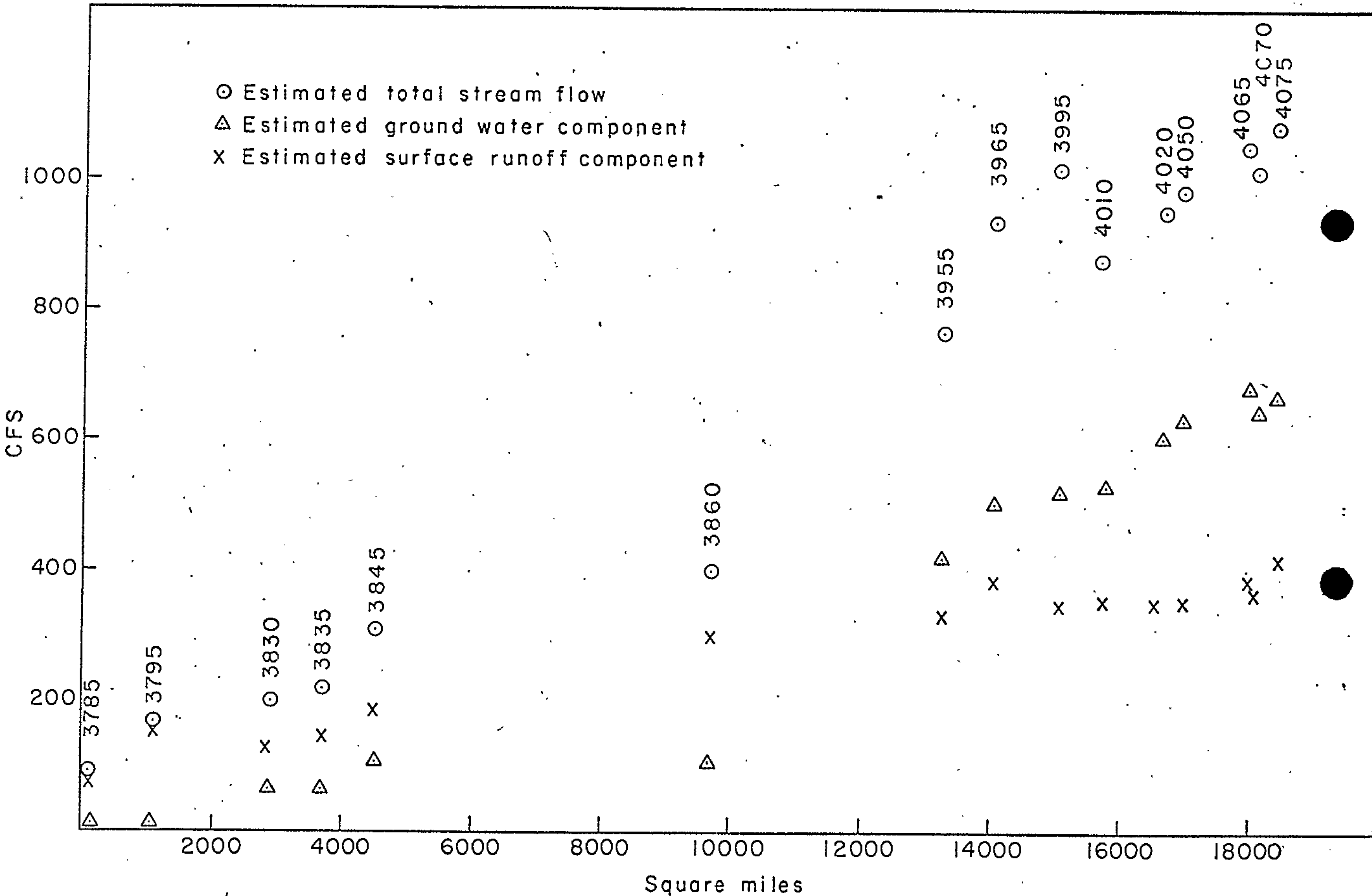
Area contributing surface runoff to the Pecos River



36°
35°
34°
33°
32°
106°
105°
104°
Las Vegas
Pecos
Santa Rosa
River
Roswell
Carlsbad
Ungaged
area
TEXAS
TEXAS
Area that does not contribute to storm flow

Figure 56

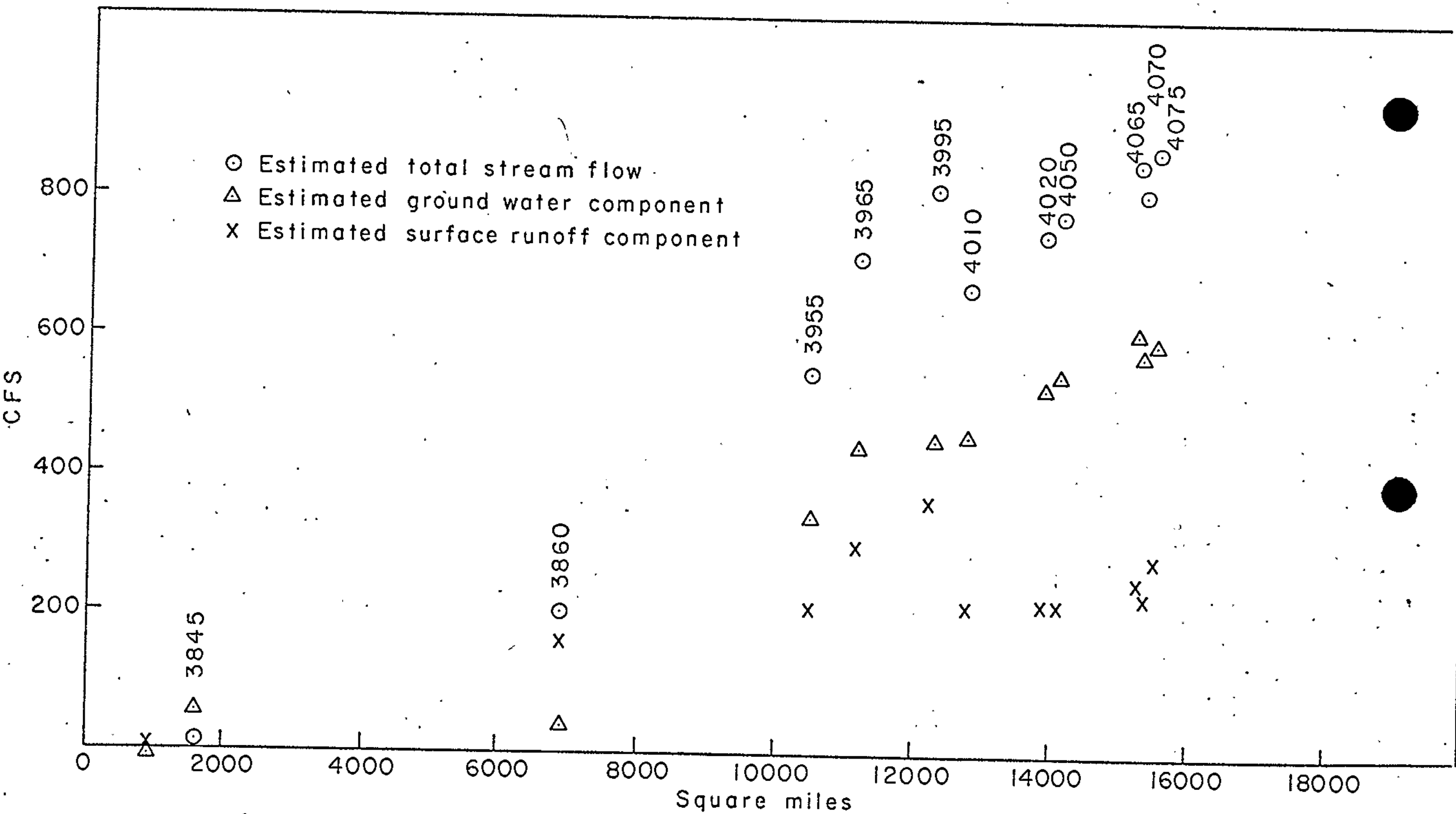
Total streamflow, total surface runoff component, and total ground-water component versus drainage area above gage



Estimated total stream flow
Estimated ground water component
X Estimated surface runoff component
CFS
1000
800
600
400
200
2000
4000
6000
8000
10000
12000
14000
16000
18000
Square miles
3785
3795
3830
3835
3845
3860
3955
3965
3995
4010
4020
4050
4065
4C70
4075

Figure 57

Total streamflow, total surface runoff component, and total ground-water component versus drainage area of the lower Pecos River basin



Estimated total stream flow
Estimated ground water component
Estimated surface runoff component
CFS
800
600
400
200
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
Square miles
3845
3860
3955
3965
3995
4010
4020
4050
4065
4070
4075

57

113

Figure 58

Map of the Pecos River basin showing the recharge and discharge areas of the lower Pecos River basin

