MOVEMENT OF GROUND WATER IN PERMIAN GUADALUPIAN AQUIFER SYSTEMS, SOUTHEASTERN NEW MEXICO AND WESTERN TEXAS

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AQUIFER SYSTEMS

Permian Guadalupian-age strata can be divided into three aquifer systems. Hiss (1975a, p. 132) described and named them the Capitan, shelf, and basin aquifers (fig. 1). In most areas, they are readily distinguished by differences in lithology, geographic position, stratigraphic relationships, hydraulic characteristics, and quality of the contained water (Hiss, 1975b and c; 1976a).

Capitan Aquifer

The Capitan aquifer is a lithosome that includes the Capitan and Goat Seep Limestones and most or all of the Carlsbad facies of Meissner (1972). Shelf-margin carbonate banks or stratigraphic reefs in the upper part of the San Andres Limestone are included within the Capitan aquifer where they cannot be readily distinguished from the Goat Seep Limestone and Carlsbad facies (Silver and Todd, 1969, figs. 12 and 13).

Shelf Aquifers

Saturated strata yielding significant quantities of water from the San Andres Limestone and the Bernal and Chalk Bluff facies of Meissner (1972) constitute the shelf aquifers. The lithologic contact between the Capitan and shelf aquifers is gradational and is difficult to discern with accuracy in some areas. Observations of the geometry and lithologic relationships of the shelf-margin rocks in the field suggest that the width of the Capitan Limestone (reef) is considerably less than is shown in many geologic reports (Dunham, 1972, fig. I-1).

The present-day ground water regimen is strongly influenced by the Pecos River in New Mexico. As a result, the hydraulic conductivity of the shelf aquifers west of the Pecos River has been greatly enhanced by the leaching of soluble beds from the Chalk Bluff facies (Meissner, 1972; Motts, 1968). Locally and west of the Pecos River valley between Carlsbad and Roswell, the hydraulic conductivities of the shelf aquifers are quite large and may be similar to that of the Capitan aquifer. The hydraulic conductivity of the shelf aquifers in the Carlsbad and Roswell underground water basins is several orders of magnitude higher than that generally encountered in the shelf aquifers east of the Pecos River at Carlsbad. The water contained in the shelf aquifers is also much better in the shallow zones exploited in these basins than elsewhere in the same aquifers within the area studied. East of the Pecos River near Carlsbad the hydraulic conductivity of the shelf aquifers is generally one to two orders of magnitude less than that of the Capitan aquifer.

Basin Aquifers

Saturated strata yielding significant quantities of water from the Brushy Canyon, Cherry Canyon and Bell Canyon Formations of the Delaware Mountain Group are referred to as the basin aquifers. Although the Capitan aquifer abuts and overlies the Delaware Mountain Group along the margin of the Delaware Basin, the lithologic and hydrologic characteristics of the basin and Capitan aquifers are quite different. The average hydraulic conductivity of the basin aquifer ranges from one to two orders of magnitude less than that of the Capitan. Therefore, only a relatively small amount of water can be expected to move from the basin aquifers to the Capitan aquifer, or vice versa. The difference in quality of water contained in the two aquifers—relatively good in the Capitan, bad in the basin—is also a distinguishing characteristic (Hiss, 1975b).

CONSTRUCTION OF POTENTIOMETRIC SURFACES

Reliable pressure-head and water-level data were adjusted to freshwater heads to construct generalized potentiometric surfaces representative of two conditions in the three aquifer systems. Figure 2 is a map representing conditions in the aquifer systems prior to both development of water supplies for irrigation and discovery and production of oil and gas and associated waste water. Figure 3 is a similar map representing the shelf and basin aquifer for the period 1960 to 1969 and of the Capitan aquifer for the latter part of 1972.

A potentiometric surface represents hydraulic head in an aquifer; the general direction of ground-water movement is inferred to be normal to the illustrated head contours. Hiss (1975, p. 220-255) discusses the computation of ground-water head and the procedures followed in determining the heads used in these maps. The potentiometric maps support the inferred movement of water shown in figure 4.

MOVEMENT OF GROUND WATER

During the latter part of the Cenozoic Era, the movement of ground water through the rocks of Permian Guadalupian age in southeastern New Mexico and western Texas has been controlled or influenced by the following: (1) the regional and local tectonics; (2) the evolution of the landscape; (3) the relative transmissivities of the various aquifers; (4) the amount of recharge; and (5) the exploitation of the petroleum and ground-water resources in the last five decades (fig. 4).

Control by Regional Tectonics

The flow of ground water through the shelf, basin and Capitan aquifers after the uplift of the Guadalupe and Glass Mountains but prior to the excavation of the Pecos River valley at Carlsbad is shown diagrammatically in figure 4A. The three aquifer systems were recharged by water originating as rain or snowfall on the outcrops along the western margin of the Delaware Basin. Evidence of major surface drainage within the Trans-Pecos area of southeastern New Mexico and western Texas has not been reported.

Ground water moved generally eastward and southeastward through the shelf and basin aquifers under a gradient of probably only a few feet per mile toward natural discharge areas along

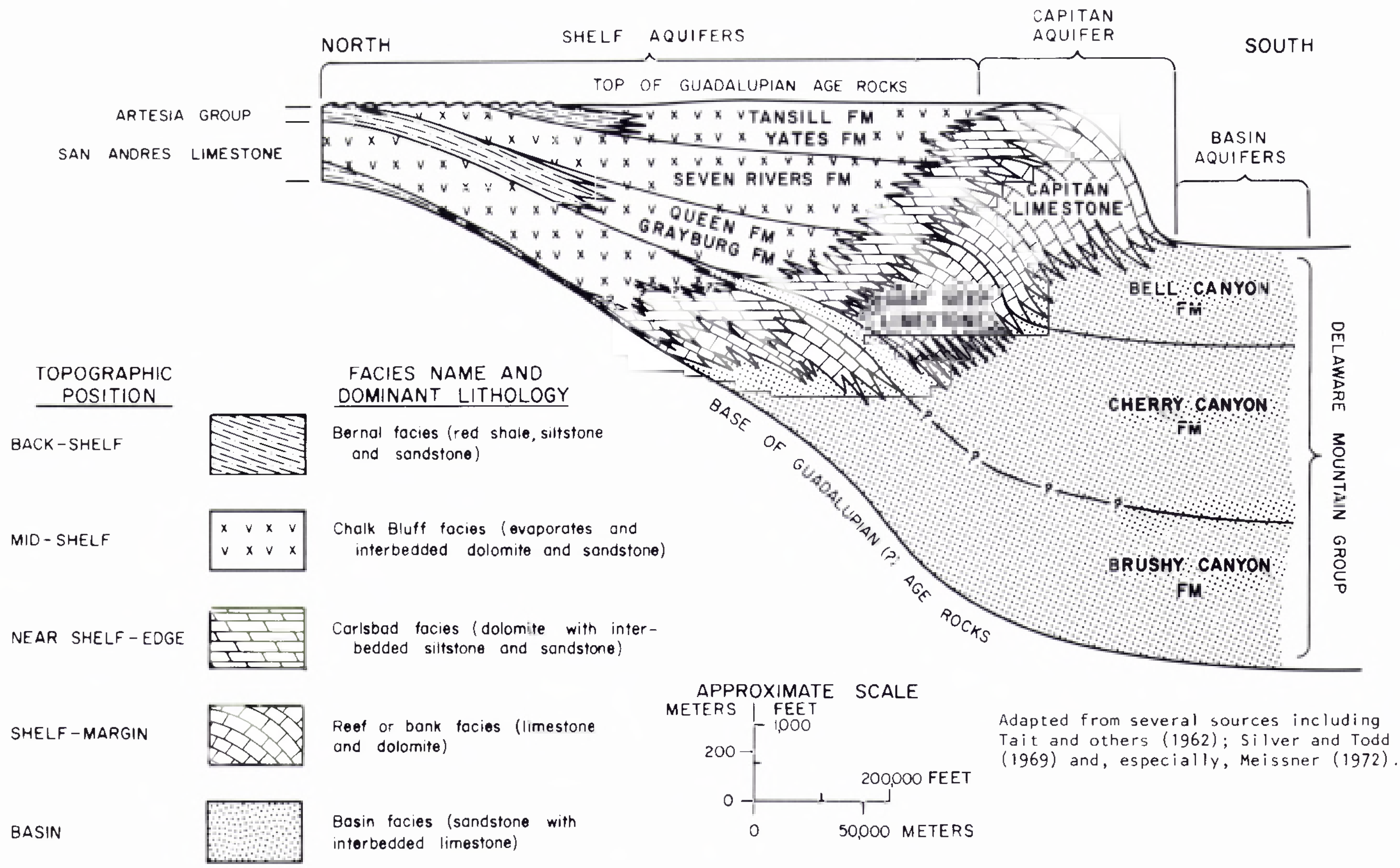


Figure 1. Highly diagrammatic north-south stratigraphic section showing the positions and relationships of the major lithofacies in the rocks of Guadalupian age, eastern New Mexico.

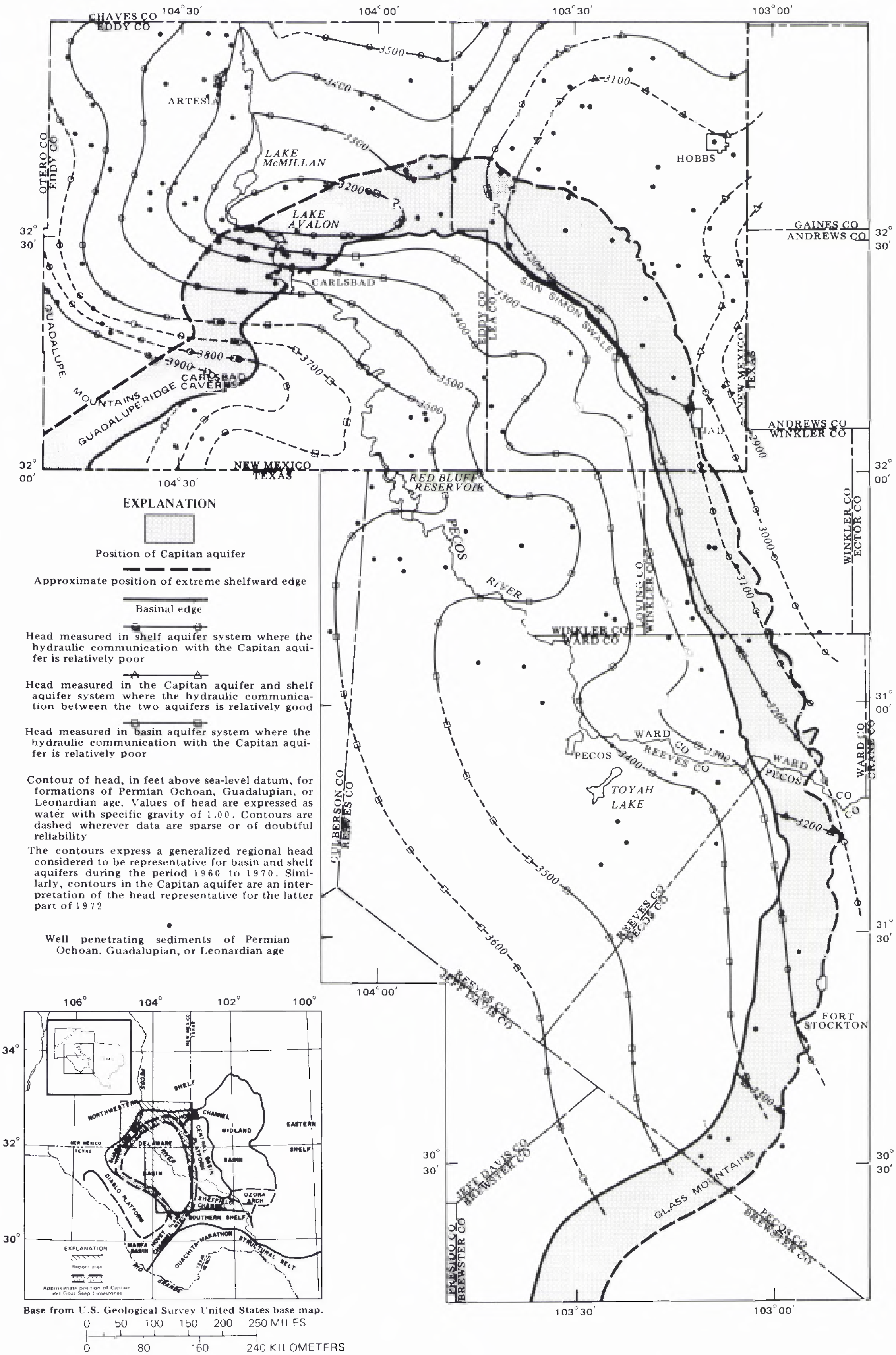


Figure 2. Pre-development potentiometric surface.

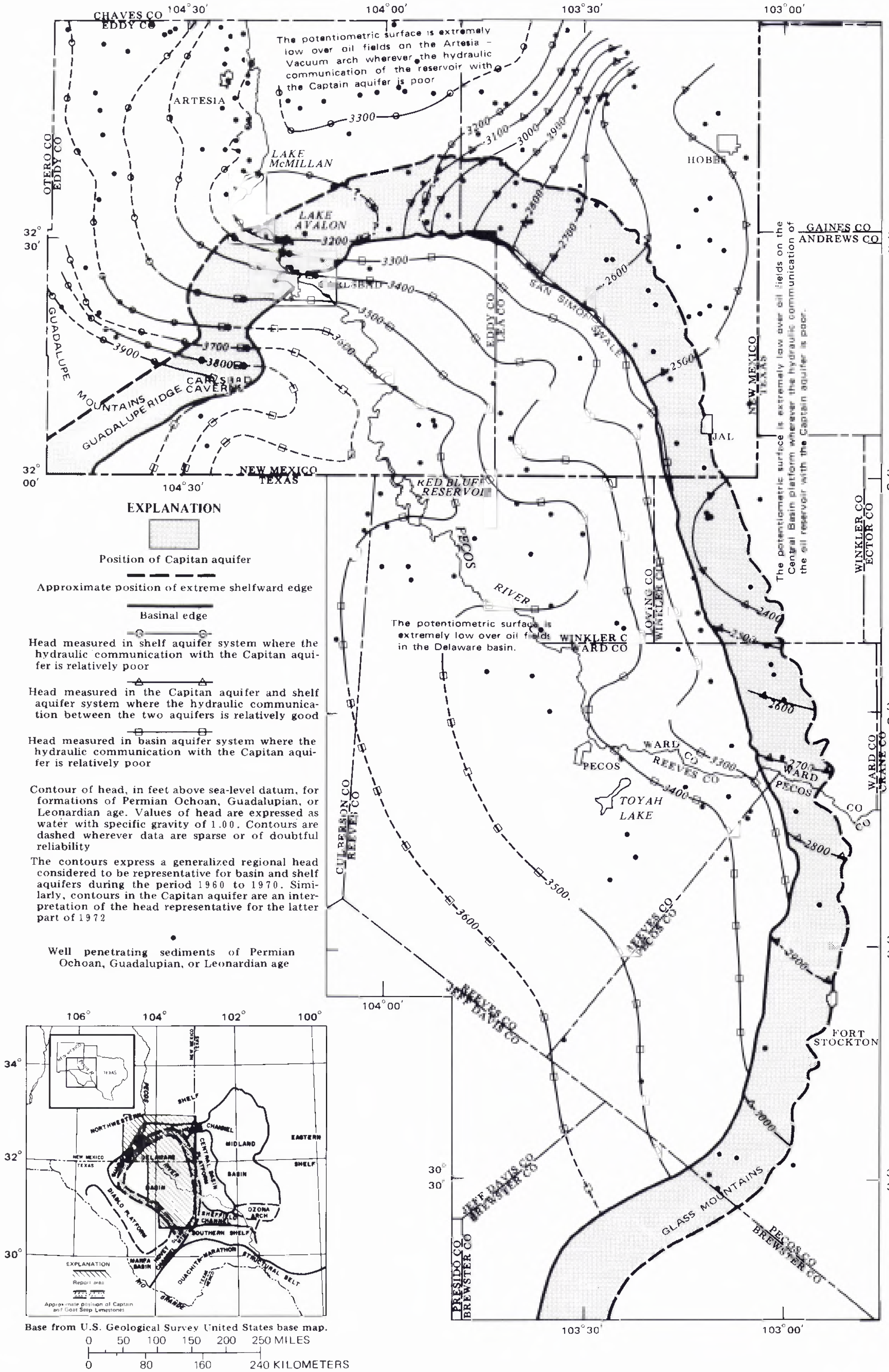
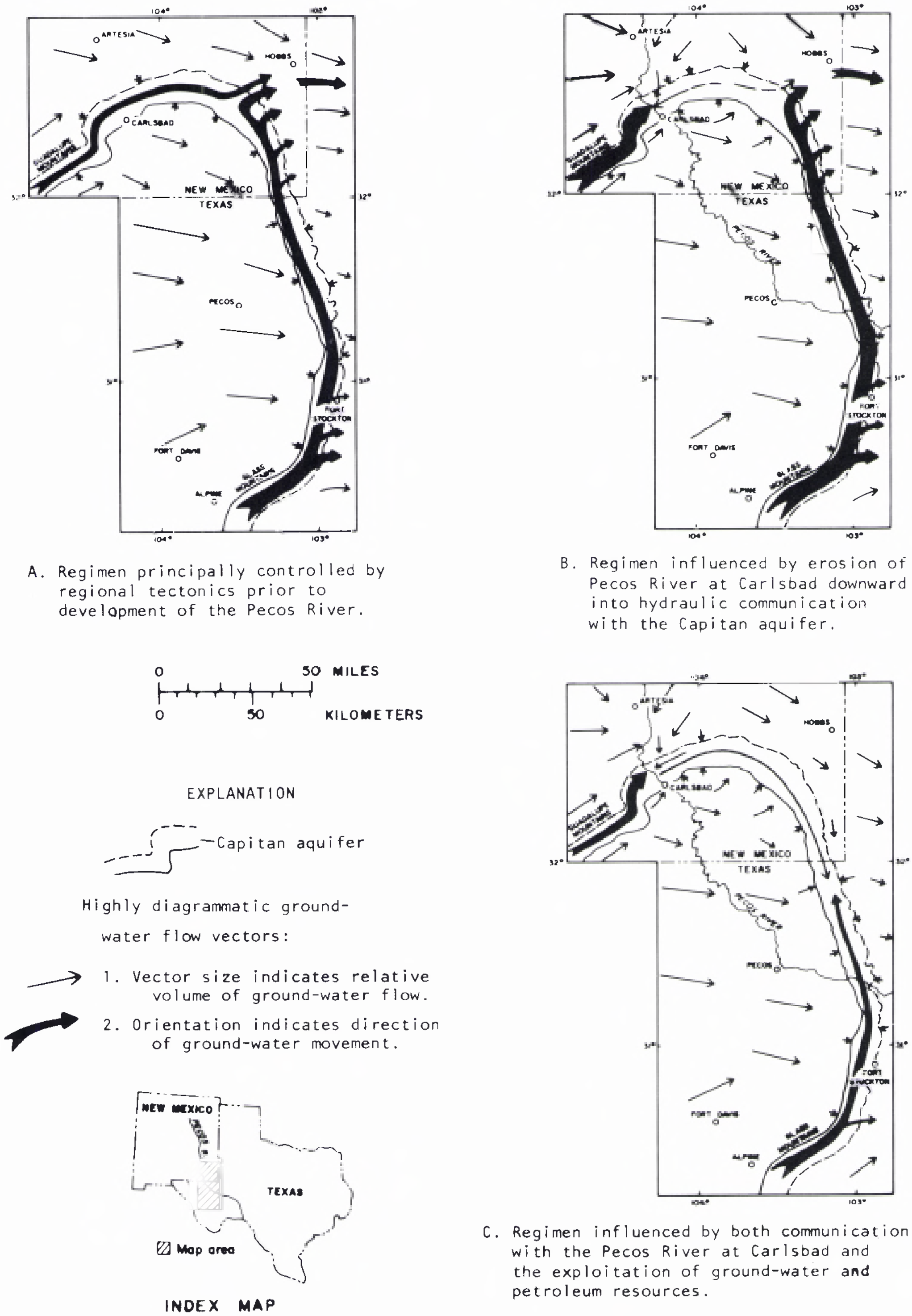


Figure 3. Post-development potentiometric surface.



A. Regimen principally controlled by regional tectonics prior to development of the Pecos River.

B. Regimen influenced by erosion of Pecos River at Carlsbad downward into hydraulic communication with the Capitan aquifer.

C. Regimen influenced by both communication with the Pecos River at Carlsbad and the exploitation of ground-water and petroleum resources.

Figure 4. Diagrammatic maps depicting the evolution of ground water regimens in strata of Permian Guadalupian age in southeastern New Mexico and western Texas.

streams draining to the ancestral Gulf of Mexico. Water entering the Capitan aquifer in the Guadalupe Mountains moved slowly northeastward and then eastward along the northern margin of the Delaware Basin to a point southwest of present-day Hobbs. Here it joined and comingled with a relatively larger volume of ground water moving northward from the Glass Mountains along the eastern margin of the Delaware Basin. From this confluence, the ground water was discharged from the Capitan aquifer into the San Andres Limestone, where it then moved eastward across the Central Basin Platform and Midland Basin, eventually to discharge into streams draining to the Gulf of Mexico.

Influence of Erosion of Pecos River at Carlsbad

Some time after deposition of the Ogallala Formation, perhaps early in Pleistocene time, the headward-cutting Pecos River extended westward across the Delaware Basin to the exposed soluble Ochoan beds. It then turned northward following this natural weakness in the sedimentary rocks to pirate the streams draining to the east from the Sacramento and Guadalupe Mountains (Plummer, 1932; Bretz and Horberg, 1949b; Thornbury, 1965). As the excavation of the Pecos River valley progressed, the hydraulic communication with formations of Guadalupian age gradually increased until the Pecos River functioned as an upgradient drain. Eventually, the hydraulic gradients in the shelf, basin and Capitan aquifer were reversed along the eastern side of the Pecos River valley, and ground water that formerly flowed eastward was diverted westward as spring flow into the Pecos River (fig. 4B). Water recharged to the same aquifers in the Guadalupe Mountains began to follow the shorter path to springs in the Pecos River. Many of the solution features observed in the Guadalupian sedimentary rocks west of the Pecos River near Carlsbad probably were initiated during this period.

Movement of water eastward toward Hobbs from the Guadalupe Mountains into the Capitan aquifer was decreased by the lowering of the hydraulic head along the Pecos River. At the same time, a trough in the potentiometric surface of the shelf and basin aquifers began to develop east of Carlsbad, and water began to drain into the Capitan aquifer from the surrounding sedimentary rocks. Meanwhile, ground water continued to move northward from the Glass Mountains in the Capitan aquifer toward a point of discharge into the San Andres Limestone southwest of Hobbs. This part of the aquifer was unaffected by the cutting of the Pecos River valley across the Delaware Basin and the Central Basin Platform.

Influence of Exploitation of Ground Water and Petroleum Resources

Regionally, the movement of ground water in the shelf and basin aquifers east of the Pecos River at Carlsbad has changed very little as a result of the exploitation of ground water and petroleum during a period of approximately 50 years (fig. 4C). Locally, however, the movement of ground water within these same aquifers is controlled by the effects of the numerous producing oil fields.

The shape of the regional potentiometric surface representative of the hydraulic head in the Capitan aquifer east of the Pecos River at Carlsbad has been changed significantly in response to withdrawal of both ground water and petroleum during the past 50 years. The westward movement of saline water from the Capitan aquifer in Eddy County east of Carlsbad into the Pecos River has been greatly diminished or eliminated by a reduction in hydraulic head.

Similarly, the movement of water in the San Andres Limestone and Artesia Group eastward across the northern part of the Central Basin Platform from New Mexico into Texas has been decreased. Eventually, the movement of water probably will be reversed. Water may be diverted from the San Andres Limestone and Artesia Group westward from Texas back toward Hobbs and then into the Capitan aquifer along the western margin of the Central Basin Platform. The effects of exploitation of the ground water and petroleum resources will continue to be the dominant factor influencing the movement of ground water in the Capitan aquifer for many years into the future.

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STRATIGRAPHY AND GROUND-WATER HYDROLOGY OF THE CAPITAN AQUIFER, SOUTHEASTERN NEW MEXICO AND WESTERN TEXAS

by

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B.S., Kansas State University, 1953

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Stratigraphy and ground-water hydrology of the Capitan aquifer, southeastern New Mexico and western Texas

Thesis directed by Professor Theodore R. Walker

The Capitan aquifer is an important source of ground water for both municipal and industrial purposes in southeastern New Mexico and western Texas. The Capitan aquifer was mapped in the subsurface as a stratigraphic reef. It extends for approximately 200 miles (320 kilometres) as a continuous arcuate unit, unbroken by faulting, parallel to the north and east margins of the Delaware basin from the Guadalupe Mountains southwest of Carlsbad, New Mexico to the Glass Mountains southwest of Fort Stockton, Texas.

At Carlsbad, where the Capitan aquifer plunges beneath the surface to the northeast away from the Guadalupe Mountains, the Pecos River is in measurable hydraulic communication with the aquifer. Large quantities of moderately to very saline water are being withdrawn from the Capitan aquifer in southeastern New Mexico and western Texas and injected into other formations to repressurize partially depleted oil fields. Water could possibly be diverted eastward from the Pecos River at Carlsbad into the Capitan aquifer in response to industrial pumping.

The cost of drilling and testing new wells precluded obtaining hydrologic data normally acquired by conventional methods. Nine abandoned deep oil and gas wells were acquired from oil companies and converted to fluid-level observation wells. Changes in head resulting from natural events and the effects of fluid production from the Capitan aquifer and other aquifers in measurable hydraulic communication were recorded.

Data, including core analyses, drill-stem tests, bottom-hole pressures, and (or) water-quality data, were obtained from oil companies for about one-third of the more than 30,000 oil and gas wells drilled within the project area. These data were coded and indexed to the Permian Basin Well Data System magnetic tape file of scout records. This approach permitted efficient and economical processing of the hydrologic data with a digital computer.

Submarine canyons and reentrants of Guadalupian and (or) earliest Ochoan age were located in the subsurface along the northern and eastern margins of the Delaware basin. These prominent features were incised into the Capitan aquifer and then filled with complexly interbedded sandstone, siltstone, and limestone with a relatively low hydraulic conductivity. The thickness and, concordantly, the transmissivity of the Capitan aquifer is reduced significantly by the more deeply incised submarine canyons that are oriented normal to the margin of the Delaware basin.

The fortuitous position of the largest submarine canyon precludes the movement of large amounts of water eastward from the Pecos River at Carlsbad into the Capitan aquifer. The water otherwise would have moved eastward in response to extensive development and production of water from this aquifer in southeastern New Mexico and western Texas.

This abstract is approved as to form and content. I recommend its publication.

Signed ______________________
Faculty member in charge of dissertation

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INTRODUCTION

Purpose of the study

This study was started during the summer of 1965 by the U.S. Geological Survey in cooperation with the New Mexico State Engineer. The primary objective was to determine the effects on the Capitan aquifer of the withdrawal of fluids from this aquifer and other aquifers in measurable hydraulic communication; and, to assess, qualitatively, the effect, if any, of continued withdrawal of fluid from this aquifer on the flow of the Pecos River at Carlsbad, N. Mex. Secondary objectives included definition of the Capitan and other associated aquifers; and determination of (1) the stratigraphic position and dimensions of the Capitan aquifer; (2) the determination of the hydraulic characteristics of the Capitan aquifer and associated formations of Permian Guadalupian age; (3) the quality of water contained in these aquifers; (4) the stratigraphic and hydrologic relationships between the Capitan aquifer and other formations; and (5) the total amount of fluids of various types produced from the Capitan aquifer and other reservoirs of Permian Guadalupian age.

The Capitan aquifer is defined elsewhere in this report but is comprised chiefly of the Capitan and Goat Seep Limestones and the Carlsbad facies of the Artesia Group. The Capitan aquifer and several stratigraphic units of equivalent age are important sources of ground water for the city of Carlsbad and for irrigation in the Pecos River basin in New Mexico and Texas. In addition to the fresh water produced for domestic, municipal, and agricultural use in New Mexico and the slightly to moderately saline water used for irrigation in Texas, large quantities of saline ground water are being withdrawn from the Capitan aquifer in Lea County, New Mexico, and Winkler and Ward Counties, Texas (Guyton and Associates, 1958; Brackbill and Gaines, 1964; and table 1). This water, along with additional saline waste water produced with oil, is transported to other areas where it is injected into several formations to repressurize partly depleted reservoirs in a number of oil fields.

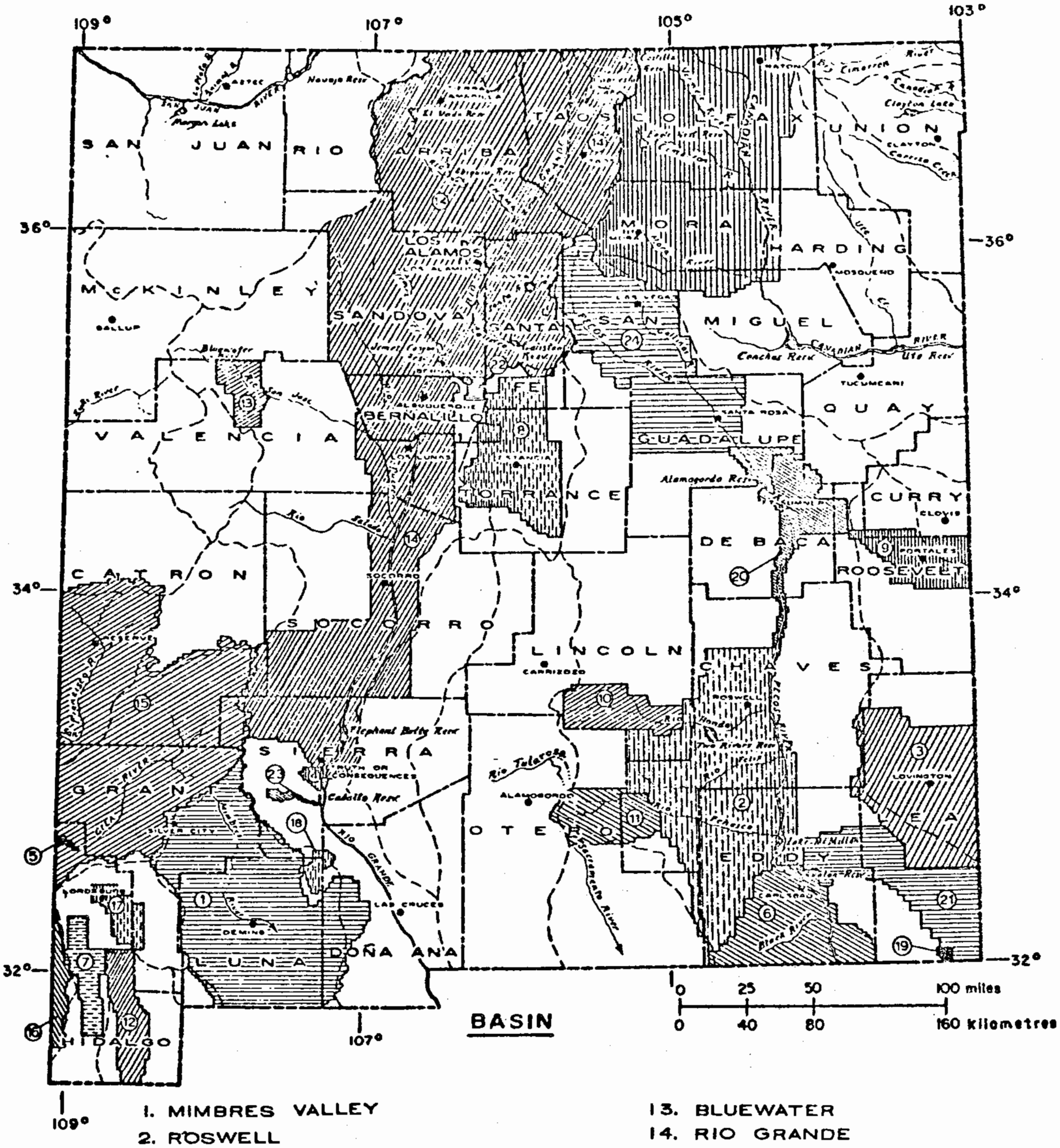
Table 1.--Classification of saline water[1/]

Description	Dissolved solids, milligrams per litre
Slightly saline	1,000 to 3,000
Moderately saline	3,000 to 10,000
Very saline	10,000 to 35,000
Brine	More than 35,000

[1/]Adapted from water-quality ranges suggested by Winslow and Kister (1956). Following the standards used by the U.S. Public Health Service (1962), the U.S. Geological Survey has defined saline water as water that contains more than 1,000 milligrams per litre of dissolved solids (Krieger and others, 1957, p. 4).

Use of surface water in the Pecos River basin is limited by an interstate stream compact between the States of New Mexico and Texas (U.S. Congress, 1949; Lingle and Linford, 1961). The use of surface water in the entire basin within New Mexico and ground water in part of the basin and adjacent areas, also within New Mexico, is administered by the New Mexico State Engineer (fig. 1; and Hutchins, 1955). In contrast, the use of ground water in adjacent areas in Texas is not controlled by State or Federal agencies. The intense competition for water within this area is reflected by the number of hearings held before the New Mexico State Engineer concerning the use of ground water from the Capitan aquifer in the vicinity of Carlsbad (New Mexico State Engineer Hearing, 1960, 1962, and 1963; New Mexico State Engineer, 1964).

The measurable hydraulic communication of the Capitan aquifer with the Pecos River at Carlsbad is an important factor considered in the administration of the right to appropriate water in New Mexico.



1. MIMBRES VALLEY
2. ROSWELL
3. LEA COUNTY
4. HOT SPRINGS
5. VIRDEN VALLEY
6. CARLSBAD
7. ANIMAS
8. ESTANCIA
9. PORTALES
10. HONDO
11. PEÑASCO
12. PLAYAS VALLEY
13. BLUEWATER
14. RIO GRANDE
15. GILA - SAN FRANCISCO
16. SAN SIMON
17. LORDSBURG VALLEY
18. NUTT - HOCKETT
19. JAL
20. FORT SUMNER
21. CAPITAN
22. SANDIA
23. LAS ANIMAS CREEK
24. UPPER PECOS
25. CANADIAN RIVER

---------BOUNDARY, SURFACE-DRAINAGE AREA

Figure 1.--Map showing underground water basins in New Mexico declared by the State Engineer as of December 31, 1973.

Disclaimer

The extensive investigation leading to the preparation of this report was funded jointly by the U.S. Geological Survey and the New Mexico State Engineer. However, the conclusions and opinions presented herein are solely those of the author and do not necessarily concur with or represent those of the sponsors. This report is subject to further review and revision by the U.S. Geological Survey.

Scope of the study

The study included the collection, compilation, and analysis of data related to ground and surface waters and to the production of water, oil, and gas within the project area. Specific items incorporated in the study included determination of (1) the location and extent of the major aquifers in the area and the relative degree of hydraulic communication between the several aquifers, (2) the chemical quality of water contained in the aquifers, (3) the quantity of ground water and oil and gas withdrawn from rocks of Permian Guadalupian age, (4) the effects of these withdrawals on aquifer head, (5) the hydraulic properties of the principal aquifers, and (6) estimates of the quantities of ground water available for use. Many procedures and techniques for handling geologic and hydrologic data with a digital computer were developed and used.

Location and extent of the area

The project area includes Eddy County and southern Lea County, New Mexico, and Winkler, Ward, Loving, Reeves, and parts of Culberson, Pecos, and Brewster Counties, Texas. This area, containing more than 16,000 sq mi (square miles) (25,700 km^2, square kilometres), is shown in figure 2. The concentration of project activities was more intensive in New Mexico than in Texas. Emphasis was placed on an arcuate strip following the trend of the Capitan aquifer along the north and east margins of the Delaware basin between the Guadalupe Mountains southwest of Carlsbad and the Glass Mountains southwest of Fort Stockton, Tex. (figs. 2 and 3).

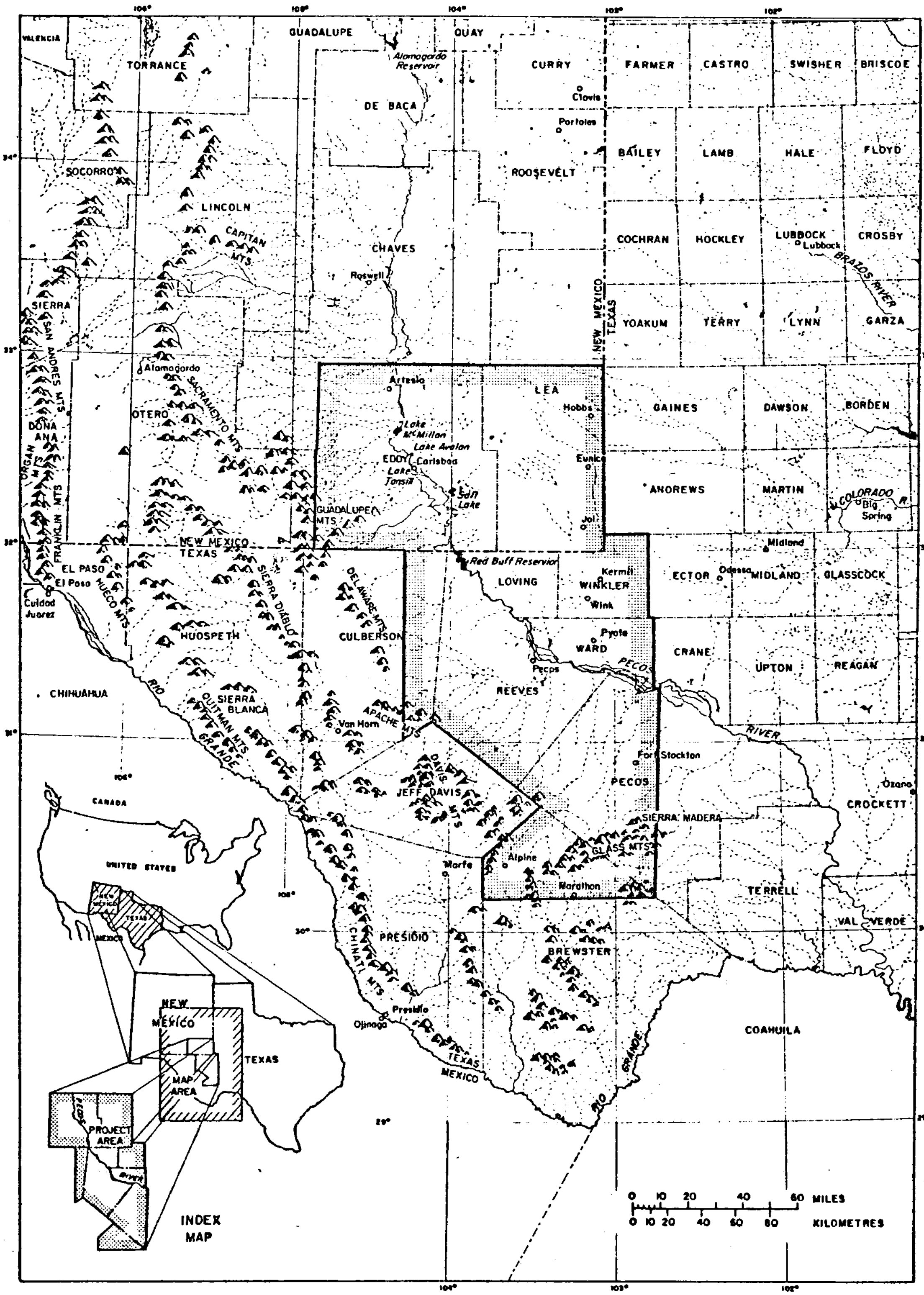


Figure 2.--Map showing location of project area.

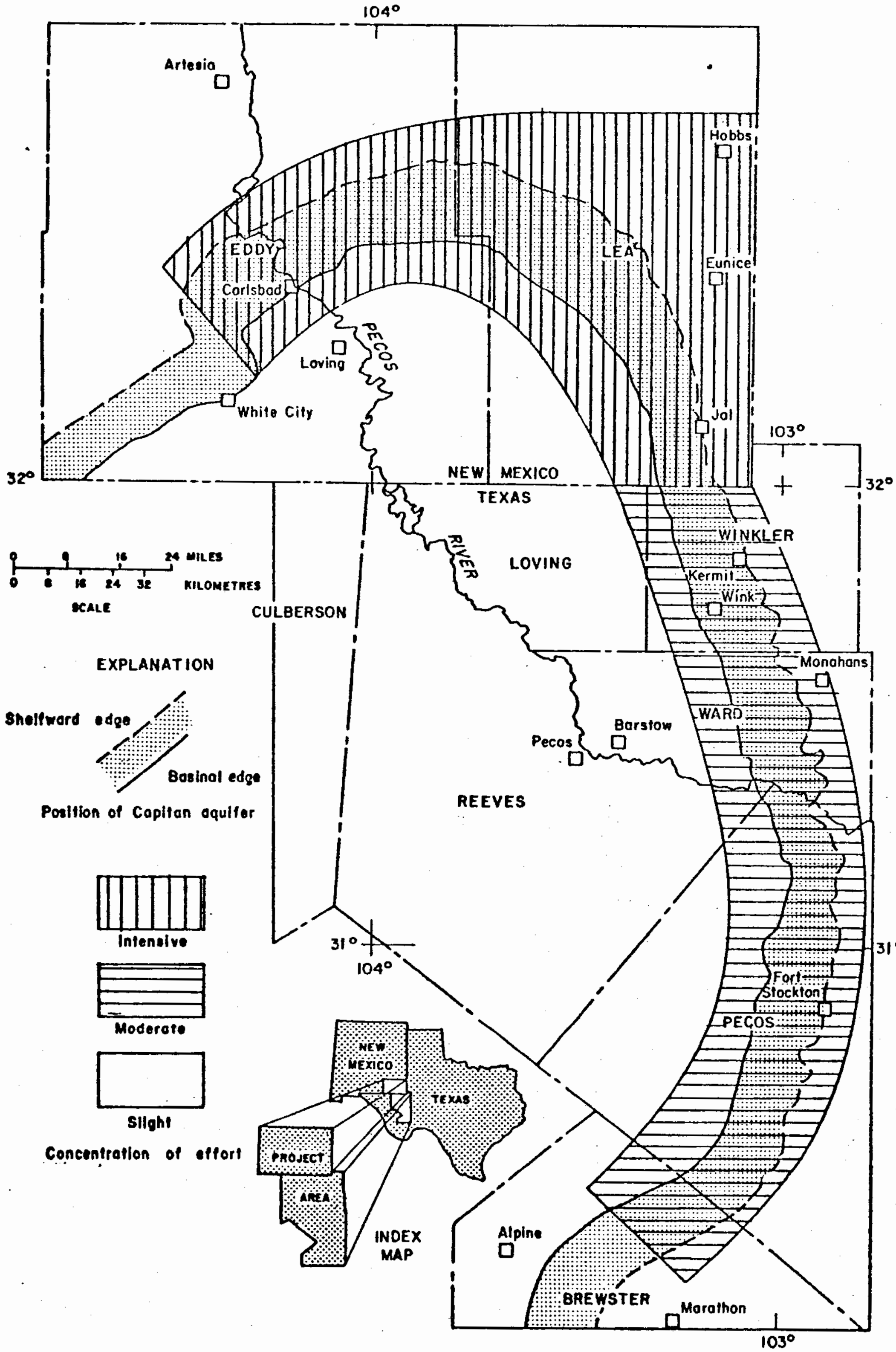


Figure 3.--Map showing concentration of effort within project area.

Conversion from English and oil-industry units to metric units

Numbers in this report are given in English units and (or) oil-industry units followed by the corresponding oil-industry or English unit and the metric equivalent in parentheses. The conversion factors used are given in tables 2 and 3.

Chemical concentrations are given only in metric units, milligrams per litre (mg/l). For concentrations less than 7,000 mg/l, the numerical value is about the same as for concentrations in the English unit, parts per million (ppm).

The altitudes, elevations, distances, depths, and volumes given in this report are often either estimated or generalized so as to be descriptive of a large area. Accordingly, the values stated are often rounded to the nearest hundred units. The values are also converted from English units to metric units and given in parentheses following the original value. The corresponding metric units are usually rounded to the nearest 5 units. However, when the magnitude of the value in English is either small or expressed with obvious precision, an attempt has been made to keep the metric conversion consistent.

Table 2.--English to metric conversion factors

English Unit	English Abbreviation	Multiplied by	Metric Unit	Metric Abbreviation
Acre	acre	0.4047	Hectare	ha
Acre-foot	acre-ft	.0012335	Cubic hectometre	hm^3
Barrels (42 U.S. gallons)	bbl	.15899	Cubic metre	m^3
Do	do	.000159	Cubic hectometre	hm^3
Cubic feet	ft^3	.02832	Cubic metre	m^3
Foot	ft	.3048	Metre	m
Gallon	gal	.003785	Cubic metre	m
Do	do	3.785	letre	l
Gallons per minute	gpm	5.45	Cubic metres per day	m^3/d
Do	do	.06309	Litres per second	l/s
Gallons per day	gpd	.003785	Cubic metres per day	m^3/d
Inch	in	2.54	Centimetre	cm
Mile	mi	1.6093	Kilometre	km
Pounds per square inch	psi	703.07	Kilograms per square metre	kg/m^2
Do	do	70.307	Grams per square centimetre	gm/cm^2
Square mile	mi^2	2.59	Square kilometre	km^2

Table 3.--Relation of units of hydraulic conductivity, permeability, and transmissivity[1/]

A. Hydraulic conductivity

Hydraulic conductivity		† Field coefficient of permeability
Feet per day ($ft\ day^{-1}$)	Metres per day ($m\ day^{-1}$)	† Gallons per day per square foot ($gal\ day^{-1} ft^{-2}$)
One 3.28 .134	00.305 One .041	7.48 24.5 One

B. Transmissivity

Square feet per day ($ft^2\ day^{-1}$)	Square metres per day ($m^2\ day^{-1}$)	† Gallons per day per foot ($gal\ day^{-1}\ ft^{-1}$)
One 10.76 .134	0.0929 One .0124	7.48 80.5 One

C. Permeability

Intrinsic permeability $k = -\frac{q\upsilon}{d\phi/dl}$ [$(\mu m)^2 = 10^{-8} cm^2$]	$Darcy = -\frac{q\mu}{dp/dl+\rho g\ dz/dl}$ [$0.987 \times 10^{-8} cm^2$]	†Coefficient of permeability P or $Pm = -\frac{q(\text{at } 60°F.)}{dl/dl}$ [$gal\ day^{-1} ft^{-2}$ at 60°F.]
One 0.987 .054	1.01 One .055	18.4 18.2 One

1/ Adapted from Lohman and others (1972). Equivalent values shown in same horizontal lines. † indicates term abandoned by the U.S. Geological Survey.

Previous investigations

A number of reports describing the ground-water resources of counties and specific localities or areas for much of the Trans-Pecos region have been published. However, the saline-water resources of this region are largely unknown because most of the published reports are concerned primarily with the availability and use of the potable ground water generally found in shallow aquifers. These reports include, by county: Eddy (Hendrickson and Jones, 1952); southern Lea (Nicholson and Clebsch, 1961); Winkler (Garza and Wesselman, 1959 and 1962); Ward (White, 1971); Pecos (Armstrong and McMillion, 1961); and Reeves (Knowles and Lang, 1947; Ogilbee, Wesselman, and Irelan, 1962).

The occurrence of ground water in the Carlsbad area has been described in reports by Hale (1945a, 1945b, and 1961), Bjorklund and Motts (1959), Halpenny and Greene (1966), and Motts (1968). Some of the testimony and exhibits in three hearings before the New Mexico State Engineer were useful in this study (New Mexico State Engineer Hearing, 1960, 1962, and 1963). The information presented in the three hearings is summarized along with important interpretations in a memorandum report prepared by the staff of the New Mexico State Engineer (New Mexico State Engineer, 1964).

Brown, Rogers, and Baker (1965) have written a generalized evaluation of the ground-water conditions in the middle Rio Grande basin in Texas. The water resources of the Pecos River basin were investigated jointly by State and Federal agencies in 1939-40 (U.S. National Resources Planning Board, 1942a and 1942b). Bjorklund (1958), Cushman (1965), Akin and Slingerland (1967), and Vandertulip (1966) have analyzed the flow of the springs in the Pecos River in the vicinity of Carlsbad and Artesia, N. Mex. Cox (1967) has described the geohydrology of an area between Lake McMillan and Carlsbad.

Methods of handling saline-water chemical data and the quality of water found in rocks of Permian Guadalupian age within the project area have been described by Hiss, Peterson, and Ramsey (1969), and Hiss (1970). Hiss (1973) described the construction of an observation-well network composed of 12 wells completed in the Capitan aquifer in southeastern New Mexico. This report and another by Hiss (1971) contain hydrographs depicting the water levels recorded in these wells. The depletion of ground water and decline of the potentiometric surface in southeastern New Mexico have been described by Spiegel (1958). Dinwiddie (1963), and Broadhurst, Sundstrom, and Weaver, (1951) have described the public supplies in southeastern New Mexico and western Texas, respectively.

Spiegel (1967) has discussed the natural geohydrologic conditions controlling ground water in the Pecos River basin. Brackbill and Gaines (1964) described the production of water from the Capitan aquifer in a large water field in Winkler County, Texas, and the use of the water in oil-field secondary recovery operations. Data relating to the production of water from the Capitan aquifer in the Toyah-Monahans area of Texas for both irrigation of crops and secondary recovery of petroleum are available in a report written by the staff of Guyton and Associates (1958). The geology and ground-water resources of the Roswell artesian basin are described in reports by Fisher (1906), Fiedler (1926), Fiedler and Nye (1933), and Kinney and others (1968). Two publications of the West Texas Geological Society (Hills, 1961, and 1962) contain a number of stratigraphic sections depicting the shallow aquifers in part of the study area. Grauten (1965) and McNeal (1965) have discussed various hydrodynamic relationships and oil entrapment in the Delaware and Permian basins, respectively.

Literature on the general geology and stratigraphy of the report area is voluminous. The Delaware basin, Central Basin platform, and surrounding shelf areas within the larger Permian basin are important oil-producing provinces. The rocks of Permian age in the Delaware basin and surrounding areas are extremely complex in nature, but have been studied extensively as a result of intensive exploration for oil, gas, and other mineral resources. Conclusions and information from many of these investigations have been incorporated into this report. These articles and reports are cited individually and (or) are included in the bibliography.

The volumes of produced oil, gas, waste water, and injected water were obtained from annual reports published by the New Mexico Oil and Gas Engineering Committee (1950-1958, 1959, 1960-1970), Railroad Commission of Texas (1939-1969); Lea County Operators Committee (1935-1942 and 1943-1949); Hobbs Pool Operators Committee (1932); Lamb and Lea County Operators Committee (1948); Lamb and Macey (1947a, 1947b, and 1947c); and Kinney, Lea County Operators Committee and New Mexico Oil Conservation Commission (1949). Many of these reports also contain limited but useful reservoir-engineering data.

Methods of investigation

Location and number of wells

More than 30,000 wells that penetrate formations of Guadalupian or older age have been drilled within the project area in search of oil and gas (table 4). Relatively few wells penetrate the narrow arcuate band of the Capitan aquifer along the edge of the Delaware basin because most of the wells are concentrated in the oil fields along the Artesia-Vacuum arch and the Central Basin platform (fig. 4). A few abandoned oil-test wells have been converted to irrigation wells in Pecos County where water is produced from the Capitan aquifer and San Andres Limestone (Armstrong and McMillion, 1961, table 4, pl. 1). Water for municipal, domestic, and irrigation use is produced from wells completed in the Capitan aquifer, San Andres Limestone, and Artesia Group in the vicinity of Carlsbad west of the Pecos River (Bjorklund and Motts, 1959).

Table 4.--Number of oil and gas wells drilled, by county, to January 1, 1971

State	County	Number of wells
New Mexico		
	Eddy	7,130
	Lea	15,932
Texas		
	Brewster	85
	Culberson	1,624
	Loving	1,352
	Pecos	9,022
	Reeves	1,756
	Ward	6,573
	Winkler	7,243
Total number of wells in nine counties		50,717[1/]

[1/] More than 30,000 of the oil and gas wells are located within the project area shown in figure 2.

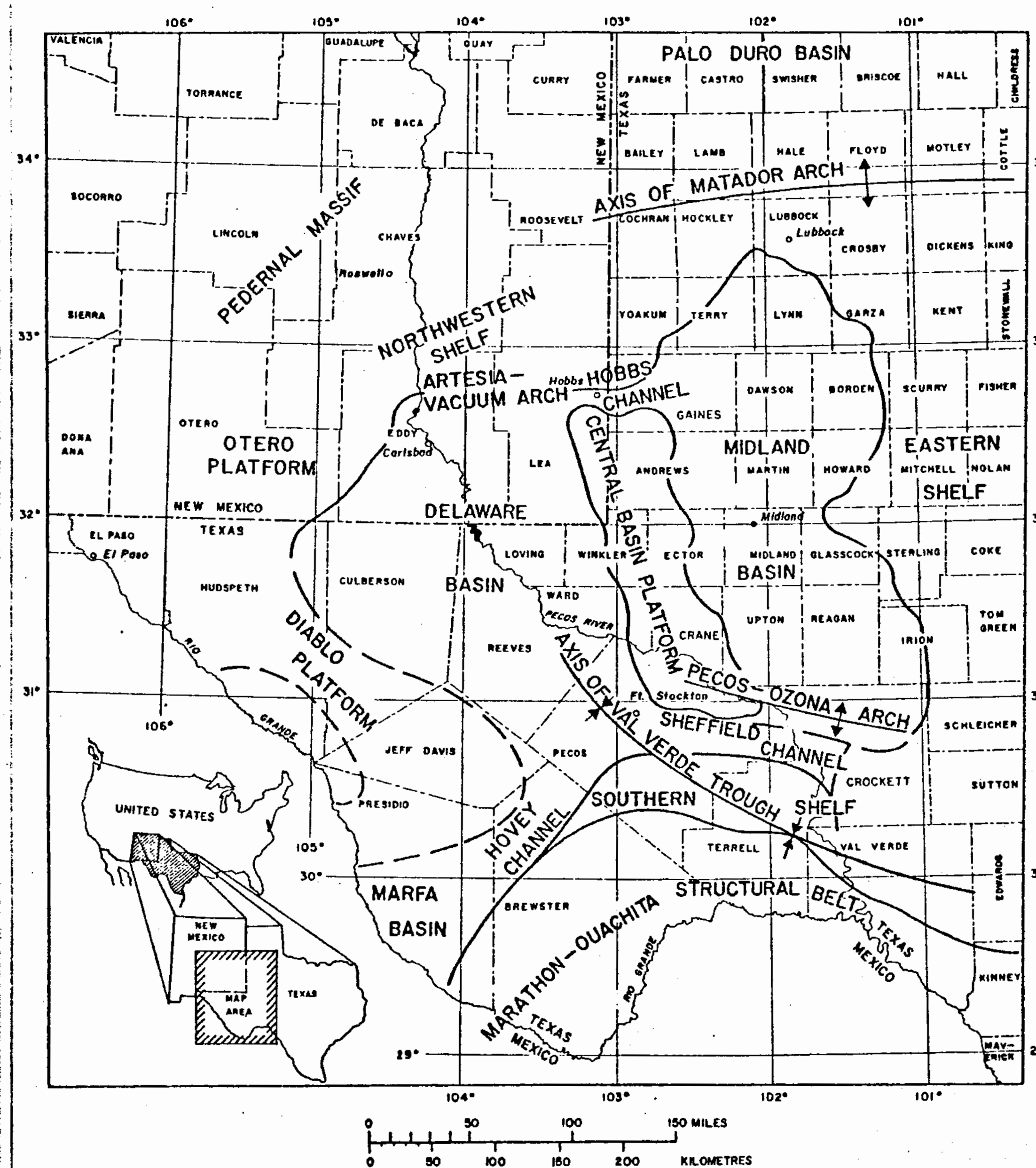


Figure 4.--Map showing position of the principal structural elements in western Texas and southeastern New Mexico during Late Paleozoic time.

Types of information available

Nearly all the information availalbe for interpretation in this study was originally collected by oil companies for industrial purposes during the drilling, evaluation, and production of the oil and gas wells. These data include: pressures measured during drill-stem or bottom-hole pressure tests; chemical analyses of water samples; permeability and porosity analyses of rock cores; aquifer or reservoir performance tests; statistical tabulations of the volume of the oil, gas, and water produced and (or) injected; lithologic and electrical logs; and fluid-level measurements. A small amount of aquifer-test and water-level data were available from published reports or in the files of the U.S. Geological Survey.

Source and ownership of information

Limited amounts of data were obtained from published reports, including the water-rights hearings before the New Mexico State Engineer, and from the public basic-data files of the New Mexico State Engineer and the U.S. Geological Survey. Other data collected, analyzed, and interpreted by Geological Survey personnel during the course of the investigation included measurements of water levels, continuous records of water-level fluctuations in a 12-well observation-well network (Hiss, 1971, and 1973), several aquifer-performance tests, chemical analyses of water samples, and lithologic logs. Several hundred electrical logs were purchased from commercial sources. Some information, including several aquifer-performance tests, was collected in cooperation with several oil companies. However, the vast majority of the data were obtained directly from the proprietary files of oil companies, geological and hydrological consultants, and members of the oil-service industry.

Acquisition of privately owned data

Almost without exception, the many segments of the oil industry offered to cooperate freely in supplying information from their private, and often confidential, files pertaining to the oil, gas, and water wells owned by them. Nevertheless, before any of this information could be obtained, it was necessary to supply the donor company with the name and location of the well for which data were being sought. Without a data-base and some form of machine-data processing capability, the search and identifications of wells would have been an impossible task considering the myriad wells drilled and the limitless possibilities of data associations for a particular well.

Fortunately, the Permian Basin Well Data System (PBWDS) magnetic tape file of scout records was being completed just as the project started (Permian Basin Well Data System, 1964; and Cooper, 1967a, and 1967b). This data base contains both the information made available to the oil industry through regular scout checks and certain facts required by regulatory agencies. Information describing the location, ownership, depth, names of formations penetrated, drilling and development history, casing records, production tests, and the completion data for all wells drilled for oil and gas within 68 counties in the Permian basin and adjacent areas of western Texas and southeastern New Mexico is included. Data pertaining to the deeper water supply and injection wells drilled for use in secondary recovery projects can frequently be obtained from this source. The PBWDS file for the nine counties in the project area contains approximately 800,000 tabulating cards as images on magnetic tape for wells drilled through 1965.

Use of the Permian Basin Well Data System file

The Permian Basin Well Data System was used both as a framework in earlier machine-data processing efforts and as a primary source of information. Lists of wells for which core analyses and drill-stem or bottom-hole pressure measurements might be available were printed on multi-part tabulating paper after execution of a detailed search of the PBWDS file. The several thousand pages of requests printed in geographic positon order within individual operator names were screened and then mailed directly to more than 70 different oil companies.

The requests were organized in a manner allowing rapid retrieval of data from manually operated central files with a minimum of clerical help. The use of multi-part paper allowed the donor company to annotate the original request list and then return one copy as a transmittal form.

Attempts were made to locate the longest cored interval in sedimentary rocks of Guadalupian age within each township in New Mexico or similar area in Ward and Winkler Counties, Texas. Similar attempts were made to locate drill-stem tests of selected intervals within the same geographic area. Approximately four times more data than needed were requested from oil companies. The response and cooperation from the oil companies was outstanding. However, due to loss of data in consolidation of offices, company mergers, transfer of ownership, and other reasons, many of the original source documents were unobtainable, and fewer data than needed were collected by this request.

The PBWDS file was searched for bottom-hole pressures and for drill-stem tests in which any of the initial or final shut-in pressures and (or) the initial or final-flow pressures were approximately equivalent. This search yielded valuable information used in the construction of the potentiometric maps.

Cross indexes (Hiss, 1970, p. 1474) were prepared after editing the township, range, and section in New Mexico (survey, block, and section in Texas), footage measurements within a section, operator and lease names, well number, total depth, file reference number (American Petroleum Institute, 1966, and 1968), decimalized latitude-longitude coordinates, reference elevations, and the spud and completion dates from the PBWDS file. Indexes in reference number order were printed first before sorting the information into location order and then into operator order to print both location and operator indexes.

Cross indexes keyed to the operator and reference number and to the geographic location, operator, and reference number were used to great advantage in locating and identifying the oil and gas wells. The oil-industry data frequently were identified only by the location, or by operator, and by lease information, so that both indexes were necessary.

Formation tops and bases, operator and lease names, location, total depth, latitude-longitude coordinates, and the reference number were edited from the PBWDS file and were used to compute the elevations of the formation tops or bases referred to sea-level datum and the thickness of selected intervals. The computed information was later employed in constructing various thickness and structural-contour maps, and in stratigraphic correlations.

Restrictions on the use of proprietary data

Most of the larger companies placed various levels of restrictions on the use and publication of data loaned to the Geological Survey. The most common restrictions concerned identification of the source of the data. Several companies restricted identification of the exact well associated with data and limited the scale of maps exhibiting the data.

Quality of the information

Most of the data obtained from the files of petroleum companies were generally of good quality, but had been collected or prepared for purposes other than the analysis of ground-water systems. Static equilibrium pressures could not be calculated from the pressures measured in the majority of the drill-stem and bottom-hole pressure tests due to the shortness of the recovery period. Almost none of the pressures measured on the drill-stem tests prior to 1958 were usable because of the poor sensitivity of the equipment.

Water samples are collected and analyzed by the petroleum industry for a variety of industrial purposes including the determination of the effectiveness of acid treatment of reservoirs, location of casing leaks, and interpretation of the effect of water flooding of partly depleted oil-bearing reservoirs. Therefore, these chemical analyses were frequently not representative of formation water and had to be verified before they could be used to prepare maps depicting ground-water quality.

Operators of many of the deeper wells concentrate only on the more prospective deep oil and gas-bearing zones and often do not collect drill cuttings or run electrical logs in the shallower formations, including those of Guadalupian age. Samples of drill cuttings were frequently not obtainable from the Capitan aquifer because of the difficulty in maintaining circulation while drilling through this formation.

Very large volumes of data were processed during the course of the study. Much of this data was discarded because it was either nonrepresentative, unreliable, or, for other reasons, unsuitable for use in ground-water studies. In many instances, the data either were not described properly or could not be located geographically.

Machine-data processing methods

Initially, all the information processed with computer methods were encoded in fixed-field formats compatible with the PBWDS file. Gradually all of the sub-files containing oil-company data, information derived from the PBWDS file, and ground-water data were blended together in the more flexible OMNIANA data file. This data-base management system was developed for use in earth science studies in New Mexico using the experience gained by working with the PBWDS file (Hiss, Garza, and Peterson, 1969; and Peterson and Hiss, 1970).

Confidential data or proprietary information edited from restricted sub-files and included in the OMNIANA data file are identified by restriction parameter codes. All data sets in the OMNIANA data file are identified by unique-reference numbers. With a few minor exceptions, oil and gas wells are identified with unique-reference numbers identical to those used by the petroleum industry (American Petroleum Institute, 1966, and 1968).

In addition to information derived from the PBWDS file, the OMNIANA data file contains a small amount of data for oil tests drilled after 1965, pressures recorded during approximately one thousand drill-stem tests, about 5,000 chemical analyses of ground water (Hiss, 1975h), approximately 30,000 water-level measurements recorded in the 12 observation wells (Hiss, 1973), porosity and permeability data from about 40,000 feet (12,200 metres) of analyzed rock cores, and about 50 digitized sonic-gamma-ray electrical logs.

Observation-well network

Purpose

Nine oil and gas test wells, drilled to depths of 10,000 (3,050 metres) to 18,000 feet (5,500 metres) and located along the trend of the Capitan aquifer in Eddy and Lea Counties, New Mexico, were acquired from oil companies at the time of abandonment. The unsuccessful oil and gas test wells were plugged back to the base of the Capitan aquifer, perforated in the Capitan aquifer, and converted to observation wells. The nine wells and three water wells previously completed in the Capitan aquifer form an observation-well network used to monitor the changes in head in the Capitan aquifer caused by natural stresses and the effects of fluid withdrawal in Lea County, New Mexico and Ward and Winkler Counties, Texas (Hiss, 1971, and 1973).

Source and ownership of observation wells

The North Cedar Hills Unit 1, Humble State 1, Yates State 1, Hackberry Deep Unit 1, Middleton Federal B 1, South Wilson Deep Unit 1, North Custer Mountain Unit 1, Federal Davison 1, and Southwest Jal Unit 1 observation wells were obtained from cooperating oil companies at the time of abandonment and converted to observation wells. The U.S. Geological Survey owns and is responsible for the future use and disposal of these wells (fig. 5).

The city of Carlsbad Water Wells 10 and 13 are owned by the city of Carlsbad, whereas the city of Carlsbad Test Well 3 is apparently still owned by Mr. Forrest Miller of Carlsbad. The three wells were drilled, completed, and developed by the city of Carlsbad during various ground-water exploration programs and are on loan to the Geological Survey (fig. 5).

The Eugene Coates 3 well is a temporarily abandoned oil well that is completed in the Seven Rivers Formation. This well was loaned to the Geological Survey for a short period of time for use as an observation well during and after aquifer performance tests in a nearby water field.

Data recorded from a crest-stage gage located near Tansill Dam were collected and compared to the hydrographs from nearby wells completed in the Capitan aquifer. The Tansill Dam crest-stage gage was discontinued in early 1970.

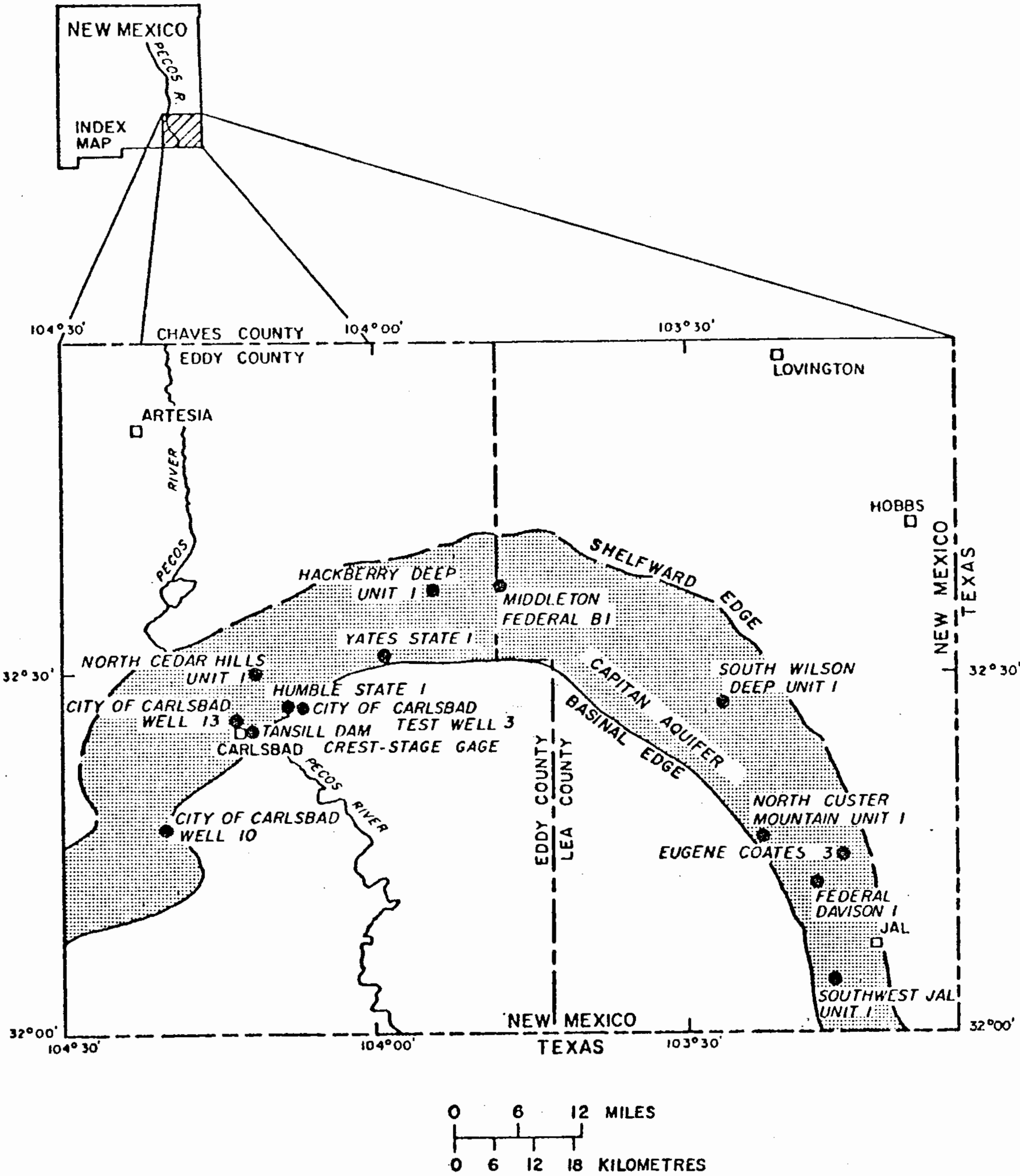


Figure 5.--Map showing location of wells in the Capitan aquifer observation-well network, southeastern New Mexico.

Well completion and development

With the exception of the North Custer Mountain Unit 1 well, a cement plug was placed by the operator at the base of the intermediate casing string that had been set through or near the base of the Capitan aquifer. The wells were then filled to the surface with either rotary drilling mud, brine, or fresh water and released to the Geological Survey. The North Custer Mountain Unit 1 well was received with the uncased interval of the borehole (12,175 to 16,000 feet; 3,711 to 4,877 metres) plugged back to 12,800 feet (3,901 metres). The well was filled with fresh water at the time of abandonment by the operator. A wire-line bridge plug was subsequently set at 5,300 feet (1,615 metres) near the base of the Capitan aquifer in this well.

The completion procedures generally followed by the Geological Survey included swabbing or bailing the mud or water from the casing, running perforating-depth control logs, perforating, swabbing to test the effectiveness of perforations, and stimulation of the well with acid as necessary to increase the well productivity. These procedures were followed by another production swab test. The position of the perforated interval in 8 of the 12 observation wells is shown in figures 6 and 7. Complete descriptions of the completion procedures and construction of the wells are given in Hiss (1973).

Acknowledgments

This study was made in cooperation with the New Mexico State Engineer. Messrs. S. E. Reynolds, State Engineer of New Mexico, and F. R. Allen, P. D. Akin, J. C. Yates, R. L. Borton, and Zane Spiegel from his staff gave encouragement and valuable technical assistance throughout the course of the study.

Much of the data, including the Permian Basin Well Data System magnetic tape file of oil-industry scout records, were furnished by various oil and oil-service companies. This study could not have been made without the generous support of the petroleum industry. Twelve wells, used in an observation-well network in southeastern New Mexico, were either assigned to the U.S. Geological Survey by oil companies or loaned by the city of Carlsbad or by private individuals.

Messrs. G. J. Gail, E. S. Hobday, and J. N. Black IV assisted with preparation and quality control of machine-processed records and supervision of data encoding. Messrs. Sergio Garza and G. J. Gail helped with tabulation of records and the preparation of several maps and stratigraphic sections. Mr. Garza also gave valuable technical assistance to the writer, including help in formulating a method used in adjusting point-water levels and bottom-hole point pressures to fresh-water heads referred to sea-level datum.

The observation wells were serviced by Messrs. E. R. Cox, J. S. Havens, C. C. Cranston, R. L. Rogers, G. E. Welder, G. E. Maddox, H. E. Lobley, J. A. Basler, J. D. Hudson, and J. D. Stevens. Messrs. E. R. Cox and J. S. Havens also assisted the author during well completion and development operations.

Computer programs were written by Messrs. J. B. Peterson, D. R. Posson, T. R. Ramsey, A. P. Trantolo, C. Z. Mitchell, Jr., J. A. Jouret, and L. E. Galyean, and Mmes. P. M. Hiss and N. R. Mitchell, Jr.

Messrs. J. N. Barbee, J. L. Kunkler, and F. C. Koopman helped with aquifer-performance tests. Dr. J. D. Bredehoeft gave valuable technical assistance and furnished one of the computer programs used in initial attempts to numerically simulate the Capitan aquifer (Peterson, Hiss, and Garza, 1969).

The New Mexico State Land Office, New Mexico State Oil Conservation Commission, Conservation Division of the U.S. Geological Survey, and the U.S. Bureau of Land Management were helpful during stages of negotiations for, and development of, the observation-well network. Latitude-longitude coordinates and elevation data for the many wells used in the study were obtained from the Permian Basin Well Data System tape file of scout records and were used with the permission of Tobin Surveys, Inc. and Laughlin-Simmons and Co. of Texas, Inc., respectively.

Computer facilities at the U.S. Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, were used for nearly all data processing. Colonel T. L. Franklin, Dr. H. F. Cooper, and Major J. T. Holland were most helpful in making the use of these facilities possible. Petroleum Information, Inc., digitized the electrical logs used in the cross sections and computed latitude-longitude coordinates for well locations not in the Permian Basin Well Data System file.

The sedimentary section and stratigraphic relationships of the Guadalupian strata were examined several times during field trips sponsored by the West Texas Geological Society and the Permian Basin Section of the Society of Economic Paleontologists and Mineralogists. The explanations and interpretations of the many obscure details to be found in these rocks by Dr. Alonza D. Jacka, Dr. Karl W. Klement, Mr. Thomas A. Bay, Jr., and many others on individual occasions in conjunction with these field trips to the Guadalupe Mountains were both highly beneficial and inspiring. It would have been most difficult to arrive at the conclusions promulgated in this report without a firm grasp of the intricate relationships of the sedimentary facies represented in the Guadalupian Series.

The base map for the Texas part of the study area was obtained from Midland Map Co., and is used with their permission. The base map for the New Mexico part of the study area was furnished by the Oil and Gas Branch, Conservation Division, U.S. Geological Survey. Messrs. W. J. LeMay and D. G. Stevens allowed the writer to use oil and gas field outlines from maps owned by them.

Messrs. W. F. Guyton, E. L. Reed, L. C. Halpenny, J. R. Barnes, E. E. Kinney, and G. A. Hill allowed the writer to use, extract, and incorporate certain proprietary data into this report.

Drs. T. R. Walker, B. F. Curtis, B. J. Chronic, W. W. Longley, and W. C. Bradley gave encouragement and counsel at many times during the study. The assistance of the many cooperating agencies, companies, and individuals is gratefully acknowledged.

STRATIGRAPHY, STRUCTURE AND GEOLOGIC HISTORY

Paleozoic Erathem

Pre-Permian Guadalupian Series

The stratigraphy, structure, and geologic history of rocks younger or older than Permian Guadalupian age is treated cursorily in this report. These rocks have very low transmissivities and are, for practical purposes, considered to be hydraulically isolated from the Capitan aquifer and San Andres Limestone, the principal aquifers of interest.

Ordovician to Mississippian Systems

A maximum thickness of approximately 7,000 feet (2,135 metres) of dolomite, limestone, sandstone, and minor shale were deposited in shallow seas in the Tobosa basin, an autogeosyncline on a broad, southward-sloping shelf developed on the craton, during the Ordovician to Mississippian Periods (Galley, 1958, p. 401-419; and Adams, 1965). Unconformities at the end of Early, Middle, and Late Ordovician time and again at the end of both the Devonian and Mississippian Periods interrupted an otherwise continuous geologic record. Some of the most important oil-producing structures in this area are located on this medial ridge. Uplift of a complex fault block, the Central Basin platform, during Late Mississippian and Early Pennsylvanian time, divided the Tobosa basin into the Delaware and Midland basins (figs. 4 and 8; and Galley, 1958, p. 401; and Adams, 1965).

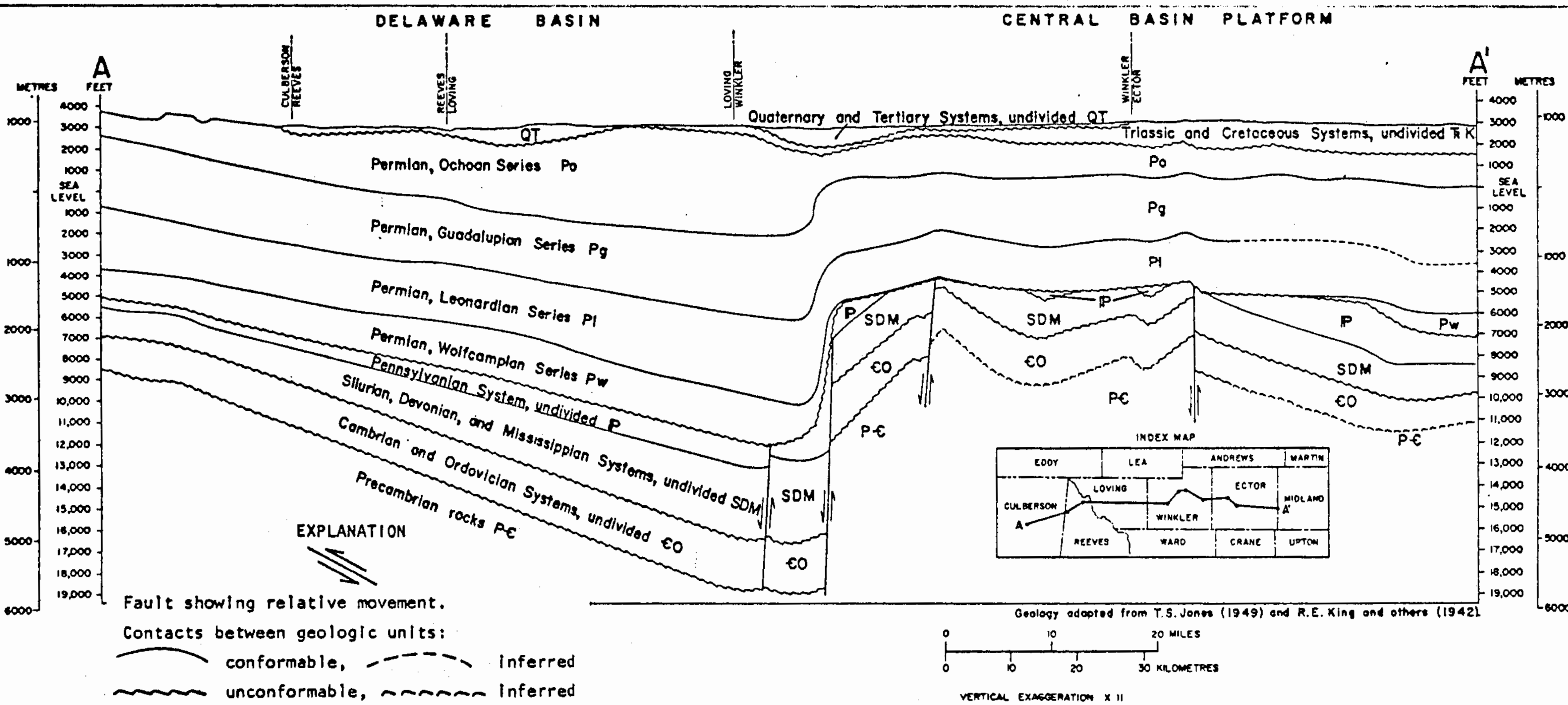


Figure 8.--Diagrammatic stratigraphic section showing structural relationship of Delaware basin and Central Basin platform.

Pennsylvanian System

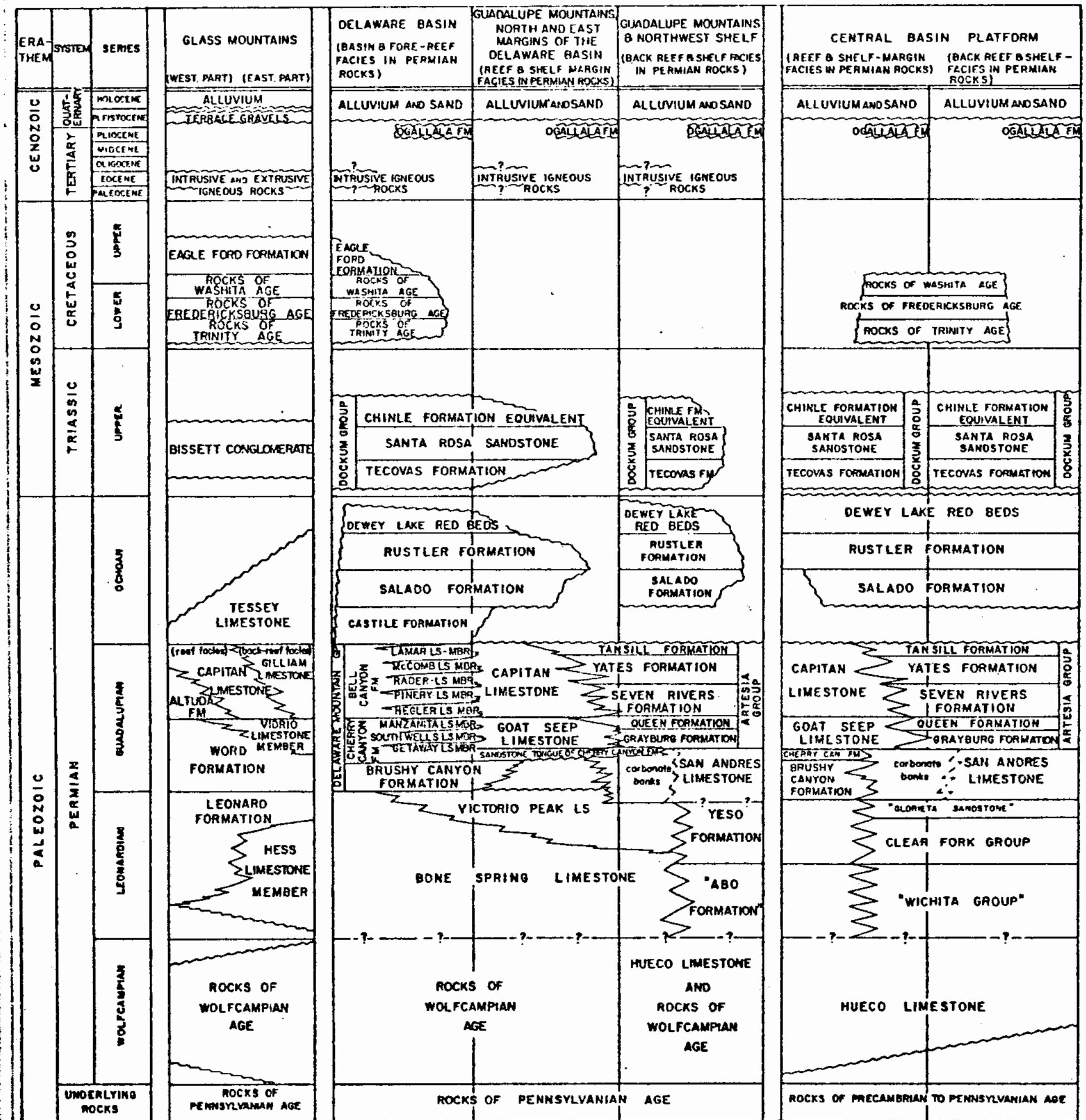
The Delaware basin subsided rapidly during the Early Pennsylvanian. Older rocks were stripped from the Central Basin platform and deposited on the flanks of this median range as clastic wedges (Vertrees, Atchison, and Evans, 1959). Material was eroded from the Pedernal massif, Diablo platform and other highlands to the north, west, and southwest of the Delaware basin, and deposited as thin sequences of sands and shales with interbedded carbonates on and along the edges of the shelves (Hills, 1963; and Galley, 1958). Carbonates are interbedded with, or take the place of, the sandstones and shales along the shelf and shelf margins but extensive, well developed limestone reefs of Pennsylvanian age have not been encountered along the shelf edge in the Delaware basin.

Sediments shed from the emerging mountains in the Marathon-Ouachita structural belt were trapped in the Val Verde trough south of the Pecos-Ozona arch until Late Pennsylvanian when sediments overflowed into the Delaware basin (Galley, 1958; Young, 1960; and Oriel, Myers, and Crosby, 1967). The maximum thickness of the Pennsylvanian System in the Delaware basin is slightly more than 2,000 feet (610 metres) west of the Central Basin platform (Galley, 1958).

Permian System

Wolfcampian Series

The Central Basin and Diablo platforms, Pedernal massif and Marathon-Ouachita belt were active uplifted areas at the beginning of the Permian Period while the Delaware basin continued to sink (Hills, 1963; and figs. 4, 8, and 9). During Wolfcampian time, more than 8,000 feet (2,440 metres) of chert, limestone, and terrigenous clastics were eroded from the Marathon-Ouachita Mountains and accumulated in the southern part of the Delaware basin where it opens into and joins the Val Verde trough. The Wolfcampian Series progressively thins to the north away from the thick section in the Val Verde trough to approximately 500 feet (150 metres) near the north and northwestern edge of the Delaware basin (Feldmen, 1962; and Vertrees, 1964). Carbonates, including some shelf-margin reefs and banks, formed the dominant facies on the Northwest shelf and the Central Basin and Diablo platforms, the more stable positive areas (figs. 4 and 8). The Val Verde trough at the southern end of the Delaware basin was filled with sediment and became less active with the close of Wolfcampian time.



[Compiled from many sources including Oriel, Myers, and Crosby (1967), Hayes (1964), McKee, and others (1959), Jones (1949 and 1953), Waldschmidt and Huffington (1949), Young, and others (1957), Young (1960), Vertrees (1964), Wilde, and others (1962), P. B. King (1930, 1937, 1942, 1948, and 1965), Newell, and others (1953), Dunbar, and others (1960), Ahlen (1958), Ahlen and Tait (1959), Roswell Geological Society (1960), Green, and others (1964), Tait, and others (1962), Society of Economic Paleontologists and mineralogists (1957), and Hollingsworth (1955). Names enclosed in quotation marks in this table and throughout the report are used locally for rock units that are probably not the same as those of the type area.]

Figure 9.--Correlation chart showing position of Permian and younger rocks in the Delaware basin and surrounding area.

Leonardian Series

After the uplift and subsequent destruction of the Marathon and Ouachita Mountains along the southern margin of the Val Verde trough and at the southern end of the Delaware basin, orogenic activity was limited to epeirogenic movement of broad areas (Hills, 1963, p. 1719; Silver and Todd, 1969; and Meissner, 1972). In this manner, the structural framework that would control the depositional environment in the Delaware basin for the remainder of the Permian Period was firmly established at the onset of the Leonardian Epoch (Galley, 1958, p. 428; Hills, 1963, p. 1719; and Adams, 1965). Three distinctive facies are identifiable in the Leonardian Series: (1) A basinal section composed of shale, siltstone, sandstone, and dark limestones, (2) shelf complexes composed of carbonates, evaporites and red beds, and (3) reef and other shelf-margin carbonates.

Dunham (1970) applied the term "stratigraphic reef" in describing the Capitan Limestone and other linear carbonate complex composed of particles wholly or largely bound with inorganically derived cement. Correspondingly, Dunham (1970) used the term "ecologic reef" to describe a similarly shaped carbonate complex built from organically bound carbonate material. Throughout this report, the work "reef" is employed in the sense of Dunham's "stratigraphic reef".

A maximum thickness of more than 4,000 feet (1,220 metres) of Leonardian age sedimentary rocks is now present in southwestern Loving County. The 2,000 to 3,500 feet (610 to 1,065 metres) of sedimentary rocks, primarily carbonates, present on and along the margin of both the Northwestern shelf and Central Basin platform are more important to the hydrology of the Capitan aquifer (Galley, 1958, p. 428 and 430).

In places, particularly along the western edge of the Central Basin platform, permeable shelf-margin carbonates of Guadalupian age are superimposed on and are probably in relatively good hydraulic communication with Leonardian sedimentary rocks having similar characteristics (Pan American Petroleum Corp. and Westbrook-Thompson Holding Corp. 1958, Defendants' Exhibit No. 47; Jones, 1949; and Silver and Todd, 1969).