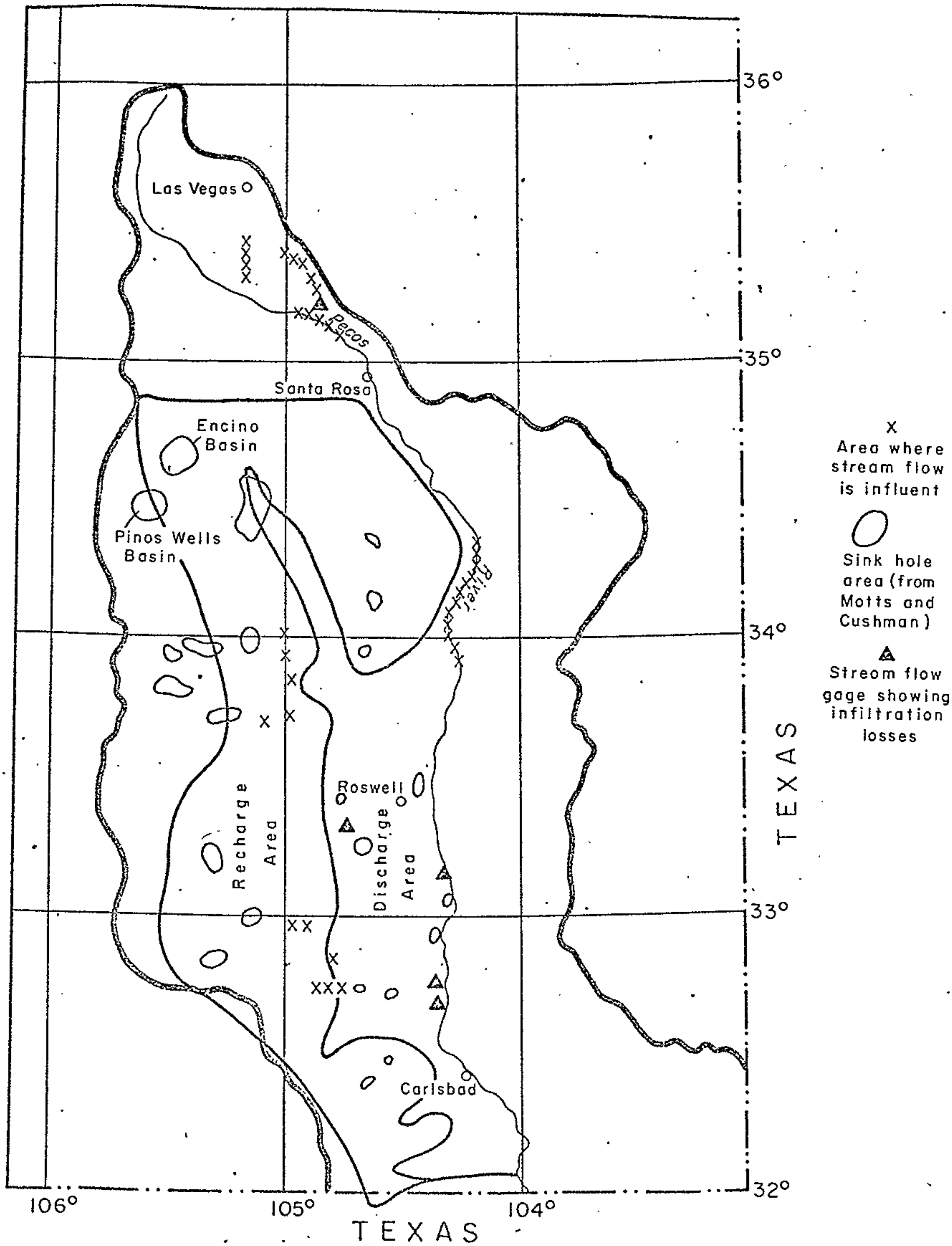
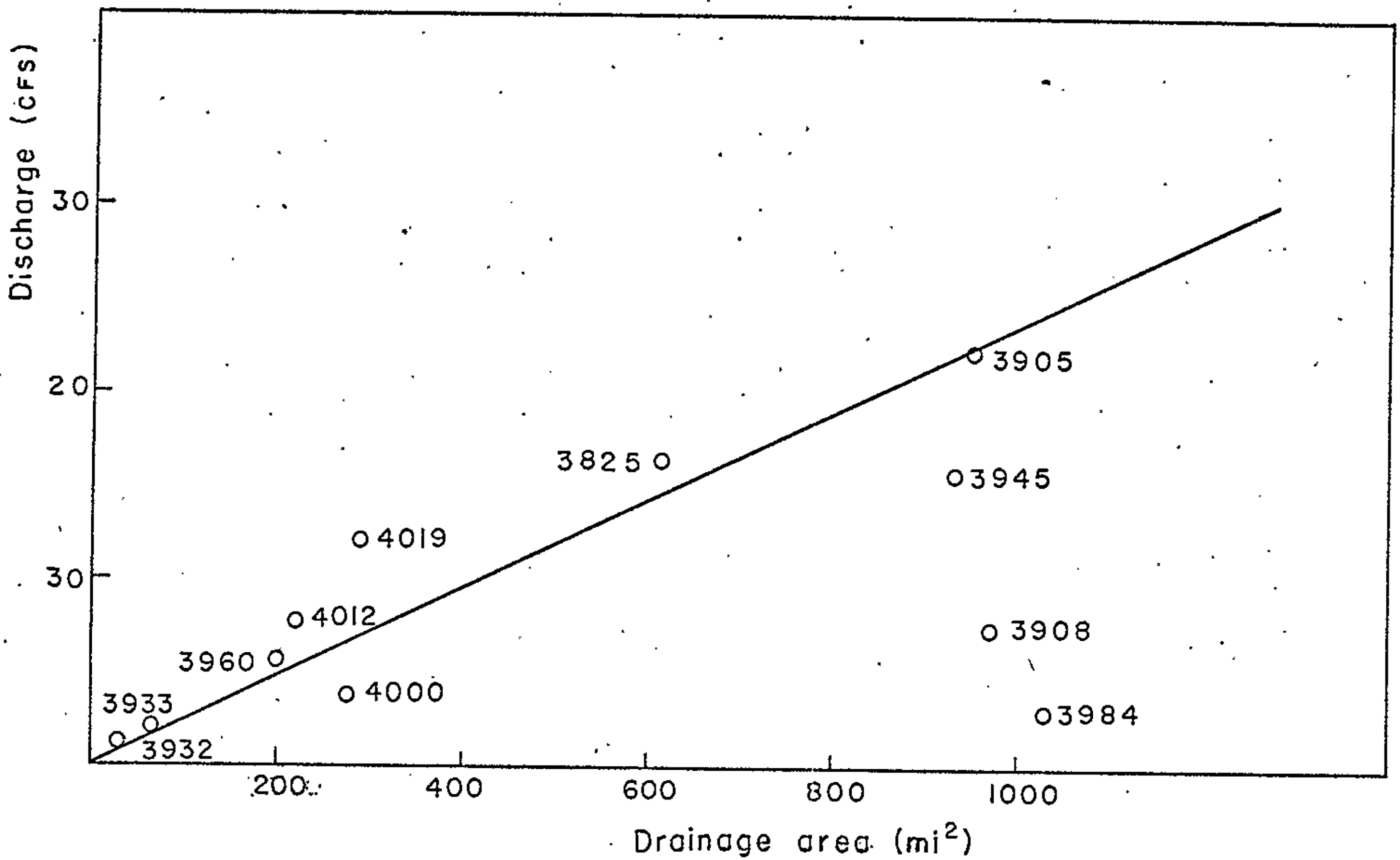

Las Vegas
Pecos
Santa Rosa
Encino Basin
Pinos Wells Basin
River
Roswell
Recharge Area
Discharge Area
Carlsbad
36°
35°
34°
33°
32°
106°
105°
104°
TEXAS
TEXAS
X Area where stream flow is influent
Sink hole area (from Motts and Cushman)
Stream flow gage showing infiltration losses

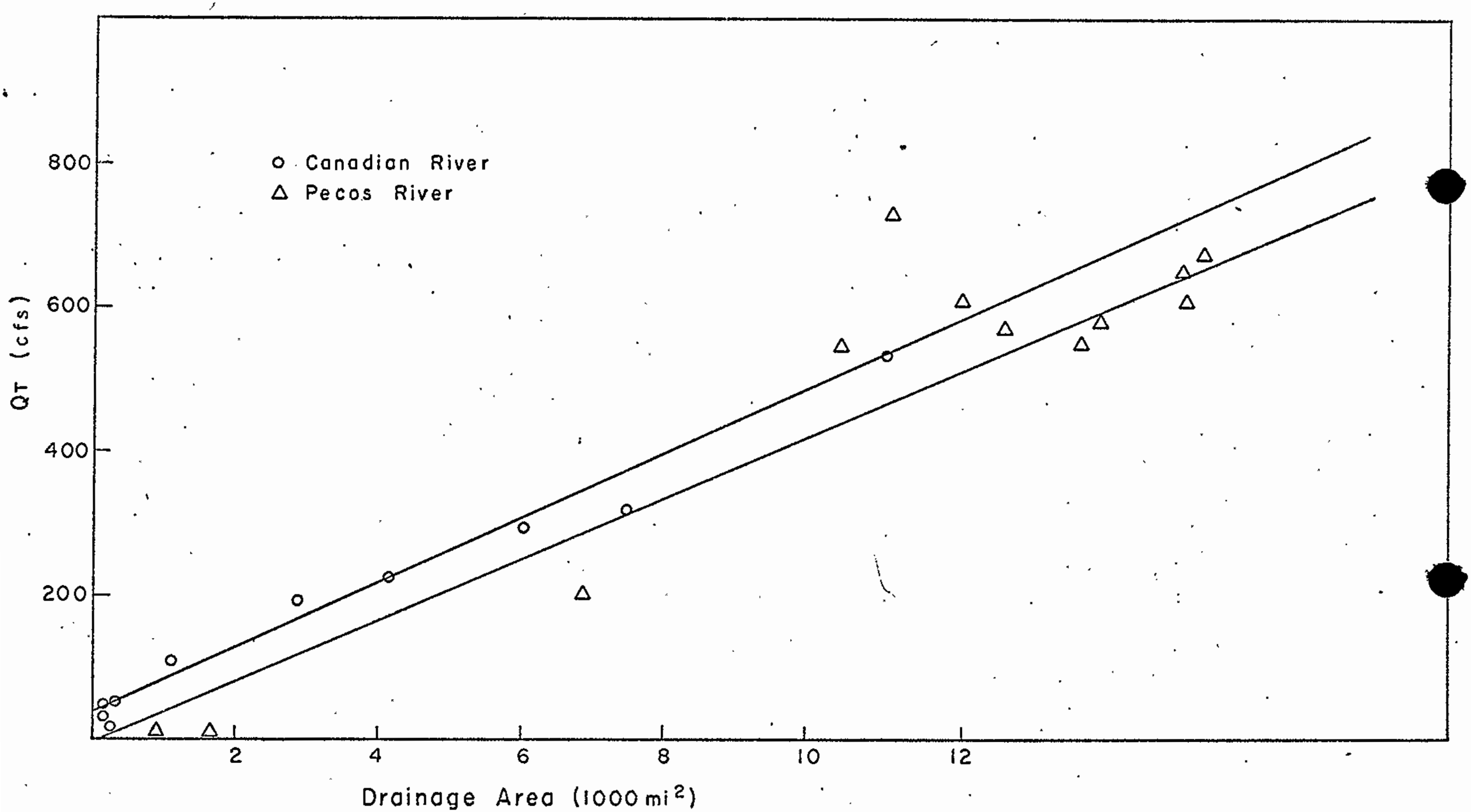
Figure 59
Relation of surface runoff areas for stations that do not discharge ground water



Discharge (cfs)
30
20
30
3905
3825
3945
4019
4012
3908
3960
4000
3933
3984
3932
200
400
600
800
1000
Drainage area (mi^2)

Figure 60

Relation of Q_t to drainage area for the Pecos and the Canadian Rivers, New Mexico



Canadian River
Pecos River
800
600
400
200
QT (cfs)
2
4
6
8
10
12
Drainage Area (1000 mi²)

PLATE I — Map of Pecos River Basin Showing Cross section Locations
(base is Geological Map of New Mexico, Dave and Bachman, 1965)