Permian Guadalupian Series

Geographic distribution

Strata of Guadalupian age are present in the subsurface throughout the Permian basin. The Artesia and Delaware Mountain Groups and the San Andres Limestone and their lateral equivalents form extensive outcrops in western Texas and southeastern New Mexico (fig. 10; and Dane and Bachman, 1958, and 1965; and Goddard, 1965). Although only about 20 percent of the volume of sedimentary rocks filling the Permian basin are Guadalupian in age; reservoir rocks within these strata contain about one-half of the more than 14 billion barrels (2.2 billion cubic metres) of oil discovered within the Permian basin (Galley, 1958).

Previous investigations

The economic importance of the Guadalupian age rocks as oil reservoirs in the Permian basin has fostered numerous extensive studies of the readily accessible exposures of these rocks in the Guadalupe Mountains by many geologists.

Several contemporary investigators, including Kendall, 1969; Silver and Todd, 1969; Tyrrell, 1962, 1964, and 1969; Ball and others, 1971; Dunham, 1969, and 1972; Meissner, 1972; and Jacka and others, 1968, and 1972, have recognized sedimentary features within the Guadalupian Series in the Permian basin that are analogous to those found in the Holocene carbonate and (or) carbonate-evaporite-sandstone depositional environments located in the Bahamas, Florida, Australia, and, in particular, the Persian Gulf. Interpretations by Kendall (1969), Silver and Todd (1969), Dunham (1972), Jacka and others (1972), and Meissner (1972) were particularly useful in understanding and defining the Permian Guadalupian aquifer systems.

Structural setting

The Permian basin of western Texas and southeastern New Mexico includes the Delaware and Midland basins, the narrow elongate Central Basin platform, and the Southern shelf and relatively broad Northwestern and Eastern shelves shown in figure 4. The Diablo and Otero platforms and the Pedernal massif are positive areas that flank the western periphery of the Permian basin.

Communication between the Delaware and Midland basins was established through the Hobbs and Sheffield channels at the north and south ends of the Central Basin platform, respectively. Paleogeologic evidence suggests that seas entered the Permian basin area from an open ocean to the southwest through present-day Mexico and spread over much of western Texas and New Mexico during Late Leonardian and Early Guadalupian time (P.B. King, 1942; Hills, 1942; and Meissner, 1972).

Paleo-positions derived from fitting the morphological outlines of continents together with consideration of the paleomagnetic and other data available suggest that the North America crustal plate on which the Permian basin resides was probably located very near the equator during the latter part of the Paleozoic Era (Dietz and Holden, 1970). Presumably, a warm climate resulted in a prolific growth of calcium carbonate secreting organisms during this time.

The area covered by the epicontinental seas was gradually reduced throughout the Guadalupian Epoch until the Hovey channel remained as the principal connection to the open oceans via the Marfa basin. The Midland basin was filled by an influx of sand and mud during Late Leonardian and Early Guadalupian time and gradually converted to an evaporite shelf (Oriel, Meyers, and Crosby, 1967; Jones, 1949; Tomkins, and others 1953; and Tait, and others, 1962). However, the structural configuration of the Delaware basin with relatively deep water surrounded by broad shelves with low topographic relief, which were alternately either covered by shallow water or exposed, prevailed until the close of the Guadalupian Epoch.

Depositional environments and characteristic sediments

Major sedimentary facies

The three major time-transgressive sedimentary facies, shelf, shelf margin, and basin, representing the topographically controlled sedimentation previously recognized in the Leonardian Series are much more evident in Guadalupian strata. Silver and Todd (1969, figs. 4 to 9 inclusive), Ball and others (1971, fig. 3), and Dunham (1969, and 1972) have prepared excellent perspective diagrams of hypothetical Guadalupian landscapes in this type of geological setting. The paleotopography shown in these sedimentary models has been defined principally by relating characteristic features found in the Guadalupian sedimentary rocks to modern analogs observed in the Persian Gulf (Wells, and Illing, 1964; Illing, Wells, and Taylor, 1965; Butler, 1969; Kinsman, 1969; and Kendall, and Skipwith, 1968, 1969a, and 1969b).

Carbonate classification

Dunham (1962) has devised a method of classifying carbonate rocks according to the retained depositional texture. Rocks in which the original deposition texture is not exhibited are referred to as crystalline carbonates, e.g., "well-bedded, microcrystalline dolomite." Three textural features are evaluated in this scheme: (1) the presence or absence of carbonate mud, a factor determined largely by the amount of hydraulic energy at the depositional site; (2) the relative abundance of carbonate grains, which may be supported by mud (mud-supported), or, in the absence of sufficient mud, be self-supporting (grain-supported); and (3) the indication of organic binding during deposition.

A muddy carbonate containing fewer than 10 percent carbonate grains is a "mudstone," whereas a rock composed of more than 10 percent carbonate particles with the particles still being mud-supported is a "wackestone." A grain-supported muddy rock is a "packstone" which is differentiated from a "grainstone" in which mud is absent. Carbonate rocks characterized by organic binding are called "boundstone." The class name is usually prefixed with "lime" or "dolomite" to indicate the major chemical class of rocks, and as many other descriptive words or phrases as may be necessary to completely describe the rock, e.g., "druse-cemented, fusulinid lime grainstone."

Dunham's classification system is followed in this report whenever a particular class of carbonate rock is described, otherwise, the general terms "dolomite" and "limestone" are used.

Cyclic sedimentation

Cyclic alternations of time-synchronous carbonate, evaporite and terrigenous clastics are characteristic of the shelf and basin sediments in the Permian basin during the Leonardian and Guadalupian Epochs. The frequent and abrupt cyclic changes in lithology, both vertically and laterally, for a given time horizon, are thought to be related to alternating periods of deposition at various stages of sea level. The cyclical fluctuation in sea levels may have been controlled by the effects of glaciation superimposed upon a relatively deep basin and a broad flat shelf complex that was slowly subsiding relative to distant uplands (Meissner, 1972).

Silver and Todd (1969), Dunham (1969), Kendall (1969), and Jacka, and others (1972) have vividly described changes in environment and the corresponding sediments that might be expected to have been deposited during the cyclical rise and (or) fall of the Guadalupian sea level. The following account of the sequence of events and the sedimentary patterns expected during a substantial decline in sea level is from Silver and Todd (1969, p. 2238-2239):

> "... /during normal sea-level stand, shelf-margin reefs and banks formed near sea level. The resultant lagoon was shallow but very broad; therefore little terrigenous sand reached the distant basin. Deposition of shelf-margin carbonates was at a maximum and the main sediments in the basin were pelagic mud and micrite.

"...[At a lower sea-level stage], shelf-margin strata were partly subaerially exposed but still were forming actively at a lower elevation. Islands developed along the topographically highest parts of the shelf margin. The lagoon was constricted and was bordered landward by an extensive algal flat. Locally, barrier islands developed during this sea-level stage. Continental and sabkha environments prograded basinward from their location at normal sea-level stand. Pelagic mud and micrite were the dominant lithic types deposited in the basin.

"...[At a substantially lower stage of sea level], continental and nearshore clastic beds continued to prograde seaward. Sabkha and algal-flat deposits replaced previous lagoonal sediments. Reefs and (or) banks ceased to develop and were replaced by an extensive stable land surface dissected by canyons and tidal channels. Tidal and near-shore currents and local rivers swept land detritus into canyon heads which were formed most commonly near salient features on the shelf margin. This clastic material was transported down the canyons by traction, slow creep, or turbulent flow. Channel and overbank systems distributed clastic material in the form of prograding submarine fans along the basin floor.

"....[At maximum low-water stage of sea level], land-derived detritus, at least locally, prograded completely across the shelf. Sediment transport was at maximum, so that sheetlike sands, perhaps more correctly described as coalescing eolian and fluvial sands, prograded over the supratidal flat to the shelf edge. Lagoonal and shelf-margin environments were exposed subaerially before being covered by prograding continental-derived sediments. Base level shifted frequently during maximum low-water stand; major degradation prior to burial beneath prograding continental sediments probably did not occur on a regional scale, but was a locally important process. Detrital sediment was carried across the shelf margin by suspension or through submarine canyons by a combination of mass transport, slow creep, and tidal and nearshore currents."

Cyclic alternations of time-synchronous carbonate and terrigenous clastic units which are thought to be related to alternating periods of deposition at high and low stages of sea level are characteristic features of shelf and basin sediments. Relatively thick sequences of light colored dolomites and limestones were produced on the shelf and shelf margin during high sea-level stages while thin, dark, laminated lime mudstone "marker" beds were deposited over widespread areas within the Delaware basin. Most of the terrigenous clastics were unable to reach the basin during high sea-level stages. During intermediate and low stands of sea level, comparatively thin terrigenous sandstones and siltstones were deposited on the shelf while thick sequences of terrigenous clastics were deposited within the Delaware basin. Some of the thin, well-bedded sandstones and siltstones deposited on the shelf persist through what are otherwise regional facies changes and can be correlated over long distances. Terrigenous clastics were not deposited on the steeply sloping shelf-margin apron.

Shelf facies

The distance across the shelf between bordering continental and shelf-margin environments ranged from a few tens of miles to perhaps more than a hundred miles depending on the stand of the sea with respect to land. At normal or slightly below normal sea levels, topographically recognizable features within the comparatively low energy shelf environment included, from land seaward, broad sabkha (salt flats) and algal flats with very low relief in the supratidal zone, a broad intertidal zone, a shallow lagoon connected to the open sea by tidal channels, barrier banks or islands on the seaward side of the lagoon, and barrier flats adjacent to the landward side of the shelf-margin reefs (Kendall, 1969; Todd and Silver, 1969; Dunham, 1972; and Jacka and others, 1972).

The sabkha facies is composed of early diagenetic, bedded, nodular anhydrite and primary anhydrite interbedded with terrigenous siltstones and irregularly laminated to stromatolitic mudstone and wackestone. Lagoonal and intertidal beds consist of thinly laminated to stromatolitic dolomite mudstone and wackestone. The laminations may be destroyed locally by burrowing animals and soft sediment deformation. Pelletoidal dolomite grainstone is interbedded locally with the mudstone and wackestone. Dunham (1972) describes the porosity of the lagoonal facies as "poor to fair", and Kendall (1969, p. 2518), while not judging the relative amount of porosity, has described the nature of the pores as "interconnected vugs which are thought to be due to the movement of gas through the sediment."

The barrier island and flat province contains both pisolitic and (or) pisolitized dolomite grainstones and skeletal-lithoclastic dolomite grainstones representing a higher energy environment nearer to the seaward edge of the shelf. Dunham (1965a, 1965b, and 1969; and Thomas, 1965, and 1968) independently established that the pisolites in the Permian sedimentary rocks in the Guadalupe Mountains represent ancient vadose caliche formed at intervals when the near shelf-edge carbonates were subaërially exposed. Kendall (1969) found that two types of pisolites were present, one of primary marine origin, the other of secondary concretionary origin. Low angle crossbedding is evident on some of the carbonate mounds. Fenestral voids in these rocks are attributed by Kendall (1969) to movement of gas and trapped air as the carbonate material was subaerially desiccated in the supratidal zone. Dunham (1972) describes the porosity of the dolomite grainstones in the near shelf-edge sediments as "good."

The dolomite of the shelf facies frequently are interbedded with thin to massive-bedded well-sorted terrigenous siltstones and very fine to fine-grained sandstones.

Shelf-margin facies

The shelf-margin environment is characterized by topographically controlled banks, reefs, and forebank or forereef talus slopes located at the extreme seaward edge of a relatively deep open-marine sea. Newell, and others (1953, p. 190) estimated from work in the Guadalupe Mountains that the Delaware basin was about 1,700 feet (520 metres) deep near the close of the Guadalupian Epoch. Silver and Todd (1969, p. 2248) suggest that the Delaware basin was about 1,800 feet (550 metres) deep midway along the western margin of the Central Basin platform but only approximately 1,400 feet (425 metres) deep at the margin of the Northwest shelf near the boundary between Eddy and Lea Counties, New Mexico at the end of Capitan time. They attribute the difference in topographic relief at the end of the deposition of the Guadalupian Series to greater tectonic activity along the Central Basin platform and Guadalupe Mountains than that in the northern end of the Delaware basin. Todd and Silver (1969, p. 2247) estimate a water depth of 700 to 900 feet (215 to 275 metres) along the north and east margins of the Delaware basin at the end of Goat Seep time which is comparable to the estimate of 900 feet (275 metres) made by Newell and others (1953, p. 190) in the Guadalupe Mountains. Apparently, the amount of topographic relief between the basin and shelf edge nearly doubled during the Guadalupian Epoch.

The marine banks are principally composed of oolite bars and muddy, weakly cemented accumulations of the skeletal debris of crinoids, sponges, calcareous algae, fusulinids, brachiopods, bryozoans, and corals. Organisms found in the main reef tract include calcareous sponges and algae of several types, bryozoans, gastropods, cephalopods, and specialized brachiopods. A fierce argument rages among contemporary students of the Capitan and Goat Seep Limestones, the principal units comprising the Guadalupian shelf-margin sedimentary rocks, as to whether or not these carbonates were wave resistant at the time of deposition in the sense of the modern-day reefs as typified by the Great Barrier Reef located offshore from Northeastern Australia (Maxwell, 1968).

Solenopora and other similar calcareous algae may have bound a framework composed of larger skeletal secreting organisms together to form the locally common algal-sponge lime boundstone. However, the reef is principally composed of poorly sorted, very fine-grained lithoclasts apparently not well suited to withstand wave action. Kendall (1969) has suggested that the Capitan Limestone may have been deposited in an environment similar to the complex of sea grass banks in Shark Bay (Davies, 1970) or to the mounds in Florida Bay (Ginsburg and Lowenstam, 1958). In such an environment, the ecological position of sea grass which evolved during the Cretaceous would be filled by bryozoa, crinoids, calcareous sponges, and algae. Contemporaneous submarine cementation has been observed to bind sediments inorganically in similar recent sublittoral environments, and may well have been the most important factor in preserving the Guadalupian shelf-margin reefs (Ginsburg, and others, 1967; Kendall, 1969; Dunham, 1972; and Land, and Goreau, 1970).

The crest or reef core of the shelf-margin facies is chiefly composed of poorly but massively bedded, very fine-grained, pelletoidal-lithoclastic-skeletal lime grainstones and wackestones which grade to skeletal lime wackestones and grainstones and coarsely lithoclastic lime wackestones in the forereef. The carbonates in the shelf-margin and basin facies are nearly all limestones contrasted with a shelf suite composed almost entirely of dolomite. Dunham (1972) describes the porosity of the Capitan Limestone as "good, with exceptions." Some of the pore space originated as voids left between large fossils or formed by local slumping and settling of sediment (Newell, 1955). Porosity and permeability may have been developed or enhanced, as well as diminished, when the shelf-margin reefs and banks were exposed to subaerial processes, including desiccation and leaching, during low stands of sea level.

Fissures formed parallel to the reef trend by seaward slumping of sediment in response to over-steepening of the reef wall. The fissures may be filled with a variety of material including litho-clasts of older sediments, and (or) they may be closed with much younger laminated calcite cement (Dunham, 1972). Additional crevices were formed by structural failure of the sediment comprising the reef when the interstitial water was lost during cyclic exposure. The crevices may also be filled with penecontemporaneous or much younger eolian or fluvial terrigenous sand and silt (Kendall, 1972, p. 2507; and Hayes, P. T., 1964). A system of near-vertical joints, one set aligned parallel to the trend of the reef, the other set trending at right angles to the reef, was developed as the rigid shelf and shelf-margin sediments were subjected to regional crustal movements. The joints are incompletely filled with diagenetic calcite druse and terrigenous quartz sand (Dunham, 1972).

Many previous investigators have recognized that the forereef or apron part of the reef is volumetrically far more significant than the reef wall (King, P. B., 1948, p. 86; Newell and others, 1953; Pratt, 1964, p. 31; Hayes, P. T., 1964; and Dunham, 1972, p. III-15). One probable reason for this is that the reef wall is always subjected to maximum wave action and, therefore, the wave-resistant structures are more or less continuously eroded and destroyed concurrently with reef development (Ladd, 1950, p. 204; and Dunham, 1972, p. III-15). Fine material was probably constantly winnowed from the reef by marine currents and carried down the steep foreslope by a combination of mass transport processes including slow creep, suspension, and turbidity flows. Large blocks probably spalled off over-steepened walls and tumbled down the foreslope, perhaps triggering avalanches of other debris or turbidity flows in the process. The foreslope deposits are distinguished from the shallow-water bank and reef sediments by their darker color, presence of chert and silicified fossils, and the numerous shelf-derived lithoclasts.

The arcuate linear reef tract was incised locally by submarine canyons that extended well back into the shelf, tidal passes, and reentrants (Silver and Todd, 1969; and Jacka and others, 1968, and 1972). Occasionally a few of the submarine canyons may have cut through the entire shelf-margin facies during lower stands of sea level. Much of the carbonate material found in the forereef and basin apparently was transported through the canyons into the Delaware basin. The slope of the forereef debris commonly is 30 degrees or more. Dr. R. J. Weimer, accompanied by the author, determined an angle of repose of 45 degrees for the foreslope at excellent exposures in Carlsbad Caverns. The well-bedded sandstones and siltstones characteristic of the shelf facies are not present in the shelf-margin facies. Apparently, all, or nearly all, of the terrigenous clastics were conveyed through the shelf-margin facies from the shelf and into the basin via submarine canyons.

Basin facies

The basin facies consists of a thick sequence of well-bedded terrigenous sandstones and siltstones interbedded with thin but areally widespread, laminated, dark-lime mudstones. The dark laminated lime mudstones grade shoreward into the lighter-colored, coarsely lithoclastic lime wackestones of the forereef facies. The coarse carbonate detritus was probably transported into the basin through submarine canyons as subaqueous slides, mudflows, or turbidity flows whereas the fine silt or clay-sized carbonate particles were carried away from the shelf and shelf margin in suspension. Additional carbonate detritus entered the basin as blocks or avalanches spalling off or sliding down and away from an overly steep reef foreslope. Graded bedding is a common textural characteristic of the limestones.

Coarse lithoclastic lime wackestone including lithoclasts as large as 14 feet (4 metres) in diameter have been found as far as 10 miles (16 kilometres) from the reef front (Newell and others, 1957, p. 71 and plates 14 and 15.) Rigby (1958, p. 313) observed disturbed bedding in the Rader Limestone Member of the Bell Canyon Formation at a distance of about 28 miles (45 kilometres) seaward from the reef tract. The Lamar Limestone Member of the Bell Canyon Formation and the Manzanita Member of the Cherry Canyon Formation of the Delaware Mountain Group are the only two of the eight named limestone members in the basin facies to be mapped across the entire Delaware basin (Silver and Todd, 1969). The light-colored dolomite or dolomitic limestone in the Manzanita Limestone Member of the Cherry Canyon Formation suggests that the Delaware sea was probably comparatively shallow near the close of Goat Seep time (Silver and Todd, 1969, p. 2248).

Terrigenous sands and silts apparently prograded across the shelf onto the shelf margin during times of low sea level where they then were swept into the heads of the submarine canyons by long shore and tidal currents (Silver and Todd, 1969; and Jacka and others, 1972). Smaller quantities of eolian or deltaic quartz sands and silts entering the back-reef shelf lagoons under normal regimes could also have been transported by marine currents along the coast of the Delaware basin. Eventually the moving sediment would be intercepted by submarine canyons analogous to the processes now active along the coast of California (Ball and others, 1971).

Several major submarine canyons are located on the northwest and north margins of the Delaware basin (fig. 11) coincidental with the thick trends shown on isopach maps of the Delaware Mountain Group (Meissner, 1972, fig. 3). King, P. B. (1948), Hull (1957), and Wilde and others (1962, p. 29) indicate that the coarser grained terrigenous clastics are limited to the western part of the Delaware basin. The generally small grain size, good sorting, and high quartz composition suggests a source remote from the Delaware basin. These several lines of evidence suggests that much of the terrigenous material was derived from uplands to the north and west of the Delaware basin.

The terrigenous clastics accumulated in the submarine canyons, often with intermixed carbonate detritus, until slides, avalanches, and (or) mud flows were triggered by overloading, storm waves or other mechanisms. The submarine canyons may have been widened and deepened during mass transport of material into the basin. Studies by Jacka and others (1968, and 1972) show that the basin facies consists almost exclusively of channel, overbank, and fringe deposits. The sediments were deposited by a variety of bottom-flow processes including inertia flows, viscous mudflows, submarine avalanches, and turbulent suspensions. Submarine fans developed in the deep seas at the mouths of the submarine canyons and gradually coalesced to form a compound submarine apron or bajada. The thickness of the deep-sea fans and component sediment grain size both decrease seaward.

As described by Jacka and others (1972), deposits in a typical single fan in the proximity of the mouth of the submarine canyon are composed "predominantly of deeply incised channels which are filled with thin, laminated, and small current-rippled flow units and thick avalanche and mudflow deposits." At an intermediate distance from the mouth, "the fan channels contain thick, clean, well-sorted, current-rippled crossbedded sandstones deposited as major flow units 3 to 10 feet (1 to 3 metres) thick." The sedimentary units in both intermediate and distal positions consist of aggradational channel, levee, and overbank deposits. The units deposited in a distal position are similar to the intermediate deposits but thinner. Laminated and small current-rippled siltstones were deposited in the overbank facies. Finely laminated, silty shales form a fringe around the typical fan (Jacka, and others, 1972).

Submarine canyons

The margins of the Delaware basin were incised by numerous submarine canyons, contemporary in age to the shelf, shelf-margin, and basin facies. Much of the sediment in the Delaware basin was transported through canyons that extended (several miles) back onto the shelf. No one has located a completely exposed submarine canyon in the field. The exact nature of the material filling the canyons on the shelf margin remains unknown (Thomas A. Bay, Jr., 1973, oral commun.). The geometry and lithology interpreted from studies of electrical logs suggest that the submarinel canyons are almost completely filled with a mixture of carbonate debris, sandstones, and siltstones resembling the basin facies near the shelf margin but may be partly filled with Ochoan evaporites.

The material in the submarine canyons has a significantly lower transmissivity than that of the adjacent and underlying Capitan aquifer. The location, depth of incision, and general dimensions of the submarine canyons are, therefore, of considerable importance because they restrict the flow of ground water through the Capitan aquifer.

Jacka and others (1968, and 1972) have mapped the position of two major submarine canyons from limited exposures in the Guadalupe Mountains on the northwest margin of the Delaware basin. Last Chance-Sitting Bull submarine canyon is in southwestern Eddy County, New Mexico (fig. 11). The other unnamed submarine canyon is partly exposed in the vicinity of the West Dog, Shumard, and Bone Canyons at the extreme southwestern end of the Guadalupe Mountains in northwestern Culberson County, Texas and southeastern Otero County, New Mexico (Jacka, 1972, p. 154-157). Silver and Todd (1969) also indicate that terrigenous clastics were transported into the Delaware basin through submarine canyons incised into the margin of the basin, but do not reveal positions of any of the canyons.

The positions of large submarine canyons and reentrants incised into the Capitan aquifer along the north and east margins of the Delaware basin were delineated as thin transverse linear zones on a thickness map of the Capitan aquifer (fig. 11). The validity of this technique was confirmed by constructing structural maps contoured on the base and top of the Capitan aquifer and by examining stratigraphic sections in areas where submarine canyons might be present (figs. 6, 7, and 12). The submarine canyons appear to be located in areas where the top of the Capitan aquifer is structurally low. Futhermore, sandstone lenses appear to become more numerous in the Capitan aquifer in some of the submarine canyons, e.g., Shell Oil Co. Federal 4-1, sec. 4, T.22 S., R.34 E., Lea County (fig. 7). The Humble State 1, sec. 23, T.21 S., R.27 E., Eddy County, one of the poorest of the wells in the Capitan aquifer observation-well network, is located on the eastern bank of one of the larger canyons.

The profiles and shape of the submarine canyons outlined by the contours of the thickness of the Capitan aquifer resemble the form of recent submarine canyons shown by Shepard and Dill (1966) and Uchupi (1965).

The features identified as submarine canyons on figure 11 are of considerable importance to the interpretation of the ground-water hydrology of the Capitan aquifer. For purposes of this report, they have been located and named as shown in table 5. The submarine canyons outlined in figure 11 will become more sharply defined and others will undoubtedly be revealed by the drilling of additional deep wells through the Capitan aquifer in this area.

Table 5.--Names and locations of the most prominent submarine canyons incised into the Capitan aquifer in Eddy and Lea Counties, New Mexico

New Mexico

Name	Location	Derivation of name
1. North Alacran	sec. 31, T.20 S., R.27 E.[1/] sec. 33, T.21 S., R.27 E.[2/]	From the overlying Alacran hills, a topographic feature located north of Carlsbad.
2. South Alacran	sec. 24, T.21 S., R.24 E.[1/] sec. 13, T.22 S., R.26 E.[2/]	Do.
3. Quahada	sec. 9, T.20 S., R.28 E.[1/] sec. 16, T.21 S., R.28 E.[2/]	From the overlying Quahada ridge, a local topographic feature.
4. West Laguna	sec. 18, T.19 S., R.31 E.[1/] sec. 3, T.21 S., R.30 E.[2/]	From the several lakes ("Lagunas" on the topographic maps) formed in closed depressions at the surface overlying this area.
5. Middle Laguna	sec. 18, T.19 S., R.33 E.[1/] sec. 5, T.21 S., R.31 E.[2/]	Do.
6. East Laguna	sec. 26, T.19 S., R.33 E.[1/] sec. 1, T.21 S., R.31 E.[2/]	Do.
7. Eunice	sec. 23 & 36, T.21 S., R.35 E.[1/] sec. 28, T.22 S., R.34 E.[2/]	From the town of Eunice located a few miles to the east.
8. Teague	sec. 14, T.23 S., R.36 E.[1/] sec. 33, T.23 S., R.35 E.[2/]	From the railroad siding of Teague located approximately above the haed of the canyon.
9. North Jal	sec. 6, T.25 S., R.37 E.[1/] sec. 12, T.25 S., R.35 E.[2/]	From the town of Jal located near the head of the canyon.
10. South Jal	sec. 18, T.25 S., R.37 E.[1/] sec. 31, T.25 S., R.36 E.[2/]	Do.

[1/] Head
[2/] Mouth

Comparison of time-diachronous with time-synchronous units

As shown diagrammatically in figure 13, continental shales, sandstones, and siltstones; supratidal, and lagoonal evaporites; supratidal, lagoonal, and barrier island and flat dolomites; shelf-margin limestones and basinal sandstones, siltstones and limestones successively replaced the preceding seaward facies during the Guadalupian Epoch. The entire sedimentary sequence prograded basinward as a series of belts paralleling the shoreline. The approximate position of the change in facies from near shelf-edge dolomites to mid-shelf evaporites in the five formations of the Artesia Group is shown in figure 14.

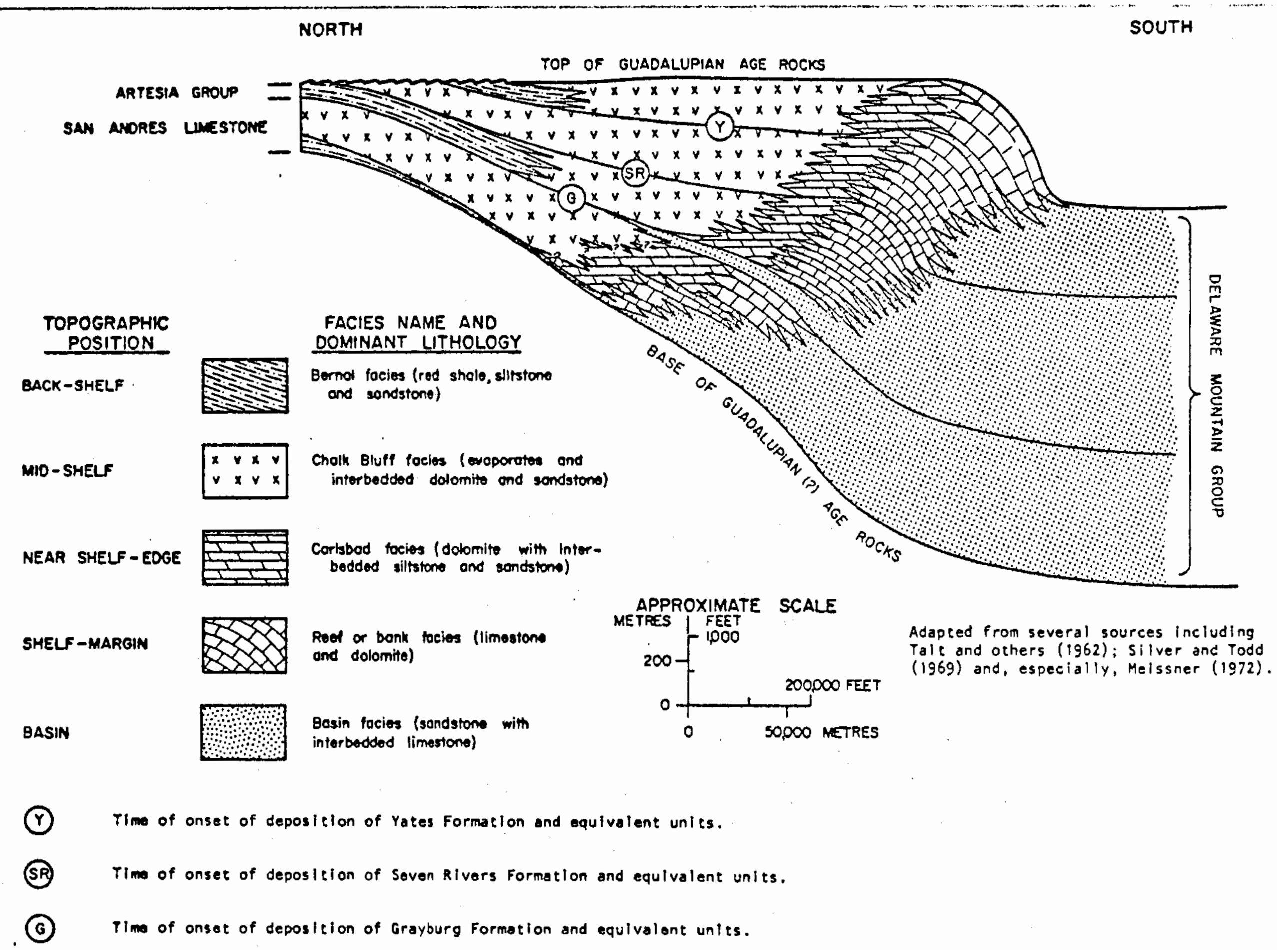


Figure 13.--Highly diagrammatic north-south stratigraphic section showing the position and relationship of the major lithofacies in the rocks of Guadalupian age in eastern New Mexico.

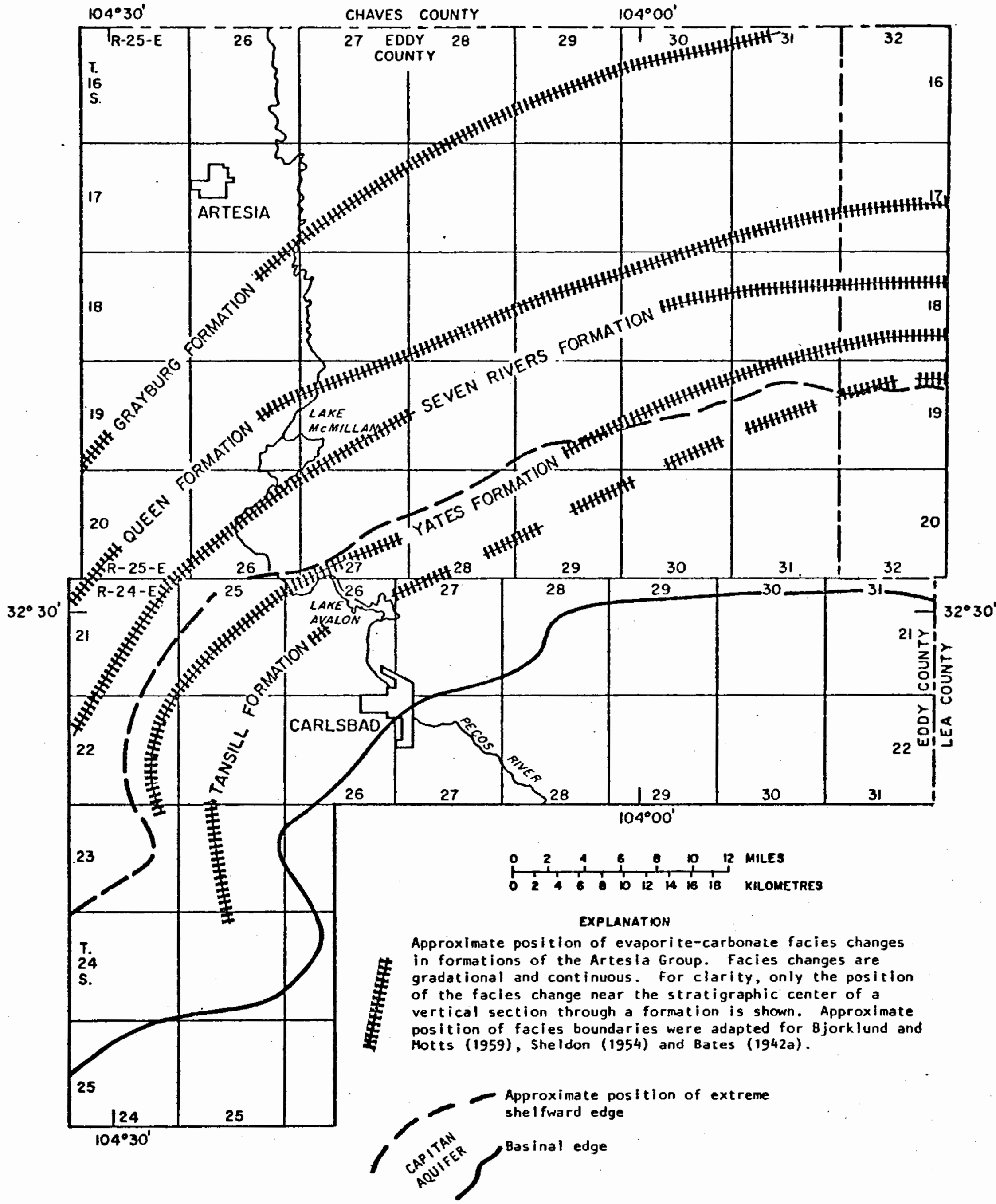


Figure 14.--Map showing evaporite-carbonate facies changes in the Artesia Group, southeastern New Mexico.

Several of the original stratigraphic units defined by geologists working on the Permian outcrops in the vicinity of Carlsbad closely followed time-transgressive lithologic boundaries between different facies in the Guadalupian Series. Lang (1937) defined the Chalk Bluff Formation to include the mid-shelf evaporites between the top of the Carlsbad Limestone and the base of the Dog Canyon Limestone (Morgan and Sayre, 1942, fig. 4). All three names were subsequently abandoned from the nomenclature by the U.S. Geological Survey. The Carlsbad Limestone was defined by Meinzer, Renick, and Bryan (1926) and subsequently modified by Lang (1937) to include the near shelf-edge dolomites and thinner interbedded sandstones above the Queen Formation and below the Castile Formation. Bachman (1953) applied the name "Bernal Formation" to a thin back-shelf section of red shales, siltstones, and sandstones. The formational names Bernal, Chalk Bluff, and Carlsbad were abandoned in the area and soon fell into disuse when the Artesia Group and the five component formations, Grayburg, Queen, Seven Rivers, Yates, and Tansill Formations, were defined and (or) redescribed and formally adopted (Tait, and others, 1962). The Bernal Formation, however, remains in good usage in north-central New Mexico but includes only a part of the red bed and evaporite sequence of the Artesia Group herein called the Bernal facies.

The position of important carbonate or clastic marker beds or zones with characteristically carbonate or clastic facies, both cyclical in nature, are employed to define the upper and lower surfaces of members, formations, and groups in the shelf section in the Permian basin. The cyclical marker beds or zones can be correlated laterally through facies changes over long distances in the subsurface and are believed by Meissner (1972) to be essentially time-synchronous (fig. 13). The lithologic character of rocks within the Artesia Group and the formations within the Artesia Group cannot be ascertained from the name of the unit because of the prominent facies changes that occur in this sequence of sedimentary rocks.

Meissner (1972, p. 206) urges that the names Bernal, Chalk Bluff, and Carlsbad be retained as a means of designating lithotopes within the Artesia Group, e.g., Carlsbad facies of the Artesia Group or simply Carlsbad facies whenever the meaning is clear within the context of the statement. The author endorses this practice as it seems much more feasible and meaningful to speak of the Chalk Bluff facies than, for example, to state "the supratidal and lagoonal evaporite facies" of the Artesia Group. The flow of ground water is often controlled by lithofacies and, therefore, the convenience and simplicity with which an aquifer can be defined and described becomes relatively important. The names Bernal, Chalk Bluff, and Carlsbad are used in this report to describe lithofacies within the Artesia Group as proposed by Meissner (1972).

Formational subdivision

San Andres Limestone

The lower part of the shelf facies in the project area is represented by the San Andres Limestone (Lee, 1909; and Needham, and Bates, 1943). The age of the San Andres Limestone is in question (Oriel, Myers, and Crosby, 1967). Lewis (1941) and Silver, and Todd (1969) assign the entire unit to the Guadalupian Epoch on the basis of physical stratigraphy and fusulinids; whereas Hills (1942), Jacka, and others (1972), and Meissner (1972), using the same approach, have assigned the upper part to the Guadalupian Epoch and the lower part to the Leonardian Epoch.

Regardless of the disputed differences in age, the upper part of the San Andres Limestone on the north and south end of the Central Basin platform is in measurable hydraulic communication with the Capitan aquifer and, therefore, is of some importance to this study.

The San Andres Limestone is composed of a lower cherty member and a thinner upper dolomite member (Hayes, 1964, p. 24; and Meissner, 1972, p. 221). Except for the Lovington Sandstone of local usage near the top of the upper member, the persistent terrigenous clastics so prevalent in the Artesia Group are absent from the San Andres Limestone. Meissner (1972) suggests that the San Andres Limestone was deposited during one major cycle of transgression and regression followed by one minor cycle near the close of San Andres time as comparedd to the numerous depositional cycles required to deposit the Artesia Group. The upper dolomite member becomes anhydritic to the north away from the shelf edge and eventually is replaced by evaporites in east-central New Mexico.

Discontinuous to continuous reefs or banks have been mapped along the margin of the Delaware basin and along the north and south ends of the Central Basin platform. Carbonate banks in the upper member of the San Andres Limestone are referred to by Silver and Todd (1969, figs. 12 and 13) as the Getaway Bank but are probably equivalent in age to the Getaway Limestone Member of the Cherry Canyon Formation (fig. 7).

Sandstone tongues of the Cherry Canyon Formation of the Delaware Mountain Group extend into the upper part of the San Andres Limestone in many localities (Boyd, 1958; and Hayes, P. T., 1964, p. 26). Most of the intertonguing relationships have been mapped using information obtained from scattered wells penetrating the section. Correlations made under these circumstances are subject to generalizations that will be improved upon as more wells are drilled. The tongues of sandstone may be related to submarine canyons as Jacka, and others (1972) have observed in the Guadalupe Mountains and probably occur at many different horizons.

The San Andres Limestone averages about 1,500 feet (455 metres) in thickness throughout much of the project area and thins irregularly to zero along a depositional facies change on the margin of the Delaware basin (Meissner, 1972, fig. 14).

Artesia Group

The upper part of the shelf facies in the Permian basin is represented by the Artesia Group (Tait and others, 1962; and Meissner, 1972, p. 221). The five formations in the Artesia Group are, in ascending order, the Grayburg Formation (Dickey, 1940; Hayes and Koogle, 1958; and Moran, 1962); the Queen Formation (Crandall, 1929; and Moran, 1954a, 1954b, and 1962); the Seven Rivers Formation (Meinzer, Renick, and Bryan, 1926; and Hayes and Koogle, 1958); the Yates Formation (Gester and Hawley, 1929; Bjorklund and Motts, 1959; and Mear and Yarbrough, 1961); and the Tansill Formation (DeFord and Riggs, 1941).

The lithology of the Artesia Group depends upon the location with respect to the shelf-margin at a specified time-synchronous horizon. Tait and others (1962) designated a reference well located in sec. 30, T.16 S., R.30 E., Eddy County, New Mexico, in which all the formations are described. The Artesia Group in the reference well is 1,710 feet (521 metres) thick and is composed of anhydrite, dolomite, sandstone, siltstone, and red shale. At this locality, the Tansill Formation is 105 feet (32 metres) thick and is dominantly anhydrite but contains a thin silt marker bed. The Yates Formation in the reference well is 261 feet (80 metres) thick and consists of interbedded sandstone, siltstone, and anhydrite. The sandstone is characterized by large, rounded, frosted, quartz grains scattered within a matrix of fine to very fine-grained sand. Tait and others (1962) indicate that the Yates Formation in the reference well can be correlated with the surface section described by Bjorklund and Motts (1959).

The Seven Rivers Formation is 565 feet (172 metres) thick and is principally composed of anhydrite but contains thin interbedded shale, dolomite, siltstone, and sandstone. Tait and others (1962, p. 514) state that some of the individual sandstones in the Seven Rivers Formation can be correlated over a wide area, and that, despite the change from anhydrite to dolomite, the thickness and lithologic character is correlative with the exposed section in the Guadalupe Mountains measured by Hayes and Koogle (1958).

The Queen Formation in the reference well is 420 feet (128 metres) thick and mainly consists of sandstone and anhydrite with thin interbedded dolomite and shale. A bed of sandstone about 30 feet (9 metres) thick near the top of the unit can be correlated over long distances in the subsurface. Tait and others (1962) indicate the section in the reference well can be correlated with the surface section of the Queen Formation measured by Hayes and Koogle (1958) in spite of the change in lithologic character from anhydrite and sandstone to dolomite and sandstone. The Grayburg Formation in the reference well is composed of dolomite with thin interbedded sandy dolomite, sandstone, and anhydrite. The basal sand in the Grayburg Formation is regionally correlative.

Meissner (1972) has described the shelf section as consisting of alternating thick carbonate and thin clastic units--each being nearly time-synchronous. The Tansill and Seven Rivers Formations of the Artesia Group and San Andres Limestone comprise the carbonate units and the Yates Formation and Queen-Grayburg Formations undivided are the clastic units. The persistent sandstones and thick carbonate-anhydrite beds permit regional correlation of the formations within the Artesia Group to be made with confidence.

The Carlsbad or carbonate facies of the Artesia Group ranges in width from 15 to 30 miles (24 to 48 kilometres) in a relatively narrow belt paralleling the margin of the Delaware basin (Meissner, 1972, fig. 3). The width of the Chalk Bluff or evaporite facies averages only 40 miles (64 kilometres) in a belt centered along the eastern edge of the Central Basin platform. A lobe of the Chalk Bluff facies extends far northward on the Northwest shelf into east-central New Mexico. The Chalk Bluff facies is surrounded by a belt of Bernal or clastic facies of variable width.

The average thickness of the Artesia Group within the northern part of the project area as depicted by Meissner (1972) is approximately 1,500 feet (455 metres). The Artesia Group thins to a thickness of about 1,000 feet (305 metres) on the southern end of the Central Basin platform.

The Artesia Group is the approximate equivalent of the Gilliam Limestone in the Glass Mountains (fig. 9).

Goat Seep Limestone

The Goat Seep Limestone was named by King, P. B., (1942, p. 588) and later restricted to include only the reef and forereef facies of the shelf margin by Newell and others (1953, p. 42-43). Hayes, P. T. (1964, p. 18) described the Goat Seep as a "light-gray, massive, fine crystalline to saccharoidal dolomite," a much different lithology than that observed in the overlying Capitan Limestone.

The Goat Seep Limestone occupies the same relative position with respect to the shelf margin as does the overlying Capitan Limestone. It is the lateral equivalent of the Grayburg and Queen Formations in the Artesia Group, and is approximately equivalent to the upper part of the Cherry Canyon Formation of the Delaware Mountain Group (figs. 9 and 13).