PLATE 2-Cross section AA'-stratigraphy

PLATE 3-Cross section BB'-stratigraphy

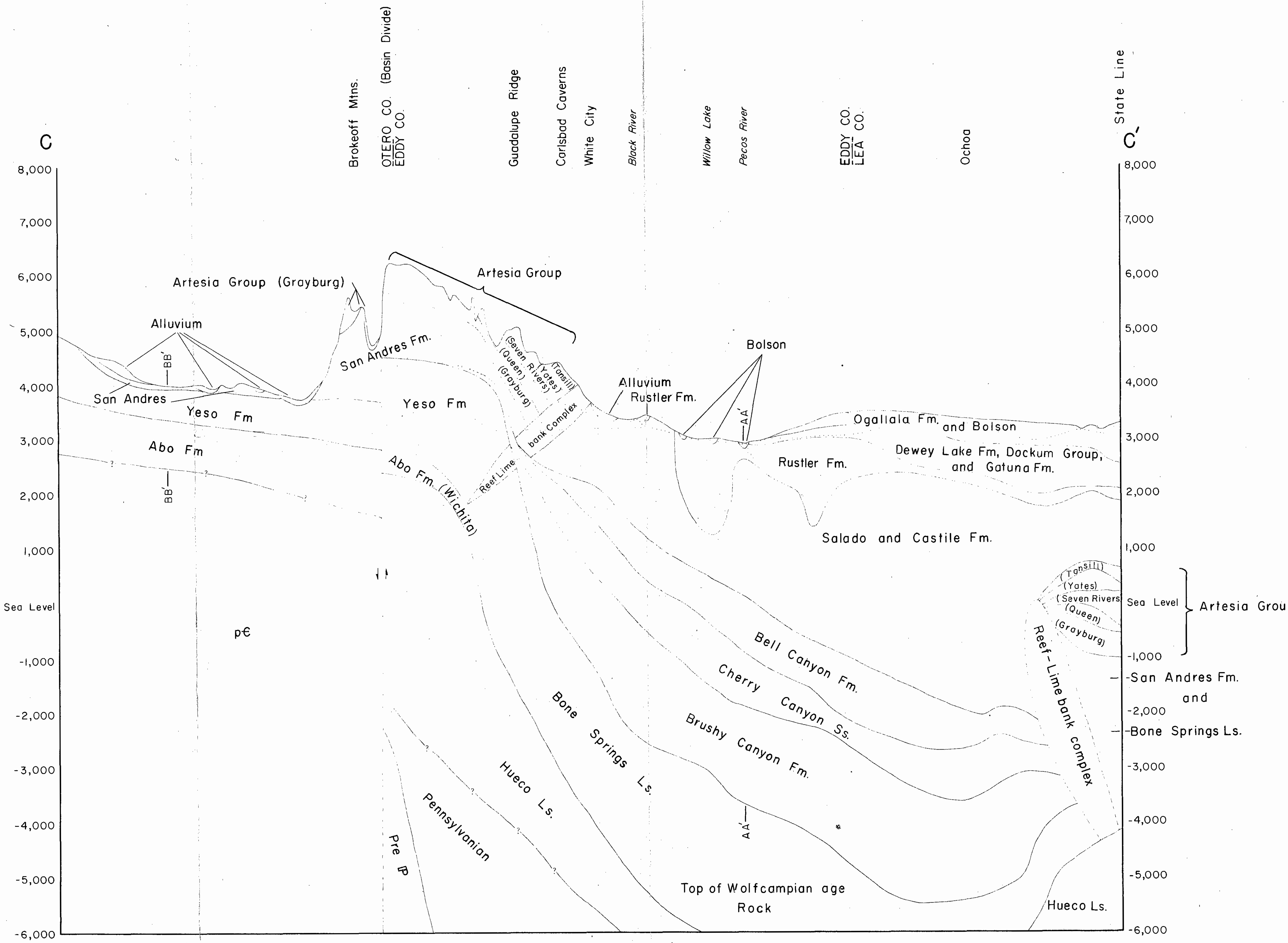


PLATE 4 - Cross section CC′ - stratigraphy

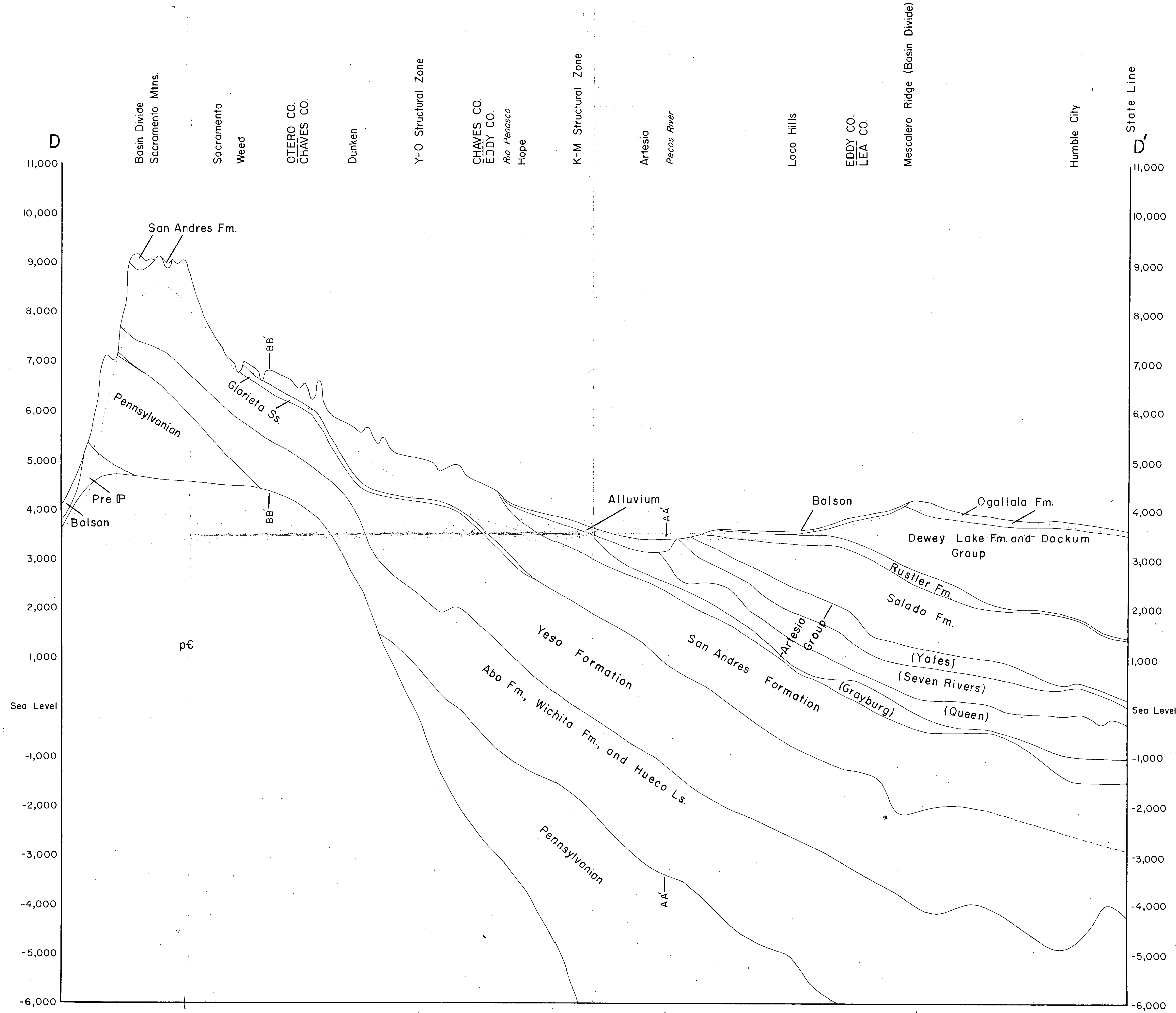


PLATE 5-Cross section DD′-stratigraphy

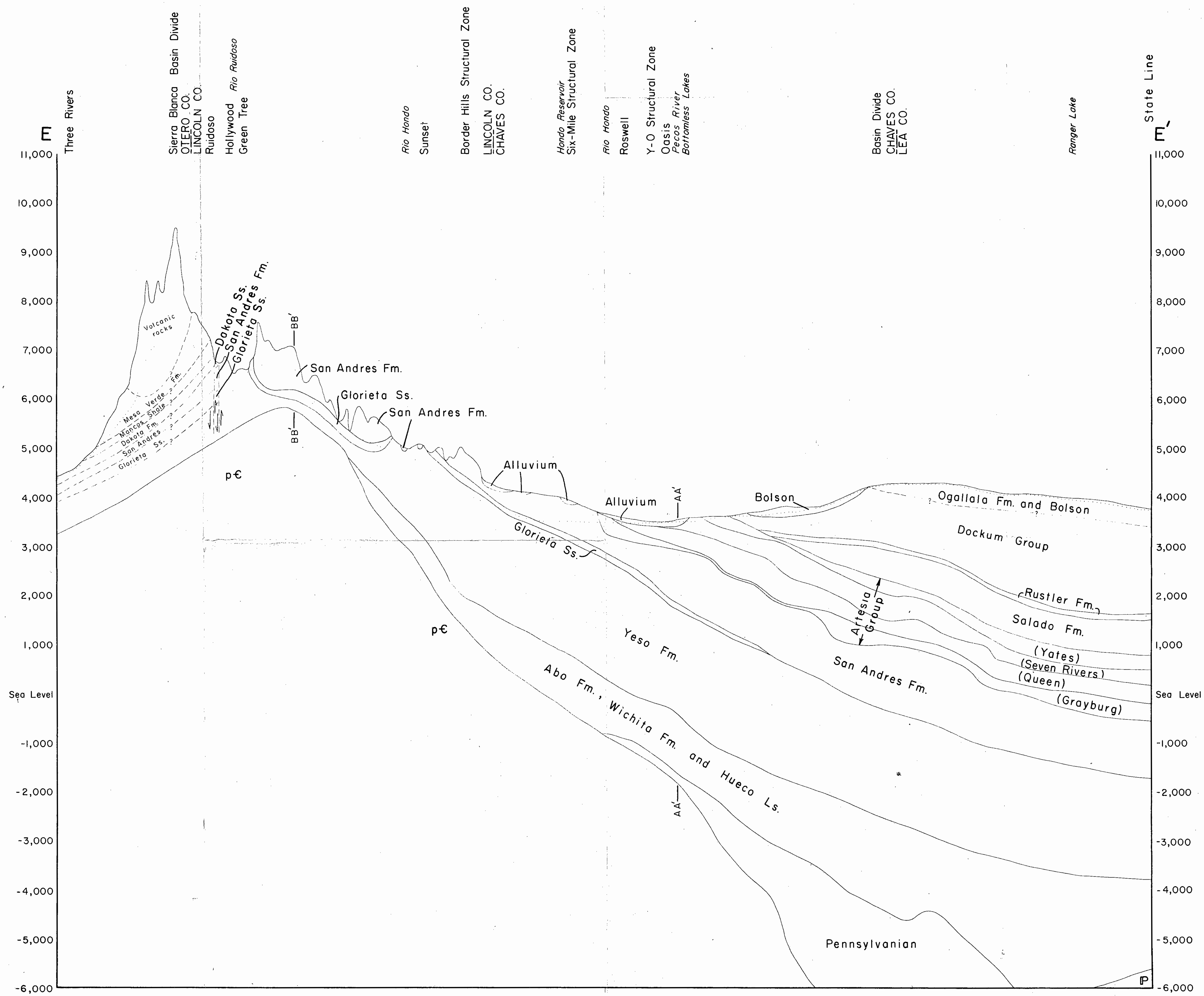


PLATE 6- Cross section EE'- stratigraphy