Capitan Limestone

The Capitan Limestone was deposited along the margin of the Delaware basin in a continuous, narrow, arcuate trending belt. Except for the narrow opening to the Hovey channel, the southern inlet to the Delaware basin, the Capitan Limestone completely encircles the basin. The Capitan Limestone crops out in the Apache, Guadalupe, and Glass Mountains and is present in the subsurface in the Salt Flat graben west of the Delaware Mountains (Reed, written commun. 1966) and along the north and east margins of the Delaware basin (fig. 6). The Capitan Limestone was named by Richardson (1904) from outcrops at the southern end of the Guadalupe Mountains and has since been the subject of many studies by geologists and the focal point of numerous discussions.

The vertical limits of the Capitan Limestone are now firmly fixed with the base at the apparently disconformable contact with the underlying Goat Seep strata (Hayes, P. T., 1964, p. 18-19) and the top at the overlying contact with evaporites of the Ochoan Series. The forereef limits are established by the rapid facies change from limestone debris into the terrigenous sandstones of the Delaware Mountain Group. However, many investigators extend the backreef limit of the Capitan Limestone shelfward more than 10 miles (16 kilometres) from the reef front and include much or all of the Carlsbad f16 kilometres) from the reef front and include much or all of the Carlsbad facies of the Artesia Group (Silver and Todd, 1969, figs. 12 and 13). The author favors restricting the Capitan Limestone to the massive and poorly bedded, lime wackestone and grainstone lithologies as shown by Dunham (1972).

Maximum overall width of the Capitan Limestone appears to be less than 5 miles (8 Kilometres) and the width at a single time-synchronous horizon is probably not more than 2 miles (3 kilometres). Thickness of the Capitan Limestone varies greatly from less than a few hundred feet in some of the incised submarine canyons to perhaps as much as 2,000 feet (610 metres) locally in some of the intercanyon areas. The Capitan Limestone is the lateral equivalent of the Tansill, Yates, and Seven Rivers Formations and the Bell Canyon Formation (figs. 9 and 13).

Delaware Mountain Group

The Delaware Mountain Group (Richardson, 1904) includes, in ascending order, the Brushy Canyon, Cherry Canyon, and Bell Canyon Formations (King, 1948), and comprises the basin facies of the Delaware basin (Hull, 1957). The Delaware Mountain Group is present in the subsurface throughout all except the extreme southern part of the Delaware basin, and is exposed in the Delaware and Guadalupe Mountains along the western side of the basin. Beds within the Delaware Mountain Group appear to stratigraphically underlie coeval shelf-margin deposits because of the original difference in depositional topography--a spatial relationship that has been preserved (fig. 13).

The Brushy Canyon and Bell Canyon Formations are generally restricted to within the encircling wall of shelf-margin carbonates on the periphery of the Delaware basin. Discontinuous beds of the Cherry Canyon Formation, the middle unit of the Delaware Mountain Group, do, however, extend north and westward onto the Northwestern shelf beyond the shelfward or back reef limit of the Capitan and Goat Seep Limestones where they intertongue with the upper part of the San Andres Limestone. Sandstone tongues of the Cherry Canyon Formation seem to occur at different stratigraphic intervals near the top of the San Andres Limestone and may represent a series of submarine canyon deposits that may not be laterally connected (Wilde and Todd, 1968, p. 18; and Jacka and others, 1972).

The Word and Altuda Formations in the Glass Mountains section are approximately equivalent to the Delaware Mountain Group (fig. 9; and King, P.B., 1930, and 1937; and Jones, 1949).

The thickness of the Delaware Mountain Group ranges from less than 2,000 feet (610 metres) in the southern part of the Delaware basin to more than 4,000 feet (1,220 metres) in southwestern Lea and eastern Eddy Counties, New Mexico.

Permian Ochoan Series

Structural setting

The Permian basin area was elevated above sea level and tectonically stable at the onset of the Ochoan Epoch. Adams (1944, p. 1598) described the Delaware basin as a deep geosynclinal bowl encircled by high, steep-faced, cliff-like carbonate reefs. Sea water entered the Castile lagoon (Adams, 1972) through a connecting channel on the southwest side of the Delaware basin.

Near the end of Castile time, regional subsidence permitted the sea to encroach beyond the Delaware basin onto the shelf where it eventually spread over a large part of the southern Permian basin (Hills, 1942, figs. 11 and 12).

Formations of Ochoan age and their importance as aquifers

The Ochoan series is represented, in ascending order, by the Castile, Salado, and Rustler Formations, and the Dewey Lake Red Beds (fig. 9; and King, P. B., 1942; Adams, 1944; and Oriel, Myers, and Crosby, 1967). The Tessey Limestone in the Glass Mountains section is approximately equivalent to the Salado and Rustler Formations elsewhere in the study area (King, 1937). The approximate position of this facies change between the Tessey Limestone and the Salado and Rustler Formations is shown on figs. 6 and 11.

The Tessey Limestone and Rustler Formation are the only units in the Ochoan that can be considered to be of importance as aquifers. The production of water from the Rustler Formation and the general water-bearing properties of this aquifer have been described in numerous publications including Hendrickson and Jones (1952), Guyton and Associates (1958), Garza and Wesselman (1959 and 1962), Armstrong and McMillion (1961), Nicholson and Clebsch (1961), and White (1971).

Although a small amount of water for ranch use may be produced from the Tessey Limestone on the north side of the Glass Mountains, virtually nothing is known about the water-bearing properties of this aquifer. Hydraulic continuity of the Tessey Limestone and the Capitan aquifer is assured by the similarity in lithology and the numerous faults and well developed joint pattern in vicinity of the Glass Mountains.

Castile Formation

Unlike younger units of the Ochoan Series, the Castile Formation is confined to the Delaware basin where it rests conformably on the sandstones of the Bell Canyon Formation. This unit consists of a dense basal limestone near the margins of the basin, a lower banded anhydrite composed of interlaminated white anhydrite and thinner brown bituminous calcite layers, halite, and an upper massive anhydrite and small amounts of terrigenous clastics (Kroenlein, 1939; Adams, 1944; Jones, 1954; Pierce and Rich, 1962; Snider, 1965; Anderson and Kirkland, 1966; and Anderson and others, 1972). The basal limestone wedge may be coeval with the upper part of the Tansill Formation (Newell and others, 1953, p. 47). The thickness of the Castile Formation ranges from approximately 1,200 feet (365 metres) in the western part of the Delaware basin to more than 2,100 feet (640 metres) in the northern and eastern part of the basin (Snider, 1965, fig. 14).

Several mappable beds of halite within the Castile Formation attain a maximum aggregate thickness of more than 1,300 feet (395 metres) in the northern part of the Ochoan trough of Snider (1965, p. 47) in the northeast part of the Delaware basin (Snider, 1965, fig. 15). The interbedded halite has been dissolved and removed from the Castile Formation along the western and southwestern part of the Delaware basin (Maley and Huffington, 1953). The beds of halite in the Castile Formation are also either absent or thin along the northern and eastern margins of the Delaware basin in a trend adjacent to, and parallel with, the Capitan aquifer (fig. 7; and Adams, 1944, figs. 2-4; Hills, 1968, pl. 1; Pierce and Rich, 1962, fig. 12; Jones, 1949; and Vertrees, 1964).

Salado Formation

The Salado Formation underlies an area of approximately 25,000 square miles (64,750 square kilometres) in southeastern New Mexico and western Texas and extends more than 100 miles (160 kilometres) to the north and east of the Delaware basin (Pierce and Rich, 1962, fig. 13; Frenzel, 1963; and Adams, 1963). The Salado Formation is composed of halite, anhydrite, and minor amounts of dolomite and terrigenous clastics. Potassium minerals occur in the Salado Formation in the northern part of the Delaware basin where they are of considerable economic importance (Jones, 1954; and Pierce and Rich, 1962, fig. 13).

The contact between the Salado Formation and the underlying Castile Formation within the Delaware basin and Guadalupian age beds on the surrounding shelf areas is unconformable (Adams, 1944, p. 1608). The exact contact between the Castile and Salado Formations is, however, difficult to pick despite the unconformable relationships, differences in lithology, and vastly different geographic distribution (Pierce and Rich, 1962, p. 32; and Snider, 1965, p. 38).

With the exception of areas where the soluble minerals have been removed by solution, the thickness of the Salado Formation varies from about 500 feet (150 metres) in the western part of the Delaware basin to more than 2,500 feet (760 metres) as noted by Snider (1965) in one well in northwestern Pecos County, Texas. Thicknesses of more than 2,200 feet (670 metres) prevail in the Ochoan trough parallel to the Central Basin platform in the eastern part of the Delaware basin (Snider, 1965, fig. 23).

Halite in the Salado Formation has either been anomalously thinned or removed in a narrow band trending above or adjacent to the Capitan aquifer along the north and eastern margins of the Delaware basin (fig 7 D-D' and E-E'; and Adams, 1944; Maley and Huffington, 1953; Jones, 1949; Vertrees, 1964; Pierce and Rich, 1962, fig. 12; and Hills, 1968, pl. 1). The thickness of the Salado Formation varies from 800 to 1,200 feet (245 to 365 metres) on the Northwest shelf and Central Basin platform near the margin of the Delaware basin. The Salado Formation thins gradually and wedges out in both northerly and easterly directions.

Rustler Formation

The Rustler is the youngest unit in the Ochoan evaporite sequence in western Texas and southeastern New Mexico and is a record of the final incursion of the Permian sea into the Permian basin. The Salado Formation was uplifted and eroded along the western margin of the Delaware basin prior to the deposition of the overlying Rustler Formation (King, P. B., 1942; and Adams, 1944). The contact between the Salado and Rustler Formations within the Delaware basin is, however, gradational and appears to be conformable (Kroenlein, 1939; and Pierce and Rich, 1962). Nevertheless, the contact between the top of the Salado Formation and the base of the Rustler Formation in the subsurface within the Delaware basin is difficult to pick and is usually placed arbitrarily at the top of the youngest prominent halite bed in the Salado Formation. The Rustler Formation extends beyond the limits of the Salado Formation and is a well-defined marker bed throughout much of the Permian basin (figs. 6 and 7; and Vertres, 1964; Jones, 1949; Scobey, 1951; Davies, 1953; Hills, 1961, and 1962; Feldman, 1962; Roswell Geological Society, 1960; Stipp, and others, 1956; Ahlen, 1958; Ahlen, and Tait, 1959; and Tait, and others, 1962).

The Rustler Formation consists of interbedded anhydrite, gypsum, red shales, mudstones and silstones, dolomite, limestone, halite, and sandstone. Potassium minerals have been found within the Rustler Formation in the northern part of the Delaware basin (Jones, 1954). Thickness of the Rustler Formation ranges from less than 200 feet (60 metres) in the western part of the Delaware basin to more than 600 feet (185 metres) in south central Reeves County, Texas (Snider, 1965, fig. 24). The content of dolomite and limestone in the Rustler Formation increases southward and southwestward in the southern part of the Delaware basin until the Rustler becomes indistinguishable from the upper part of the Tessey Limestone in the Glass Mountains.

The Rustler Formation is a major source of the water used to flood partly depleted oil fields in southern Lea County, New Mexico, and Winkler, Ward, and Pecos Counties, Texas. Water produced from the Rustler is generally highly mineralized. However, in southern Ward and western Pecos Counties, Texas, the salinity decreases progressively toward the south and water from the Rustler is used to irrigate salt-tolerant crops.

Dewey Lake Red Beds

The Dewey Lake Red Beds, the youngest formation in the Ochoan Series, consist of orange-red siltstone with some mudstone and sandstone. This formation has been removed from the western and southern parts of the Delaware basin by post-Permian erosion but is present in the subsurface throughout most of the principal area of interest outlined in figure 3. The thickness of the Dewey Lake Red Beds varies from about 200 feet (60 metres) to as much as 600 feet (185 metres). The Dewey Lake Red Beds are separated from rocks of similar lithology in the basal part of the overlying Dockum Group primarily on a contrast in color (the Dockum Group is darker red) and a significant decrease in natural radioactivity in a thin zone immediately below the contact between the two units (Adams, 1944, p. 1615; and Garza and Wesselman, 1959, p. 18). The end of deposition of the Dewey Lake Red Beds marks the close of the Permian Period in the Permian basin and the commencement of a long period of erosion or non-depositon in western Texas and southeastern New Mexico.

Tessey Limestone

King, P. B., (1930, and 1937) has described the Tessey Limestone as a massive dolomite about 1,000 feet (305 metres) thick at sections measured in the Glass Mountains. The change from the carbonate lithology in the Tessey Limestone to the evaporites in the Rustler Formation is a very narrow band in the subsurface parallel to the southern margin of the Delaware basin a short distance to the north of the Glass Mountains. A paleogeographic map by King, P. B. (1942, p. 752) suggests that the carbonate facies of the Tessey Limestone was developed across the narrow Hovey channel that connected the Delaware evaporite basin to the more normal marine waters to the southwest.

Mesozoic Erathem

Structural movements

The Delaware basin and the other tectonic features shown in figure 4 were no longer active and had been topographically obliterated by the close of the Permian Period. The region now known as western Texas and eastern New Mexico became a low, monotonous plain with outcrops of red shale and sand and some exposures of limestone, dolomite, and gypsum. The landscape might have resembled the surface as some would describe it today (McKee, and others, 1959; and Hills, 1963). In Late Triassic time, a broad interior basin draining toward other interior basins to the northwest formed above the ancestral Permian basin. This basin was filled with continental red beds and sandstones. At the close of the Triassic, the region was gradually elevated without significant local tectonic activity. Triassic continental deposits were eroded from the western part of the project area as the region remained above sea level throughout the Jurassic (McKee and others, 1959, pl. 9).

A fundamental change in the paleogeography occurred in Early Cretaceous time when the interior basins with highlands to the east and south gave way to a gentle slope toward what is now the Gulf of Mexico. Shallow marine seas gradually and progressively invaded the area from the south and eventually overlapped beds ranging in age from Precambrian to Triassic in western Texas and southeastern New Mexico. Before withdrawing near the end of the Mesozoic, the Cretaceous seas from the Gulf had joined with seas encroaching from the Arctic to form a seaway through the western interior of the North American continent.

Stratigraphy

Triassic System

Dockum Group

Rocks assigned to the Dockum Group of Late Triassic age overlie Permian sedimentary rocks throughout much of southeastern New Mexico and western Texas where they are locally exposed at the surface (fig. 10; and Oriel, Myers, and Crosby, 1967, fig. 18). The Dockum Group gradually increases in thickness from an erosional wedge-edge along the western and southern part of the study area to more than 2,000 feet (610 metres) at a thick-center point located about 50 miles (80 Kilometres) north northeast of Hobbs (McKee and others, 1959). The Tecovas Formation, the oldest unit in the Dockum Group, consists of from 0 to approximately 300 feet (90 metres) of red shale, siltstone, and fine-grained sandstone.

The Santa Rosa Sandstone, the middle unit in the Dockum Group, is composed of from less than 100 (30 metres) to as much as 650 feet (200 metres) of red, brown, and gray sandstone. The Santa Rosa Sandstone is one of the principal aquifers in Winkler and Ward Counties, Texas, where it is a source of both fresh and saline water (Garza and Wesselman, 1959, and 1962; and White, 1971).

The Chinle Formation equivalent, the youngest unit in the Dockum Group, varies from 0 to as much as 1,300 feet (395 metres) in eastern Lea County, New Mexico, and is composed of red, maroon, and purple shales and siltstones, and lenticular beds of fine-grained red-to-gray sandstone.

A small amount of water of generally poor quality is produced from sandstones in the Chinle Formation equivalent at scattered localities. The Chinle becomes anomalously thin over the western part of the Central Basin platform in Winkler County, Texas, and southern Lea County, New Mexico, suggesting that the Central Basin platform was uplifted again after the close of the Triassic (Garza and Wesselman, 1962, pl. 2 and 3).

Bissett Conglomerate

The Bissett Conglomerate, crops out in and is geographically restricted to the vicinity of the Glass Mountains. It is approximately equivalent in age to the Dockum Group in the remainder of the western Permian basin. The Bissett Conglomerate is composed of rounded fragments of dolomite and limestone derived from the underlying Permian beds. Some interbedded layers of sandstone and limestone and lenticular beds of red shale have also been observed in the Bissett Conglomerate. King, P. B. (1930) measured a maximum thickness of 720 feet (220 metres) of Bissett Conglomerate on the north flank of the southwestern terminus of the Glass Mountains. This unit is of no hydrologic significance.

Cretaceous System

Rocks of Jurassic age are not present in this part of western Texas and southeastern New Mexico (McKee and others, 1956). Rocks of Cretaceous age are geographically restricted to the southern and southwestern part of the project area where the Cretaceous is separated from the underlying Permian or Triassic by an angular unconformity (figs. 8 and 9). Although interrupted by several regressive phases, Cretaceous seas advanced progressively from the southeast and apparently eventually inundated all of the project area (Lang, 1947; Sloss, Dapples, and Krumbein, 1960; and Hendricks and Wilson, 1967). Approximately 1,500 feet (455 metres) of lower and lowermost Upper Cretaceous limestone, sandstone, shale, and claystone are present in most of Pecos County, the southern part of Reeves County, and the northern part of Brewster County, Texas.

Large quantities of ground water are produced from the Cretaceous limestone wherever the transmissivity has been enhanced by solution and fracturing, and from the sandstone of Trinity age in Pecos and Reeves Counties (Armstrong and McMillion, 1961; Ogilbee, Wesselman, and Irelan, 1962; and Brown, Rogers, and Baker, 1965). With the exception of isolated remnants, Cretaceous rocks have been eroded from the remainder of the project area. Hydraulic communication between the Capitan aquifer and rocks of Cretaceous age in southern Pecos County, Texas, is probably good wherever joints, fractures or faults are well developed.

Cenozoic Erathem

Structural movements

Late in the Cretaceous Period or very early in the Tertiary Period, western Texas and southeastern New Mexico was elevated by a broad epeirogenic uplift and tilted slightly to the east and northeast. Laramide folding comparable to that in the Rocky Mountains did not take place in the Permian basin. Hills (1963) suggests that the Laramide stresses were absorbed and distributed by the massifs of northeastern New Mexico and the Texas Panhandle, and the tightly folded Paleozoic rocks of the Marathon-Ouachita belt and associated tectonic elements along the southern edge of the basin. In this manner, the buried structural framework established in Late Wolfcampian and Early Leonardian time was preserved and remained intact until the Guadalupe, Delaware, Apache, and Glass Mountains were formed by basin and range block faulting late in the Cenozoic.

Sediment eroded from emerging highlands in central New Mexico and in Texas west of the Pecos River, accumulated, and was spread across eastern New Mexico and western Texas by eastward-draining streams during the Middle and Late Tertiary Period. Several scattered intrusions and extrusions in the fault block mountains along the southern and western margins of the Delaware basin are the only record of igneous activity in the Permian basin during the Cenozoic Era.

Most of the faulting and the main uplift of the Guadalupe, Delaware, Apache, and Glass Mountains probably started late in the Pliocene and continued on into the Pleistocene. The major block faulting quite likely was preceded by slight warping or folding and other minor adjustments as noted in the Glass Mountains by King, P. B. (1937). Whether or not the Guadalupe and other block fault mountains along the western margin of the Delaware basin were covered by the Pliocene Ogallala Formation at an earlier stage is a matter of conjecture. Thin remnants of terrigenous siliceous sandstone and conglomerate on top of the Guadalupe Mountains were considered to be Cretaceous in age by Hayes, P. T. (1964) but may be Pliocene. Sandstone dikes and crevice fillings exposed in Jurnigan Draw in the Guadalupe Mountains southwest of Carlsbad seem to more closely resemble the Ogallala Formation than any of the sandstones of Cretaceous age observed by the author in western Texas.

Structural configuration of the Guadalupian Series

As shown in figure 15, strata of Late Guadalupian age on the Northwestern shelf dip gently southeastward away from the Sangre de Cristo Mountains toward the Central Basin platform and Midland basin at an average of about 100 feet per mile (19 metres per kilometre). Rocks in the Delaware Mountain Group dip gently eastward from the Delaware and Guadalupe Mountains, northeast from the Apache Mountains, and northward from the Glass Mountains, toward the center of basin in eastern Reeves and northern Pecos Counties, Texas, at about the same rate. The Central Basin platform appears as a complex anticlinorium with local closures trending south-southeastward from Hobbs toward Fort Stockton. The Central Basin platform was actively uplifted by block faulting through Wolfcampian time (fig. 4). However, outside the faulting associated with late Cenozoic mountain building along the southern and western margins of the Delaware basin, the Guadalupian strata within the project area do not appear to have been displaced by faulting of any magnitude.

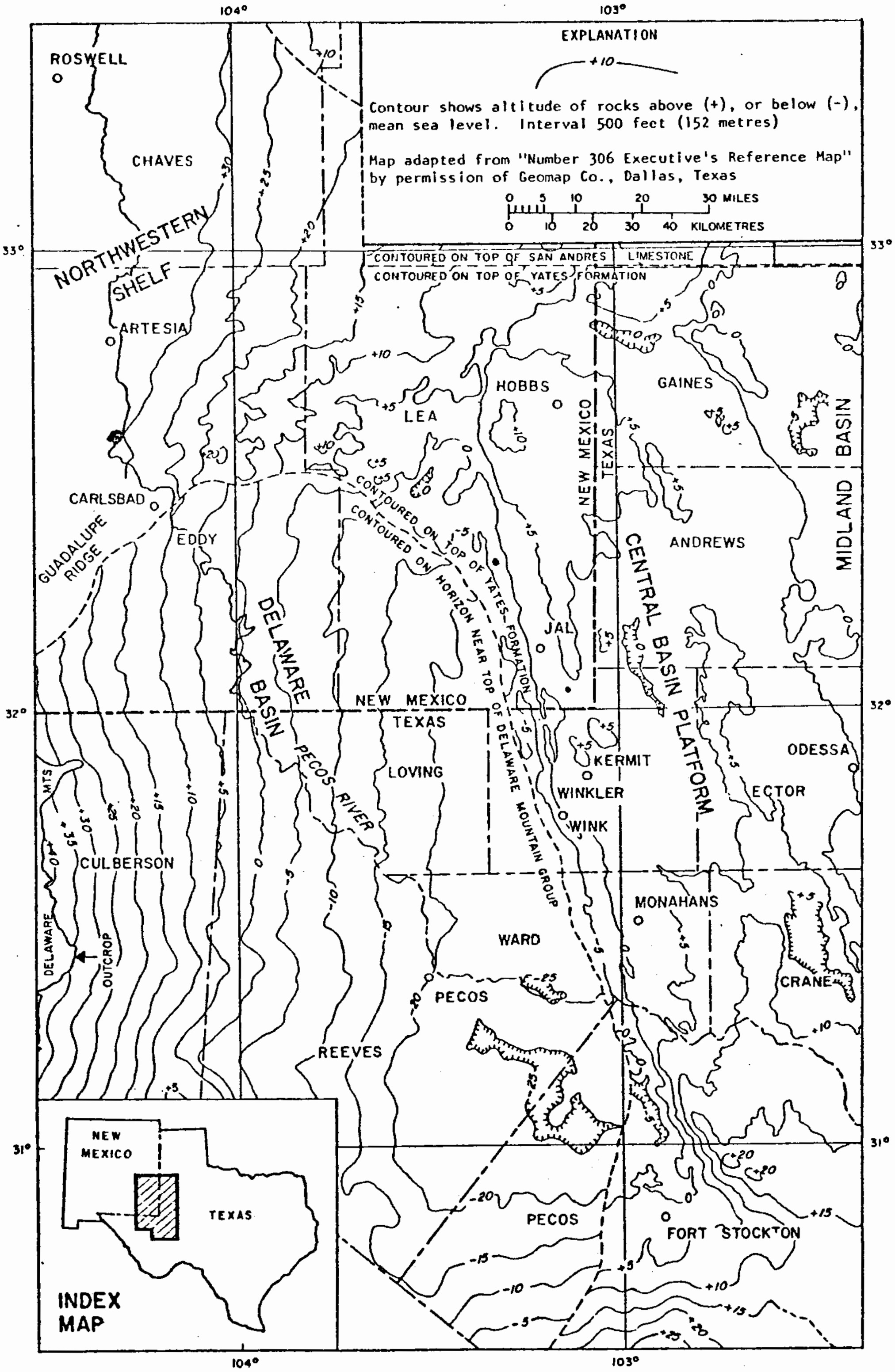


Figure 15.--Map showing structural configuration of the Delaware basin, Northwestern shelf, and Central Basin platform near the top of rocks of Permian Guadalupian age.

Structural configuration of the Precambrian basement

The generalized position of the surface of the Precambrian basement in the Delaware basin and surrounding areas is shown in figure 16. The axis of the Delaware basin trends south-southeastward from a point approximately midway between Carlsbad and Hobbs to the deepest part of the basin near Fort Stockton. At the southern end of the Central Basin platform, the axis of the Delaware basin is aligned to coincide with the axis of the southeastward-trending Val Verde basin. The more than 25,000 feet (7,620 metres) of sedimentary rocks that have accumulated in the deeper part of the Delaware basin reflects the relatively stable position of the dominant structural elements in this area during the Paleozoic Era. The Delaware basin is flanked on the east by the Central Basin platform, on the south by the complexly deformed Marathon uplift, and on the west by the Diablo platform and other smaller fault blocks.

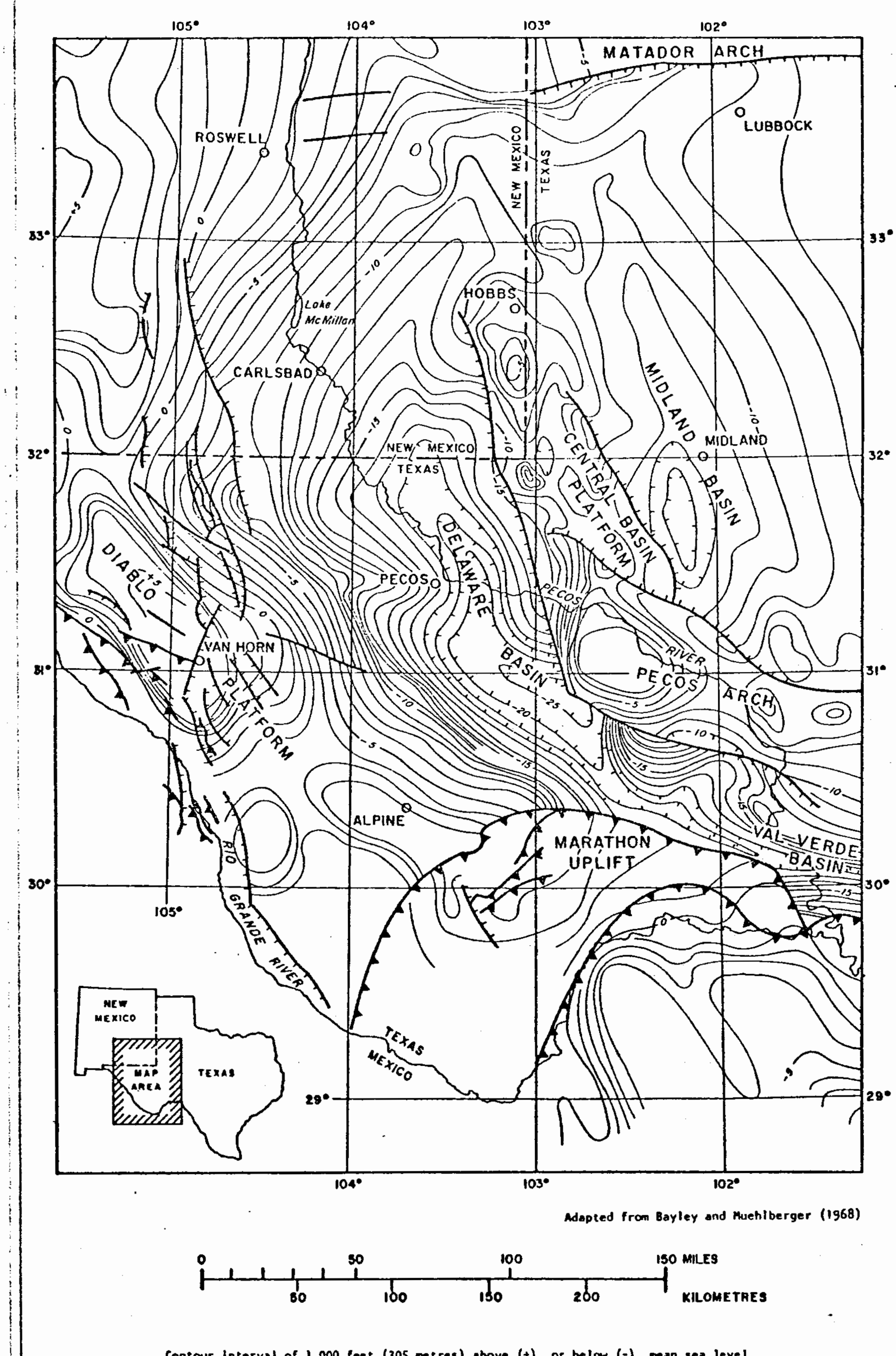


Figure 16.--Map showing structural configuration of Precambrian basement rocks in the Delaware basin and surrounding areas.

Lower Paleozoic sedimentary rocks have been displaced more than 20,000 feet (6,095 metres) by faulting along the Central Basin platform in the vicinity of Fort Stockton. Displacement along the faulted western edge of the Central Basin platform becomes progressively less toward the north, but is still more than 5,000 feet (1525 metres) at the southeast corner of New Mexico. The Capitan aquifer overlies, but postdates, the faulted western margin of the Central Basin platform. The Capitan aquifer undoubtedly has been fractured by minor movements along this older fault system as the Central Basin platform and Delaware basin were adjusted to the burden and position of the large volume of overlying sedimentary rocks.

Structure of the Rustler Formation

Map preparation

The widespread occurrence, distinctive lithology, and relatively uniform thickness of the Rustler Formation over the Delaware basin, Northwest shelf, and Central Basin platform make it an ideal marker bed that can be readily distinguished in drill cutting samples and on electric logs. The structural map contoured on top of the Rustler Formation (fig. 17) was prepared using data obtained from a number of sources. Tops were taken directly from the Permian Basin Well Data System data file and stratigraphic sections prepared by the Roswell and West Texas Geological Societies, from electrical lithological logs, and from maps prepared by Guyton and Associates (1958), Garza and Wesselman (1962), White (1971), Armstrong and McMillion (1961), and Ogilbee, Wesselman and Irelan (1962).

Regional structure

Regionally, the surface of the Rustler slopes irregularly to the east reflecting the late Mesozoic and Cenozoic uplift and eastward tilting of the western part of the Permian basin. Several of the many anomalous local features superimposed on the larger regional trend coincide with the structural configuration of the older Permian strata shown in figure 15. The Hobbs, Eumont, Langlie-Mattix, Hendrick and many other oil fields are located within structural closures (figs. 15 and 17). The low centered in T.25 S., R.33 E., Lee County, New Mexico, is probably due to regional subsidence rather than solution of underlying evaporites.

Salt-solution troughs

Maley and Huffington (1953), Olive (1957), Garza and Wesselman (1959), and White (1971) have demonstrated that some of the structural features represented by the configuration of the Rustler Formation accurately depict both the location and amount of solution of the older Ochoan evaporites and the accumulation of alluvium that filled the resulting depressions.

Salt-solution troughs are located along the eastern margin of the Delaware basin and at the westernmost extension of the soluble salts of the Ochoan Series in the west and west-central part of the Delaware basin. The two troughs are filled with a variety of sedimentary rocks ranging in age from Triassic to Holocene that form excellent ground-water reservoirs. The troughs probably were formed contemporaneously with the Pliocene-Pleistocene uplift of the Delware basin and the emplacement of the Pecos River.

A series of irregular lens-shaped coalescing troughs extends northward from Balmorhea near the boundary between Reeves and Jeff Davis Counties, Texas, to Pecos, Texas where the trough then extends north along the Pecos River to near Loving in Eddy County, New Mexico. The Ochoan evaporite section was elevated and probably exposed to at least some extent as the Delaware basin was uplifted and tilted to the east. Soluble minerals, particularly halite, were consequently removed by action of surface and ground water and the western limit of the halite beds gradually retreated to a position now coincidental with the Balmorhea-Pecos-Loving trough herein named for purposes of this report (fig. 17).

Another series of linear lens-shaped depressions form a trough 8 to 12 miles (13 to 19 kilometres) wide extending northward from near Belding in southwestern Pecos County, Texas, in an arcuate trend above and parallel to the Capitan aquifer to T.22 S., R.35 E., in the vicinity of the San Simon swale in southern Lea County, New Mexico (fig. 17). Halite and other soluble minerals also have been removed from both the Castile and Salado Formations underlying the Belding-San Simon trough, herein named for purposes of this report (fig 17; and Maley and Huffington, 1953, pl. 2). Non-soluble beds in the Ochoan Series and Triassic and Cretaceous Systems have collapsed into the void left by the solution and removal of the soluble minerals.

Coincident with subsidence of the surface, a network of streams developed as a surface manifestation of the Belding-San Simon trough. As a result, more than 1,000 feet (305 metres) of alluvium is now present in some of the depressions. Garza and Wesselman (1962, p. 14) have mapped some of the southward-draining ancient stream channels in Winkler County. The Monument Draw in Ward and Winkler Counties, Texas, and a small lake formerly used by oil companies for communal waste-water disposal about 1.5 miles (2.4 kilometres) northwest of Wink, Texas, are the present-day remnants of this drainage system.

A complimentary stream system undoubtedly originated in the vicinity of the ancestral Glass Mountains and flowed to the north, although no similar surface expression of such a system is evident today. Cretaceous sediments were partially stripped from the surface above the Belding-San Simon trough prior to burial by alluvium in Pecos County (Armstrong, and McMillion, 1961). Cenozoic alluvium rests directly on the Triassic Dockum Group farther to the north in Ward and Winkler Counties, Texas, and Lea County, New Mexico.

The Capitan acquifer and overlying competent sandstones and carbonates within the Artesia Group were apparently strongly jointed and perhaps even fractured by movements in the western Permian basin during the Laramide orogeny (Adams, 1944, p. 1623; and Adams and Frenzel, 1950, p. 301). Ground water from the Capitan acquifer was able to move through the factures and joints in the overlying Artesia Group and attack the soluble beds in the Castile and Salado Formations. The orginial relatively high hydraulic conductivity of the Capitan aquifer was also enhanced by the fracturing and jointing.

Soluble beds in the adjacent Castile and overlying Salado Formations along the western edge of the Central Basin platform were dissolved during late Cenozoic time and removed by undersaturated ground water. The ground water flowed northward through the Capitan aquifer as a consequence of uplift of the Glass Mountains. The rate of movement and solution undoubtedly varied greatly and depended in part upon the amount of precipitation, the relief of the Glass Mountains, and the hydraulic gradient imposed upon the water in the Capitan aquifer. Historical records of subsidence in the San Simon swale suggest that solution and collapse processes are still operative (Nicholson and Clebsch, 1961, p. 13-17). The route of ground-water movement is recorded by the quality of water in the Capitan aquifer and other Guadalupian age sedimentary rocks and is substantiated by maps of the potentiometric surface.

The Pecos River, the dominant factor in controlling the movement of the ground water in the northwestern part of the project area, very obviously is younger than the Pliocene Ogallala Formation. The present drainage system and landscape was probably established in very late Pliocene or early Pleistocene time (Plummer, 1932; Motts, 1968; Hayes, P. T., 1964; and Thornbury, 1965).

The depressions in the surface of the Rustler Formation above the Capitan aquifer east of Carlsbad are undoubtedly also due to the solution and removal of the underlying halite. The Pecos River at Carlsbad has been in good hydraulic communication with the Capitan aquifer and has functioned as an upgradient drain for a long period of time. Therefore, these solution-collapse features were probably caused by eastward-moving ground water prior to the excavation of the Pecos River valley in Eddy County. The solution-collapse features above the Capitan aquifer east of Carlsbad are fewer in number and smaller in size than those formed along the western margin of the Central Basin platform. This is a probable consequence of both the less extensive system of joints or fractures and the smaller amount of ground water that has moved through the Capitan aquifer.

Stratigraphy

Tertiary System

Ogallala Formation

The Ogallala Formation of Pliocene age underlies the High Plains or Llano Estacado of eastern New Mexico and the panhandle of Texas and forms many of the prominent ridges in southern Lea County, New Mexico (Dane and Bachman, 1965; and Nicholson and Clebsch, 1961). This widespread formation is a heterogeneous complex of terrestrial sediments that cover an irregular erosion surface cut by eastward-draining streams into the underlying Cretaceous and Triassic sedimentary rocks. The thickness of the Ogallala Formation ranges from a few inches to more than 300 feet (90 metres). It is predominantly composed of calcareous, unconsolidated sand, but contains beds of clay, silt, and gravel and is generally capped by a dense layer of caliche. The Ogallala Formation is an excellent source of potable ground water.

Prior to the cutting of the present-day Pecos River valley, the Ogallala Formation probably extended westward to source areas in the ancestral Sandía-Manzano, Sangre de Cristo, and San Juan uplifts (Plummer, 1932; Kelley, 1972; and Thomas, 1972). Dikes filled with sandstone similar to that in the Ogallala have been observed to cut across beds of Permian age in the Guadalupe Mountains. These sandstone dikes are probably Pliocene deposits (King, P. B., 1948; and Horberg, 1949, p. 466) but may be Cretaceous (Hayes, P. T., 1957, and 1964, fig. 22. p. 37).

Igneous rocks

A northeasterly trending dike or system of relatively thin, steeply dipping basaltic and lamprophyric dikes in the northern Delaware basin has been reported by Jones and Madsen (1959). Igneous rocks have been penetrated in three oil test wells located 1,980 feet (604 metres) from the south line and 2,302 feet (702 metres) from the east line, sec. 12, T.18 S., R.34 E., and 1,980 feet (604 metres) from the south and east lines, sec. 21, T.20 S., R.33 E., Lea County, New Mexico, and 660 feet (201 metres) from the south and east lines, sec. 9. T.22 S., R.32 E., Eddy County, New Mexico, and in potash mines located in sec. 31, T.20 S., R.32 E., Lea County, and sec. 36, T.21 S., R.29 E., Eddy County (C. L. Jones, oral commun., 1972).

The thickness of the dike(s) varies from less than 4 to 15 feet (1.2 to 4.5 metres) in the exposures in the potash mines (John M. Swales and David Rice, oral commun., 1972). A well developed system of joints is present in the dikes where exposed in the potash mines. The projected trend of the dike(s) passes through the Capitan aquifer along a line extending from sec. 1, T.21 S., R.30 E., immediately west of the boundary between Eddy and Lea Counties, New Mexico, to sec. 21, T.19 S., R.33 E. (fig. 11).

Pratt (1954) described the occurrence of several subparallel north-northeast trending alkali trachyte dikes in secs. 11, 12, 13, 14, and 15, T.26 S., R.24 E., Eddy County, New Mexico (Dane and Bachman, 1965). These dikes are on trend with the dikes reported by Jones and Madsen (1959). Other minor occurrences of Tertiary igneous intrusive rocks in the vicinity of the southern Guadalupe Mountains are described in Pratt (1964) and Hayes, P. T. (1964, p. 40). Tertiary igneous rocks are exposed in the Glass Mountains in a few scattered areas west of the boundary between Pecos and Brewster Counties, Texas. Extrusive and intrusive Tertiary igneous rocks crop out over a large area in Jeff Davis, Brewster, Reeves, and Pecos Counties to the west and northwest of the Glass Mountains (fig. 10). No other occurrence of igneous rocks, especially those that might penetrate the Capitan aquifer in the subsurface along the north and east margins of the Delaware basin, has been described.

Tertiary(?) and Quaternary Systems, undivided

Alluvium of probable latest Tertiary and Quaternary age unconformably overlies rocks of Permian, Triassic, and Cretaceous age throughout much of the area (fig 10). The alluvium consists of unconsolidated sand, silt, gravel, and clay and is often capped with a layer of caliche. The greatest thicknesses of the alluvium are found in the north-south trending Balmorhea-Pecos-Loving and Belding-San Simon slumpage troughs that have developed as a result of solution of underlying evaporities (fig. 17). Thicknesses of alluvium of 600 to 700 feet (180 to 215 metres) are common and may exceed 1,500 feet (455 metres) in local areas within the troughs (Brown, Rogers, and Baker, 1965, p. M-31 and pl. M-5). Elsewhere the thickness of the alluvium is highly variable but is seldom more than a few hundred feet thick. Large supplies of water of generally good quality have been developed from wells tapping the alluvium in many areas (White, Gale, and Nye, 1941).

Quaternary System

A few inches to about 250 feet (75 metres) of windblown sands mantle the older alluvium, Ogallala Formation, and other exposures of older sediments in part of the area. Except locally, the water table is generally below the base of the dune deposits. Although small quantities of fresh water are pumped from shallow wells in the sand in a few places, the windblown deposits are more important as a site of recharge for the underlying aquifers.

GROUND-WATER HYDROLOGY

Aquifer systems

Strata of Permian Guadalupian age have been divided into three aquifers that, for purposes of this report, are referred to as the shelf, basin, and Capitan aquifers. The shelf and basin aquifers were not studied as thoroughly as the Capitan aquifer.

Shelf aquifers

Saturated strata yielding significant quantities of water from the San Andres Limestone and the Bernal and Chalk Bluff facies of the Artesia Group comprise the shelf aquifers. The contact between the Capitan and shelf aquifers is gradational and is difficult to discern with accuracy in some areas.

The present-day ground-water regimen is strongly influenced by the Pecos River in New Mexico. As a result, the hydraulic conductivity of the shelf aquifers west of the Pecos River has been greatly enhanced by the leaching of soluble beds from the Chalk Bluff facies (Meissner, 1972). In and west of the Pecos River valley between Carlsbad and Roswell, the hydraulic conductivities of the shelf aquifers, locally, are quite large and may be similar to that of the Capitan aquifer. The hydraulic conductivity of the shelf aquifers in the Carlsbad and Roswell underground water basins (fig. 1) is several orders of magnitude higher than that generally encountered for the shelf aquifer within the project area. The water contained in the shelf aquifers is also much better in the shallow zones exploited in these basins than elsewhere in the same aquifers within the project area.

However, in most areas, the shelf aquifers are readily distinguished from the Capitan aquifer by differences in the lithology, the geographic position, and the stratigraphic relationships. East of the Pecos River valley in New Mexico, the two aquifers can also be identified by the differences in hydraulic characteristics and the quality of the water.

Basin aquifers

Saturated strata yielding significant quantities of water, herein defined as the basin aquifers, are present in the Brushy Canyon, Cherry Canyon, and Bell Canyon Formations in the Delaware Mountain Group. Although the Capitan aquifer abuts and overlies the Delaware Mountain Group along the margin of the Delaware Basin, the lithologic and hydrologic characteristics of the basin and Capitan aquifers are quite different. The average hydraulic conductivity of the basin aquifer is much less than that of the Capitan. Therefore, a relatively small amount of water can be expected to move from the basin to the Capitan aquifer, or vice versa, over a relatively short period of several decades.

Some of the sandstones of the Delaware Mountain Group, particularly those in the Cherry Canyon Formation, intertongue with the shelf carbonates within a narrow band parallel to the margin of the Delaware basin. Irregardless of the juxtaposition of the two aquifers, the relatively low transmissivities of both aquifers limits the amount of water transferred. The basin aquifer can be readily identified as a distinct aquifer system on the basis of lithology, geographic position, and stratigraphic relationships with other strata.

Capitan aquifer

In general, the position and dimensions of the Capitan aquifer closely agree with the Capitan and Goat Seep Limestones and carbonate banks in the upper part of the San Andres Limestone (Silver and Todd, 1969, figs. 12 and 13). However, observations of the geometry and lithologic relationships of the shelf-margin and shelf-sedimentary rocks in the field suggest that the width of the Capitan Limestone (reef) is considerably less than is usually shown. The relationships between the now obsolete Carlsbad Limestone and Capitan Limestone mapped by Dunham (1972, fig. I-1) appear to closely match the field relationships observed in the vicinity of Carlsbad and White City, N. Mex.