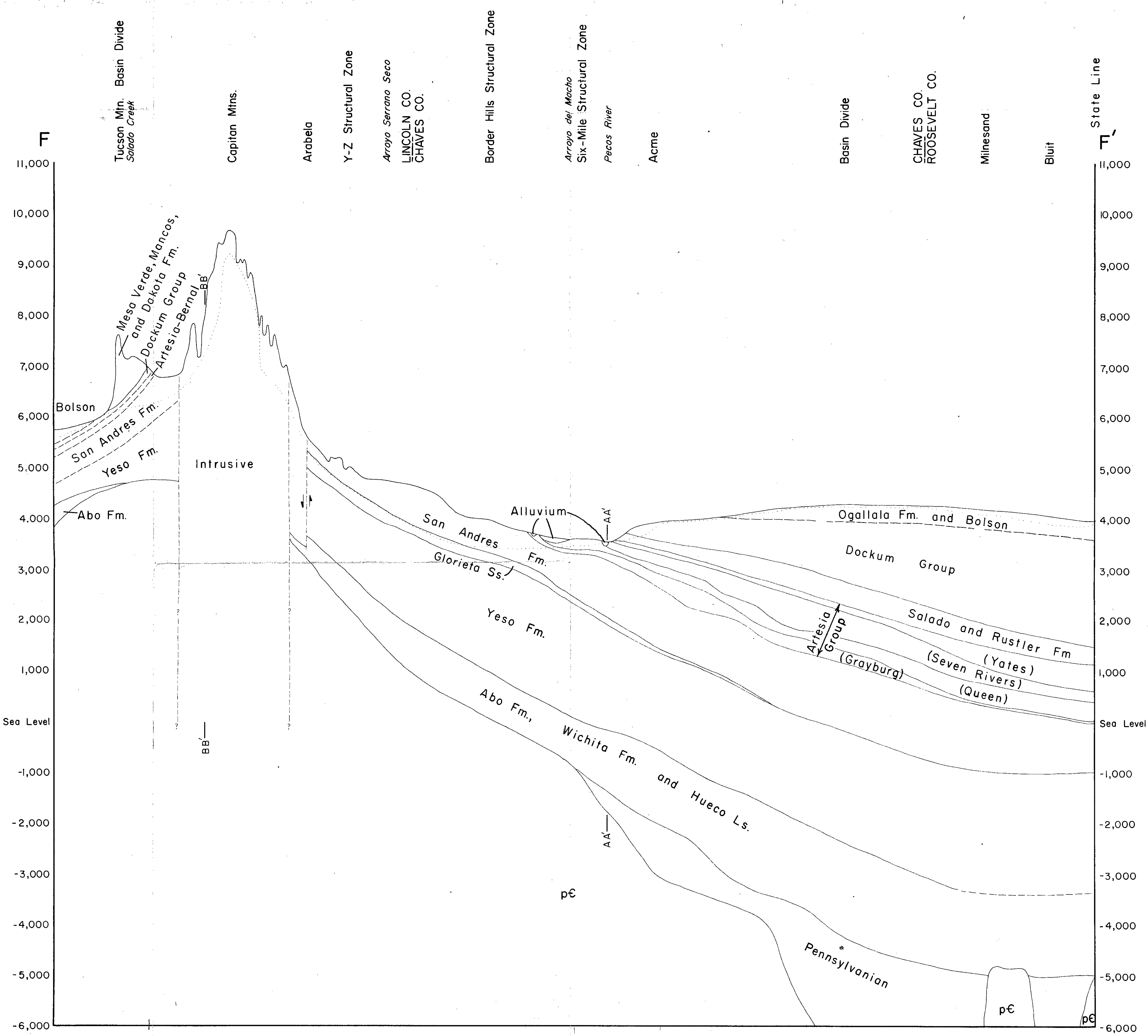


PLATE 7- Cross section F F′- stratigraphy

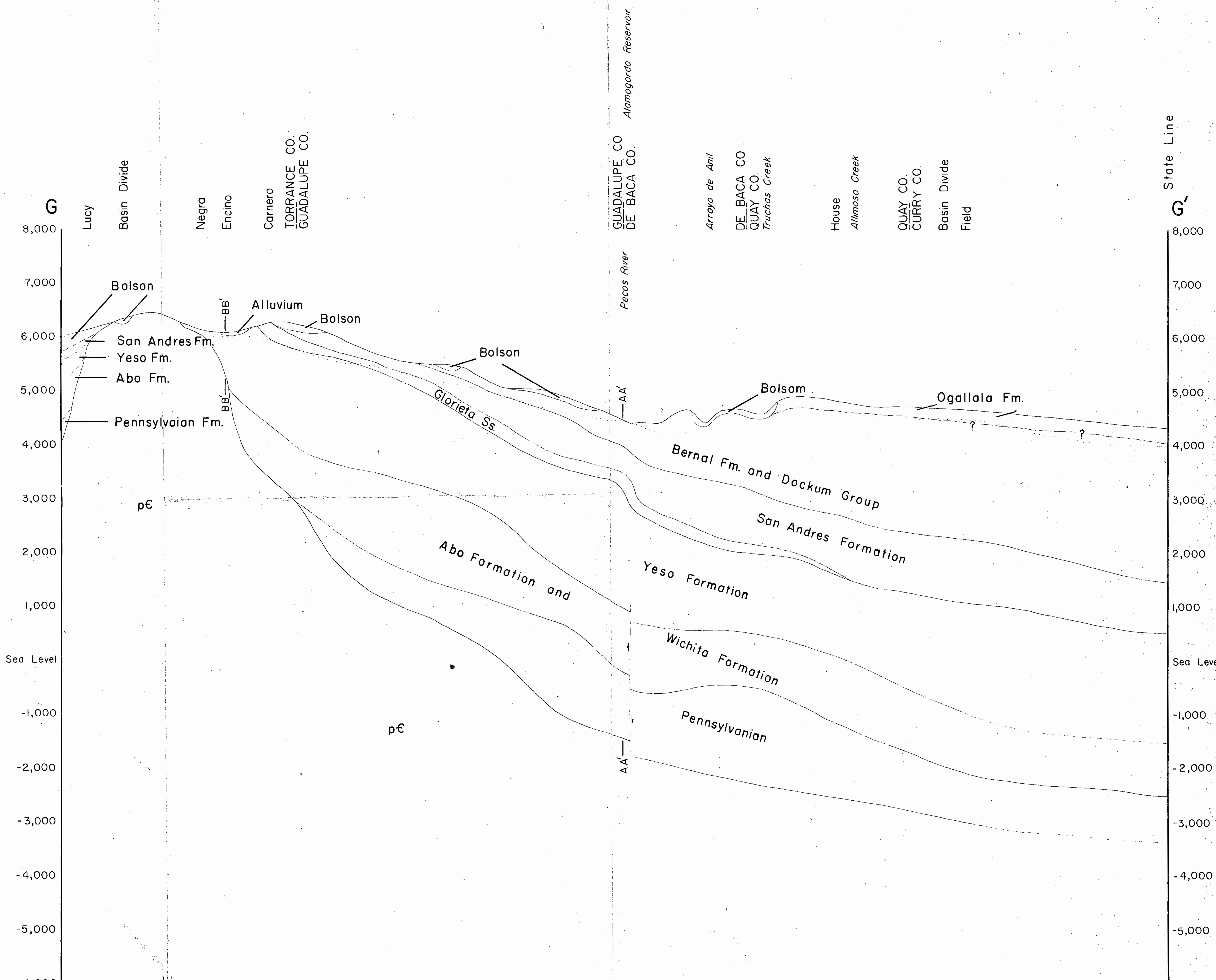


PLATE 8 - Cross section GG′- stratigraphy

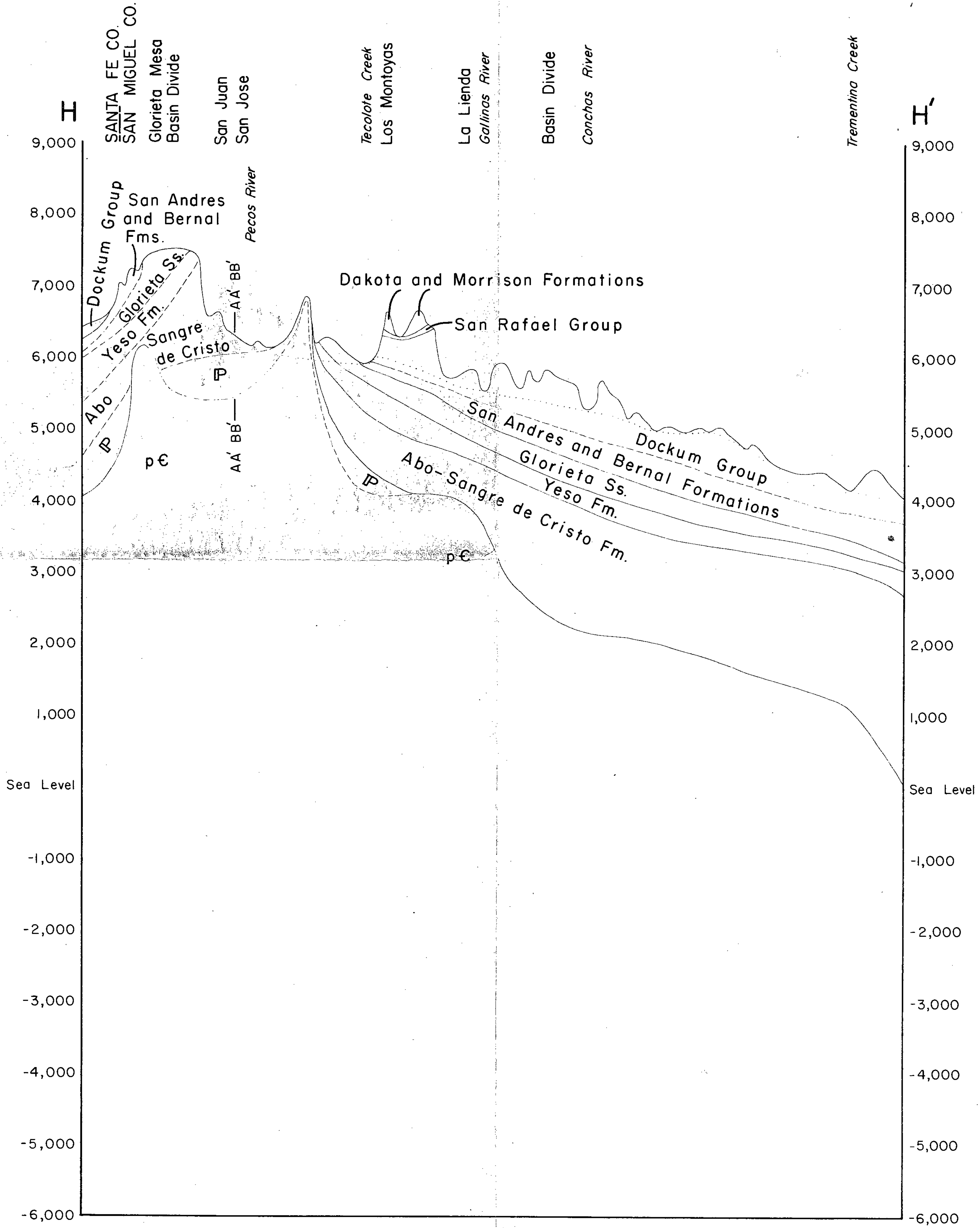


PLATE 9- Cross section HH' - stratigraphy

PLATE 10— Cross section AA lithology

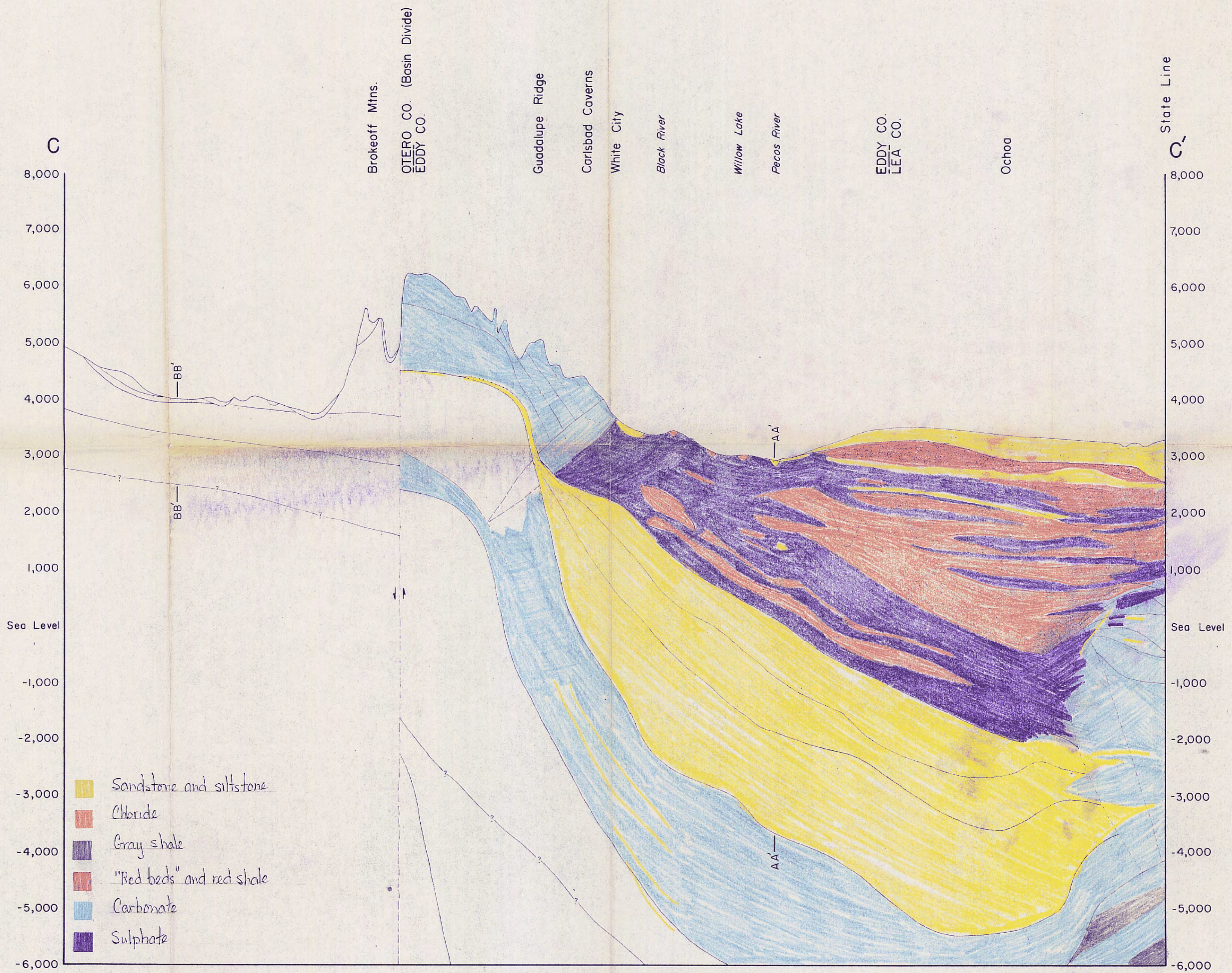


PLATE II-Cross section CC'-lithology

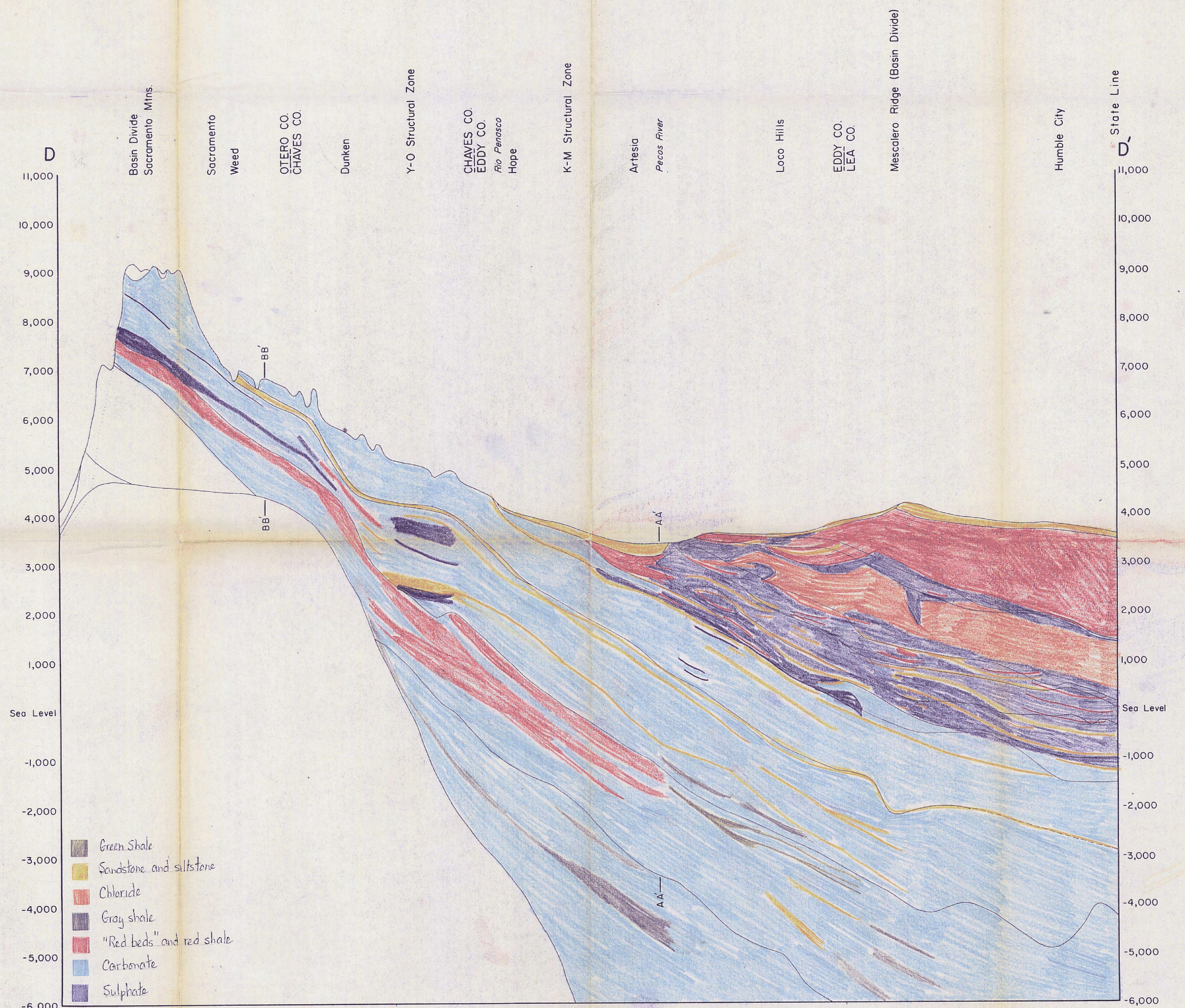


PLATE 12 — Cross section CC — lithology

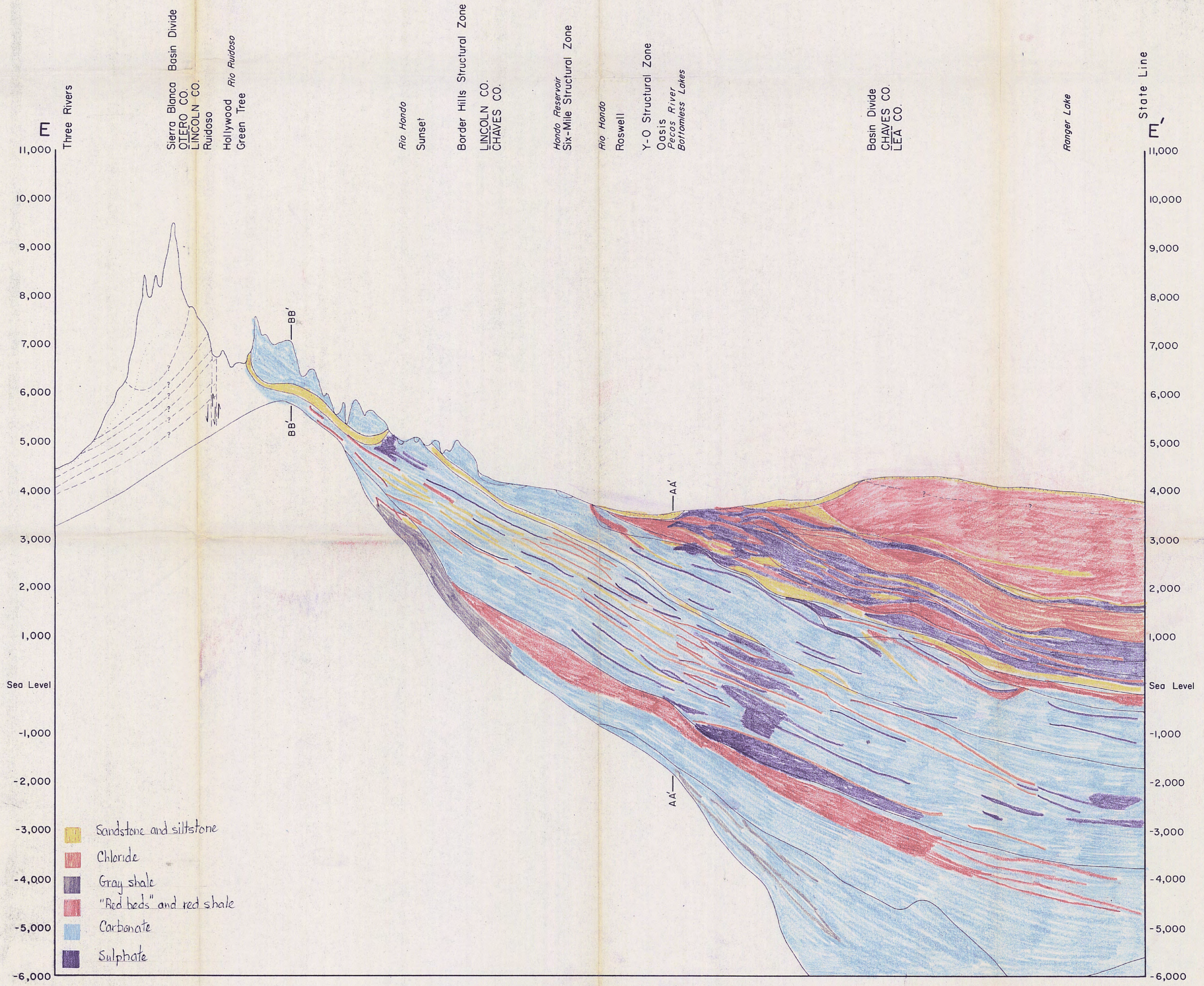


PLATE 13- Cross section EE'-lithology

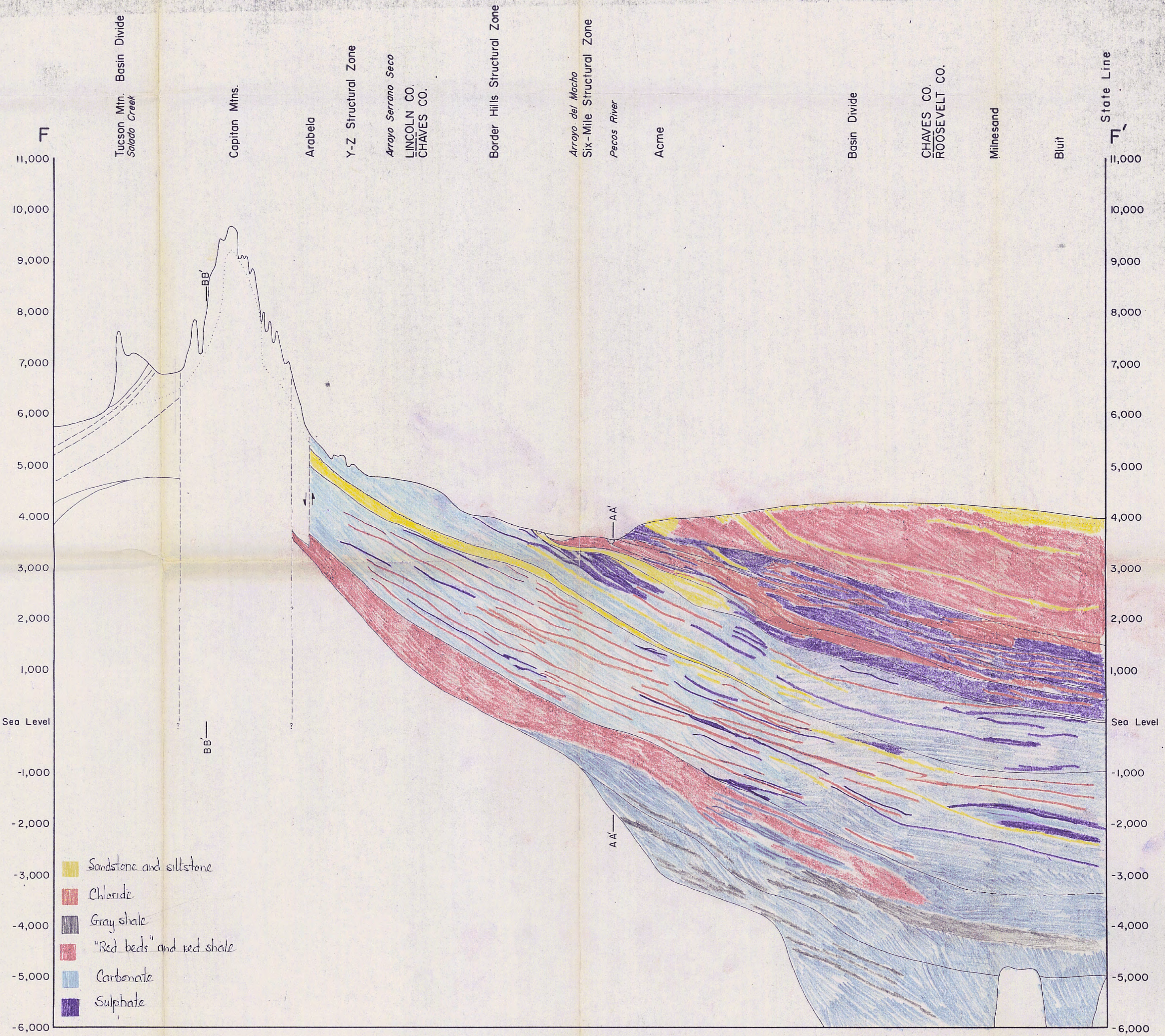


PLATE 14-Cross section FF'-lithology