For all practical purposes, the Capitan aquifer is a lithosome that includes the Capitan and Goat Seep Limestones and most or all of the Carlsbad facies of the Artesia Group (Meissner, 1972). Some of the shelf-margin carbonate banks or stratigraphic reefs in the upper part of the San Andres Limestones are included within the Capitan aquifer whenever they cannot be readily distinguished from the Goat Seep Limestone and Carlsbad facies.

The Capitan aquifer is generally composed of a relatively "clean" carbonate, especially near the fore-reef edge. The radio-activity recorded on a gamma-ray electrical log of the Capitan and (or) Goat Seep Limestones is characteristically very low as shown in figures 6 and 7. Notable exceptions include the Capitan aquifer penetrated in the Shell Oil Co. Federal 4-1, sec. 4, T.22 S., R.34 E., Lea County, New Mexico (fig. 7 C-C'); and, in Pecos County, Texas (fig. 7 F-F'), the Aaron, Linehan, and Stoltenberg Grieson 1, sec. 72, block OW, M. J. Hawkins Survey; the Pan American Petroleum Corp. Butz Gas Unit 1, sec. 9, block 106, T + STL Survey; and the Skelly Oil Co. South Gomez Unit, sec. 1, block 106, T + STL Survey.

The tops and bases of the Capitan aquifer were determined primarily on the basis of the vertical extent of the relatively "clean" carbonate as indicated by the low gamma-ray activity levels shown on the electrical logs and the general stratigraphic position. Lithologic logs, oil field scout tops, reports of lost circulation, and other information were used whenever available to confirm these picks. Zones containing 50 percent or less of interbedded back or fore-reef lithofacies were arbitrarily included with the Capitan aquifer as a matter of convenience. Therefore, the net aggregate thickness of the Capitan aquifer may have been increased slightly.

It is often difficult or impossible to distinguish between other reefs and carbonate mounds in the back-reef sedimentary rocks and the Capitan and Goat Seep Limestones solely on the basis of the responses recorded on gamma-ray, sonic, and neutron electrical logs. Shelf and shelf-margin strata in the Carlsbad facies of the Artesia Group adjacent to the Capitan and Goat Seep Limestones are included whenever (1) the chemical composition of water in the back-reef sedimentary rocks is similar to the water produced from the Capitan Limestone, (2) the changes in water-levels in response to withdrawal of fluids is similar to the changes in hydraulic head measured in wells completed in the Capitan Limestone, and (3) the level of natural radioactivity measured in the formations adjacent to the Capitan or Goat Seep Limestone is low, suggesting a clean carbonate without significant clay, sand, silt, or shale.

Units previously referred to as reefs of Yates and Seven Rivers age, part of the Grayburg Formation, and the shelf-margin carbonate banks in the upper part of the San Andres Limestone are considered to be part of the Capitan aquifer if they cannot be distinguished as separate entities, and whenever the water quality, electrical log characteristics, or hydraulic responses justify inclusion.

The locations of nearly 400 deep wells that have been drilled within the project area are plotted on figures 11 and 12. Gamma-ray-neutron, or other combinations of electrical logs of the Capitan aquifer interval were obtained for nearly all these wells. Electrical logs were not available for (1) a few wells that were drilled before the invention of these tool and (2) many deep wells drilled to explore deeper formations where the shallower Permian Guadalupian strata were not logged due to efforts to reduce costs. Lithologic logs were available for approximately 15 percent of the wells.

Dimensions of the Capitan aquifer

Lateral extent

The Capitan aquifer parallels the northern and eastern margins of the Delaware basin in an arcuate strip extending from the Guadalupe Mountains southwest of Carlsbad to the Glass Mountains southwest of Fort Stockton (fig. 11). Exposures of the Capitan aquifer may be found in the Glass, Guadalupe, Apache, and Delaware Mountains. The Capitan aquifer undoubtedly is present elsewhere in the subsurface along the western and southwestern margins of the Delaware basin (fig. 10; and Darton, Stephenson, and Gardner, 1937; Dane and Bachman, 1965; and Barnes, 1968).

As shown in figures 6 and 11, the Capitan aquifer is one continuous unit along the north and east margins of the Delaware basin. Major displacements of the Capitan aquifer by faulting appear to be limited to the mountainous areas along the western and southern margin of the Delaware basin, because faults have not been observed in the subsurface along the western edge of the Central Basin platform and the southern edge of the Northwestern shelf. The irregular top and bottom surfaces and the lobate fore and back-reef edges are depositional forms (figs. 11 and 12).

The abrupt change in alignment of the Capitan aquifer in the vicinity of T.23 S., R.25 E., approximately 15 miles (24 kilometres) southwest of Carlsbad, is not due to post-Capitan age faulting (fig. 11). The change in alignment of the Capitan reef and increase in width and thickness of the Capitan aquifer in this area probably is due to growth of the Capitan reef along pre-Guadalupian age fault-controlled alignment and structural attitude of the margin of Delaware basin (Hills, 1963, p. 1715, fig. 4).

The width of the Capitan aquifer varies from 10 to more than 14 miles (16 to 23 kilometres) along the edge of the Northwestern shelf from the vicinity of Carlsbad to the central part of southern Lea County, New Mexico. The Capitan aquifer is much more restricted along the western edge of the Central Basin platform, where it seldom exceeds 11 miles (18 kilometres) in width.

The fore-reef edge of the Capitan aquifer in the subsurface appears to be relatively abrupt throughout the area and if exposed, would probably resemble the reef escarpment southwest of Carlsbad in the Guadalupe Mountains (Green, and others, 1964; and Newell, and others, 1953). Well control is adequate for definition of the subsurface fore-reef slope of the Capitan aquifer in several locations. Approximately 1,200 feet (365 metres) of vertical relief along the fore-reef edge of the Capitan aquifer was detected in two oil tests drilled within a few hundred feet of horizontal distance in secs. 5 and 9, T.22 S., R.33 E., Lea County (fig 18; and Meissner, 1972, pl. II). Similar evidence of the steepness of the fore-reef slope is found where deep drilling is concentrated in the ROC and Block 16 oil fields in the vicinity of Pyote, Texas; the Block 21, Mag-Sealy and South Wink oil fields, southwest of Wink, Texas; and in the Coyonosa, Gomez, and Oates N.E. oil fields located about 20 miles (32 kilometres) northwest, 8 miles (13 kilometres) northwest, and 15 miles (24 kilometres) southwest of Fort Stockton, Texas, respectively (fig. 19).

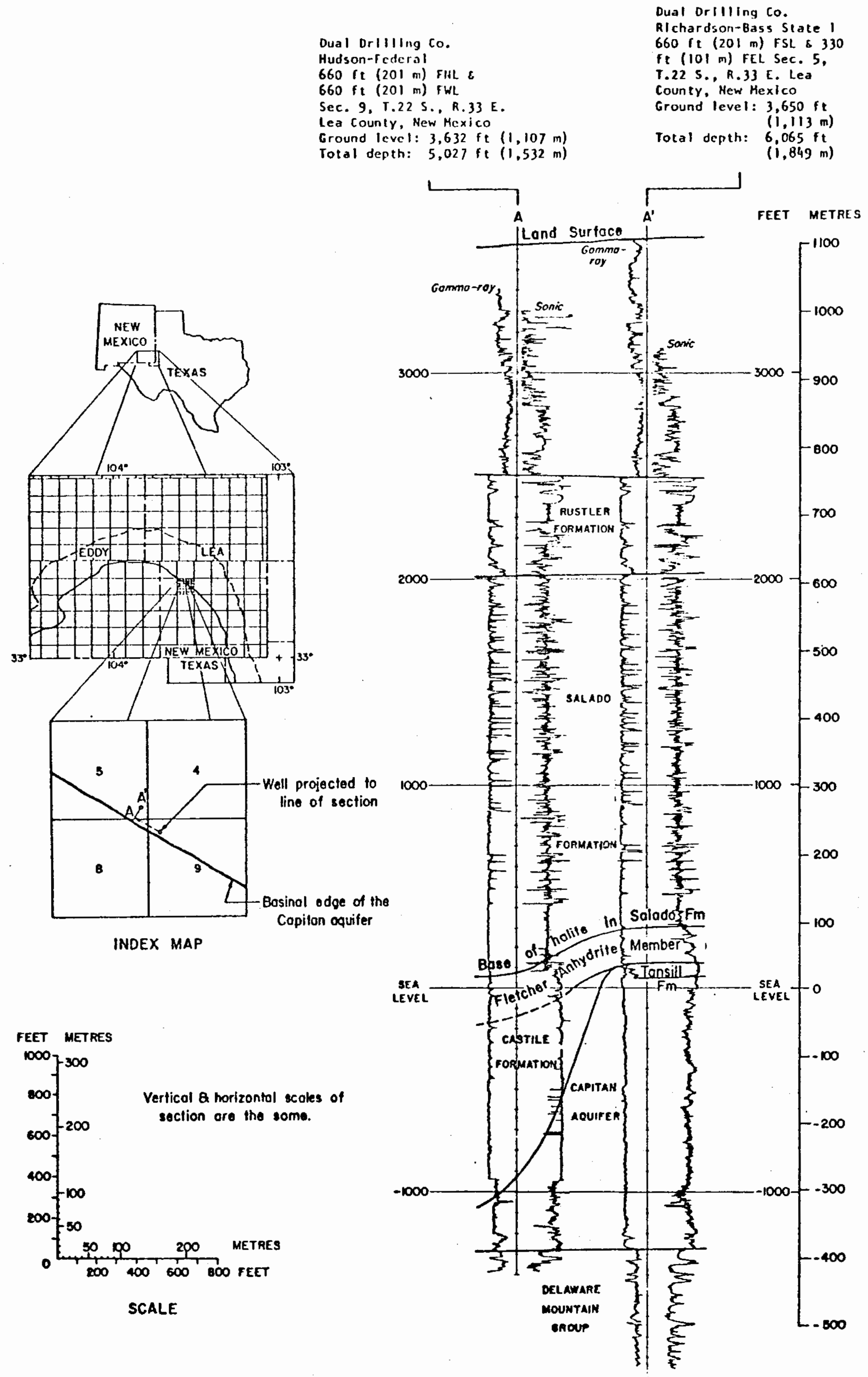


Figure 18.--Oblique stratigraphic section showing steepness of basinal edge of Capitan aquifer.

The back-reef edge of the Capitan aquifer is much more irregular than the fore-reef edge and is gradational in nature (fig 7). In some areas, especially along the western edge of the northern part of the Central Basin platform, it is difficult to distinguish the Capitan aquifer from the upper part of the San Andres Limestone. In this area the Capitan aquifer has been extended to include the carbonate banks developed in the upper part of the San Andres Limestone because of the proximity, and the similar lithology and hydraulic behavior of the two units (fig. 7 E-E').

Thickness

The thickness of the Capitan aquifer is quite variable (fig. 11). The Capitan aquifer appears to be composed of irregularly shaped and spaced, alternating thick and thin accumulations of carbonate rock. Many of the locally thick areas are well behind the reef front and may represent carbonate banks, islands, or mounds that flourished behind the protection of the reef crest (Kendall, 1969, p. 2509, and pls. 2 and 3). Motts (1962, and 1972) has mapped and described both current-oriented and irregularly oriented "shelf dome" carbonate mounds in the vicinity of Dark Canyon southwest of Carlsbad.

A number of small oil fields located along the trend of the Capitan aquifer are apparently localized on carbonate "buildups" that have been referred to by Stipp and Haigler (1956) as "reef knobs" interspersed between "surge channels." The majority of these carbonate mounds or "buildups" are also located within the thick areas shown in the Capitan aquifer thickness map (fig. 11). The Capitan aquifer attains a maximum thickness of 2,357 feet (718 metres) in the Odessa Natural Gas Federal Dooley well located on one of these mounds in sec. 24, T.20 S., R.29 E., about 13 miles (21 kilometres) northeast of Carlsbad . figs. 6 and 11).

The Capitan aquifer is slightly thicker along the edge of the Northwestern shelf in New Mexico than in Texas. In addition, the areal extent of the individual thick areas is correspondingly larger (fig. 11). A statistical summary of the thickness of the Capitan aquifer is illustrated graphically by county and State in figure 20.

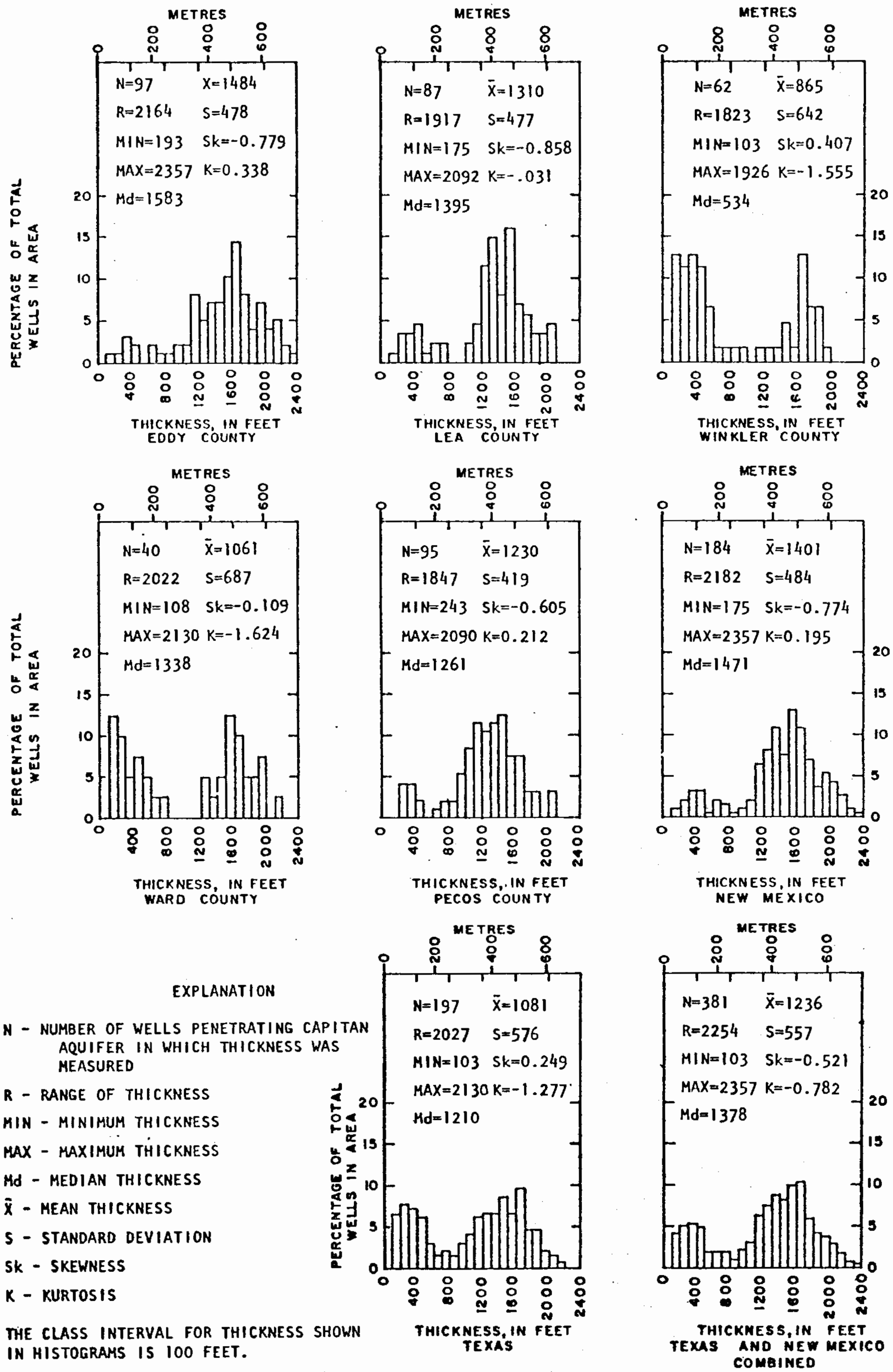


Figure 20.--Graph showing statistical summary of the thickness of the Capitan aquifer.

Thicknesses greater than 1,500 feet (455 metres) have been observed in approximately 49 and 29 percent of the wells that have penetrated the Capitan aquifer in New Mexico and Texas, respectively. More than 56 percent of the wells that have been drilled through the Capitan aquifer in Eddy County penetrated thicknesses greater than 1,500 feet (455 metres). About 12 percent of the wells drilled through the Capitan aquifer in Eddy County penetrated thicknesses of more than 2,000 feet (610 metres). Fewer than 5 percent of the wells in all other counties combined penetrated this great a thickness.

The bimodal distribution of thickness of the Capitan aquifer in Winkler and Ward Counties, as shown in figure 20, is primarily due to the bias resulting from the many wells, in comparison to other areas, that penetrate relatively thin sections of the Goat Seep Limestone and the carbonate banks in the San Andres Limestone on the extreme shelfward limit of the Capitan aquifer.

The Alacran, Quahada, Laguna, Eunice, Teague, Jal, and other submarine canyons have been cut into the Capitan aquifer in eastern Eddy and southern Lea Counties (fig. 11). The submarine canyons are oriented transversely to the arcuate main trend of this aquifer. In places, the thickness of the aquifer is reduced by one half or more. The significance of this thinning of the Capitan aquifer is not recognizable in the statistical summary.

Structural position of the Capitan aquifer

The structural position of the Capitan aquifer is shown in a longitudinal section and in a structural map with contours of the top of the Capitan aquifer (figs. 6 and 12, respectively). At first glance, an impression of a series of closed structural highs alternating with plunging synclines may be conveyed to the viewer by the pattern of structural contours of the top of the Capitan aquifer. However, when the configurations of the contours of the structural position and thickness of the Capitan aquifer are compared, the striking resemblance becomes obvious. Apparently, most of the features contoured as structural lows on figure 12 are depressions in the surface of the Capitan aquifer and are due to nondeposition or erosion in surge channels and submarine canyons of Permian Guadalupian age rather than warping of the Capitan aquifer.

In a similar manner, most of the features resembling structural highs are not due to structural uplift but are probably carbonate mounds. The Hendrick, Monument, and other fields along the western margin of the Central Basin platform produce from closed highs depicted on structural maps with contours of the top of the Yates Formation (fig. 15). The carbonate mounds described by Stipp and Haigler (1956), and Motts (1972) that form the traps for the small fields east of Carlsbad are probably not primarily due to structural deformation. Apparently, very few closed structures in the Capitan have been found along the northern margin of the Delaware basin.

The Capitan aquifer plunges to the northeast away from the Guadalupe Mountains and passes beneath the surface about 10 miles (16 kilometres) southwest of Carlsbad. The crest of the Capitan aquifer is at an altitude of approximately 3,000 feet (915 metres) at Carlsbad. At this point the Capitan aquifer turns eastward and continues to plunge in the subsurface, until altitudes of 500 to 750 feet (150 to 230 metres) below sea level are reached along the Central Basin platform west of Eunice, N. Mex. The crest of the Capitan aquifer generally remains at altitudes between 500 and 750 feet (150 and 230 metres) below sea level along the western margin of the Central Basin platform from the vicinity of Jal, N. Mex., southward to near Belding, southwest of Fort Stockton, Texas. The Capitan aquifer rises steeply southward from Belding to exposures in the Glass Mountains, where altitudes exceed 4,000 feet (1,220 metres) above sea level.

Depths to the top of the Capitan aquifer from the land surface in New Mexico vary from not more than a few hundred feet in the Pecos River valley at Carlsbad to more than 4,300 feet (1,310 metres) in the western part of southern Lea County (fig. 6). Depths to the Capitan aquifer in Ward, Winkler, and northern Pecos Counties range from less than 2,500 to more than 3,300 feet (760 and 1,005 metres, respectively).

Hydraulic characteristics of the aquifer systems

Sources of data

Wells completed in the Capitan aquifer were not generally available for evaluation of the aquifer characteristics. New wells could not be drilled for this purpose due to economic limitations. Normal pumping tests could not be run on the wells in the observation-well network due to both the high operating costs and anticipated large well losses that would occur as a consequence of the limited capacity of the wells.

A small amount of permeability and porosity data have been published in reports describing individual fields in publications of the West Texas and Roswell Geological Societies, the Texas Petroleum Research Committee, and the Texas Bureau of Economic Geology. Hogan and Sipes (1966) compiled a statistical summary of reservoir-engineering data for formations of several geologic ages in the Texas part of the Permian basin with the aid of a computer-based data bank containing information relative to approximately 500,000 samples. Unfortunately, the data are not tabulated by individual county and the number of core analyses available are not specified for each formation.

Very little information relating to the hydraulic characteristics of Permian Guadalupian age aquifers is available in the ground-water reports prepared for individual counties, because only the shallow aquifers containing potable ground-waer supplies are emphasized in these publications.

Table 6.--Permeability and porosity information obtained from oil industry rock core analyses[1/]

EDDY COUNTY

Geologic unit	Number of feet (metres) of core analyzed: Permeability	Number of feet (metres) of core analyzed: Porosity	Average permeability	Average porosity	Number of samples analyzed: Permeability	Number of samples analyzed: Porosity
Yates Formation	567.2 (172.9)	567.2 (172.9)	11.29 (0.028; 0.008)	10.21	543	543
Seven Rivers Formation	59.0 (18.0)	59.0 (18.0)	2.47 (.0060; .002)	10.65	58	58
Queen Formation	384.8 (117.3)	386.8 (117.9)	1.98 (.0048; .002)	9.21	315	317
Grayburg Formation	302.5 (92.2)	302.5 (92.2)	1.73 (.0042; .001)	6.00	161	161
Grayburg Formation-San Andres Limestone, undivided	1,763.5 (537.5)	1,944.4 (592.6)	3.46 (.0084; .003)	5.80	1,404	1,525
Delaware Mountain Group	1,097.2 (334.4)	1,114.2 (339.6)	4.25 (.010; .003)	14.44	927	944
Average for county	4,174.2 (1,272.3)	4,374.1 (1,333.2)	4.45 (.011; .003)	8.96	3,408	3,548

Table 6.--Permeability and porosity information obtained from oil industry rock core analyses - Continued

LEA COUNTY

Geologic unit	Number of feet (metres) of core analyzed		Average permeability	Average porosity	Number of samples analyzed	
	Permeability	Porosity			Permeability	Porosity
Tansill Formation	440.9 (134.4)	423.9 (129.2)	1.76 (0.0043; 0.001)	4.00	325	308
Yates Formation	7,696.3 (2,345.8)	7,738.3 (2,358.6)	11.56 (.028; .008)	9.12	7,140	7,183
Seven Rivers Formation	4,251.7 (1,295.9)	4,442.9 (1,354.2)	58.98 (.140; .043)	6.50	3,902	4,020
Queen Formation	4,933.3 (1,503.7)	5,404.1 (1,647.2)	16.29 (.040; .012)	7.30	4,281	4,614
Grayburg Formation	1,925.2 (586.8)	1,956.6 (596.4)	15.04 (.037; .011)	7.32	1,780	1,812
Grayburg Formation-San Andres Limestone, undivided	7,026.1 (2,141.6)	7,148.1 (2,178.7)	16.03 (.039; .012)	5.71	5,589	5,719
"Glorieta Sandstone"	1,362.6 (415.3)	1,331.9 (406.0)	10.28 (.025; .008)	8.44	1,057	1,038
Delaware Mountain Group	1,148.7 (350.1)	1,149.7 (350.4)	10.75 (.026; .008)	19.81	997	998
Average for county	28,784.8 (8,773.6)	29,595.5 (9,020.7)	20.45 (.050; .015)	7.76	25,071	25,692

Table 6.--Permeability and porosity information obtained from oil industry rock core analyses - Continued

WINKLER COUNTY

Geologic unit	Number of feet (metres) of core analyzed		Average permeability	Average porosity	Number of samples analyzed	
	Permeability	Porosity			Permeability	Porosity
Tansill Formation	74.0 (22.6)	72.0 (21.9)	6.98 (0.017; 0.005)	5.58	74	73
Yates Formation	2,348.8 (715.9)	2,585.3 (788.0)	9.96 (.024; .007)	11.29	2,224	2,453
Seven Rivers Formation	323.5 (98.6)	327.5 (99.8)	2.13 (.005; .002)	7.13	319	323
Queen Formation	2,416.2 (736.5)	2,405.2 (733.1)	6.12 (.015; .005)	8.19	2,098	2,087
Grayburg Formation-San Andres Limestone, undivided	61.1 (18.6)	61.1 (18.6)	4.27 (.010; .003)	10.16	62	62
"Glorieta Sandstone"	1,711.5 (521.7)	1,712.8 (522.0)	12.31 (.030; .009)	9.99	1,999	2,005
Delaware Mountain Group	221.5 (67.5)	222.5 (67.8)	14.41 (.035; .011)	17.80	216	217
Average for county	7,156.6 (2,181.3)	7,386.4 (2,251.4)	8.93 (.022; .007)	9.92	6,992	7,226

Table 6.--Permeability and porosity information obtained from oil industry rock core analyses - Continued

WARD COUNTY

Geologic unit	Number of feet (metres) of core analyzed				Average permeability	Average porosity	Number of samples analyzed	
	Permeability		Porosity				Permeability	Porosity
Yates Formation	1,537.6	(468.7)	1,301.6	(396.7)	8.02 (0.020; 0.006)	10.12	1,380	1,199
Seven Rivers Formation	113.7	(34.7)	113.7	(34.7)	117.85 (.290; .088)	5.04	85	85
Queen Formation	739.4	(225.4)	739.4	(225.4)	7.96 (.019; .006)	9.34	630	630
Grayburg Formation-San Andres Limestone, undivided	9.1	(2.8)	9.1	(2.8)	6.35 (.015; .005)	7.60	7	7
"Glorieta Sandstone"	100.6	(30.7)	100.6	(30.7)	2.17 (.005; .002)	4.70	72	72
Delaware Mountain Group	2,394.4	(729.8)	2,319.4	(707.0)	5.06 (.012; .004)	13.79	2,227	2,262
Average for county	4,894.8	(1,491.9)	4,583.8	(1,397.1)	8.99 (.022; .007)	11.60	4,511	4,255

Table 6.--Permeability and porosity information obtained from oil industry rock core analyses - Continued

Data for Eddy and Lea Counties, N. Mex. and Winkler and Ward Counties, Tex. combined

Geologic unit	Number of feet (metres) of core analyzed		Average permeability	Average porosity	Number of samples analyzed	
	Permeability	Porosity			Permeability	Porosity
Tansill Formation	514.9 (156.9)	495.9 (151.2)	2.51 (0.006; 0.002)	4.23	399	381
Yates Formation	12,149.9 (3,703.3)	12,192.4 (3,716.2)	10.79 (.026; .008)	9.74	11,287	11,384
Seven Rivers Formation	4,747.9 (1,447.2)	4,943.1 (1,506.7)	55.81 (.140; .043)	6.56	4,364	4,485
Queen Formation	8,473.7 (2,582.8)	8,935.5 (2,723.5)	12.01 (.029; .088)	7.79	7.324	7.648
Grayburg Formation	2,227.7 (679.0)	2,259.1 (688.6)	13.24 (.032; .010)	7.15	1,941	1,973
Grayburg Formation-San Andres Limestone, undivided	8,859.8 (2,700.5)	9,162.7 (2,792.8)	13.44 (.033; .010)	5.76	7,062	7,313
"Glorieta Sandstone"	3,174.7 (967.6)	3,145.3 (958.7)	11.12 (.027; .008)	9.16	3,128	3,115
Delaware Mountain Group	4,932.7 (1,503.5)	4,876.7 (1,486.4)	6.70 (.016; .005)	15.65	4,549	4,493
Average for all four counties	45,010.4 (13,719.2)	45,939.8 (14,002.5)	15.88 (.039; .012)	8.63	39,982	40,721

Table 6.--Permeability and porosity information obtained from oil industry rock core analyses - Concluded

Data for shelf sedimentary rocks for Eddy and Lea Counties, N. Mex. and Winkler and Ward Counties, Tex.

Geologic unit	Number of feet (metres) of core analyzed		Average permeability	Average porosity	Number of samples analyzed	
	Permeability	Porosity			Permeability	Porosity
Tansill, Yates, Seven Rivers, Queen, and Grayburg Formations, "Glorieta Sandstone", and San Andres Limestone combined	36,939.5 (11,259.2)	37,954.3 (11,568.5)	17.53 (0.043; 0.013)	7.69	32,360	33,168

Data for shelf sedimentary rocks for Lea County, N. Mex. in area bounded by 103.06 and 103.50 degrees east longitude and 32.00 and 32.75 degrees north latitude, Lea County, N. Mex. on the northern end of the Central Basin platform.

Geologic unit	Permeability (feet (metres))	Porosity (feet (metres))	Average permeability	Average porosity	Samples: Permeability	Samples: Porosity
Tansill, Yates, Seven Rivers, Queen, and Grayburg Formations, and San Andres Limestone combined	20,996.6 (6,399.8)	21,875.2 (6,667.6)	24.47 (0.060; 0.018)	7.44	18,697	19,365

Data for Grayburg Formation and San Andres Limestone in area bounded by 103.06 and 103.50 degrees east longitude and 32.00 and 32.75 degrees north latitude, Lea County, N. Mex. on the northern end of the Central Basin platform.

Geologic unit	Permeability (feet (metres))	Porosity (feet (metres))	Average permeability	Average porosity	Samples: Permeability	Samples: Porosity
Grayburg Formation-San Andres Limestone, undivided	3,364.1 (1,025.4)	3,513.6 (1,070.9)	27.85 (0.068; 0.021)	6.96	2,792	2,941
Grayburg Formation	2,973.6 (906.4)	3,010.6 (917.6)	19.47 (.048; .015)	6.72	2,417	2,452
San Andres Limestone	219.5 (66.9)	219.5 (66.9)	68.68 (.17; .052)	10.01	188	188

1/ Permeability given in millidarcies with approximate equivalent hydraulic conductivity in ft/day (m/day). Porosity is effective porosity as percent of rock volume.

Table 7.--Hydraulic characteristics of the Capitan and San Andres aquifers

Location of aquifer test[1/]	Aquifer	Date of completion of test	Interval tested Depth, in feet (metres), below land surface or other reference datum		Hydraulic conductivity determined from interval tested		Remarks
			Top	Bottom	ft/day	(m/day)	
2,310 ft (704 m) FNL and 2,970 ft (905 m) FEL, sec. 7, T.20 S., R.38 E., Lea County, N. Mex.	San Andres	7-26-66	4,200 (1,280)	4,550 (1,387)	0.2	0.06	Drawdown test. Effects measured in pumped well. Well produced through open-hole completion. Well pumped at rate of 92 gpm (501 m^3/d) for 96 hours.
Do.	do.	7-27-66	4,200 (1,280)	4,550 (1,387)	.2	.06	Recovery test. Effects measured in pumped well. Well recovery measured for 24 hours.
1,993 ft (607 m) FEL and 3,060 ft (934 m) FNL, sec. 5, T.21 S., R.27 E., Eddy County, N. Mex.	Capitan	8-12-69	1,007 (306.7) 1,024 (312.1) 1,042 (317.6) 1,059 (322.8 1,167 (355.7	1,014 (309.1) 1,025 (312.4) 1,044 (318.2) 1,060 (323.1) 1,170 (356.6)	2.4	.73	Recovery test. Effects measured in pumped well. Well produced through 14 ft (4 m) net of perforations in casing. Well was acidized with 6,000 gal (22.7 m^3) of 15 per-cent hydrochloric acid. Well was swabbed at an estimated 85 gpm (463 m^3/d) for 3 1/3 hrs prior to shut in for test. Recovery measured for 140 hours.
1,650 ft (503 m) FNL and 1,650 ft (503 m) FWL, sec.30, T.21 S., R.28 E., Eddy County, N. Mex.	do.	8- 9-61	640 (195.1)	1,060 (323.1)	16	4.98	Recovery test. Effects measured in pumped well. Well produced through open-hole com-pletion. Aquifer was not treated with acid. Water produced with air lift at estimated rate of 100 gpm (545 m^3/d) for 4 hours. Re-covery period of only 28 minutes. Driller reported lost circulation zone during pene-tration of Capitan Limestone. A similar hydraulic conductivity was estimated from specific capacity.
1,650 ft (503 m) FSL and 330 ft (101 m) FWL, sec.24, T.21 S., R.34 E., Lea County, N. Mex.	do.	1-14-65	3,547 (1,081.1)	5,020 (1,530.1)	3.0	.92	Hydraulic conductivity estimated from specific capacity of well. Specific capacity was de-termined after well pumped at rate of approx-imately 240 gpm (1,308 m^3/d) over a period of about 207 hours. Well produced from open-hole completion after acidizing with 15,000 gal (57 m^3) of 15 percent hydrochloric acid.

Table 7.--Hydraulic characteristics of the Capitan and San Andres aquifers - Continued

Location of aquifer test[1/]	Aquifer	Date of completion of test	Interval tested Depth, in feet (metres), below land surface or other reference datum		Hydraulic conductivity determined from interval tested		Remarks
			Top	Bottom	ft/day	(m/day)	
1,650 ft (503 m) FWL and 660 ft (201 m) FNL, sec.14, T.21 S., R.35 E., Lea County, N. Mex.	Capitan	7- 8-62	4,178 (1,273.5)	4,663 (1,421.3)	1.7	.52	Hydraulic conductivity estimated from specific capacity of well. Specific capacity was determined after well pumped at rate of approximately 270 gpm (1,472 m^3/d) over a period of about 90 hours. Well produced from open-hole completion.
Do.	do.	10-15-66	4,178 (1,273.5)	4,663 (1,421.3)	3.5	1.07	Drawdown test. Effects measured in pumped well. Well pumped only 28 minutes before equipment failure. Open-hole completion. Aquifer treated with 5,000 gal(19 m^3) of 15 percent hydrochloric acid on March 3, 1965. Periodic cleaning of "silt"[2/] from borehole required to maintain production.
Do.	do.	12-14-66	4,178 (1,273.5)	4,663 (1,421.3)	1.9	.58	Drawdown test. Effects measured in pumped well. Well pumped for approximately 26 hrs. Average discharge rate of 328 gpm (1,788 m^3/d) during test.
Do.	do.	12-15-66	4,178 (1,273.5)	4,663 (1,421.3)	1.4	.43	Recovery test. Effects measured in production well. Well recovery measured for approximately 4 hours.
660 ft (201 m) FNL and 200 ft (61 m) FWL, sec.29, T.22 S., R.37 E. Lea County, N. Mex.	San Andres	11-22-66	3,922 (1,216.8)	4,985 (1,519.4)	.3	.09	Drawdown test. Drawdown measured in observation well 2,216 ft (675 m) from pumped well. Well drawdown measured for 120 hours with well pumped at constant rate of 190 gpm (1,036 m^3/d). Well shut in for 48 hrs prior to start of test. Well produced through 291 casing perforations. Well acidized with 65,000 gal (246 m^3) of hydrochloric acid. Storage coefficient of 1.5×10^{-5} determined.

Table 7.--Hydraulic characteristics of the Capitan and San Andres aquifers - Concluded

Location of aquifer test[1/]	Aquifer	Date of completion of test	Interval tested Depth, in feet (metres), below land surface or other reference datum		Hydraulic conductivity determined from interval tested		Remarks
			Top	Bottom	ft/day	(m/day)	
1,313 ft (400 m) FSL and 1,327 ft (404 m) FWL, sec. 4 T.24 S., R.36 E., Lea County, N. Mex.	Capitan	2-28-68	3,875 (1,181.1)	4,500 (1,371.6)	24	7.32	Drawdown test. Effects measured in pumped well. Well produced through open-hole completion. Well pumped at rate of 550 gpm (2,998 m^3/d) for 10 hours after being shut in for more than 24 hours. Open-hole completion without acid treatment. Driller reported two lost circulation zones while drilling through the Capitan Limestone.
Do.	do.	2-28-68	3,875 (1,181.1)	4,500 (1,371.6)	25	7.62	Hydraulic conductivity estimated from specific capacity of well as determined during drawdown test above.
1,313 ft (400 m) FSL and 1,310 ft (399 m) FWL, sec.16, T.24 S., R.36 E., Lea County, N. Mex.	do.	10- 4-67	3,955 (1,205.5)	4,500 (1,371.6)	4.4	1.34	Hydraulic conductivity estimated from specific capacity of well. Specific capacity was determined after well pumped approximately 47 hours at rate of 504 gpm (2,747 m^3/d). Well was not treated with acid. Driller reported that tools dropped from 2 to 6 ft (0.6 to 1.8 m) several times while drilling in Capitan Limestone. Lower 200 ft (61 m) of hole caved in after rotary tools were removed. Sand pump and boiler was used to remove rock fragments. The largest pieces recovered were 2 to 3 in (5 to 8 cm) in diameter. Open-hole completion.

1/ Location of well site from nearest section lines are expressed by an acronym composed of 3 letters. "F" and "L" represent "from" and "line", respectively. The middle letter represents the compass direction, N-north; E-east; S-south; and W-west.

2/ "silt" recovered from well was determined to be calcium sulphate that was presumably precipitated from water during pumping (L. S. Land, personal communication, 1972).

Oil companies supplies core analyses from oil and gas test wells in response to requests made after searching the Permian Basin Well Data System scout records. Data extracted from these core analyses appear to provide a representative coverage of the hydraulic characteristics of the basin and shelf aquifers in Lea and Eddy Counties, New Mexico and Winkler and Ward Counties, Texas (table 6). Several aquifer performance tests of the Capitan and San Andres aquifers were conducted in cooperation with oil companies, and a limited amount of additional information was obtained from private sources (table 7). The aerial distribution of these data are shown by individual well in figure 21.

The values of hydraulic conductivity and porosity given in tables 6 and 7 are in good agreement with those reported by Hogan and Sipes (1966) and with the generalized information provided in studies or statistical summaries of individual fields published by the Texas Petroleum Research Committee, the Roswell and West Texas Geological Societies, and the Texas University Bureau of Economic Geology.

Sections of anhydrite, shale, gypsum, halite, and other "dense" or "tight" beds recovered from a cored interval are frequently discarded prior to determining the permeability and porosity. Also, cores are normally cut only in the most prospective part of the geologic section in exploratory wells and in the producing reservoir in development wells. Therefore, the values of permeability and porosity determined from cores and given in reports may be, and quite likely are, larger than values representative of the entire shelf and basin sections.

A pulse-type aquifer-performance test of very short duration was attempted on five of the observation wells east of the Pecos River in Eddy County. The tests were accomplished by pumping compressed air into the previously enclosed casing and slowly depressing the water surface in the well column. After a sufficiently long stabilization period, the air was suddenly released and the rise in water level measured very accurately with a transducer and strip chart recorder. Unfortunately, the results of these aquiferpulse tests proved to be inconclusive.

Capitan aquifer system

Quantitative information

Single well aquifer-performance tests were accomplished in cooperation with an oil company during October 1966 and again in December 1966 on a well completed in the Capitan aquifer in sec. 14, T.21 S., R.35 E., Lea County. A similar performance test had been conducted previously by another oil company on the same well. Values of hydraulic conductivity determined from recovery and drawdown tests and estimated from measurements of the specific capacity range from 1.4 to 3.5 ft/day (0.43 to 1.07 m/day) for this well (table 7).

A multiple-well performance test was attempted on wells completed in the Capitan aquifer in cooperation with an oil company during October 1967. The pumped well was located in sec. 16, T.24 S., R.36 E., approximately 3,800 feet from the USGS Federal Davison 1 observation well in sec. 20, T.24 S., R.36 E., Lea County. Unfortunately, pressure fluctuations caused by the passage of an intense cold front during the test prevented accurate measurements of the drawdown and recovery in the observation well. However, a hydraulic conductivity of 4.4 ft/day (1.34 m/day) was estimated from the specific capacity of the pumped well.

Hydraulic conductivities of 24 and 25 ft/day (7.3 and 7.6 m/day) were determined from measurements of the drawdown and estimated from the specific capacity, respectively, in another well with a similar open-hole completion in the Capitan aquifer located about 2 miles (3 kilometres) to the north in sec. 4, T.24 S., R.36 E., in the same well field.

Records maintained during the prolonged testing of a well completed in the Capitan aquifer in sec. 24, T.21 S., R.34 E., Lea County, near the USGS South Wilson Deep Unit 1 observation well, were made available by an oil company. A hydraulic conductivity of 3.0 ft/day (0.92 m/day) was determined from the specific capacity of this well.

A crude single well recovery test was conducted in the USGS North Cedar Hills Unit 1 well, sec. 5, T.21 S., R.27 E., Eddy County, during August 1969. A hydraulic conductivity of 2.4 ft/day (0.73 m/day) was determined from the data collected during this test.

A single well recovery test of the Capitan aquifer was accomplished during August 1961 by consultants for the city of Carlsbad in the city of Carlsbad Test Well 3 (Miller Nix-Yates Federal 1) in sec. 30, T.21 S., R.28 E., Eddy County. This well is now in the USGS Capitan aquifer observation-well network. A hydraulic conductivity of approximately 16 ft/day (4.9m/day) was determined from re-interpretation of the short recovery test data and the specific capacity of the well. This value is about one-fifth as large as that given in the New Mexico State Engineer Hearing (1962) by Mr. J. R. Barnes, expert witness for the city of Carlsbad.

Brackbill and Gaines (1964) report permeabilities of 1 to 6 darcies (0.73 to 4.5 m/day) for the El Capitan water field in northern Winkler County, Texas (fig. 19). However, subsequent discussions with oil company employees suggest that a permeability of 1 darcy (0.73 m/day) would be more representative for this large water field and the general area.

Hydraulic conductivities of 5.2 and 2.4 ft/day (1.6 and 0.73 m/day) were estimated from specific capacities of two wells completed in the lower part of the Capitan aquifer in the O'Brien water field in northern Ward County, Texas (figs. 7 C-C', and 19; and White, 1971).

Qualitative information

Development of secondary porosity and permeability

The solution, removal, recrystallization, and redeposition of carbonate material by the selective action of moving ground water during two major periods of time has unquestionably enhanced the porosity and permeability of the Capitan aquifer.

Ground-water action during the Late Permian

Vadose solution and cementation features, including caliche pisolites, floored cavities, collapse breccia, clastic dikes, and teepee structures, indicate that the shelf and shelf-margin sediments were apparently repeatedly exposed and subjected to subaerial erosion during the Guadalupian Epoch and the initial (Castile) part of the Ochoan Epoch (Dunham, 1965a, 1965b, 1969, and 1972; Thomas, 1965 and 1968; and Meissner, 1972). Feldspar in the terrigenous sandstones within the Capitan aquifer has been altered to koalinite by the intense leaching action of percolating ground water (Dunham, 1972).

Ground water moving through the shelf and shelf-margin carbonates in the phreatic zone during the cyclic low stands of sea level also undoubtedly contributed to the development of solution porosity. Collapse features typical of a karst topography were formed during the Guadalupian Epoch within beds in the Carlsbad facies of the Artesia Group. This is evident in at least one surface exposure in Walnut Canyon west of White City on the road to Carlsbad Caverns (A. D. Jacka, oral commun.).

Much of the secondary porosity and permeability that originated during the Late Permian apparently has not been reduced by later cementation and infilling. The original hydraulic characteristics were, and still are, an important factor in influencing the flow of ground water through the aquifer.

Ground-water solution during the Late Cenozoic Uplift of the Guadalupe and Glass Mountains

According to Hayes (1964, p. 54), the majority of the faulting and the principal uplift of the Guadalupe Mountains probably occurred late in the Pliocene and early in the Pleistocene. The age of the block faulting in the Glass Mountains is not as well known, but it probably was more or less contemporaneous with the uplift of the Guadalupe, Delaware, and Apache Mountains along the western margin of the Delaware basin. The present drainage system, landscape, colluvium, alluvium, and other sedimentary deposits have formed since the uplift of these mountains and are still being modified.

The joints and fractures resulting from mountain building activity are most extensive in the Capitan aquifer in the Glass and Guadalupe Mountains but are also apparently well developed along the western margin of the Central Basin platform.