PLATE 15 - Cross section AA'-permeability

PLATE 16 — Cross section CC' — permeability

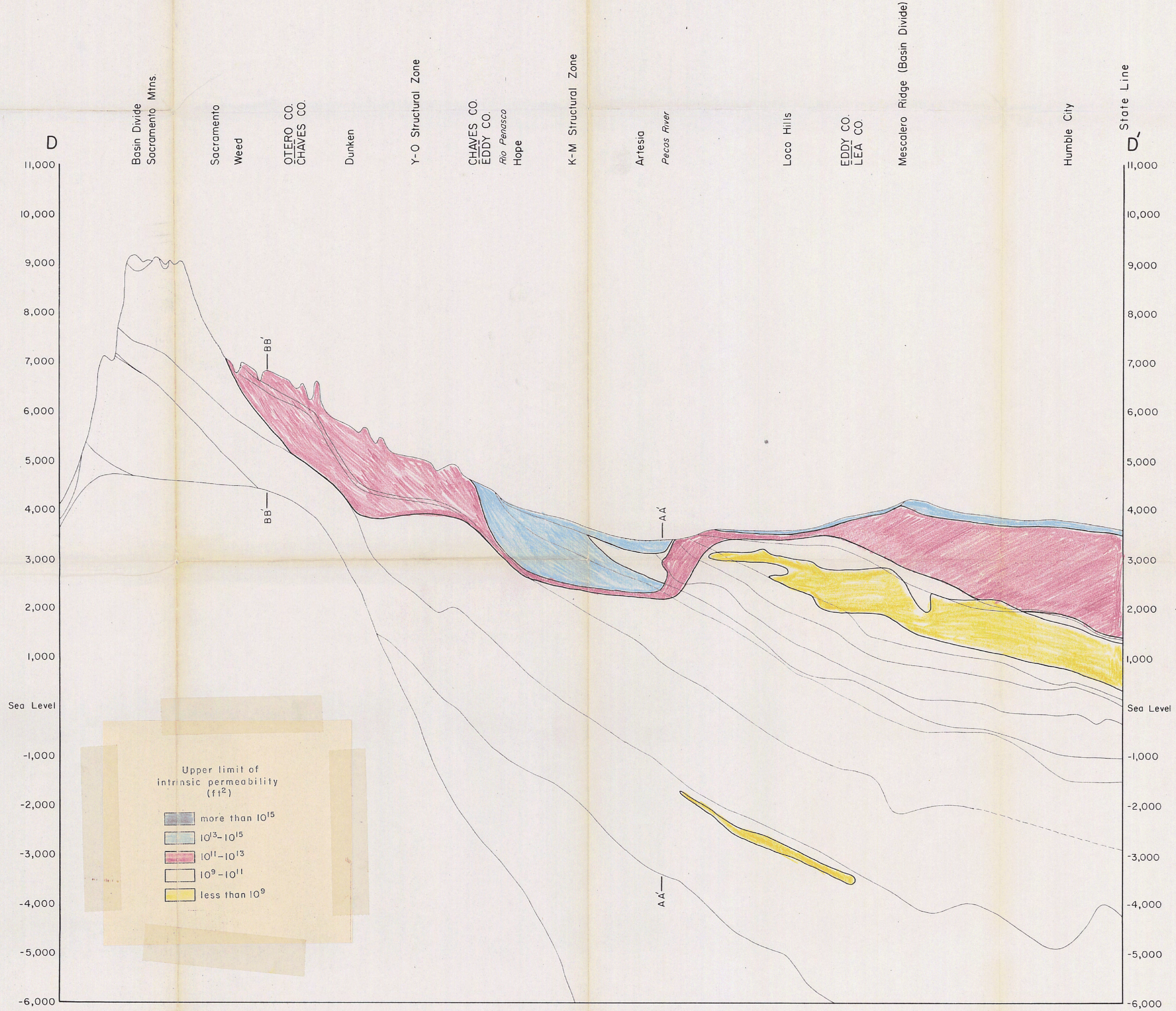


PLATE 17 — Cross section DD' — permeability

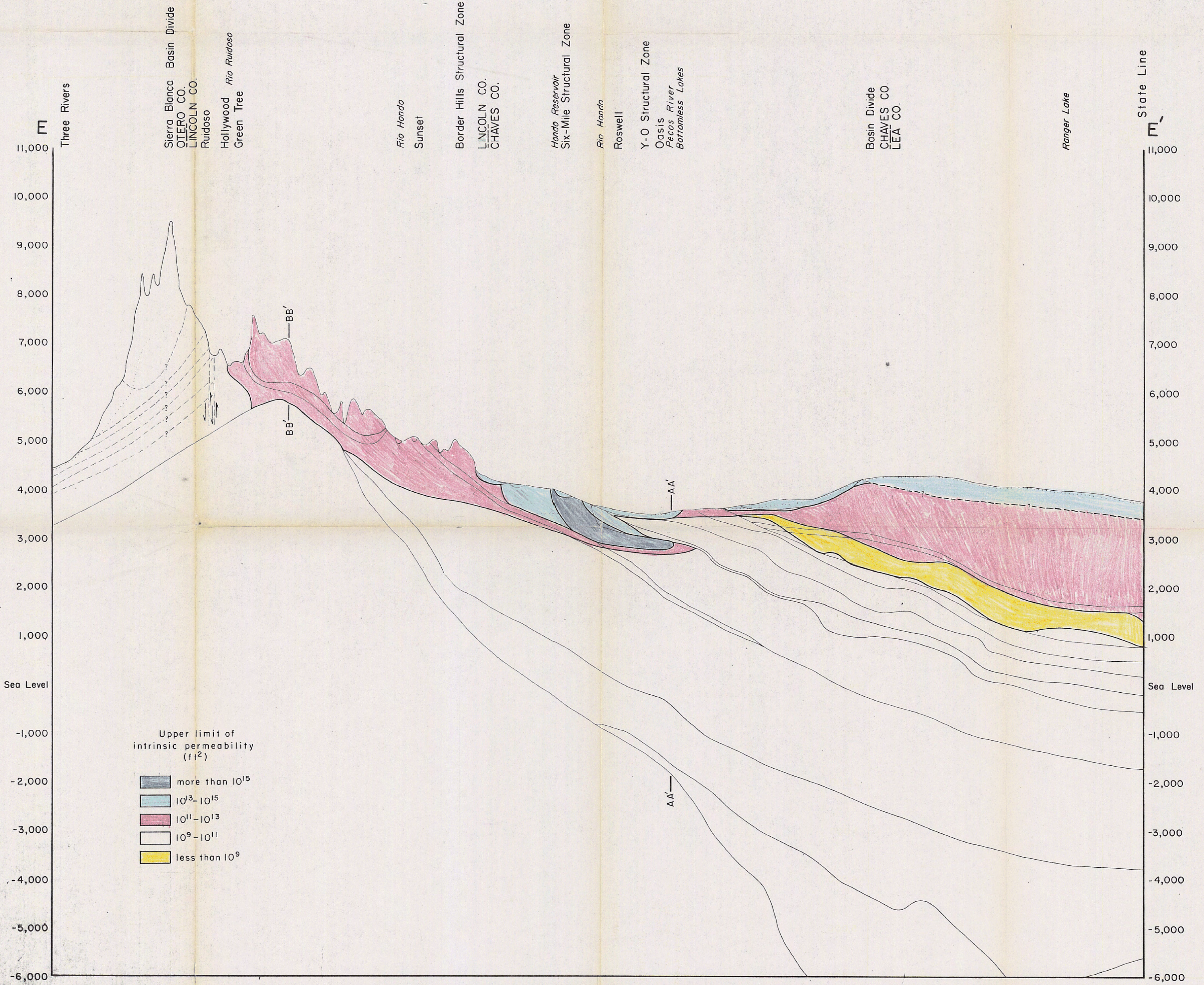


PLATE 18-Cross section EE-permeability

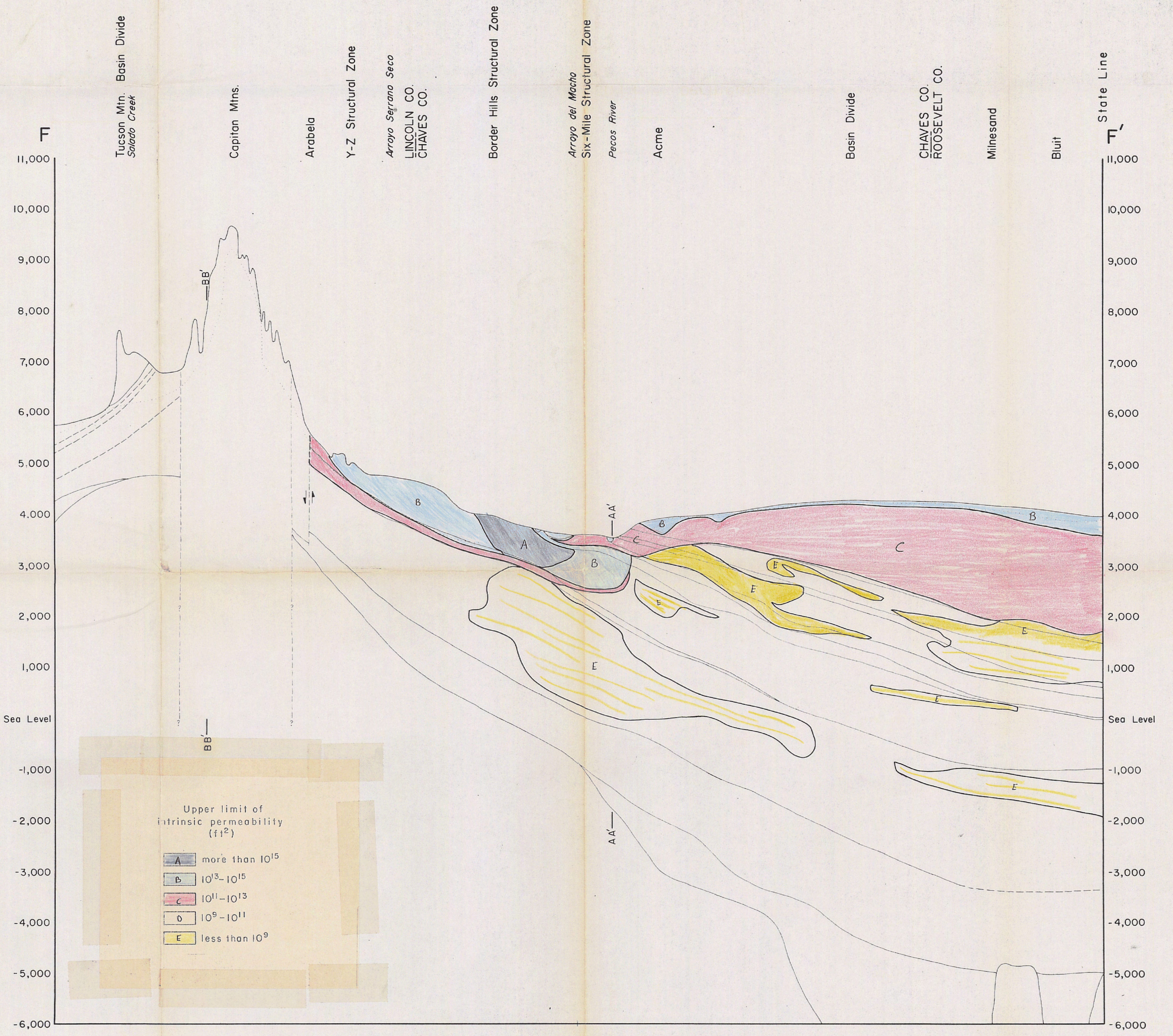


PLATE 19 — Cross section FF' — permeability

PLATE 20: WATER TABLE MAP

PLATE 21 – Cross section AA' – Fresh-water potential

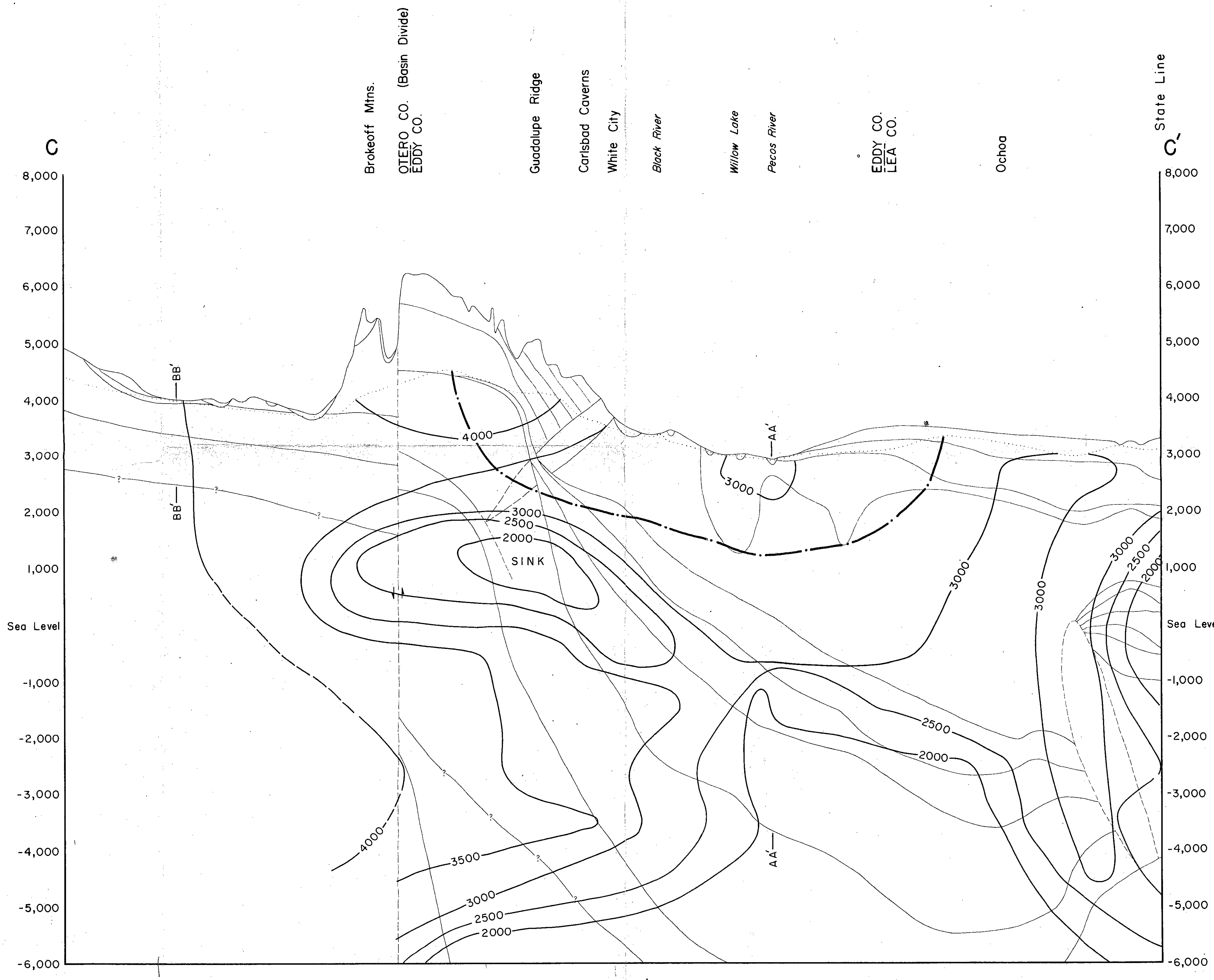


PLATE 22-Cross section CC′-Fresh-water potential

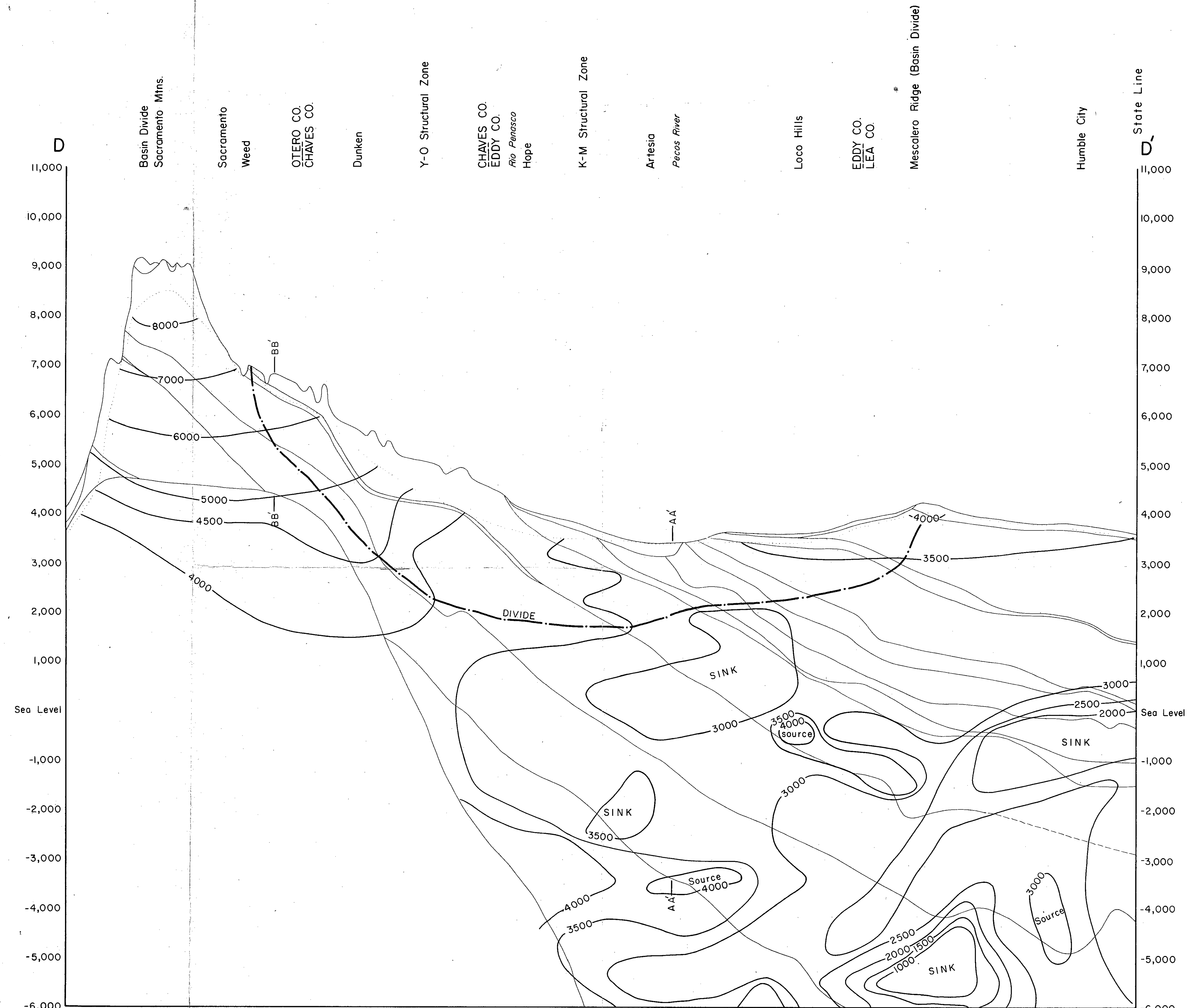


PLATE 23—Cross section DD'-Fresh-water potential

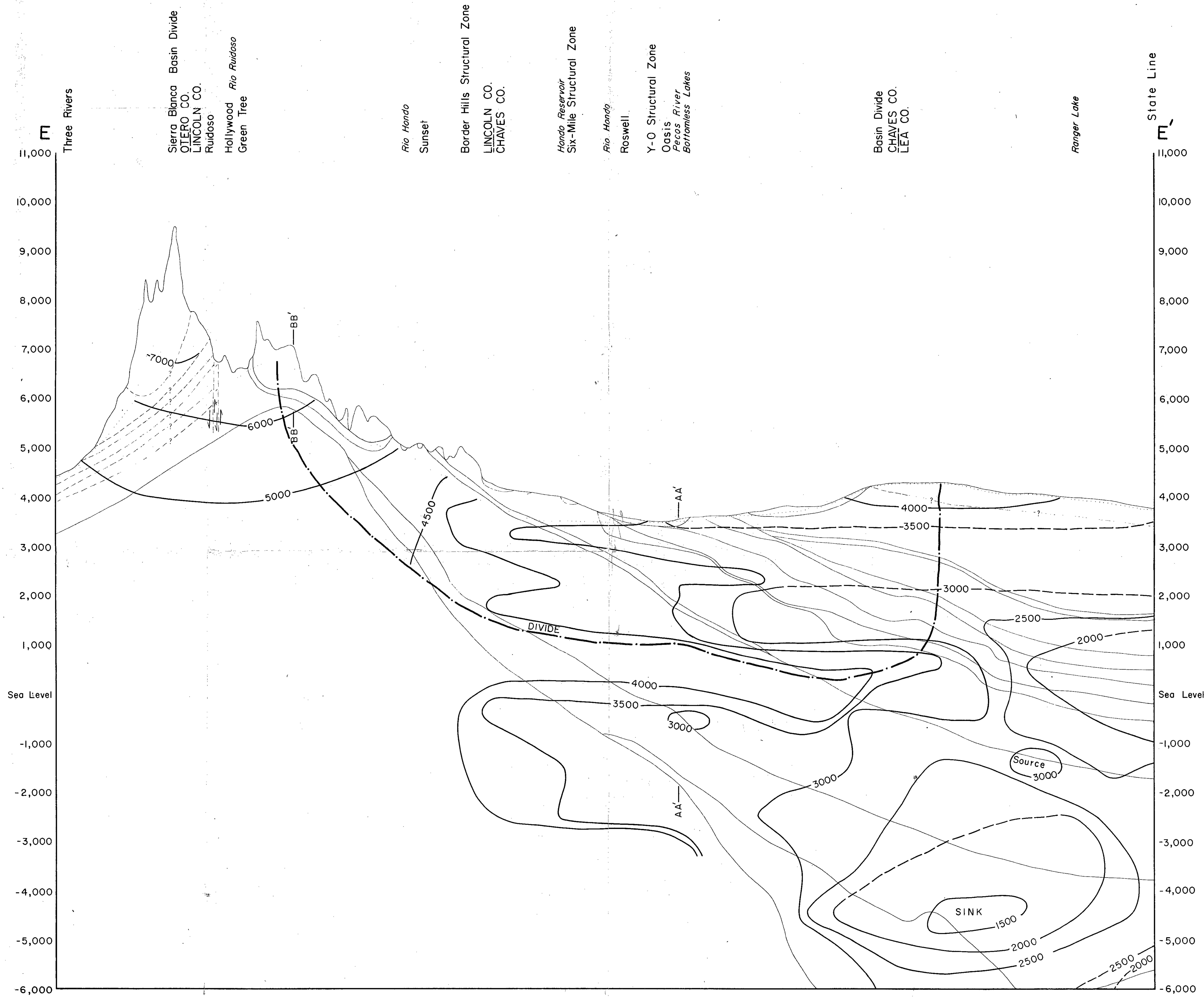