A large amount of fractured limestone and dolomite were reported to have been bailed from the Skelly Oil Co. Jal Water Supply Well 1, sec. 16, T.24 S., R.36 E., Lea County after an open-hole section in the Capitan aquifer caved during completion of this well. Angular pieces of limestone ranging in size from less than an inch to several inches were observed at the well site after completion of this water well. Abnormally high rates of production from some of the oil wells located on the Central Basin platform have been attributed to increased hydraulic conductivities resulting from fractured reservoir rock.

Caves in the Guadalupe Mountains

Relatively good hydraulic communication between the Pecos River and the Capitan aquifer probably was first established late in the Pliocene Epoch or early in the Pleistocene after deposition of the Ogallala Formation. From that time, the movement of ground water through the Capitan aquifer in the Guadalupe Mountains has been controlled principally by the stage of the Pecos River at Carlsbad. (Dark Canyon and some of the other northeastward or eastward oriented drainage cutting across the Capitan aquifer in the Guadalupe Mountains may predate the Pecos River. If so, formation of the prominent caves and other late Cenozoic solution features may have been initiated earlier in the Pliocene Epoch.) The several well-defined levels of cave development that have been mapped in the Guadalupe Mountains are attributed to long periods of stability in the level of the water table (Gale, 1957; and Hayes, 1964, p. 50). The distinct changes in the altitude of the water table may have resulted from eposodic uplift of the Guadalupe Mountains and (or) periodic changes in the local base level of the Pecos River drainage system.

Carlsbad Caverns are the largest and, by far, the most famous of numerous caves carved into the Capitan, Goat Seep, and San Andres Limestones and the Artesia Group in the Guadalupe Mountains southwest of Carlsbad (Bretz, 1949; Gale, 1957; and Hayes, 1964). The solution of limestone in the strata comprising the Guadalupe Mountains fault block probably commenced along joints, because these and other fractures were the conduits through which ground water could move most easily. Consequently, the patterns of individual caves now closely parallel the regional joint system. In addition to the tectonic control, all the caves are localized in the more soluble limestone in preference to the dolomites in the carbonate lithofacies of the Guadalupian age strata (J. S. McLean, personal commun., 1973). Caves and other large-scale ground-water solution features are either absent or rarely observed in the basin and shelf aquifer in the vicinity of the Guadalupe Mountains although they are abundant in the Roswell basin in the vicinity of Roswell and Artesia. Cave development in Guadalupian strata in New Mexico is restricted to areas west of the Pecos River valley at Carlsbad.

Rauch and White (1970) have studied the development of solution porosity in Ordovician and Cambrian carbonate aquifers in Pennsylvania extensively and have determined that most of the caves were developed entirely within limestones. Caves developed in dolomite were rarely found. Furthermore, the largest caves were associated with limestones containing relatively low fractions of dolomite, clay, and other impurities. The caves were also associated with fine-grained limestones (lime mudstones?) rather than the coarser grained limestones and dolomites.

Motts (1968) found that the greatest amount of solution in the Guadalupian shelf-carbonate facies southwest of Carlsbad occurred along joints in the coarser textured carbonates. However, he also observed that the limestones were much more readily dissolved by the action of moving ground water than were the dolomites or dolomitic limestones.

Kendall (1969, p. 2517) in a discussion of the diagenetic changes that have occurred in the barrier island and flat facies of the Carlsbad facies (former Carlsbad Group) in the Guadalupe Mountains has described a process involving the selective leaching of calcite from some of the dolomites, thus "leaving an insoluble residue of unconsolidated powdery dolomite and some quartz." Kendall attributed the residue of dolomite to relatively recent solution of the calcite by downward precolation of fresh ground water.

Caves in the Glass Mountains

The "blowing and sucking of air," a phenomenon typical of the interchange of air between caverns and the atmosphere in response to seasonal or daily variations in barometric pressure and air temperature, has been observed to be associated with wells penetrating the Capitan aquifer in the Glass Mountains (Dr. D. J. Sibley, Jr., personal commun., 1972). Drillers also have reported the penetration of small caverns during the drilling of water wells in the Glass Mountains. However, extensive interconnected systems of caverns similar to those found in the Guadalupe Mountains have not been found in the Glass Mountains, nor have they been delineated in the Capitan aquifer in the subsurface along the margin of the Delaware basin east of Carlsbad or north of the Glass Mountains.

Water entering the Guadalupe Mountains as rain or snowmelt flows relatively rapidly through the Capitan aquifer, dissolving some of the calcareous sediments through which it moves, and then discharges into the Pecos River at Carlsbad as spring flow. The Glass Mountains are not drained by nearby deeply-incised streams. Water entering the Glass Mountains as precipitation must move comparatively slowly northward and eastward following tortuous paths toward points of natural discharge into adjacent aquifers. In comparison with the Guadalupe Mountains, much less water has moved through the aquifer system in the Glass Mountains and, consequently, fewer and smaller caverns have been excavated in the carbonate rocks.

Anomalously high porosity in the subsurface

Relatively thin zones of very high porosity have been detected occasionally in the Capitan aquifer along the northern and eastern margins of the Delaware basin east of the Pecos River valley at Carlsbad. The porous zones often can be located through interpretation of the "breaks" encountered by operators during the drilling of oil and gas wells and from examination of sonic or acoustic velocity types of electrical logs to locate intervals with "cycle skipping."

Typical examples of the "cavernous" zones with high porosity have been found at intervals described in the following wells: In Eddy County--Barton Mobil Federal 1, sec. 24, T.21 S., R.26 E., from 518 to 530 feet (158 to 162 metres) and from 1,792 to 1,829 feet (546 to 557 metres); Pan American Petroleum Corp., Big Eddy Unit 18, sec. 3, T.21 S., R.29 E., from 2,600 to 2,660 feet (792 to 811 metres); E. C. Hale Federal 2, sec. 22, T.20 S., R.30 E., from 2,387 to 2,411 feet (728 to 735 metres); and in Lea County--Bass Brothers Enterprises, Inc. (USGS) North Custer Mountain Unit 1, sec. 28, T.23 S., R.35 E., from 4,485 to 4,518 feet (1,367 to 1,377 metres) (fig. 6). Gail (1974) has defined several of the porous zones within the Capitan aquifer in eastern Eddy County.

Information obtained from an oil company drill-cuttings log indicated that a section composed almost entirely of limestone was penetrated in the Barton Mobil Federal 1 well, sec. 24, T.20 S., R.26 E. Lithologic information was not available for the other wells described above. All the wells described above are located near the forereef edge of the shelf-margin facies and probably penetrate a section composed of limestone rather than the less soluble dolomite of the Carlsbad facies.

Most of the thin zones of high porosity noted on electrical logs or from drillers' records probably are not true caverns in the sense of the numerous large caves in the Guadalupe Mountains. Probably they represent limestones with either original highly porous textures, e.g., the poorly cemented algal lime grainstone recovered from the Skelly Oil Co. Jal Water Supply 1, sec. 16, T.24 S., R.36 E., or secondary "honeycomb" solution structures.

Preferential solution of carbonates by moving ground water

The hydraulic conductivity of the Capitan aquifer has been markedly enhanced by the selective solution and removal of carbonate material. The amount of rock dissolved appears very clearly to be primarily a function of (1) the total amount of ground water that has moved through the aquifer, (2) the lithology of the aquifer, with limestones being dissolved in preference to dolomites, (3) the jointing and fracturing of the aquifer---mainly due to small-scale crustal movements except for that due to the regional tilting and block faulting of the Glass and Guadalupe Mountains, and (4) the texture of the rock.

The original depositional textures appear to have been of critical importance in controlling the flow of ground water and, in turn, influencing the solution of carbonate material in the vadose and phreatic zones during the Guadalupian Epoch. However, the fractures and joints apparently were more important factors in controlling the movement of ground water during the late Cenozoic solution phase.

The hydraulic conductivity of the Capitan aquifer southwest of Carlsbad is extremely high due to the development of an extensive system of caverns, caves, and other voids by ground-water solution of the calcareous strata within the aquifer (Bretz, 1949; Hale, 1945a, and 1945b; and Motts, 1968). For similar reasons, the hydraulic conductivity of the Capitan aquifer in the Glass Mountains, while not nearly as high as that observed in the Guadalupe Mountains, is apparently much greater than it is in the subsurface farther to the north along the western margin of the Central Basin platform.

An analysis of the reconstructed late Cenozoic hydrogeologic history of the region suggests that much more ground water has moved through the Capitan aquifer along the eastern margin of the Delaware basin and for a longer period of geologic time than has moved through the aquifer along the northern margin of the Delaware basin between the Pecos River at Carlsbad and the middle of southern Lea County. Therefore, the increase in the hydraulic conductivity of the Capitan aquifer in the subsurface due to solution of calcareous rocks along the eastern margin of the Delaware basin is probably relatively greater than it is along the northern margin.

The location of the caverns and other ground-water solution structures in the Guadalupe Mountains is certainly controlled to a large extent by the relatively high solubility of limestone in comparison with that of dolomite. Similarly, the effects of ground-water solution in the Capitan aquifer along the north and east margins of the Delaware basin also seem to be restricted to the calcareous strata. Therefore, in any randomly selected transverse section of the Capitan aquifer, the highest hydraulic conductivities should be localized within the poorly bedded lime grainstone and wackestone of the Capitan and Goat Seep Limestones along the extreme seaward edge of the shelf margin, as defined by Dunham (1972).

Restricted movement of ground water in eastern Eddy County, New Mexico

Several lines of evidence point to an area with relatively low transmissivity in the vicinity of the boundary between Eddy and Lea Counties, New Mexico. The most important are: (1) the shape and configuration of the present-day potentiometric surface, (2) the fluctuation of water levels in the observation wells in the area, (3) interpretations of the cause for existing differences in the salinity of ground water, and (4) geologic evidence for the restriction of ground-water movement.

Shape of the potentiometric surface

Figures 22 and 23 are maps showing the pre and postdevelopment potentiometric surfaces representing the three systems of aquifers. These will be discussed more completely in a later section. Reference is made to the maps in relation to the area of restricted circulation of ground water in the Capitan aquifer.

The potentiometric surface developed in extreme eastern Eddy and western Lea Counties resembles the typical configuration expected to form as pressure declines reach an area with reduced transmissivity (figs. 22, 23, 24, and 25 and tables 8 and 9). Eastward gradients of about 25 feet per mile (5 m/km) have been developed in the Capitan aquifer in the vicinity of T.19-20 S., east one-half of R.30 E., and R.31 E., Eddy County. The gradient decreases rapidly to about 15 feet per mile (3 m/km) in the vicinity of T.20 S., R.33-34 E., Lea County. A much lower gradient of about 6 feet per mile (1 m/km) is present over the remainder of southern Lea County. The steepest gradients are located across the inferred restriction in the Capitan aquifer and are approximately 75 miles (120 kilometres) from the regional center of pumping just west of Kermit, Tex. The gradient across and to the east of the inferred restriction will continue to increase as indicated by the consistently large declines in water levels observed in the Middleton Federal B 1 well, sec. 31, T.19 S., R.32 E., Lea County, New Mexico (figs. 24 and 25).

Table 8.--Average monthly changes in water levels observed in the Capitan aquifer, southeastern New Mexico

Name of well	Location of well[1]	Date of start and end of period used in computing average changes	Number of months	Total change in water level, feet (metres) (-) - decline (+) - rise	Average change in water level, feet (metres) per month (-) - decline (+) - rise
City of Carlsbad Well 10 (Dark Canyon Well 1)	SW¼NW¼NE¼ sec. 24, T. 23 S., R. 25 E., Eddy County, New Mexico	Jan. 1, 1967 to Jan. 1, 1973	72	- 0.08 (0.024)	-0.001 (0.0003)
City of Carlsbad Well 13 (La Huerta East Well)	NW¼NE¼NE¼ sec. 36, T. 21 S., R. 26 E., Eddy County, New Mexico	Jan. 1, 1967 to Jan. 1, 1973	72	+ .68 (.207)	+ .009 (.0027)
Pecos River above Tansill dam at Carlsbad, N. Mex.[2]	NW¼NW¼NW¼ sec. 5, T. 22 S., R. 27 E., Eddy County, New Mexico	Jan. 1, 1967 to Jan. 1, 1970	36	+ .12 (.0366)	+ .003 (.0009)
North Cedar Hills Unit 1	1,993 feet (607 metres) FEL, 3,060 feet (934 metres) FNL, sec. 5. T. 21 S., R. 27 E., Eddy County, New Mexico	Jan. 1, 1967 to Jan. 1, 1973	72	+ .27 (.082)	+ .004 (.0012)
Humble State 1	660 feet (201 metres) FSL, 660 feet (201 metres) FWL, sec. 23, T. 21 S., R. 27 E., Eddy County, New Mexico	Feb. 1, 1968 to Jan. 1, 1973	59	+ 9.74 (2.97)	+ .165 (.050)
City of Carlsbad Test Well 3 (Miller Nix-Yates Federal 1)	1,650 feet (503 metres) FNL, 1,650 feet (503 metres) FWL, sec. 30, T. 21 S., R. 28 E., Eddy County, New Mexico	Jan. 1, 1967 to Jan. 1., 1973	72	- 2.05 (.625)	- .028 (.0085)
Yates State 1[3]	660 feet (201 metres) FSL, 1,650 feet (503 metres) FWL, sec. 32, T. 20 S., R. 30 E., Eddy County, New Mexico	Jan. 1, 1968 to Dec. 1, 1971 and Jan. 1, 1972 to Jan. 1, 1973	59	+ 7.01 (2.14)	+ .119 (.036)
Hackberry Deep Unit 1[3]	1,650 feet (503 metres) FNL, 990 feet (302 metres) FWL, sec. 31, T. 19 S., R. 31 E., Eddy County, New Mexico	Jan. 1, 1967 to Jan. 1, 1973	72	-22.90 (6.98)	- .318 (.097)

Table 8.--Average monthly changes in water levels observed in the Capitan aquifer, southeastern New Mexico - Concluded

Name of well	Location of well[1/]	Date of start and end of period used in computing average changes	Number of months	Total change in water level, feet (metres) (-) - decline (+) - rise	Average change in water level, feet (metres) per month (-) - decline (+) - rise
Middleton Federal B 1	660 feet (201 metres) FNL, 660 feet (201 metres) FWL, sec. 31, T. 19 S., R. 32 E., Lea County, New Mexico	Jan. 1, 1967 to Jan. 1, 1973	72	-119.90 (36.5)	-1.67 (.509)
South Wilson Deep Unit 1	1,980 feet (604 metres) FSL, 660 feet (201 metres) FWL, sec. 23, T. 21 S. R. 34 E., Lea County, New Mexico	Feb. 1, 1967 to Jan. 1, 1973	71	-93.48 (28.5)	-1.32 (.402)
North Custer Mountain Unit 1	660 feet (201 metres) FNL, 1,980 feet (604 metres) FWL, sec. 28, T. 23 S., R. 35 E., Lea County, New Mexico	Feb. 1, 1967 to Jan. 1, 1973	71	-88.58 (27.0)	-1.25 (.381)
Eugene Coates 3	660 feet (201 metres) FSL, 660 feet (201 metres) FWL, sec. 3, T. 24 S., R. 36 E., Lea County, New Mexico	Jan. 1, 1968 to Mar. 13, 1968 and Mar. 15, 1968 to Jan. 1, 1969	12	-16.80 (5.12)	-1.40 (.427)
Federal Davison 1	660 feet (201 metres) FNL, 1,980 feet (604 metres) FEL, sec. 20, T. 24 S., R. 36 E., Lea County, New Mexico	Jan. 1, 1967 to Jan 1, 1973	72	-126.13 (38.4)	-1.75 (.533)
Southwest Jal Unit 1	1,980 feet (604 metres) FNL, 1,980 feet (604 metres) FEL, sec. 4, T. 26 S., R. 36 E., Lea County, New Mexico	Jan. 1, 1967 to Jan. 1, 1973	72	-91.93 (28.0)	-1.28 (.390)

1/ Location of well site from nearest section lines are expressed by an acronym composed of 3 letters. "F" and "L" represent "from" and "line", respectively. The middle letter represents the compass direction, N=north; E=east; S=south; and W=west.
2/ Crest-stage gage.
3/ Change calculated from water levels adjusted for oil influx.

Table 9.--Narrative remarks referenced to hydrographs from observation-well network

City of Carlsbad Well 10:

1. Daily high water-level readings used through 12-31-65. Recorder installed.
2. Recorder not operating correctly from 8-7-66 to 8-10-66 due to flooding in nearby Dark Canyon.
3. Noon water-level readings begin.
4. Clock replaced and reset.
5. Records influenced by rain or flood from 6-30-67 to 7-2-67.
6. Records influenced by rain or flood from 8-30-68 to 9-1-68.
7. Records missing between 9-7-69 and 9-17-69. Paper supply depleted.
8. Records influenced by rain or flood from 9-17-69 to 9-19-69.
9. Records influenced by rain or flood from 10-20-69 to 10-24-69.
10. Records influenced by rain or flood from 9-17-70 to 9-22-70.
11. Records influenced by rain or flood from 10-5-70 to 10-10-70.
12. Clock stopped from 9-16-71 to 10-15-71. Counterweight hung on float wheel.
13. Records influenced by rain or flood from 9-2-72 to 9-19-72.

City of Carlsbad Well 13:

1. Daily high water-level readings used through 12-31-65. Recorder installed.
2. Noon water-level readings begin.
3. Weight came off. Float line loose from 6-15-67 to 6-27-67.
4. New clock installed.
5. Records influenced by rain or flood from 9-2-72 to 9-16-72.

Table 9.--Narrative remarks referenced to hydrographs from observation-well network - Continued

Tansill Dam Crest-Stage Gage:

1. Records influenced by rain or flood from 8-22-66 to 9-8-66.
2. Record missing between 12-4-66 and 1-11-67. Lake level lowered for city repairs.
3. Crest-stage gage discontinued.

North Cedar Hills Unit 1:

1. Acidized well.
2. Swabbed well.
3. Installed recorder.
4. Swabbed and acidized well.
5. Swabbed well.
6. Recorder reinstalled.
7. Tape measurement.
8. Tape measurement.
9. Clock replaced.
10. Swabbing completed. Tape measurement taken 139 minutes after pumping ceased.
11. Tape measurement.
12. Chart paper roll changed.
13. Started to add float line and lost it down well.
14. Records influenced by rain or flood from 9-1-72 to 9-25-72.

Table 9.--Narrative remarks referenced to hydrographs from observation-well network - Continued

Humble State 1:

1. Swabbed and acidized well.
2. Swabbed well.
3. Swabbed well.
4. Swabbed and acidized well.
5. Recorder installed.
6. Tape measurement.
7. Tape measurement.
8. Pen reset. Screws in clock had come off, and float was pulled up.
9. Tape measurement.
10. Tape measurement.
11. Tape measurement.
12. Recorder and shelter removed on 12-29-71. Fluid column sampled on 12-30-71. Recorder reinstalled on 1-6-72. 1.2 feet (0.037 metres) of oil on top of fluid.
13. 3.3 feet (1.0 metres) of oil on top of fluid column on 2-28-72.
14. New float and clock weight installed.
15. Records influenced by rain or flood from 9-15-72 to 9-27-72.

City of Carlsbad Test Well 3:

1. Digital recorder installed.
2. Daily high water-level readings used.
3. Data from 11-25-68 to 12-19-68 omitted because of unreliability.
4. Records influenced by rain or flood from 8-27-72 to 9-24-72.

Table 9.--Narrative remarks referenced to hydrographs from observation-well network - Continued

Yates State 1:

1. Swabbed from 8-29-67 to 9-1-67.
2. Recorder installed.
3. Chart roll changed and pen inked.
4. Pen removed to check for oil in well.
5. Clock stopped from 4-21-69 to 5-21-69. Negator spring was binding.
6. Recorder replaced 6-18-69.
7. Pulse test. Recorder was not operating from 9-3-69 to 10-15-69.
8. Recorder replaced 11-18-69.
9. Recorder and shelter removed on 10-20-71. Length of oil column was 77.4 feet (23.6 metres). Oil bailed from well on 10-22-71. Recorder reinstalled on 10-27-71.
10. Recorder and shelter removed on 12-27-71. Cast iron bridge plug set at 2,550 feet (777 metres) (KB) and well swabbed on 12-28-71 and 12-29-71. Recorder reinstalled on 1-6-72.
11. No oil present at top of water on 2-28-72.
12. Records influenced by rain or flood from 9-3-72 to 9-25-72.
13. Float line replaced with a line of a smaller diameter on 11-2-72.

Table 9.--Narrative remarks referenced to hydrographs from observation-well network - Continued

Hackberry Deep Unit 1:

1. Treated with acid and swabbed. Ran aquifer performance test.
2. Recorder installed.
3. Swabbed and acidized well.
4. Wire line measurement.
5. Poured 1 gallon (3.8 litres) of motor oil down well to free the line from the casing. Wire line measurement.
6. Wire line measurement used to make a correction to subsequent water-level data.
7. Measurement with logger.
8. Continual bubbling noise heard from well due to leakage of gas into borehole.
9. Can still hear bubbling noise.
10. Can hear only faint bubbling noise.
11. No audible bubbling noise.
12. Chart roll changed.
13. Clock stopped from 8-15-69 to 9-4-69 for pulse test.
14. Recorder and shelter removed. Length of oil column was 95.7 feet (29.2 metres) on 10-20-71. Oil bailed from well on 10-21-7. Recorder reinstalled on 10-27-71
15. Tape parted in hole on second measurement, jamming float.
16. Float reinstalled and recorder in operation on 12-14-71.
17. Poured 1 gallon (3.8 litres) of motor oil down well to free the line from the casing.
18. Float tape parted on the counterweight side of the recorder. Float line removed from well and replaced on 1-22-73.

Table 9.--Narrative remarks referenced to hydrographs from observation-well network - Continued

Middleton Federal B 1:

1. Installed recorder.
2. Swabbed 245 barrels (39 cubic metres) of water in 5 hours.
3. Pen skipping from 4-3-67 to 5-2-67.
4. Wire line measurement ignored.
5. Measurement with logger.
6. Conterweight caught on shelf from 9-9-68 to 9-19-68.
7. Added 12.13 feet (3.7 metres) of wire to float line. Water-level reading measured after unhooking counterweight.
8. Chart roll changed.
9. Wire added to float line.

South Wilson Deep Unit 1:

1. Recorder installed.
2. Wire line measurement.
3. Measurement with logger. Water-level reading missing from 5-18-68 to 5-19-68. New float line installed.
4. Cattle rubbing against shelter. Unreliable readings from 6-27-68 to 7-17-68.
5. Pen reset. Beads on float wheel slipped.
6. Wire added.

Table 9.--Narrative remarks referenced to hydrographs from observation-well network - Continued

North Custer Mountain Unit 1:

1. Swabbed approximately 330 barrels (52.5 cubic metres) of water
2. Depthometer measurement.
3. Approximately 330 barrels (52.5 cubic metres) of water swabbed and bailed.
4. Acidized with 1,000 gallons (3.8 cubic metres) regular 15 percent acid.
5. Swabbed approximately 540 barrels of (85.9 cubic metres) of water at 42 gallons per minute (229 cubic metres per day).
6. Static level after swabbing.
7. Recorder installed. Tape measurement.
8. Wire line measurement.
9. Measurement made but not used.
10. Logger and steel-tape measurement.
11. Beads out of holes on float wheel. Counterweight 0.3 feet (0.09 metre) from float wheel. Added 8.93 feet (2.72 metres) of float cable. Pen reset at 865.64 feet (263.85 metres).
12. Wire added.
13. Float line slightly hung from 9-12-69 to 9-17-69.
14. Weight hung on wheel. Added 10 feet (3 metres) of float line.

Eugene Coates 3:

1. Recorder installed.
2. Wire line measurement ignored.
3. Measurement with logger.
4. Beads out of holes on float wheel. Float line slightly hung from 8-2-68 to 8-14-68.

Table 9.--Narrative remarks referenced to hydrographs from observation-well network - Continued

Eugene Coates 3 - Concluded

5. Float line added.

6. Records missing from 1-23-69 to 2-20-69. Pen left in "up" position.

7. Recorder and shelter removed and well records discontinued on 5-6-69.

Federal Davison 1:

1. Recorder installed.

2. Clock replaced.

3. Added 20 feet (6 metres) of wire.

4. Wire line measurement.

5. Wire line measurement.

6. Large rise in water level. Duration of rise was 9 hours.

7. New clock installed.

8. Correction from logger measurement added to water-level readings from 4-17-68 to 5-16-68.

9. Float counterweight ran out of wire; weight hanging on float wheel. Wire spliced and added.

10. Float line added.

11. Cable added to float line.

12. Float line slightly hung from 7-18-69 to 8-19-69.

13. Recorder and shelter removed and water column sampled for the New Mexico State Engineer on 11-15-72.

Table 9.--Narrative remarks referenced to hydrographs from observation-well network - Concluded

Southwest Jal Unit 1:

1. Swabbed and acidized.
2. Measurement with logger.
3. Water-level recorder installed.
4. Wire line measurement ignored in preference to logger measurement of 5-16-68.
5. Wire line measurement ignored in preference to logger measurement.
6. Measurement with logger.
7. Float counterweight hung on float wheel between 10-9-68 and 10-17-68. Float line lengthened.
8. Float line lengthened.
9. Float line slightly hung.

Effects of long and short-term stresses

The water levels measured in the westernmost 6 of the 7 observation wells in Eddy County appear to respond to climatic conditions and the use of water in the Pecos River valley at Carlsbad but not recognizably to the withdrawal of water from the aquifer farther to the southeast. However, the water levels recorded in one well in extreme eastern Eddy County and five wells scattered throughout the Capitan aquifer in southern Lea County are obviously declining in response to withdrawal of water from the Capitan aquifer and other formations in measurable hydraulic communication with it in Lea County, New Mexico, and Ward and Winkler Counties, Texas (figs. 24 and 25).

Pulses in the potentiometric surface generated by floods on the Pecos River at Carlsbad and changes in the rate of pumping in the water fields located between Jal, N. Mex. and Monahans, Tex. do not appear to be transmitted, in a detectable magnitude, through the Capitan aquifer in either direction beyond the Eddy-Lea County boundary.

Comparison of the predevelopment and postdevelopment potentiometric surfaces (figs. 22 and 23, respectively) suggests that over a period of about 40 years, the head in the Capitan aquifer has been reduced approximately 200 feet (61 metres) in the vicinity of the Eddy-Lea County boundary. Declines of a similar magnitude have not occurred elsewhere in eastern Eddy County east of the Pecos River.

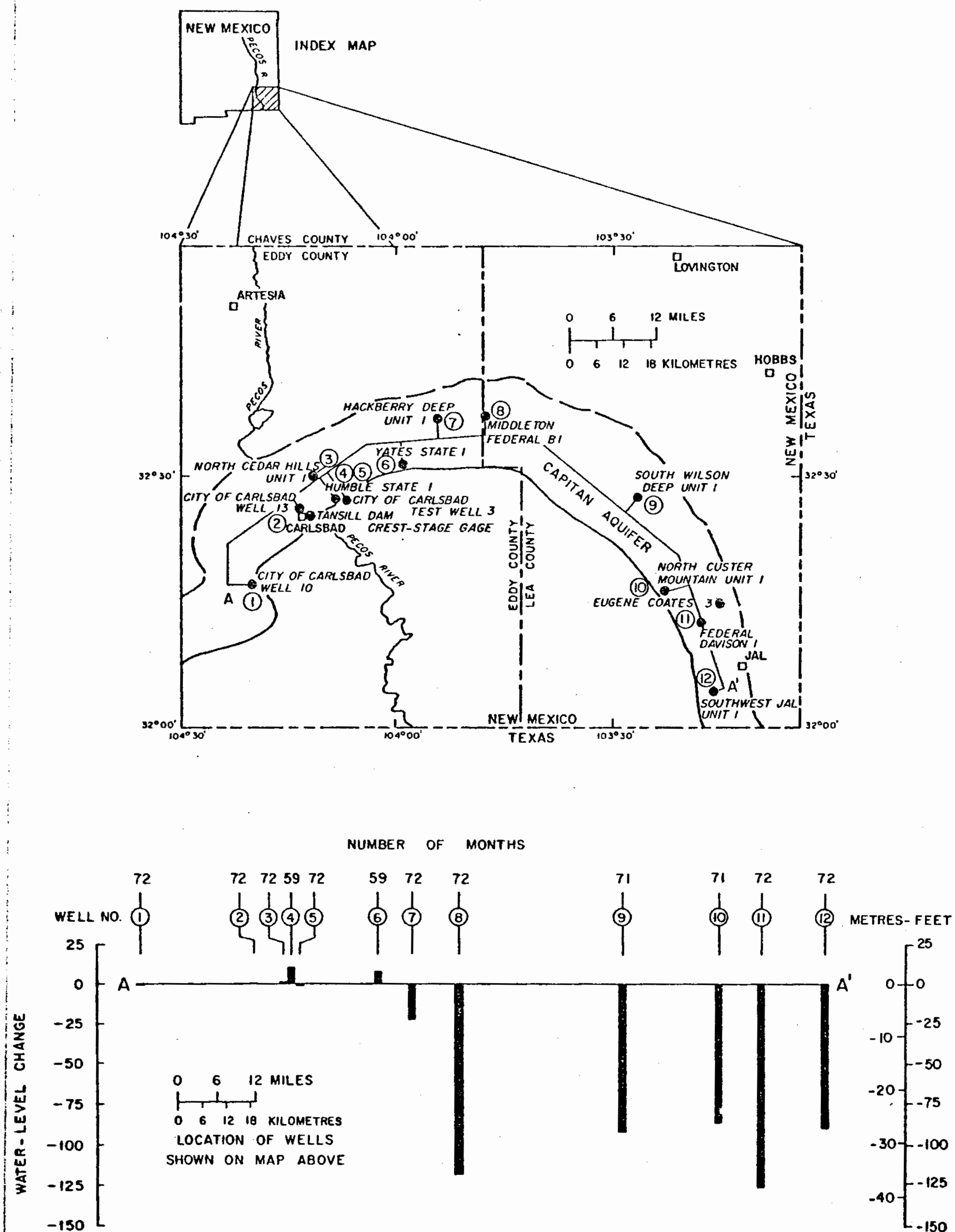


Figure 25.--Graph showing cumulative changes of water level in the Capitan aquifer observation wells, southeastern New Mexico.

Inferences from relative salinity of water

Relatively good water was emplaced in the Capitan aquifer east of Carlsbad prior to the excavation of the Pecos River at Carlsbad. Subsequently, highly mineralized water has leaked into the Capitan aquifer from the shelf and basin aquifers. The mixing of the two waters has taken place for an unknown time during the Pleistocene and Holocene Epochs. However, the available data suggest that the salinity of the water in the Capitan aquifer east of Carlsbad in New Mexico was never as low as the salinity of the water produced from this aquifer in Brewster, Pecos, Ward, and Winkler Counties, Texas (fig. 26). Apparently, the volume of fresh water that flowed eastward from the Guadalupe Mountains was not adequate to flush the original brines from the Capitan aquifer in Eddy and the northern part of southern Lea Counties.

The comparatively higher salinity of the water in the Capitan aquifer east of Carlsbad can be attributed to three factors: (1) an inadequate volume of water moving eastward due to lower transmissivity of the aquifer, (2) the establishment of hydraulic communication between the aquifer and the Pecos River very early in the geomorphic evolution of the Carlsbad area and consequent reduction in the total amount of water that flowed eastward from the Guadalupe Mountains, and (3) the subsequent leakage of higher salinity water into the Capitan aquifer from adjacent aquifers.

Geologic nature of the restriction

The igneous dike or dikes noted in the discussion of Tertiary igneous activity cut the Capitan aquifer east of the Middleton Federal B-1 observation well located in sec. 31, T.19 S., R.32 E. Lea County (figs. 11 and 21). Water levels in this well have declined consistently at the rate of approximately 1.7 feet (0.5 metres) per month over a period of 72 months, in contrast to the relatively small declines or rises in the water levels recorded in wells located farther to the west in Eddy County (table 8). Therefore, the dike or dikes do not appear to act as restrictions or barriers to movement of ground water.

The thickness of the Capitan aquifer is reduced to several hundred feet by the West Laguna submarine canyon in eastern Eddy County (fig. 11). The most prominent transverse linear thins, the West, Middle, and East Laguna submarine canyons, are located in the vicinity of the boundary between Eddy and Lea Counties where they coincide with both the position of the large increase in the eastward gradient in the potentiometric surface and the point where the largest declines in the hydraulic head commence. The transmissivity in this area has undoubtedly been reduced to a minor fraction of the average transmissivity of the Capitan aquifer by the Laguna submarine canyons, thereby restricting the movement of water eastward.

Regional hydraulic conductivity

Meager data of often-questionable reliability, in conjunction with an interpretation of the geohydrological history of the region, suggest that the hydraulic conductivity of the Capitan aquifer along the western margin of the Central Basin platform in Texas and New Mexico ranges from 1 to 25 ft/day (.3 to 7.6 m/day) (table 7). The hydraulic conductivity of the Capitan aquifer probably averages 5.0 ft/day (1.5 m/day) in most of southern Lea County, New Mexico, but appears to increase progressively southward to an estimated 10.0 ft/day (3.0 m/day) near the Pecos-Brewster County boundary in Texas. The hydraulic conductivity of the Capitan aquifer in the Glass Mountains is probably very high because of the numerous small caverns developed in this area (D. J. Sibley, Jr., personal commun.).

An average hydraulic conductivity of 5.0 ft/day (1.5 m/day) also would seem to be reasonable for the Capitan aquifer over a span of approximately 15 miles (24 kilometres) immediately east of the Pecos River valley at Carlsbad. Values of hydraulic conductivity in the Capitan aquifer west of the Pecos River at Carlsbad are apparently larger by as much as several orders of magnitude (Hale, 1945a and 1945b).

Local variations in transmissivity

The transmissivity of the Capitan aquifer in a small area near the boundary between Eddy and Lea Counties, New Mexico, in the vicinity of the deeply incised Laguna submarine canyons appears to be the lowest enocuntered anywhere within the project area.

A representative transmissivity for this major restriction has not yet been determined. However, the general response to stresses placed on the aquifer by (1) withdrawal of water in the water fields to the east, (2) recharge by floods in the Pecos River valley, and (3) precipitation in the Guadalupe Mountains to the west, suggest that the transmissivity must be at least one and perhaps two orders of magnitude lower than the average transmissivity of the Capitan aquifer.

Values of transmissivity for the Capitan aquifer in the area extending east of the Pecos River at Carlsbad around the northern and eastern margins of the Delaware basin to the Pecos-Brewster County boundary in Texas are estimated to range from approximately 10,000 ft^2/day (900 m^2/day) in the thicker intercanyon nodes to less than 500 ft^2/day (450 m^2/day) in the vicinity of the more deeply incised submarine canyons.

Shelf aquifers

Artesia Group

Aquifer-performance tests were not available for any of the formations in the Artesia Group on the Northwestern shelf east of the Pecos River between Carlsbad and Artesia, or on the Central Basin platform. The average hydraulic conductivities and porosities of the Grayburg, Queen, Seven Rivers, Yates, and Tansill Formations within the Artesia Group, the Grayburg Formation-San Andres Limestone, undivided, and the "Glorieta Sandstone" are shown on figure 21 and given in summary form in table 6 for Eddy and Lea Counties, New Mexico, and Ward and Winkler Counties, Texas. The average hydraulic conductivity and porosity of the shelf aquifers were determined to be 0.043 ft/day (0.013 m/day) and 7.69 percent, respectively. More than 32,000 measurements representing approximately 37,000 feet (11,300 metres) of core cut in wells scattered throughout the four-county area were statistically examined.

The hydraulic conductivity of the Seven Rivers Formation is significantly higher in Lea County, New Mexico, and Ward County, Texas than in the other two counties. This difference is apparently due to the more favorable location of some of the cored sections in the shelf-margin facies of the Seven Rivers Formation in Lea County and to the statistically small sample in Ward County rather than to a regional change in the lithology.

Values of permeability and porosity given by Hogan and Sipes (1966) for the Grayburg, Queen, Seven Rivers, and Yates Formations in a statistical summary representing an unknown number of analyzed cores from wells drilled in many of the counties in western Texas tend to be slightly larger than those shown in table 6, but, overall, are in general agreement.

An average hydraulic conductivity of .073 ft/day (.002 m/day) was computed from 26 typical productivity indexes measured by several oil companies in 14 oil wells producing from various pay zones within the Artesia Group. The wells were randomly located within the Premier field, Eddy County, and the Eumont, Eunice South, Jalmat, and Langlie-Mattix fields, Lea County. Little variation was noted between the computed values, the lowest value being .004 ft/day (.001 m/day) in the Jalmat field and the highest value being .167 ft/day (.05 m/day) in the Eumont field.

San Andres Limestone on the northern end of the Central Basin platform

A multiple-well test of the San Andres Limestone was accomplished during November 1966 in cooperation with an oil company. The pumped well was located in sec. 29, T.22 S., R.37 E., Lea County, approximately 2,200 feet (670 metres) from the observation well in the Langlie-Mattix oil field. A hydraulic conductivity of 0.3 ft/day (.09 m/day) and a storage coefficient of 1.5×10^{-5} was determined from the 120-hour drawdown test (table 7). Vertical leakage between the San Andres and adjacent aquifers was also indicated during the test.

Information recorded during the drawdown and recovery periods of 96 and 24 hours, respectively, for a single well test of the San Andres Limestone located in sec. 7, T.20 S., R.38 E., in the Warren-McKee oil field on the northern edge of the Central Basin platform in southern Lea County was made available to the USGS through the cooperation of both an oil company and a consultant. A hydraulic conductivity of 0.2 ft/day (.06 m/day) was computed from analysis of these data (table 7).

A limited amount of permeability data for the San Andres Limestone on the north end of the Central Basin platform was obtained during the search for core analyses. The hydraulic conductivity of approximately 0.17 ft/day (.05 m/day) computed from these data confirms the relatively high permeability of the San Andres Limestone on the northern end of the Central Basin platform in comparison with the permeabilities determined from core analyses of the San Andres elsewhere and for other formations in the shelf aquifers (table 6, and fig. 21).

Stratigraphic reefs and carbonate mounds or banks have been reported to occur in the San Andres Limestone along both the northern and western margins of the Central Basin platform. A zone of relatively high transmissivity in the San Andres Limestone on the northern part of the Central Basin platform is inferred from a map of the chloride-ion concentration in water in rocks of Guadalupian age (fig. 26). Limited hydraulic conductivity data combined with stratigraphic and water-quality information, suggest that the hydraulic conductivity of the San Andres Limestone on the northern end of the Central Basin platform is significantly higher than the hydraulic conductivities of the Artesia Group and the San Andres Limestone in the remainder of the project area east of the Pecos River valley between Carlsbad and Artesia. Similar relatively high hydraulic conductivities are also probably present in the San Andres Limestone at the southern end of the Central Basin platform.

San Andres Limestone on the Northwest shelf
and Central Basin platform

Cores cut in the lower part of the Artesia Group and upper part of the San Andres Limestone are most often identified by the operator as Grayburg Formation-San Andres Limestone, undivided, and it was impossible to distinguish between the two formations when the data were processed. However, as shown on figure 21 and in table 6, the hydraulic conductivities of the Grayburg Formation and the Grayburg Formation-San Andres Limestone, undivided, on the northern end of the Central Basin platform, are only 0.048 and 0.068 ft/day (.015 and .02 m/day), respectively. These values are almost an order of magnitude lower than the hydraulic conductivities of the San Andres aquifer determined from the two aquifer performance tests (table 7). Similarly, the average hydraulic conductivity of the Grayburg Formation-San Andres Limestone, undivided, in Ward and Winkler Counties, Texas, and Eddy and Lea Counties, New Mexico, was determined from statistical analyses of the core data to be only 0.033 ft/day (.01 m/day).

Permeabilities reported by Kinney (1969) for the San Andres Limestone in southeastern New Mexico range generally from 0.1 to 5 millidarcies (hydraulic conductivities of approximately 0.00024 to 0.0122 ft/day or 0.000073 to 0.0037 m/day). Hogan and Sipes (1966) report an average permeability of 6.9 millidarcies (approximately 0.017 ft/day or 0.005 m/day) for an area including Ward, Winkler, Ector, Andrews, Gains, Yoakum, and Terry Counties, Texas, and an average permeability of 9.7 millidarcies (about 0.024 ft/day or 0.0073 m/day) for a large area in western Texas that does not include these seven counties.

An average porosity of about 10 percent was determined from core analyses from the San Andres aquifer on the northern end of the Central Basin platform. Kinney (1969) gives a general range of 3 to 5 percent for the porosity of the San Andres Limestone in southeastern New Mexico. The average porosity of the Grayburg Formation and San Andres Limestone, undivided, in Eddy and southern Lea Counties was determined from core analyses to be about 6 percent. Hogan and Sipes (1966) report porosities of 7 percent for Ward, Winkler, Ector, Andrews, Gaines, Terry, and Yoakum Counties and 15.5 percent for a large area in western Texas excluding the previously mentioned counties.

The hydraulic conductivity and porosity data given above are representative of the oil and saline water-bearing rocks outside of the Roswell and Carlsbad underground water basins (fig. 1) where much higher values for these parameters have been determined.

Basin aquifers

Delaware Mountain Group

An average hydraulic conductivity and porosity of 0.016 ft/day (0.0049 m/day) and 15.65 percent, respectively, were determined from approximately 4,500 samples of rock core cut from the Delaware Mountain Group in Eddy and Lea Counties, New Mexico and Ward and Winkler Counties, Texas (fig. 21, and table 6). An approximate hydraulic conductivity of 0.015 ft/day (0.0046 m/day) was computed from productivity indexes (approximately equivalent to specific capacities) obtained from an oil company for two wells in the El Mar field located on the boundary between Lea County, New Mexico, and Loving County, Texas.

Hogan and Sipes (1966) report permeability values of 12.9 to 24.5 millidarcies (hydraulic conductivities of approximately 0.031 to 0.060 ft/day or 0.0095 to 0.018 m/day), and porosities of 17.9 to 21.0 percent for much of the same part of the Delaware basin.

The values of hydraulic conductivity and porosity of the Delaware Mountain Group are in the same general range as those of the Artesia Group and the San Andres Limestone.

Comparative hydraulic characteristics of the aquifers

Except for a small area in eastern Eddy County, the average hydraulic conductivity of the Capitan aquifer is apparently a minimum of two orders of magnitude larger than the average hydraulic conductivity of the adjacent and partially enclosing shelf and basin aquifers, and one order of magnitude larger than the average hydraulic conductivity of the San Andres aquifer on the northern end of the Central Basin platform.

The transmissivity of the Capitan aquifer in extreme eastern Eddy County in the vicinity of the Laguna submarine canyons is apparently much less than the average for this aquifer and may be similar to the transmissivity of the shelf and basin aquifers.

Salinity of the water in rocks of Guadalupian age

Regional salinity

Water containing relatively low chloride-ion concentration is produced from the Capitan aquifer throughout the region, from the San Andres Limestone and Artesia Group where these units are in close association with the Capitan aquifer along the margin of the Northwestern shelf and Central Basin platform, and from the San Andres Limestone and the lower part of the Artesia Group at both ends of the Central Basin platform (fig. 26).

Fingers of the less mineralized water extend into the Capitan aquifer from potential fresh-water recharge areas in the Guadalupe and Glass Mountains. The 5,000 mg/l (milligrams per litre) isochlore in the Capitan aquifer extends only a few miles east of Carlsbad, whereas the same isochlore extends northward from the Glass Mountains to north of Hobbs. This indicates that relatively good water containing 1,000 to 5,000 mg/l chloride ion may be found in the Capitan aquifer on the northeastern and eastern edge of the Delaware basin and the northern and southern ends of the Central Basin platform. Water containing less than 1,000 mg/l chloride ion concentration is present in the Capitan aquifer in a tongue extending northward from the Glass Mountains to just north of the New Mexico-Texas border in southernmost Lea County.

In sharp contrast to the water of relatively good quality that is found in the Capitan aquifer, the rocks of Guadalupian age on the Northwestern shelf northwest of Hobbs, on the Central Basin platform, and in the Delaware basin, contain water with relatively high concentrations of chloride ion (fig. 26). Chloride-ion concentrations greater than 150,000 mg/l are present over large areas in the San Andres Limestone and Artesia Group on the Northwestern shelf and in the Delaware Mountain Group in the Delaware basin. Similarly, water containing chloride-ion concentrations of more than 100,000 mg/l is found in the San Andres Limestone and Artesia Group over much of the central part of the Central Basin platform.

Emplacement of the relatively better quality water

The water of better quality is found in rocks with the highest permeability and, conversely, the water of poorest quality is found in rocks with the lowest permeability. The water of relatively low salinity found in the Capitan aquifer, the Artesia Group, and San Andres Limestone in southeastern New Mexico and western Texas is most probably a result of selective displacement of original brines by movement of fresh water from the Glass and Guadalupe Mountains into the formations with regionally highest transmissivities.

Water entering the Capitan aquifer in the Guadalupe and Glass Mountains apparently moved toward a point southwest of present-day Hobbs, where it then entered the San Andres Limestone and formations in the lower part of the Artesia Group. The water then flowed eastward via a northeast-trending zone of relatively higher transmissivity in the shelf-margin rocks. The water moved into Andrews and Gaines Counties, Texas from the vicinity of Hobbs and eventually discharged into streams draining toward the Gulf of Mexico (Stevens, and others, 1965). The configuration of the isochlores in figure 26 suggests that the bulk of the water now in the Capitan aquifer in Lea County, New Mexico and Winkler, Ward, and Pecos Counties, Texas, came from the Glass Mountains.

Halite has been wholly or partially dissolved and removed from the Salado and Castile Formations wherever they are in juxtaposition with the Capitan aquifer along the northeast and eastern margins of the Delaware basin (figs. 7, D-D' and E-E', and 17; and Maley and Huffington, 1953; and Pierce and Rich, 1962). The anomalous thinning of the Salado and Castile Formations coincides with the location of the water of low salinity in the Capitan aquifer. Apparently, relatively fresh ground water has moved through the Capitan aquifer and dissolved the halite in adjacent formations. The tongues of water of better quality and anomalously thin areas in the Salado and Castile Formations are clues that aid in the explanation of the pattern of flow through the Guadalupian age strata.

The present-day potentiometric surface has adjusted to the Pecos River, which either incises or is in measurable hydraulic communication with the Capitan aquifer at Carlsbad and acts as an ungradient drain for the Permian formations. Discharge from the Permian rocks into the Pecos River appears to preclude the movement of large quantities of water toward the vicinity of Hobbs under present-day natural conditions (Spiegel, 1967). Therefore, most of the water of relatively low salinity in the Capitan aquifer in eastern Eddy and western Lea Counties east of Carlsbad probably was emplaced during Cenozoic time prior to the post-Pliocene cutting of the Pecos River.

Because of the incision of the Pecos River, the eastward gradient in the potentiometric surface east of Carlsbad was decreased and eventually reversed in part of the aquifer. The heads in the Capitan aquifer adjusted more rapidly to the new regimen in the Pecos River valley than the surrounding shelf and basin aquifer system because of the relatively higher hydraulic conductivity of the Capitan aquifer. The highly mineralized water in the shelf and basin aquifers east of Carlsbad then began leaking into the Capitan aquifer and, over a long period of time, commingled with the previously emplaced water of relatively better quality to produce the present moderately saline water found in the Capitan aquifer in eastern Eddy County. The water within the 5,000 mg/l isochlore that bends westward to T.20 S., R.34 E. in southern Lea County, New Mexico is probably a remnant of the better quality water that once filled the Capitan aquifer from this point westward to Carlsbad (fig. 26).

Waste water produced from the Cedar Hills, Getty, Barber, and PCA oil fields in Eddy County, New Mexico; Halfway, Teas, Lynch, Wilson, and San Simone oil fields in Lea County, New Mexico; and Hendrick field in Winkler County, Texas, is similar in chemical composition to the water in the adjacent and underlying Capitan aquifer (figs. 19 and 26; and Stripp and Haigler, 1956). Large volumes of water, in relation to the oil production, have been produced from the Yates Formation in these fields. Water quality and other reservoir data suggest that oil has been produced from all these fields under water-drive reservoir conditions. Water produced from the San Andres Limestone and Grayburg Formations in the Hobbs field and from other fields on the northern end of the Central Basin platform also is similar in chemical composition to the water produced from the Capitan aquifer in Lea County, New Mexico (figs. 19 and 26).

The quality of water and reservoir engineering data suggest that the hydraulic communication between the Capitan and shelf aquifers is relatively good at both ends of the Central Basin platform and where the two aquifers are juxtaposed along the margin of the Delaware basin.

Fresh-saline water interface near Carlsbad

The chloride-ion content and specific conductance of the circulated drilling fluid composed of a mixture of air and water was monitored in three wells drilled into the Capitan aquifer near Carlsbad. One well is located approximately 6 miles (10 kilometres) southwest of the city of Carlsbad, another is about 4 miles (6 kilometres) southwest of the city of Carlsbad water field, and the other is located in Happy Valley immediately to the west of Carlsbad. The specific conductivity data was plotted against well depth in figure 27.

The well drilled in sec. 34, T.21 S., R.26 E. was started in dolomite and sandstones in the Tansill Formation and bottomed in the Capitan Limestone. Water with an odor of sulfur was detected in the circulated drilling fluid commencing at a depth of about 760 feet (231 metres). A slight increase in the salinity of the drilling fluid was noted at a depth of 793 feet (242 metres). Comments made by the driller regarding the small amount of water being produced while drilling suggest that the permeability of the section penetrated in this well was very low. A conductivity of 35,850 micromhos per centimeter was measured in a sample of drilling fluid taken while drilling at a depth of 1,217 feet (371 metres).

The saline-fresh water interface was apparently encountered at an unknown distance below a depth of 760 feet (231 metres) and above 1,217 feet (371 metres). The saline-fresh water interface was inferred to be at an altitude of approximately 2,300 feet (700 metres) above sea level from the graph of conductivity versus depth (fig. 27).

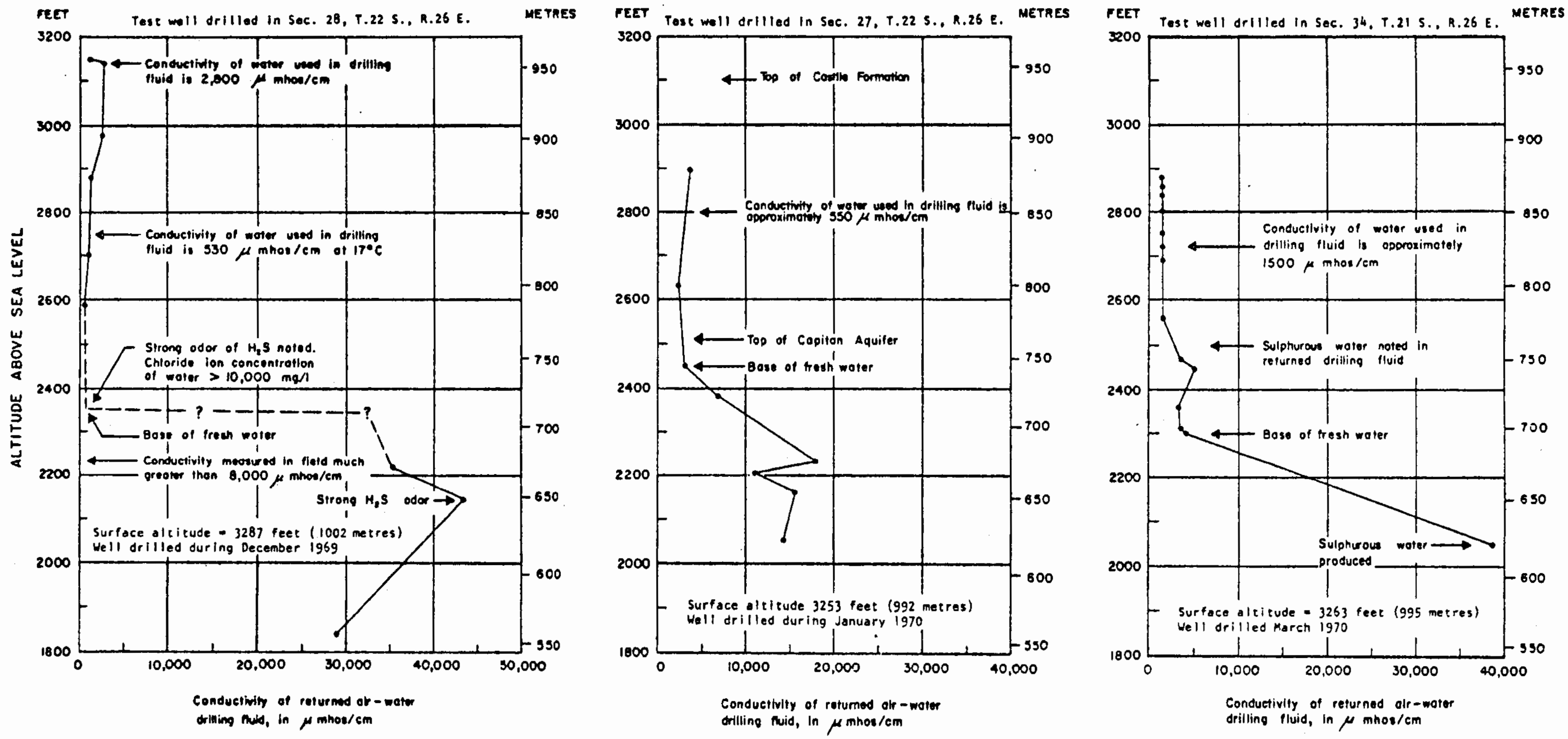


Figure 27.--Diagram showing altitude of the fresh-saline water interface in the vicinity of Carlsbad, New Mexico.

The Capitan Limestone was penetrated at a depth of 745 feet (227 metres) in the well drilled in sec. 27, T.22 S., R.26 E. very near the extreme basinward edge of the Capitan Limestone in Eddy County. A gradual but persistent increase in the conductivity of the returned drilling fluid was noted at a depth of 804 feet (245 metres) suggesting that the base of the fresh water is near an altitude of 2,449 feet (746 metres) at this locality.

Approximately 25 feet (7.6 metres) of alluvium was penetrated before the Capitan Limestone was encountered in the well drilled in sec. 28, T.22 S., R.26 E., a short distance east of the position of the depositional reef crest of the Capitan Limestone. The records from this well are incomplete; however, water containing more than 10,000 mg/l chloride ion was sampled from the returned drilling fluid starting at a depth of 937 feet (286 metres) and continuing to the total depth of 1,455 feet (443 metres). The saline-fresh water interface at this locality is probably just below an altitude of 2,354 feet (718 metres).

The depth to water in the new municipal water field for the city of Carlsbad, located about 4 miles (6 kilometres) southwest of this well (fig. 19), is about 400 feet (122 metres). The altitude of the water table in the city of Carlsbad well field is about 3,100 feet (945 metres). Comparison of the altitudes of the saline-fresh water interface in the well located in sec. 28, T.22 S., R.26 E. with the altitude of the water table in the same area suggests that there is approximately 750 feet (229 metres) of fresh water on top of the saline water in the vicinity of the city of Carlsbad well field.

The volume of water that has moved through the Capitan aquifer during the Cenozoic Era either has been inadequate to completely flush the original saline water from this system, or brines from the lower part of the adjacent shelf and underlying basin aquifers are leaking into the lower part of the Capitan aquifer and mixing with fresh water.

Hydraulic head in aquifers of Guadalupian age

Collection and preparation of data

Efforts were made to locate and collect hydraulic-head data representative of the aquifer head at the time of the discovery or early stages of exploitation of petroleum and the development of water supplies for irrigation in southeastern New Mexico and western Texas.

Water levels for the Roswell Artesian basin were obtained from Fiedler (1926) and Fiedler and Nye (1933) and other records maintained by the U.S. Geological Survey and the New Mexico State Engineer. Water-level measurements in the Carlsbad area were taken from reports published by Hendrickson and Jones (1952) and Bjorklund and Motts (1959). Very few reliable water-level measurements representative of the Permian Guadalupian aquifers during the period 1920 to 1930 were available for the remainder of the project area. In some instances, it was possible to compute reasonable values of head for this period by extrapolating backward from current water-level or pressure measurements by assuming average rates of decline.

Original bottom-hole pressures measured in some of the oil fields on the Central Basin platform and Artesia-Vacuum arch were obtained from the literature (Lea County Operators Committee, 1935-1942; Stipp and others, 1956; Sweeney and others, 1960; Ackers, DeChicchis and Smith, 1930; DeFord and Wahlstrom, 1932; Winchester, 1933; Carpenter and Hill, 1936; and Bates, 1942b). A search of the records kept by the Railroad Commission of Texas in Austin yielded a small amount of information for the southern part of the Central Basin platform. Unfortunately, many of the pressures cited in various reports, particularly those written by geologists, have no reference datum and are therefore virtually meaningless. A few original bottomhole pressure measurements were obtained through the cooperation of individual oil companies. Bottom-hole measurements were not available for many of the oil fields producing from Upper Permian rocks in Eddy County. The shallow wells in these oil fields were often drilled and completed by small operators with cable tool rigs and placed on production without apparent regard to sound engineering practices.

A list of wells in which drill-stem tests had been run in Upper Permian formations was prepared by searching the Permian Basin Well Data System data file. Copies of pressure build-up charts and other data recorded during drill-stem tests were then requested from individual oil companies. Copies of additional drill-stem test charts and records were obtained on microfilm from Petroleum Research Corp., Denver, Colo. Several thousand drill-stem test charts were reviewed during the course of more than a year. The undisturbed reservoir pressure could not be determined by extrapolation from an analysis of the build-up curve in most of the tests because the shut-in time was too brief. Unfortunately, most of the drill-stem test records were examined and discarded as unusable due to either the brief recovery period, borehole damage, or other mechanical malfunctions.

Data from several hundred drill-stem tests were encoded and punched into tabulating cards. The recovery curve was then plotted with the aid of a computer program, and the test evaluated following methods described by Bredehoeft (1965), Johnston Testers (no date), Halliburton Co. (1968), Murphy (1967), Matthews and Russell (1967), and Lynch (1962). A computer program was written to statistically fit the plot of the pressure recovery versus the logarithm of the ratio of the total test time divided by the shut-in period. A large number of drill-stem tests were evaluated in a short amount of time in this manner.

The practice of lengthening the shut-in or recovery period became more common during the late 1950's and early 1960's (Odeh and Selig, 1963). About this same time, the technique of utilizing the drill-stem tool to record the results of two production and recovery periods was adopted. The first brief test period is referred to as "initial" the other test period is relatively long in duration and is referred to as "final." Both tests are accomplished during the same trip into the well with the drill string. Consequently, the percentage of usable reservoir pressure information obtained by the drill-stem test increased enormously. However, by this time, most of the drilling was directed toward evaluation of deeper and older formations and not many of the improved tests were run in reservoirs of Guadalupian age that had not been partially depleted.

The Permian Basin Well Data System file of scout records contains some information describing drill-stem tests that were performed during the drilling and evaluation of an oil or gas test well. Initial and final flow, initial and final hydrostatic, and initial and final shut-in pressures, time periods corresponding to the flow and shut-in phases, and fluid recovery information are generally available. Incremental pressures necessary to evaluate the recovery curve are not available in the scout records.

If pressure equilibrium is reached during the course of a drill-stem test, the final flow and shut-in pressures or initial flow and initial shut-in pressures may be very nearly the same value. A computer program was written to search the drill-stem pressures in the PBWDS file and to detect this condition of repetitive pressures. Initial and final shut-in pressures were compared to one another and to all corresponding flow pressures, and, if the difference between the pressures was less than plus or minus 2 percent of either or both the initial or final shut-in pressures, the complete data set was retrieved from the PBWDS file for further inspection.

More than 2,700 sets of records representing successful drill-stem tests of formations of several geologic ages were retrieved, but only about 10 percent were found to be suitable and applicable to the Permian formations of interest. Most of these pressures were not used in the construction of the potentiometric maps because the tests were taken at times when the oil and gas-bearing reservoirs were partially depleted. This technique does appear to merit the attention of those who may have similar problems but are investigating areas that have not yet been as thoroughly exploited.

Accuracy and reliability of data

Pressure data obtained from drill-stem and bottom-hole reservoir tests are either computed and reported by oil and related service companies or may be calculated from the available pressure-recovery charts. Errors may result from mistakes made in reading and interpreting the records or from inherent mechanical limitations of the equipment, or both. A Bourdon-tube pressure recording device is commonly used in drill-stem tests and also in bottom-hole pressure surveys. Bredehoeft (1965) reports that frequent calibration of this device, plus the use of a microscopic micrometre chart reader, will reduce the gage error to ± 1 to ± 2 psi (pounds per square inch) (± 70 to ± 140 gm/cm^2) at pressures as high as 4,000 to 5,000 psi (281,000 to 352,000 gm/cm^2). Manufacturers and service companies claim an accuracy of much less than one percent of the full-scale range of the gage for pressure recorders used after the middle 1950's (Johnston Testers, personal commun., 1967). Prior to this time, a one percent accuracy is claimed for most good tests in the field. Pressures recorded for the aquifers studied in the project area generally range from about 1,500 (105,000 gm/cm^2) to several thousand psi. Errors due to inaccuracies of the relatively modern pressure-recording instruments used in the project area may amount to only a few psi, but an average error for the older instruments may be approximately 25 psi (1,760 gm/cm^2).

Bottom-hole pressure surveys are special pressure tests normally conducted at regular intervals to determine the performance of a reservoir during the production of oil and gas. Some of these tests are associated with proration activities. Many are published or filed with regulating agencies, such as the New Mexico Oil and Gas Conservation Commission and the Railroad Commission of Texas, while others are made and retained by oil companies for internal use. The duration of the normal bottom-hole pressure recovery survey made in the oil fields on the Artesia Vacuum arch and Central Basin platform is generally only 24 to 72 hours. Static equilibrium reservoir pressures apparently are seldom attained during this length of time, and, therefore, the resulting pressure measurements are frequently too low to be even remotely representative of the true formation pressures in this area. In addition, the datum for the reservoir pressure obtained in a bottom-hole pressure survey is often not given, thus negating the possible usefulness of the pressure measured.

Water levels are measured by the U.S. Geological Survey to hundredths of feet. The accuracy of these measurements is probably within a few tenths of feet, and errors due to mechanical difficulties are small, relative to those made with pressure-recording devices.

In view of the type of pressure and hydraulic head data available in the study area, and also in view of the care exercised in the selection and adjustment of this data, it is believed that a contour interval of 100 feet (30 metres) is applicable in the construction of generalized potentiometric maps. This interval is most acceptable in areas encompassing the Capitan aquifer and parts of the San Andres Limestone and the Artesia Group. It is generally acceptable for most of the remaining areas in the study area, and only in a few areas in the Delaware Mountain Group is it considered marginal.

Computation of ground-water head

Complications due to variations in density

The Capitan aquifer and associated formations of Guadalupian age contain water of variable density and quality (fig. 26). Values of head measured in an aquifer must be adjusted to a common datum and corrected for variations in density before relative comparisons between the magnitude of the hydraulic heads can be made (Lusczynski, 1961; Bond, 1972, and 1973; and Bond and Cartwright, 1970). The procedures followed in adjusting the ground-water heads in the aquifers studied are described below.

Review of basic concepts

Ground-water head at a point, such as in a well, is the height of the water column above or below some reference level (commonly mean sea level). This head will vary with the chosen reference level and the type of water in the well and in the aquifer. The relation between ground-water head and the pressure at a point in a well is illustrated in figure 28 and expressed by the hydrostatic equation (Hubbert, 1953, and 1969) as follows:

$$H = p/\gamma + Z$$

where

H = ground-water head above (+), or below (-), mean sea level, or other datum, in feet,

p = pressure at a point in a well, in pounds per square foot,

γ = specific weight of the water; it is the weight per unit volume, in pounds per cubic foot, that takes into account the magnitude of the local gravitational force. It is also equal to the product of the fluid density, ρ, and the local gravitational acceleration, g,

Z = distance above (+), or below (-), mean sea level of the point where the pressure is measured; it is the altitude of the pressure point.

This equation shows that the ground-water head is dependent on the point pressure, the reference datum, and the type of water in the well column. The point pressure reflects the internal changes in a ground-water system or aquifer. Heads are adjusted to a horizontal reference level, mean sea level, in this report, so that heads at different wells can be compared in order to determine hydraulic gradient. The height of the column of water above the pressure point is equivalent to p/γ, which is dependent on the type of water in the column.

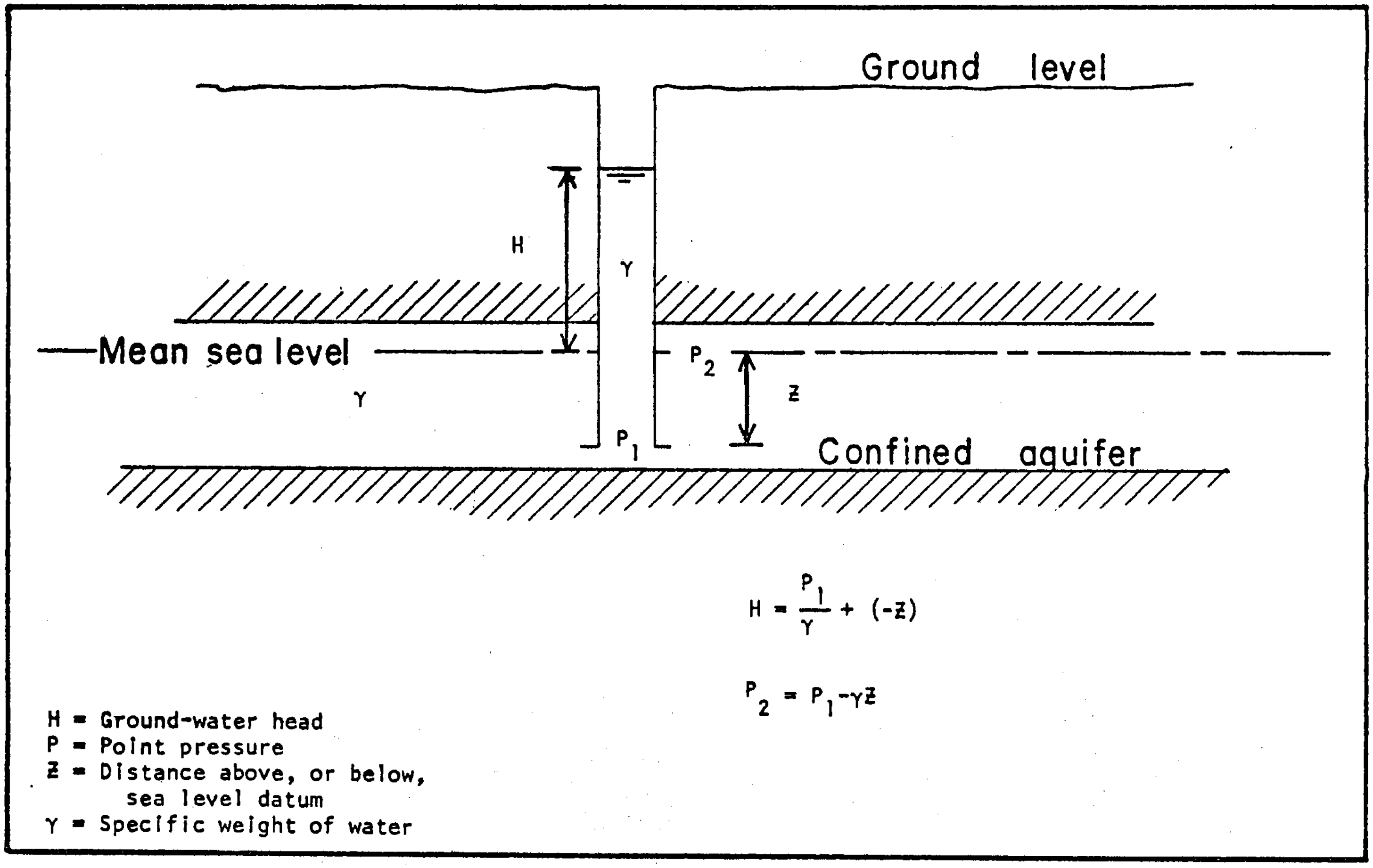


Figure 28.--Diagram showing computation of pressure at a datum.

Point-water head

Pressure at a point in a well tapping an aquifer containing water of variable density may be expressed as a ground-water head which reflects the type of water in the well column. Lusczynski (1961, p. 4247) defined point-water head as the water level, referred to mean sea level or other datum, in a well filled sufficiently with the water of the type at the point to balance the existing pressure at the point. In figure 29 which shows three wells tapping a confined aquifer, H_1 and H_2 are both point-water heads. If γ_1 represents the specific weight of fresh water, then H_1 is a fresh-water head.

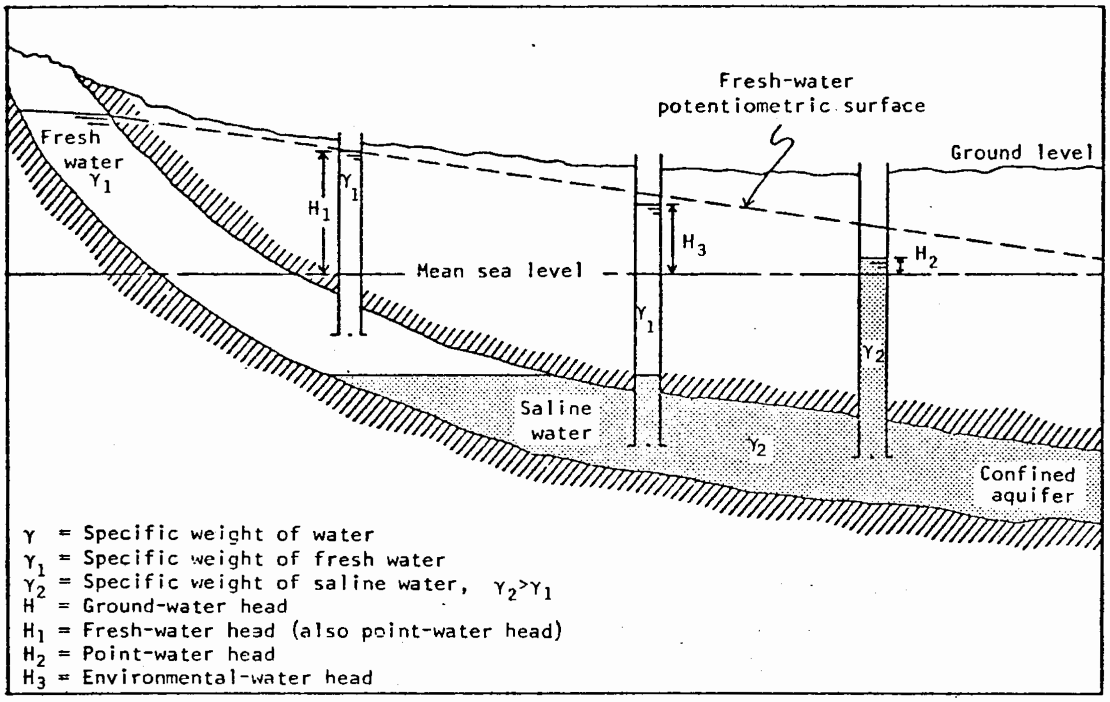


Figure 29.--Diagram showing heads and fresh-water potentiometric surface for confined aquifer containing water of variable density.

Environmental-water head

Environmental water was defined by Lusczynski (1961, p. 4248) as that water between a given point in an aquifer and the top of the zone of saturation. The water may be of constant or variable density and occurs in the environment along a vertical between the given point and the top of the zone of saturation. For confined aquifers the environmental zones may be projected to the vertical well column from points along the aquifer section (fig. 30).

The environmental water head was then defined by Lusczynski as a fresh-water head reduced by an amount corresponding to the difference of salt mass in fresh water and that in the environmental water. The well column of the middle well of figure 29 is filled with the equivalent of the environmental water found in the aquifer at this point. The environmental-water head, H_3, of the middle well in figure 29 is less than the fresh-water head would be at this location.

The fresh-water potentiometric surface shown in figure 29 represents ground-water head as it would be if the aquifer system were full of fresh water only. In later sections of this report the concept of environmental water is used in connection with adjustments of pressure and water-level data for use as fresh-water heads in potentiometric maps (fig. 30). Environmental-water head, which defines gradient along a vertical, i.e., in a well column, was not used.

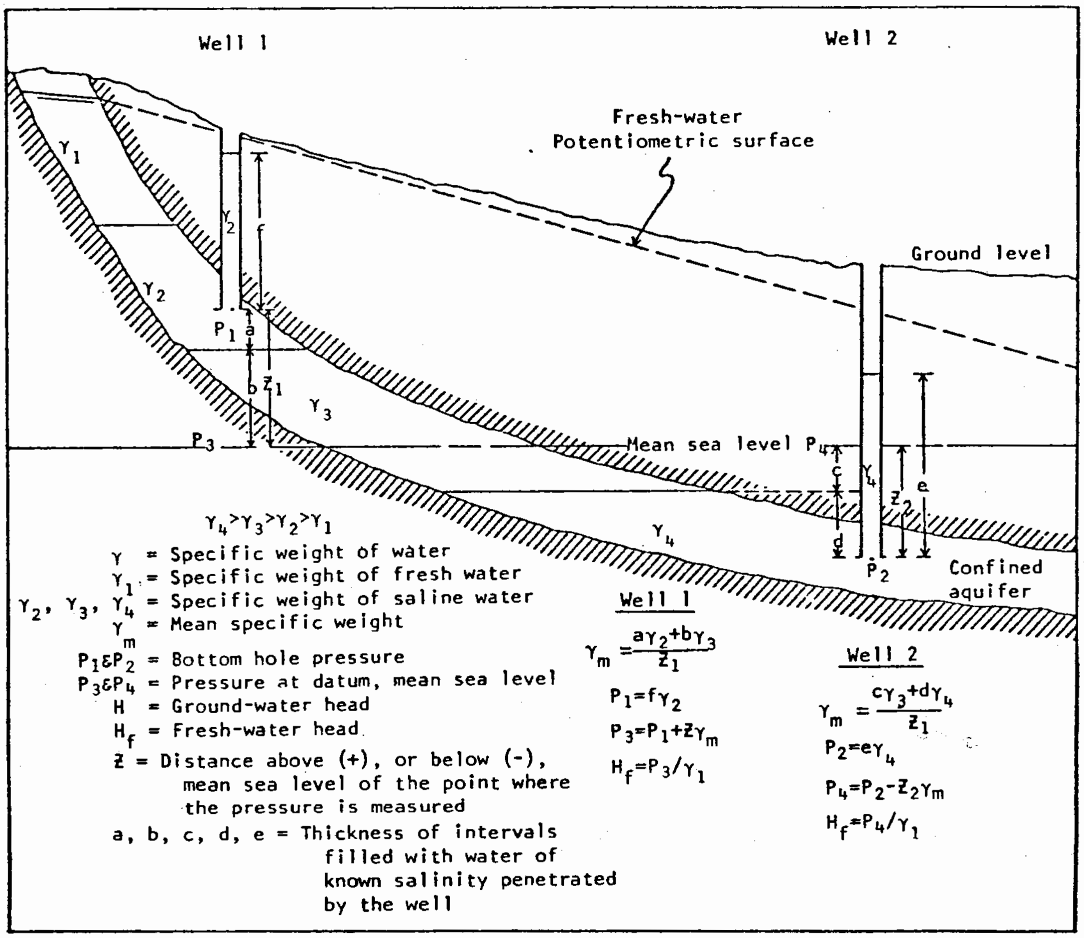


Figure 30.--Diagram showing computation of fresh-water head for wells tapping a confined aquifer containing water of variable density.

Determination of fresh-water head

The head relationship between two hydraulically connected wells tapping the same confined aquifer containing water of variable density is shown in figure 31. The example is simplified by assuming that the point pressures in each well are the same and are located at mean sea level, $Z = 0$. The specific weight, γ_1, of the water in well 1 is assumed to be that of fresh water, and the specific weight of the water in well 2 is assumed to be greater. The ground-water head, H_1 and H_2, in each well is a point-water head. H_1 is also a fresh-water head. If γ_2 is greater that γ_1, then H_1 is greater than H_2. Measurement of water levels in each well, without consideration of the density variations, would result in an erroneous indication of water moving from left to right. Because the pressures at sea level in each well are equal, no movement of water should occur in this illustration. Conversion of the pressure head in the well on the right in figure 31 to a fresh-water head should give a ground-water head equal to H_1. Ground-water heads in aquifers containing water of variable density must be adjusted so they represent ground water of a common density, such as fresh water, before the hydraulic gradient can be determined.

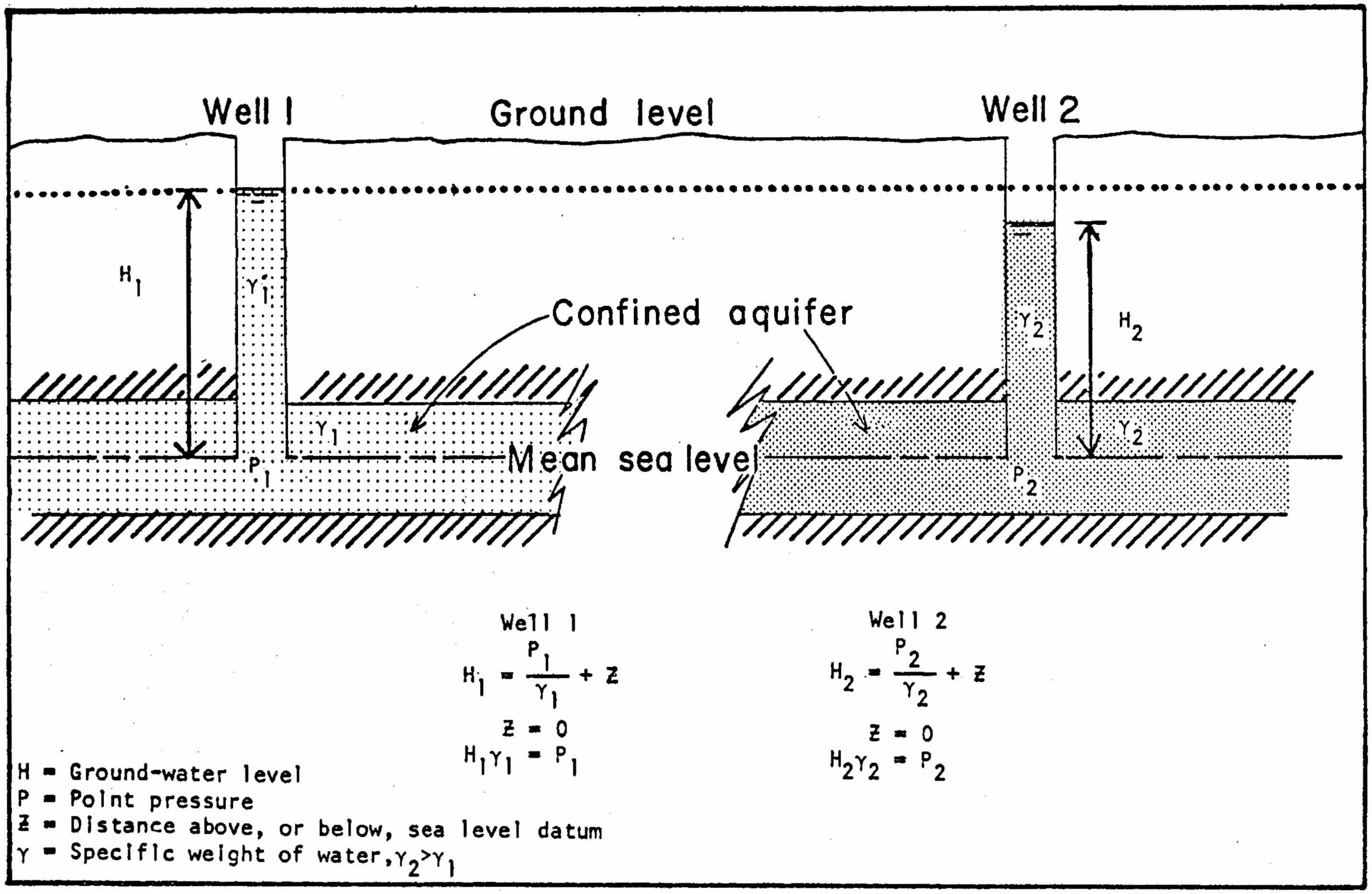


Figure 31.--Diagram showing head relationships in wells tapping a confined aquifer containing water of variable density.

When only water levels in the wells of an example similar to that of figure 31 are available, the average density of the water in each well column must be known before fresh-water head and hydraulic gradient can be computed. The possibility of error in comparison of ground-water heads without an adjustment for density becomes greater with increased variation of density. If the pressure at a horizontal level common to each well is known, no density data are needed for hydraulic gradient computations, provided that the density of the water in the interval between the level common to the wells and the datum does not vary. However, this is a condition which rarely occurs over wide areas in the field.

The condition illustrated in figure 28 is encountered more often. In this case, the pressure at sea level, p_2, must be computed using the bottom-hole pressure, p_1, and the average density of the environmental water in a vertical column, Z. Once p_2 is known, a fresh-water head from the common datum may be computed. If only the water level in the well is known, the average density of the water in the well column from the water level to uppermost perforation and the environmental-water density from column Z must be known in order to compute the fresh-water head with reference to sea level. This example has been simplified by making the specific weight of the water in the well column and the environmental water in the Z column the same. In many cases, this is not so. Frequently, an approximation of the average specific weight of water must be made, because vertical variations in density in the environmental water are complex and sometimes may preclude assignment of a valid average density from the available data.

In the example of figure 28, consideration of the environmental water is limited to within the confined aquifer, because the Ƶ factor is similarly limited. This section of water is only a fraction of the total environmental water, which extends in the aquifer to the top of the zone of saturation in the outcrop area in one direction and to other levels in the opposite direction until it discharges from the aquifer. In some field cases, the datum (and resulting distance, Ƶ) may be above the top or below the bottom of the confined aquifer, and the environmental water which should be considered may extend laterally for great distances. Extensive variations in the water density may further complicate the problem.

A simplified example where variations in density extend laterally is shown in figure 30. The computation of fresh-water head will depend on several factors which may be difficult to determine in the field. If the values of γ_1, γ_2, γ_3, γ_4, a, b, c, d, e, p_1, and p_2, are considered known or determinable, the values for the sea-level pressures, p_3 and p_4, can be computed and with these, the fresh-water heads. The determination of the average density (γ_m) for the environmental water within each distance, Z, is an intermediate step. Determination of the sea-level pressure depends on γ_m, the average density of the environmental water and p_1 or p_2, the bottom-hole pressure. The pressures p_1 and p_2 may be determined from a bottom-hole pressure gage or from the water level and density of the water in the well column ($p_1 = f\gamma_2$ and $p_2 = e\gamma_4$). Geologic and quality-of-water information may be available to make approximations of the other factors, but complex variations in both density and space distribution of density zones may be difficult to treat. In general, the larger the distance, Z, and the greater the magnitude of density variation, the greater the errors will be in the computation of fresh-water head in this and similar examples.

The computation of hydraulic gradient in a system of variable density is valid only if there is a viable hydraulic communication throughout an aquifer system. Hydraulic communication may exist between two of more characteristically dissimilar aquifers, and it may be possible to treat a series of aquifers as one. If such is the case, the preceding principles concerning adjustment of head data should apply to a multiaquifer system containing water of variable density. However, hydraulic communication between aquifers is largely a matter of degree, which is a function of the diffusivity and the transmissivity in an unsteady state. Correct interpretation of this degree of communication is essential before valid comparison of ground-water head in different aquifers can be made. Fortunately, because the hydraulic conductivities in the shelf and basin aquifers are much smaller than is the Capitan aquifer, the hydraulic communication is relatively slight and, for this reason, the Capitan aquifer could be regarded as a single entity.

The examples given above illustrate the head relationship in confined aquifers containing water of variable density. The same general principles relating head, pressure, and density of water apply to unncconfined or water-table systems.

Adjustment of head

The Capitan basin, and shelf aquifers of Permian Guadalupian age contain water of variable density. Most of these aquifers within the project area generally are confined by extensive thicknesses of relatively impermeable material such as shale, sandstones, salt, and anhydrite. The outcrops or recharge regions of the Guadalupian age aquifers are generally northwest, west, and south of the Delaware basin. Because of the density variation in the water contained in these aquifers, the procedures described previously were adopted in adjusting all the head data that was used in constructing potentiometric maps.

Variation in the density of water

Several thousand analyses of the water produced from formations of Permian Guadalupian age throughout the area were collected from oil and related service companies and from producing wells whenever possible. The chloride-ion concentrations of representative analyses have been plotted and interpreted in a map depicting the lowest chloride-ion concentration expected to be found in the water produced from an area (fig. 26). The relationship between the chloride-ion concentration and density of the water was determined statistically and found to be almost linear. Therefore, a map showing the variation in density of the ground water in the same strata was not prepared. A close approximation of the variation in density is given by relating the chloride-ion concentration shown in figure 26 to density. The densities used in adjusting the point-water heads to fresh-water heads were obtained by first visually selecting the representative chemical quality of the environmental water from figure 26. The relationship between chloride ion and density was then used to estimate the average density.

Typical ranges of density found in the strata of Permian Guadalupian age are illustrated in two simplified and diagrammatic stratigraphic profiles (figs. 32 and 33). The section shown in figure 32 extends from the outcrops of the Delaware Mountain Group in the Delaware Mountains of Culberson County, Texas, across the Delaware basin through the Capitan aquifer into the shelf sedimentary rocks near the middle of the Central Basin platform in Ector County, Texas. The largest contrast in the densities of water in these strata is encountered along the western margin of the Central Basin platform where the relatively dense brines of the Delaware Mountain Group are in juxtaposition with the relatively low salinity water in the Capitan aquifer.

A highly diagrammatic longitudinal profile of the Capitan aquifer, as it extends from the Guadalupe Mountains southwest of Carlsbad, around the northern and eastern margins of the Delaware basin to outcrops in the Glass Mountains southwest of Fort Stockton, is illustrated in figure 33. Fresh water rests on saline water in the Capitan aquifer in the vicinity of the Guadalupe and Glass Mountains. The water with the greatest density in the Capitan aquifer is found in eastern Eddy County. However, the density of the poorest quality water found in the Capitan aquifer is less than the density of the water in all the adjacent surrounding rocks with the exception of the water in the San Andres Limestone on the northern and southern ends of the Central Basin platform.