PLATE 24—Cross section EE'-Fresh-water potential

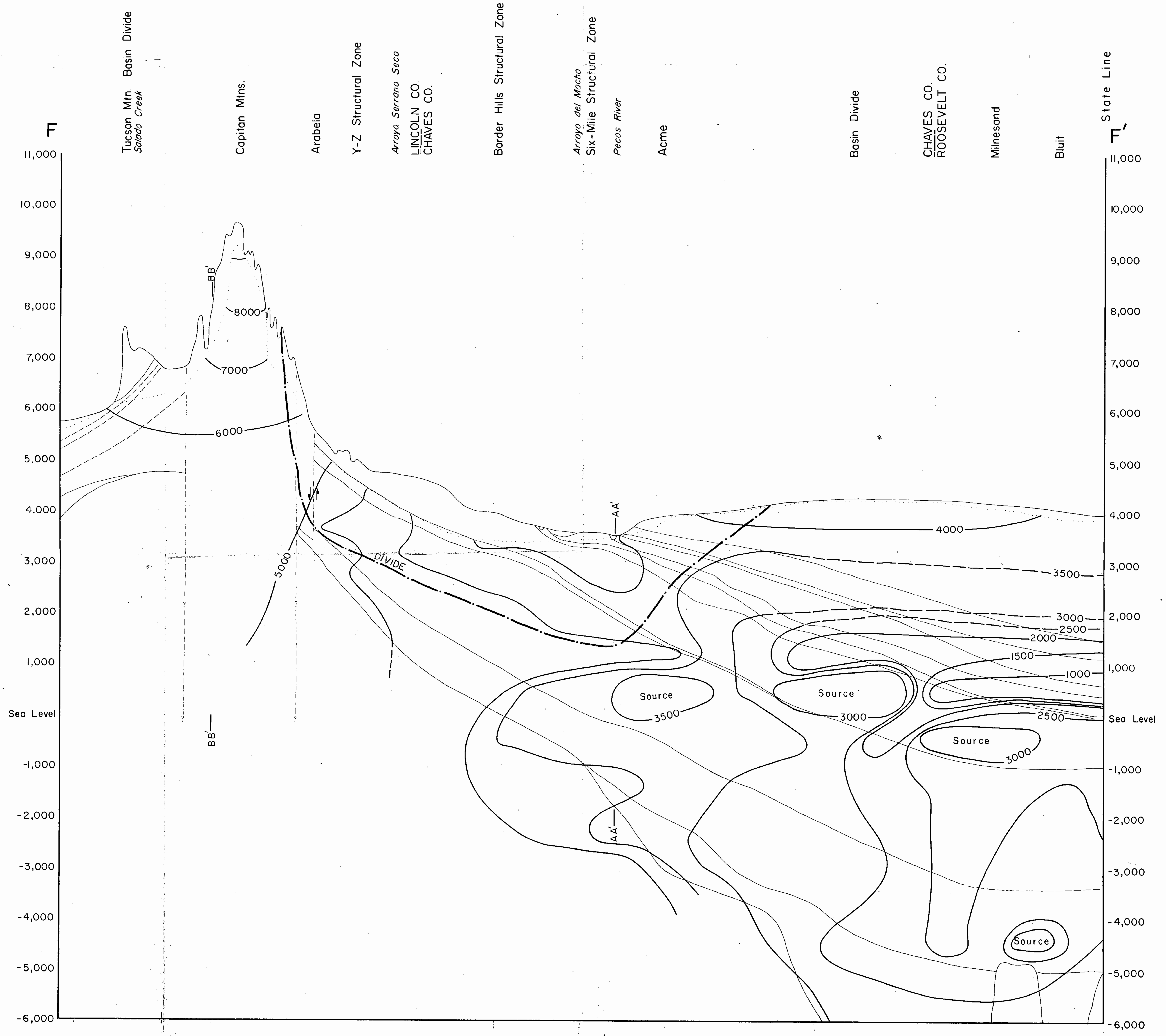


PLATE 25 – Cross section FF′ – Fresh-water potential

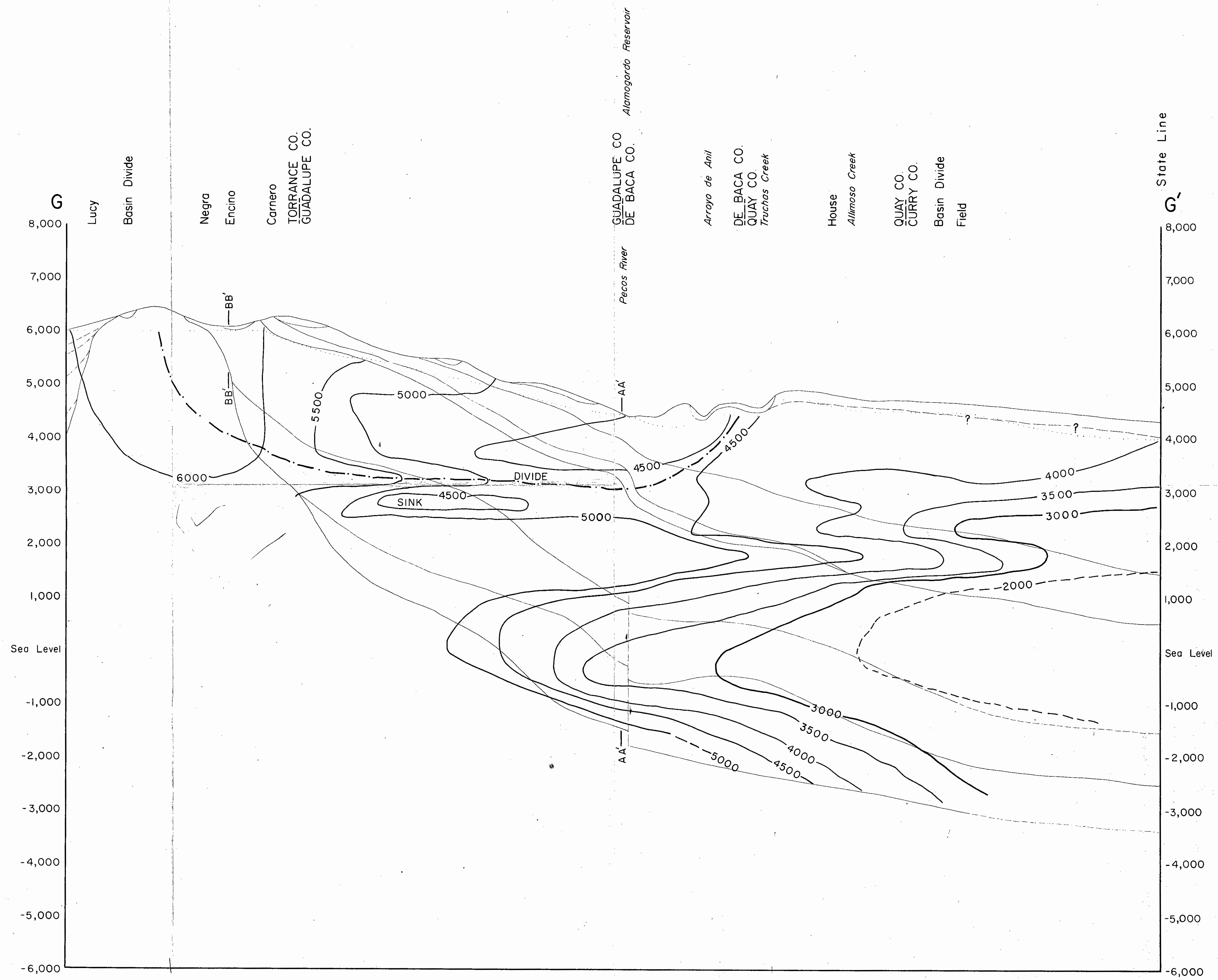


PLATE 26—Cross section GG′—Fresh-water potential

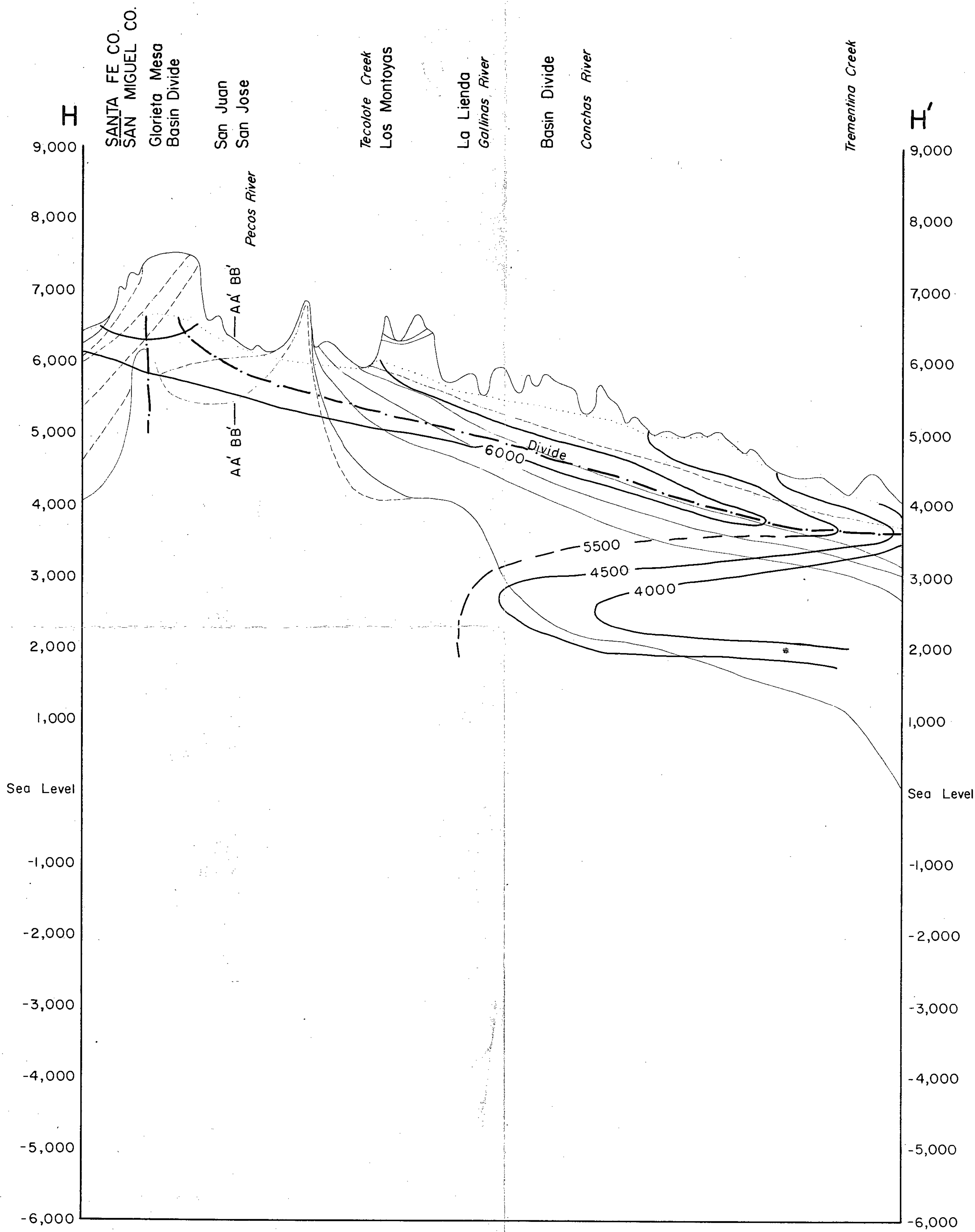


PLATE 27—Cross section HH′—Fresh-water potential