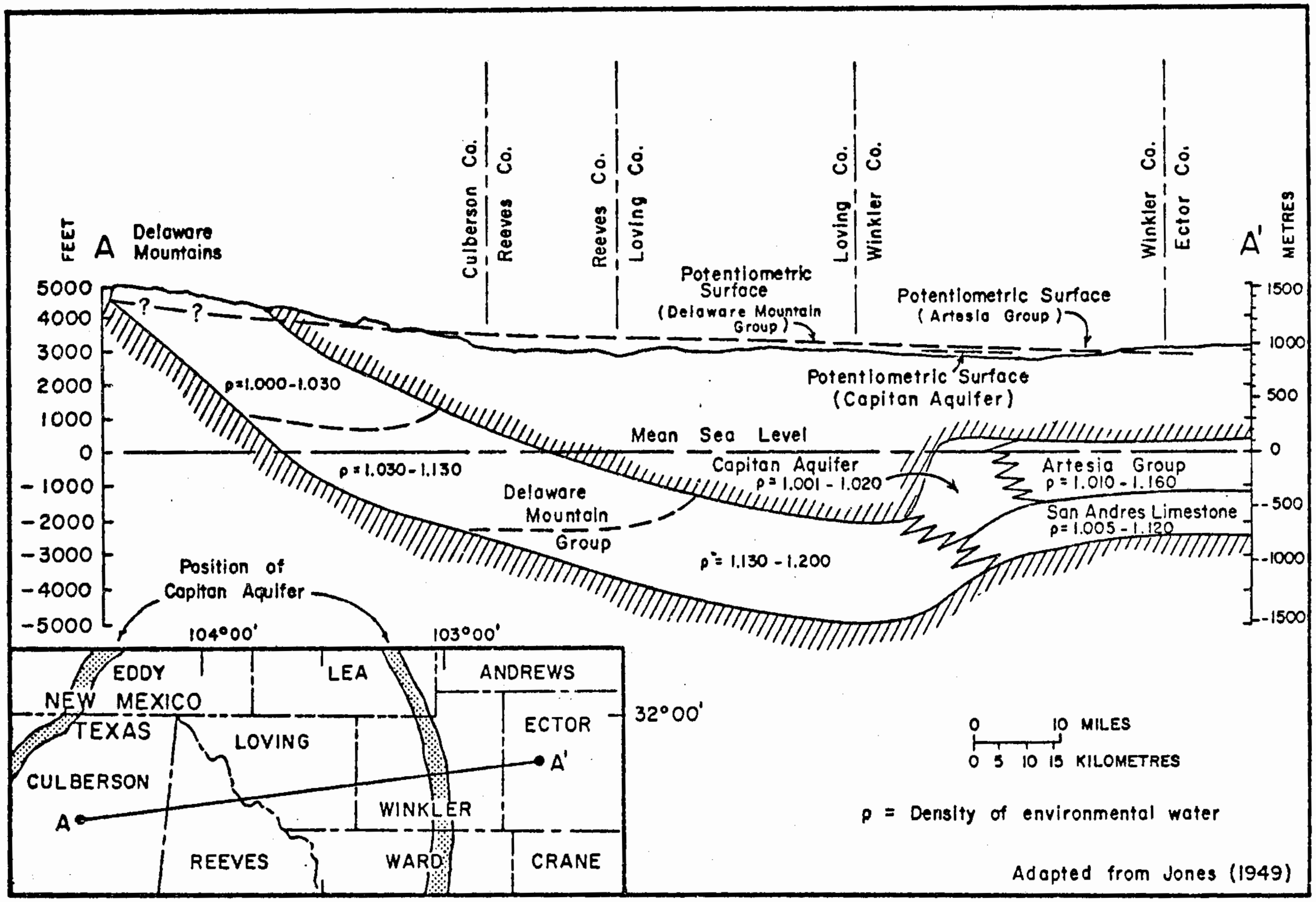


Figure 32.--Diagrammatic profile of Capitan and associated aquifers across western Texas showing pre-oil-discovery potentiometric surfaces and variation in the density of the ground water.

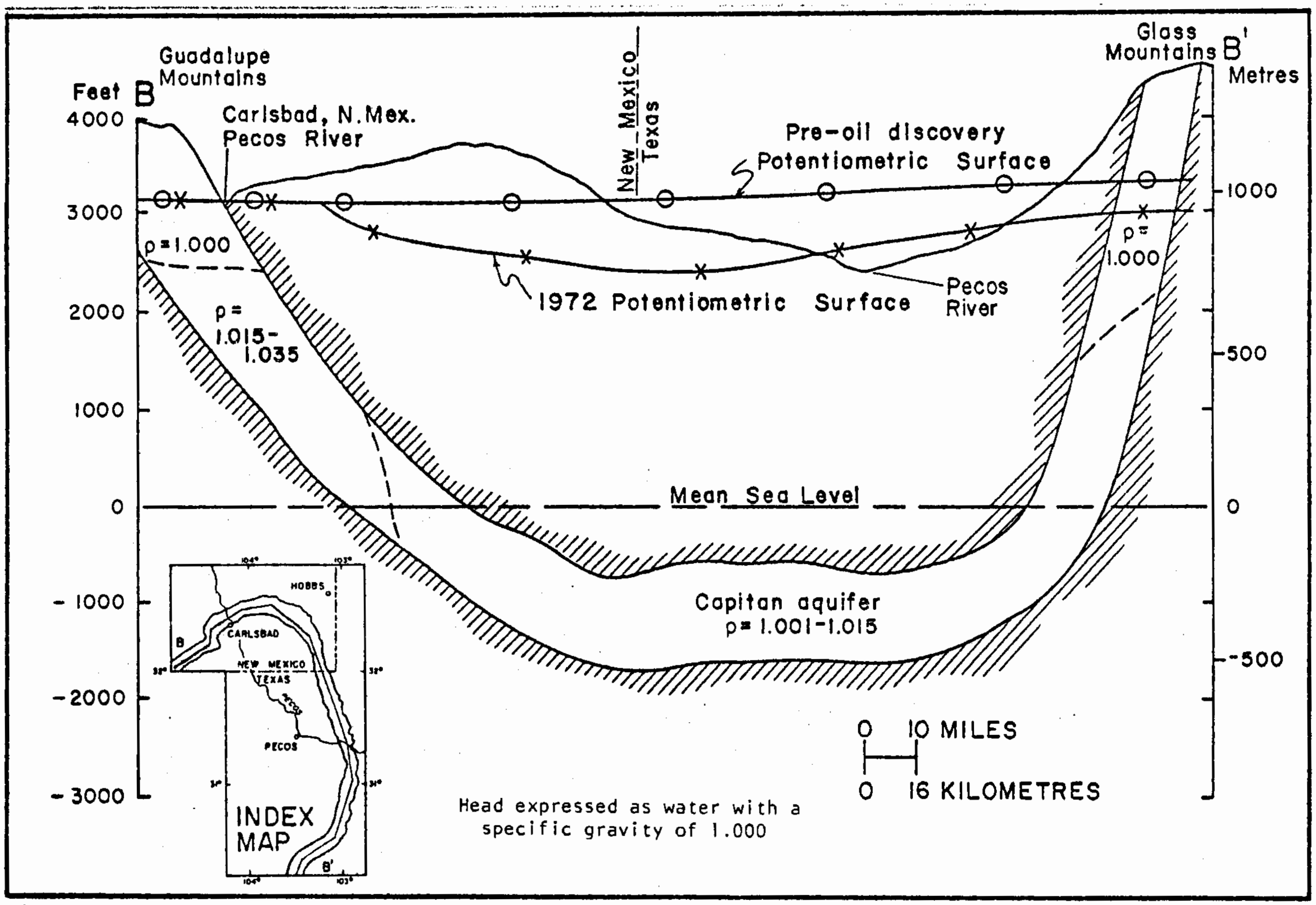


Figure 33.--Diagrammatic profile of Capitan aquifer showing potentiometric surface and variation in density of the ground water.

Adjustment of pressure data

Within the study area, most of the important head data were obtained from oil companies as unadjusted bottom-hole and drill-stem test pressures. This type of pressure-head data is convenient to work with because it can be expressed in terms of the desired density of water. For purposes of computing hydraulic gradient, the available point pressures were first adjusted to pressures at a sea level datum, and then expressed as fresh-water heads. The following precedure was adopted for handling point pressures within the project area.

(1) The altitude of the pressure point within the well column was determined. Essentially, the distance, Z, between the pressure point and sea level was determined.

(2) An average specific weight, γ_m, of the environmental water within the aquifer section equivalent to the distance, Z, is determined from the distribution of the chemical quality of the water in the various aquifers.

(3) The sea-level pressure, p_2, is computed from the point pressure, p_1, by:

$$p_2 = p_1 + [\gamma_m(\pm Z)]$$

Z is negative if the pressure point is below sea level and positive if the pressure point is above sea level.

(4) The fresh-water head, h_f, is then computed using p_2 and the specific weight of fresh water, γ_f

$$h_f = p_2/\gamma_f$$

Adjustment of water-level data

During the course of the study, several abandoned oil and gas test wells completed in the Capitan aquifer were secured for use as observation wells. Depth to water in these wells is measured and recorded continuously by water-level sensing instruments. The water in the fluid column in some of the wells is not representative of the environmental water in the aquifer. For example, the specific gravity of the water in the fluid column of one observation well is 1.115 but the specific gravity of the environmental water is 1.018. The following equation from Hiss (1973) was used to compute fresh-water head from water-level measurements in the observation wells:

$$h_f = r_1 (E_{1s} - D_p) + r_2 (D_p - D_w)$$

where

h_f = fresh-water head, in feet, above mean sea level

r_1 = specific gravity of the environmental water in the aquifer (dimensionless)

r_2 = specific gravity of the water in the well column (dimensionless)

E_{1s} = altitude of land surface, in feet, above mean sea level

D_p = depth to top of perforated well section, in feet, below land surface

D_w = depth to the non-representative water in well, in feet, below land surface

This equation relates fresh-water head directly to the parameters associated with observation-well data. It is also possible to determine the bottom-hole point pressure, p, at the perforated interval with the equation, $p = [(r_2)\ (62.5)\ (D_p - D_w)]$. This pressure then may be adjusted to sea-level pressure and converted to fresh-water head as outlined previously.

Fresh-water heads computed for water levels measured on January 1, 1973, for eachh of the observation wells completed in the Capitan aquifer, are shown in table 10 along with the supporting data. The location of the wells is shown in figures 5, 24, and 25. The maximum difference in fresh-water head between the five observation wells located in the immediate vicinity of Carlsbad, and the Pecos River is only 5 feet (1.5 metres).

The fresh-water head computed for the Yates State 1 observation well, located in sec. 32, T.20 S., R.30 E., approximately 15 miles east of Carlsbad, is 3,133 feet (955 metres) above sea level and ranges from 8 to 12 feet (2.4 to 3.7 metres) lower than the heads computed for the five wells nearer to Carlsbad. This difference in head suggests that a slight eastward hydraulic gradient of less than a foot per mile exists east of Carlsbad. However, errors made in estimating the density of the environmental water in the aquifer could easily account for these differences in head. Differences in head determined over a relatively long period of time, i.e., several decades, would appear to be a better indicator to use to definine changes to the gradient in the potentiometric surface for the Capitan aquifer in the vicinity of and immediately east of Carlsbad where the differences in head are small.

Table 10.--Fresh-water head in Capitan aquifer observation wells

Symbols	r_2	D_p	D_w	E_{ls}	a	r_1	h_f
Observation wells	Average specific gravity of water in fluid column	Depth to uppermost perforation adjusted to the land surface datum, feet (metres)	Depth to water Jan. 1, 1973, feet (metres)	Altitude of land surface, feet (metres)	Distance of point-pressure or equivalent above (+) or below (-) sea level datum, feet (metres)	Average specific gravity of representative environmental water in the aquifer	Fresh-water head on Jan. 1, 1973 above mean sea level feet (metres)
City of Carlsbad Well 10	1.000[a/]	Open-hole completion	400 (122)	3,502 (1,067)	+3,102 (+945)	1.014	3,145 (959)
City of Carlsbad Well 13	1.000	289 (88)	21 (6)	3,122 (952)	+2,833 (+863)	1.014	3,141 (957)
North Cedar Hills Unit 1	1.020	990 (302)	196 (60)	3,280 (1,000)	+2,290 (+698)	1.018	3,141 (957)
Humble State 1	1.032	1,538 (469)	160 (49)	3,230 (984)	+1,692 (+516)	1.018	3,145 (959)
City of Carlsbad Test Well 3	1.012	630 (192)	94 (29)	3,182 (970)	+2,552 (+778)	1.020	3,145 (959)
Yates State 1	1.030	2,223 (678)	323 (98)	3,365 (1,026)	+1,142 (+348)	1.030	3,133 (955)
Hackberry Deep Unit 1	1.115	3,726 (1,136)	639[b/] (195)	3,397 (1,035)	- 329 (-100)	1,030	3,103 (946)
Middleton Federal B 1	1.020	2,913 (888)	614 (187)	3,518 (1,072)	+ 605 (+184)	1.016	2,960 (902)
South Wilson Deep Unit 1	1.010	4,169 (1,271)	1,124 (343)	3,717 (1,133)	- 452 (-138)	1.010	2,619 (798)
North Custer Mountain Unit 1	1.030	4,451 (1,357)	936 (285)	3,387 (1,032)	-1,064 (-324)	1.008	2,548 (777)
Federal Davison 1	1.109	4,252 (1,296)	1,198 (365)	3,355 (1,023)	- 897 (-273)	1.005	2,485 (757)
Southwest Jal Unit 1	1.106	4,199 (1,280)	844 (257)	2,985 (910)	-1,214 (-370)	1.005	2,491 (759)

a/ estimated

b/ adjusted for oil at top of water column

Reliability of computed fresh-water head

The fresh-water heads computed for the Capitan and associated aquifers depend largely on the determination of a representative value for the average specific gravity of the environmental water that encompasses an aquifer section equivalent to Z, the distance of the pressure point above or below the sea-level datum. The larger the distance, Z, the greater the need for a more precise determination of the average specific gravity of the environmental water.

The magnitudes of the errors that may be introduced into the computation of fresh-water heads for various aquifers due to erroneous estimates of specific gravities of environmental water are tabulated in table 11. Sets of Z factors for each aquifer group have been selected to represent the averages for the low and high ranges found in the field.

For each set of Z factors, three possible magnitudes of error in assigning specific gravity have been computed. The first represents the maximum error expected if the environmental water is erroneously considered to be fresh and adjustments for variation in specific gravity are not made; the second represents what can be considered to be a large error that could result from the incorrect determination of an average specific gravity from the environmental water data available for this study area; and the third value represents an average error, certainly not the minimum possible, but an error in computation of head believed to be consistent with the type, quantity, and quality of information available for the three aquifers.

Table 11.--Magnitude of possible errors in computing fresh-water head for the Capitan and associated aquifers due to incorrect estimates of the specific gravity of environmental water

Aquifer	Z factor, the distance of the pressure point above, or below, sea level, in feet (metres)	Error in estimating specific gravity of environmental water	Error in computed[1/] fresh-water head, in feet (metres)
Capitan aquifer	400 (122)	0.03	12 (3.7) E
	400 (122)	.01	4 (1.2) L
	400 (122)	.005	2 (.6) A
	1,000 (305)	.03	30 (9.1) E
	1,000 (305)	.01	10 (3.0) L
	1,000 (305)	.005	5 (1.5) A
	2,000 (610)	.03	60 (18.3) E
	2,000 (610)	.01	20 (6.1) L
	2,000 (610)	.005	10 (3.0) A
	3,000 (915)	.03	90 (27.4) E
	3,000 (915)	.01	30 (9.1) L
	3,000 (915)	.005	15 (4.6) A
Basin aquifer (Delaware Mountain Group)	1,500 (457)	0.16	240 (73.2) E
	1,500 (457)	.05	75 (22.9) L
	1,500 (457)	.02	30 (9.1) A
	2,500 (762)	.16	400 (121.9) E
	2,500 (762)	.05	125 (38.1) L
	2,500 (762)	.02	50 (15.2) A
Shelf aquifer (Chalk Bluff and Bernal facies of the Artesia Group and San Andres Limestone)	300 (91)	0.16	48 (14.6) E
	300 (91)	.03	9 (2.7) L
	300 (91)	.01	3 (.9) A
	1,000 (305)	.16	160 (48.8) E
	1,000 (305)	.03	30 (9.1) L
	1,000 (305)	.01	10 (3.0) A
	2,000 (610)	.16	320 (97.5) E
	2,000 (610)	.03	60 (18.3) L
	2,000 (610)	.01	20 (6.1) A

1/ General magnitude of error indicated by E=extreme, L=large, and A=average

The potential for error in the fresh-water heads computed for the Capitan aquifer is greatest in the vicinity of Carlsbad because of the large distance of the point pressures above sea level (Z factor) and the very rapid change in the specific gravity of the environmental water in the Capitan aquifer. Within a span of approximately 25 miles (40 kilometres) extending westward from the eastern boundary of Eddy County, New Mexico, the Z factor increases from about 300 feet (91 metres) below to approximately 3,000 feet (915 metres) above sea level. Approximately 750 feet (230 metres) of fresh-water overlies saline water in the Capitan aquifer southwest of Carlsbad.

As shown in figures 26 and 33, the water in the Capitan aquifer becomes progressively more saline east of the Pecos River near Carlsbad until a maximum salinity is reached in eastern Eddy County. The average specific gravity of the environmental water in the Capitan aquifer changes from 1.014 southwest of Carlsbad and the Pecos River valley to at least 1.035 in eastern Eddy County. Errors of 10 to 30 feet (3 to 9 metres) can be expected in the values of the computed fresh-water heads in this area. Larger errors of 30 to 90 feet (9 to 27 metres) would result if the heads were unadjusted for the variation in specific gravity. Errors made in computing the fresh-water head for the Capitan aquifer elsewhere should be relatively small due to the small Z factor, the generally small amount of variation in the specific gravity of the water in the aquifer, and the relatively low specific gravity of the water.

The water in the shelf and basin aquifers is much more saline and correspondingly denser than water in the Capitan aquifer. Errors of several hundred feet would result if the heads in the Delaware Mountain and Artesia Groups and the San Andres Limestone were to be compared to heads in the Capitan aquifer without adjusting for the differences in the specific gravity of the environmental water. The potential for large errors is greatest along the northern and eastern margins of the Delaware basin and in other areas where both the Z factor and the contrast in specific gravity between the waters in the different aquifers are large (fig. 32 and table 11). Errors in the value of fresh-water head computed for the shelf and basin aquifers can be expected to range from 10 to 50 feet (3 to 15 metres) where data are adequate for control of interpretations and from 30 to 125 feet (9 to 38 metres) where data are sparse.

The density of the water in the San Andres Limestone at both ends of the Central Basin platform is similar to that in the Capitan aquifer. The magnitude of the errors made in computing fresh-water heads for the San Andres Limestone in these areas should be quite small.

Movement of water in aquifers of Guadalupian age

Construction of potentiometric surface maps

Reliable pressure-head and water-level data were adjusted to fresh-water heads for the purpose of constructing potentiometric surface maps representing the early and late-development conditions in the aquifer systems (figs. 22 and 23). A potentiometric surface represents hydraulic head in an aquifer, and the general direction of ground-water movement is inferred to be normal to the illustrated head contours.

A considerable amount of subjective judgment was used in contouring the data. In general, two factors, (1) the year in which the head was measured, and (2) and the reliability of the data, were weighed in considering each data point. The pressures and water levels were measured at various dates scattered over a period of about 40 years. The earliest available data were used in the construction of the predevelopment potentiometric surface, and the latest data were used for the postdevelopment potentiometric surface. Fluid levels measured in water wells were generally considered to be more reliable than pressure data. Initial oil field bottom-hole pressures were usually considered to be more reliable than pressure determined from the analysis of drill-stem tests.

In many instances, where data representing values of the head under natural conditions forty to fifty years ago were unavailable; a value of a head was computed by extrapolating backward from the available head data using assumed rates of decline. Values of head determined for Leonardian and Ochoan age aquifers were occasionally used as supplementary information in areas where data for the Guadalupian age aquifers were inadequate or unavailable. The relatively large differences in hydraulic conductivities of the shelf, Capitan, and basin aquifers were a factor that was considered when contouring the potentiometric surface maps.

Predevelopment potentiometric surface

Definition

The regional potentiometric surface, representing hydraulic head prior to the extensive development of oil, gas, and water in the Capitan and associated aquifers, is shown in figure 22. The contours on this map depict the approximate values of head during the early 1920's and are highly interpretative in areas where there is little control. A longitudinal profile of the potentiometric surface for the Capitan aquifer also is shown on figure 6.

Basin aquifers

Aquifers in the Delaware Mountain Group are naturally recharged at outcrops in the Delaware, Guadalupe, Apache, and Glass Mountains and from leakage downward through younger rocks in areas where the soluble Ochoan evaporites have been removed in the western and southern parts of the Delaware basin (Brown, Rogers, and Baker, 1965, pl. M-7 and M-9).

The hydraulic head in the basin aquifers is in excess of 3,900 feet (1,190 metres) above sea level in the southern part of the Guadalupe Mountains and the Delaware Mountains, but declines to less than 3,200 feet (975 metres) along the northeastern, eastern, and northern margins of the Delaware basin. Water in the basin aquifers flows very slowly northward and northeastward under a gradient of 25 to 40 feet per miles (1 to 5 m/km) from the vicinity of White City along the Guadalupe Mountains toward a potential trough or low northeast of Carlsbad where the water slowly discharges upward into the overlying Capitan and shelf aquifers and laterally into the intertonguing San Andres Limestone. Water entering the Capitan aquifer moves southwestward and eventually is discharged into the Pecos River through Carlsbad Springs. Some of the water that enters the shelf aquifers may move eastward toward Hobbs.

The head differential between the basin aquifers and the Capitan aquifer ranges from more than 800 feet (245 metres) at White City to less than 100 feet (30 metres) at Carlsbad. The head in the basin aquifers is always greater than the corresponding head in the Capitan aquifer at any location along the margin of the Delaware basin. The large differences in head reflect the great differences in the hydraulic conductivities of the two aquifer systems.

The fresh-water heads computed from drill-stem pressures measured in the shelf and basin aquifers during 1956-1960 in the vicinity of the Eddy-Lea County boundary reflect some of the head loss resulting from production of oil, gas, and waste water during the preceding 30 years. Isopotentials for the basin aquifer in this area are based solely on the known relationships between the shelf and basin aquifers, the relatively recent head measurements, and the assumed rates of head loss, because no other information is available. A sharply defined ground-water divide appears to have been present in both the basin and shelf aquifers in the vicinity of the Eddy-Lea County boundary prior to the exploitation of the oil and gas reserves in this area (fig. 22). The shelf and basin aquifers are separated into two distinct ground water regimens by this divide, one controlled by the Pecos River at Carlsbad, the other by the regional drainage to the Gulf of Mexico.

Elsewhere, water in the basin aquifer moves very slowly across the Delaware basin to the northeast and east under gradients ranging from less than 4 to as much as 15 feet per mile (1 to 3 m/km) and discharges into the laterally equivalent San Andres Limestone and Artesia Group along the margins of the Delaware basin or upward into the overlying Capitan aquifer. Beds of the Delaware Mountain Group extend shelfward and intertongue with the San Andres Limestone and the lower part of the Artesia Group shelfward of the Capitan aquifer. The hydraulic characteristics of the shelf and basin aquifers are very similar and the two aquifer systems appear to respond to stresses in a like manner. Along the margins of the Delaware basin, the heads in both the shelf and basin aquifers are represented by the same isopotential contours on figure 22 because differences in head between the two aquifer systems cannot be distinguished with the control available.

The basin aquifers in the western part of the Delaware basin contain water of relatively better quality due to the replacement of original brines by relatively less saline water over a long period of geologic time (fig. 26). Most of the oil fields with production from the Delaware Mountain Group are located in the northeastern two-thirds of the Delaware basin in areas where the produced water is relatively saline compared to other areas upgradient. Migration and entrapment of petroleum in the Delaware Mountain Group also may have been influenced by the slow movement of water through the basin aquifers within the Delaware basin (Hiss, 1975a).

Movement of substantial quantities of water from the basin aquifers upward into the younger Cretaceous and Cenozoic aquifers in the Balmorhea-Pecos-Loving trough is impeded by the beds of anhydrite in the Castile Formation.

Shelf aquifers

Over a long period of years, gypsum and anhydrite have been dissolved and removed from the Chalk Bluff facies of the Artesia Group west of the Pecos River at Carlsbad by circulating ground water. The hydraulic conductivity of these sedimentary rocks was originally very low but has been greatly increased by dissolution of the evaporites.

Bjorklund and Motts (1959) and Motts (1968) have mapped the potentiometric surfaces of two perched water-bearing zones formed by relatively impermeable sandstones in the evaporite facies of the Yates and Queen-Grayburg Formations of the Artesia Group in the foothills of the Guadalupe Mountains southwest of Carlsbad. These surfaces are several hundred feet higher than the potentiometric surface for the San Andres Limestone, the principal aquifer in the same area. Water perched above sandstones in the Queen-Grayburg Formations discharges as springs into arroyos that are tributaries of the Pecos River. The water perched above sandstones in the Yates Formation moves to the northeast and apparently either discharges into the Pecos River or flows into the potentiometric low northeast of Carlsbad. Water reaching the potential low eventually moves downward into the Capitan aquifer and flows toward discharge points on the Pecos River near Carlsbad.

According to Bjorklund and Motts (1959) and Motts (1968), water in the San Andres Limestone southwest of Carlsbad moves northeastward and drains into the Roswell basin. However, contours of the potentiometric surface of the same shelf aquifer prepared for a larger area (fig. 22) suggest that most of this water moved generally northeastward and eastward toward the low in the potentiometric surface northeast of Carlsbad. Water moving into this low must commingle with water contributed by the intertonguing basin aquifers and then move upward into the Capitan aquifer to eventually be discharged as spring flow into the Pecos River at Carlsbad.

The head in the San Andres Limestone west of White City is approximately 800 feet (245 metres) higher than the head in the Capitan aquifer. The head differential illustrates the relatively poor communication between the shelf and Capitan aquifers.

Data obtained from Fiedler and Nye (1933), Fisher (1906), and others suggest that water in the San Andres and Grayburg aquifers west of Artesia moved eastward under a gradient that ranged from 8 to 25 feet (1.5 to 5 m/km). The evaporites and some of the carbonate material in both the Chalk Bluff facies of the Artesia Group and the evaporite facies of the San Andres Limestone have been dissolved and removed by circulating ground water that moved the relatively short distance from the surface exposures west of Artesia and Carlsbad to the vicinity of the Pecos River. Consequently, the original saline water in the San Andres and Grayburg aquifers everywhere west of the Pecos River has been flushed to an unknown depth and replaced with potable water (Hood, Mower, and Grogin, 1960). Simultaneously, the hydraulic conductivity of the San Andres and Grayburg aquifers has been greatly increased.

The regional flow of water in the shelf aquifers east of the Pecos River between Carlsbad and Roswell is probably toward the east and southeast, similar to that shown by Spiegel (1967). A similar conclusion is not so readily apparent from a potentiometric-surface map of the San Andres Limestone prepared by McNeal (1965, fig. 6). The contours of head depicted by McNeal appear to be influenced by declines caused by the production of petroleum and associated waste water from many oil fields on the Central Basin platform and Artesia-Vacuum arch. Water in the shelf aquifer in the area between the Pecos River and the boundary between Lea and Eddy Counties moves slowly toward the southwest. Some of this highly mineralized water probably flowed into the Pecos River between Artesia and Lake McMillan prior to the lowering of the potentiometric surface by large withdrawals of water for irrigation. Most of the water moves toward the potentiometric low northeast of Carlsbad under an average gradient of about 15 feet per mile (3 m/km). Water moving in response to the gradient developed by the potentiometric low eventually flows upward or laterally into the Capitan aquifer and then discharges into the Pecos River at Carlsbad.

The potentiometric surface slopes eastward with a gradient of about 25 feet per mile (5 m/km) from the axis of the ground-water divide located a few miles west of the Eddy-Lea County boundary. Control for the ground-water divide in the basin and shelf aquifers is provided by several values of head greater than 3,200 feet (975 metres) above sea level determined in relatively recent drill-stem tests. These pressures initially may have been somewhat higher because they have probably been influenced by head losses resulting from the production of oil, gas and water from oil fields and the withdrawal of water from the Capitan aquifer during the forty years preceding the measurements.

Water moving northward in the Capitan aquifer from the Glass Mountains apparently was discharged into the shelf aquifer along the juxtaposition of the two aquifers between Jal and a point northwest of Eunice, N. Mex. (figs. 22 and 26). Most of the water flowed into the San Andres Limestone, in preference to other strata, because of the higher hydraulic conductivity of this aquifer. Water in the shelf aquifers probably moved generally southeastward across the northern part of the Central Basin platform between Eunice and Hobbs. The water moved northeastward from the Capitan aquifer into the shelf aquifers, then east and south within the shelf aquifers to a central area located about 15 miles (24 kilometres) southwest of Hobbs. The water then apparently moved eastward from Hobbs and Eunice under a regional gradient of about 25 feet per mile (5 m/km). The widely spaced contours southwest of Hobbs (fig. 22) also suggest that the transmissivity of the rocks comprising the shelf aquifers in this area is much higher than in the surrounding areas.

Water in the shelf aquifer on the Central Basin platform in Texas appears to move generally eastward under a gradient ranging from 8 to 25 feet per mile (1.5 to 5 m/km). The wider spacing of the head contours in the vicinity of Fort Stockton suggests that the transmissivity of the shelf aquifer is relatively high on the southern end of the Central Basin platform (fig. 4). The relatively good water in the shelf aquifer and, in particular, the San Andres Limestone, supports this conclusion (fig. 26).

Capitan aquifer

Stratigraphically, the Capitan aquifer is adjacent to, and partly enclosed by, the basin and shelf aquifers. Because of the position and the relatively higher transmissivity, it functions either as a drain or as a source of water for the shelf and basin aquifers, depending on the relative differences in head between the aquifers.

The Capitan aquifer crops out in the Guadalupe Mountains southwest of Carlsbad and in the Glass Mountains southwest of Fort Stockton. Water in the Capitan aquifer is under water-table conditions southwest of the Pecos River at Carlsbad. Artesian conditions prevail from the pecos River at Carlsbad around the northern and eastern margins of the Delaware basin to the vicinity of the Glass Mountains southwest of Fort Stockton. Northeast of the Glass Mountains, the change from artesian to water-table conditions probably takes place near the border between Pecos and Brewster Counties, but the exact location is not known.

Water entering the Capitan aquifer in the Guadalupe Mountains moved northeastward under a gradient of about 1 to 2 feet per mile (1.2 to .4 m/km) toward Carlsbad. After reaching Carlsbad, most of this water then discharged through Carlsbad Springs into the Pecos River.

Head data representative of the period prior to development, and production of water from the Capitan aquifer, are not available for a large area east of Carlsbad. The ground-water heads in this regimen are controlled by the Pecos River, which acts as a drain for the Permian aquifers in hydraulic communication. A slight westward gradient of a few feet per mile on the potentiometric surface has been interpreted as representative for the early 1920's (fig. 22). Heads developed in the Carlsbad area shortly after relatively good hydraulic communication between the Pecos River and the Capitan aquifer established during the headward erosion of the Pecos River are probably also represented by the interpretation.

The magnitude of the ground-water divide, representative of the predevelopment period in the Capitan aquifer in the vicinity of the Eddy-Lea County boundary, is unknown. However, the rate of decline of head in the Capitan aquifer has been determined with a high degree of precision for a 6-year period (figs. 24 and 25; and table 8). Crude but useful estimates of original heads can be made by extrapolating backward in time using assumed rates of head decline based on the recent observations and other fragmentary records gathered over a period of about 40 years.

A rate of decline of 20 feet per year (6 m/yr) has been recorded in the Middleton Federal B 1 observation well, sec. 31, T.19 S., R.32 E. Using this rate of decline, a head of about 3,300 feet (1,005 metres) was computed for the Capitan aquifer at the Eddy-Lea County boundary during 1956. This is comparable to heads measured in the shelf and basin aquifer systems in the same vicinity. The water level in the Hackberry Deep Unit 1 observation well, sec. 31, T.19 S., R.31 E., has declined at a relatively consistent rate of 0.318 feet per month (.097 m/month) over a 6 year period. A head of about 3,175 feet (968 metres) can be projected back to 1956 by assuming that this rate of head decline in this well is valid for the preceding 10-year period.

Leakage from both the shelf and basin aquifers is a source of the water required to maintain the ground-water divide in the Capitan aquifer. The ground-water regimen west of the divide is completely different from that to the east. Evidence suggesting these differences are provided by the recorded behavior of head in the aquifer (figs. 24 and 25) and the chemical quality of water in the aquifer (fig. 26). Leakage into the Capitan aquifer west of the ground-water divide is quickly released to the nearby Pecos River. The magnitude of the extrapolated possible hydraulic head for the predevelopment period in the Capitan aquifer in the vicinity of the Eddy-Lea County boundary is additional evidence that suggests that the Capitan aquifer in this area has an extremely low transmissivity compared to the aquifer characteristics on either side of the divide.

Water in the Capitan aquifer on the east side of the ground-water divide moved eastward toward a point northwest of Eunice, where it then flowed into the San Andres Limestone and other formations in the Artesia Group as noted above. The eastward flow of water in the Capitan aquifer, after the establishment of the Pecos River at Carlsbad, could have been maintained only by leakage from the shelf and basin aquifers.

Projections based on rates of decline, computed from water levels measured in a few wells in southwestern Pecos County, Texas suggest that the head in the Glass Mountains was more than 3,300 feet (1,005 metres)--probably near 3,400 feet (1,035 metres)-above sea level in the 1920's. Prior to development of production of water for industrial purposes, water in the Capitan aquifer moved northward from the Glass Mountains toward New Mexico under an average gradient of 2.5 feet per mile (.5 m/km) or less. Some of this water moved eastward from the Capitan aquifer into the San Andres Limestone and Artesia Group before reaching a point west of Fort Stockton. The remainder of the water in the Capitan aquifer appears to have moved to the north end of the Central Basin platform without significant losses to the adjacent shelf aquifers. In New Mexico, water moved from the Capitan aquifer into the San Andres Limestone, primarily, but also into other formations within the Artesia Group, and then flowed eastward into Texas.

The predevelopment potentiometric and chloride-ion concentration maps (figs. 22 and 26, respectively) suggest that the majority of the water found in the Capitan aquifer along the western margin of the Central Basin platform originated in the Glass Mountains. Only a small amount of the water in the Capitan aquifer in Lea County appears to have been derived from the Carlsbad area after the Pecos River cut down into a position where it was in hydraulic communication with the Capitan aquifer.

Postdevelopment potentiometric surface

Definition

The regional potentiometric surface, representative for the Capitan, basin, and shelf aquifers, after extensive development of oil, gas, and water within the project area, is shown in figure 23. The contours depicting a generalized regional fresh-water head for the basin and shelf aquifers are considered representative of the period 1960-70. The generalized head contours for the Capitan aquifer are considered representative of the latter part of 1972. A longitudinal profile of the postdevelopment potentiometric surface in the Capitan aquifer is also shown on figure 6.

Basin aquifers

The regional potentiometric surface for the basin aquifers apparently has changed only slightly during the period 1920 to 1970. Heads in the Delaware Mountain Gronup have been reduced by a small amount in the vicinity of Carlsbad, probably due to continued upward leakage into the Capitan and shelf aquifers.

The potentiometric surface has probably been lowered by an unknown amount along the eastern margin of the Delaware basin in response to the increased head differential between both the Capitan and shelf aquifers and the basin aquifers. In addition, the potentiometric surface of the basin aquifers has been depressed very sharply over the local areas surrounding oil fields completed in the Delaware Mountain Group. Heads are often below sea level in the local depressions and are not shown on this generalized regional potentiometric surface.

Interpretation of the data shown on the pre and postdevelopment potentiometric maps (fig. 22 and 23) suggests that the head in the basin aquifers has declined approximately 100 feet (30 metres) during the period 1920 to 1970 in the vicinity of the ground-water divide immediately west of the Eddy-Lea County boundary. The decline in head is probably due to the increased leakage upward into the Capitan aquifer in response to the lowering of the potential in that aquifer and the general regional head loss in the basin and shelf aquifers caused by the production of oil, gas, and water from these reservoirs.

Shelf aquifers

The potentiometric surface west and south of Artesia has been lowered generally less than 100 feet (30 metres) as a result of the withdrawal of water from the Roswell artesian basin for irrigation purposes during the period 1906 to 1969 (Fisher, 1906; Fiedler, 1926; and Fiedler and Nye, 1933). The potentiometric surface for the shelf aquifers west and southwest of Carlsbad probably has not changed significantly, although information is inadequate for any exact determination of the changes.

Reservoir pressures in several of the shelf aquifers on the Artesia-Vacuum arch east of the Pecos River have been reduced to minor fractions of the original pressures as a result of the exploitation of the petroleum. Head data representative of a regional potentiometric surface for the shelf aquifers in this area were generally unavailable because of the complex reservoir conditions created by the production of oil, gas, and water simultaneous with the injection of water. The problem is further complicated by the varying degree of hydraulic communication between the many different reservoirs and zones in this area from which oil and gas are produced.

Nearly all the oil on the Artesia-Vacuum arch is produced from reservoirs under solution gas drives. Therefore, the pressures in nearly all of the exploited reservoirs have declined very rapidly and are now extremely low. However, there are several areas where pressures have been artifically increased by injection of water in secondary recovery programs (New Mexico Oil and Gas Association, 1966; and New Mexico Oil and Gas Engineering Committee, 1950-1958, 1959, and 1960-1970). The regional potentiometric surface east and southeast of Artesia, but west of the ground water divide near the Eddy-Lea County boundary is estimated to have been lowered by approximately 150 feet (45 metres) due to withdrawal of oil, gas, and water during the 45-year period from 1925 to 1970 (fig. 23).

The hydraulic head in the shelf aquifers in the vicinity of the ground-water divide near the Eddy-Lea County boundary has declined approximately 100 feet (30 metres) over a period of about 45 years (figs. 22 and 23). Part of this decline in head may be attributed to the increased leakage downward and laterally into the Capitan aquifer, where the potential has been lowered due to production. The regional head loss in the basin and shelf aquifers also has been caused by the production of oil, gas, and associated waste water from these reservoirs.

No attempt has been made to map the complex potentiometric surface of those units of the shelf aquifers not in measurable hydraulic communication with the Capitan aquifer on the eastern part of the Artesia-Vacuum arch in Lea County. The potentiometric surface representative of the reservoirs within the shelf aquifers that appear to be in reasonably good hydraulic communication with the Capitan aquifer has been lowered from 100 to more than 600 feet (30 to 180 metres) in an area north and west of Eunice in southern Lea County.

Hydraulic gradients east of the axis of the predevelopment ground-water divide at the Eddy-Lea County boundary have been increased from about 25 feet per mile to about 40 feet per mile (5 to 8 m/km) by the withdrawal of fluids from the many oil and water fields in this area and in Texas downgradient to the east. A slight westward shift in the ground-water divide is suggested by comparing the predevelopment potentiometric surface map to the post-development map (figs. 22 and 23). An eastward gradient of about 2.5 feet per mile (0.5 m/km) has been induced in an area southwest of Hobbs, where the predevelopment potentiometric-surface gradients (fig. 22) were formerly ill-defined.

The direction of water movement in the shelf aquifers west and south of Eunice has changed from east to southeast. The direction of movement in the shelf aquifers on the northern part of the Central Basin platform may eventually be reversed in response to continual and (or) increased withdrawal of water from the Capitan aquifer. Water will then move westward from the shelf aquifers into the Capitan aquifer.

The regional postdevelopment potentiometric surface of the shelf aquifers has not been mapped south of Jal due to the complex nature of the system. Bottom-hole pressure data were available from various engineering reports describing the oil fields on the Central Basin platform. However, very few of the pressures reported were measured in a reservoir under near equilibrium conditions. The aquifer head in some of the oil field reservoirs has apparently been lowered below sea level. These effects have not spread very far into surrounding areas due to the very low transmissivity of the shelf aquifers.

Capitan aquifer

Aquifer head in the Capitan aquifer in the vicinity of Carlsbad is principally controlled by the Pecos River. Other than small head fluctuations due to variations in climatic conditions, the general configuration of the potentiometric surface in the Capitan aquifer between Carlsbad and White City has not changed from 1920 to 1972.

Under present-day conditions, a small amount of water moves east of Carlsbad during short periods of heavy rainfall in the Guadalupe Mountains or high streamflow-stages of the Pecos River. However, any water moving eastward into the Capitan aquifer under these conditions of increased head at Carlsbad behaves as bank storage and appears to return to the Pecos River as spring flow within a period of a few months (fig. 24).

A comparison of the postdevelopment and predevelopment potentiometric surfaces indicates that the aquifer head has been lowered approximately 150 feet at the predevelopment ground-water divide located in the vicinity of the Eddy-Lea County boundary. The head in the Capitan aquifer has declined in response to the withdrawal of water from the Capitan aquifer in southern Lea County, New Mexico, and Winkler and Ward Counties, Texas. The production of oil, gas, and water from reservoirs in measurable hydraulic communication with the Capitan aquifer also has contributed to the total decline in head.

The westward hydraulic gradient between the Pecos River at Carlsbad and the Eddy-Lea County boundary has been progressively reduced and, in places, reversed during the 45-year period preceding 1973. The ground-water divide inferred at the Eddy-Lea County boundary in the predevelopment potentiometric surface map has been removed. An apparent westward gradient of about 0.7 foot per mile (0.13 m/km) between the City of Carlsbad Well 13, on the east bank of the Pecos River, and the City of Carlsbad Test Well 3, about 6 miles (10 kilometres) east of the Pecos River, was computed for heads measured on January 1, 1973 (fig. 24 and table 10). Eastward hydraulic gradients for the same period have been computed between other observation wells as follows: between the City of Carlsbad Test Well 3 and the Yates State 1, 1.3 feet per mile (0.25 m/km); between the Yates State 1 and a point 6 miles (10 kilometres) south of the Hackberry Deep Unit 1, 6 feet per mile (1.1 m/km); and between the Hackberry Deep Unit 1 and the Middleton Federal B 1, 24 feet per mile (4.5 m/km) (fig. 24 and table 10).

These gradients were computed using relative differences between the fresh-water heads in the observation wells. Errors made in estimating the density of the environmental water in the Capitan aquifer could easily account for the difference of 12 feet of head (3.7 metres) over the 15 mile (24 kilometre) distance between the Pecos River and the Yates State 1 observation well. The average eastward gradient of less than 1 foot per mile (0.189 m/km) between the Pecos River and the Yates State 1 observation well is not supported by declines in the water level in the Yates State 1 well for the period of record.

Therefore, it appears that the hydraulic gradient in the Capitan aquifer for a distance of at least 15 miles (24 kilometres) east of Carlsbad cannot be defined with accuracy sufficient to permit calculation of the movement of ground water in the aquifer. Diversion of significant quantities of water from the Pecos River at Carlsbad into the Capitan aquifer should be indicated more reliably by (1) sustained declines in the water levels in the Yates State 1 and City of Carlsbad Test Well 3 observation wells, and (2) an increase in the rate of decline in the water level now being observed in the Hackberry Deep Unit 1 well (fig. 24).

A small amount of saline water probably was discharged from the Capitan aquifer in eastern Eddy County westward into the Pecos River at Carlsbad prior to exploitation of water and petroleum in southeastern New Mexico and western Texas. The reduction or reversal of the westward hydraulic gradient has probably decreased or eliminated any contribution of saline water to the flow of the Pecos River from the Capitan aquifer east of Carlsbad.

Although the data are inadequate for accurate control, the head in the Capitan aquifer in the vicinity of the Eddy-Lea County boundary appears to have been reduced slightly more than the heads representative of the shelf and basin aquifers. Leakage from the shelf and basin aquifers is not sufficient to maintain a comparable head in the Capitan aquifer, primarily because of the relatively low hydraulic conductivities in the shelf and basin aquifers. The head differential between the shelf and basin aquifers and the Capitan aquifer can be expected to increase rapidly because of the continued withdrawal of water from water fields in New Mexico and Texas, and the production of oil, gas, and waste water from reservoirs in measurable hydraulic communication with the Capitan aquifer. The differences between the heads on both sides of the zone of restricted transmissivity in the vicinity of the Eddy-Lea County boundary can also be expected to increase (fig. 24).

Approximately 90 percent of the total water produced from the Capitan aquifer east of the Pecos River at Carlsbad was withdrawn from water fields in Winkler and northern Ward Counties, Texas. Very large volumes of waste water are also produced from reservoirs that are in good hydraulic communication with the Capitan aquifer in the Hendrick oil field near Kermit, Texas. During a 45-year period more than twice as much water has been produced from the Hendrick field as a waste by-product as has been produced from the water fields supplying water to secondary recovery projects. The regional center of pumping for the entire Capitan aquifer system east of the Pecos River at Carlsbad is located a few miles west of Kermit, Tex. (fig. 23), where the potentiometric surface for the Capitan aquifer has been lowered about 700 feet (215 metres) during a period of approximately 45 years. The effects of pumping have spread from this center southward through the Capitan aquifer to the Glass Mountains, where the potentiometric surface has declined an estimated 300 feet (90 metres) and northward to the vicinity of the boundary between Eddy and Lea Counties, New Mexico, where the potentiometric surface has declined an estimated 150 feet (90 metres) (figs. 22 and 23).

The relationship of the withdrawal of fluid from oil and water fields in Winkler County and vicinity to the decline in head in the Capitan aquifer is shown in figure 34. The several increases in the rate of decline suggested by the limited data probably coincide with increases in production of water for use in secondary recovery projects.

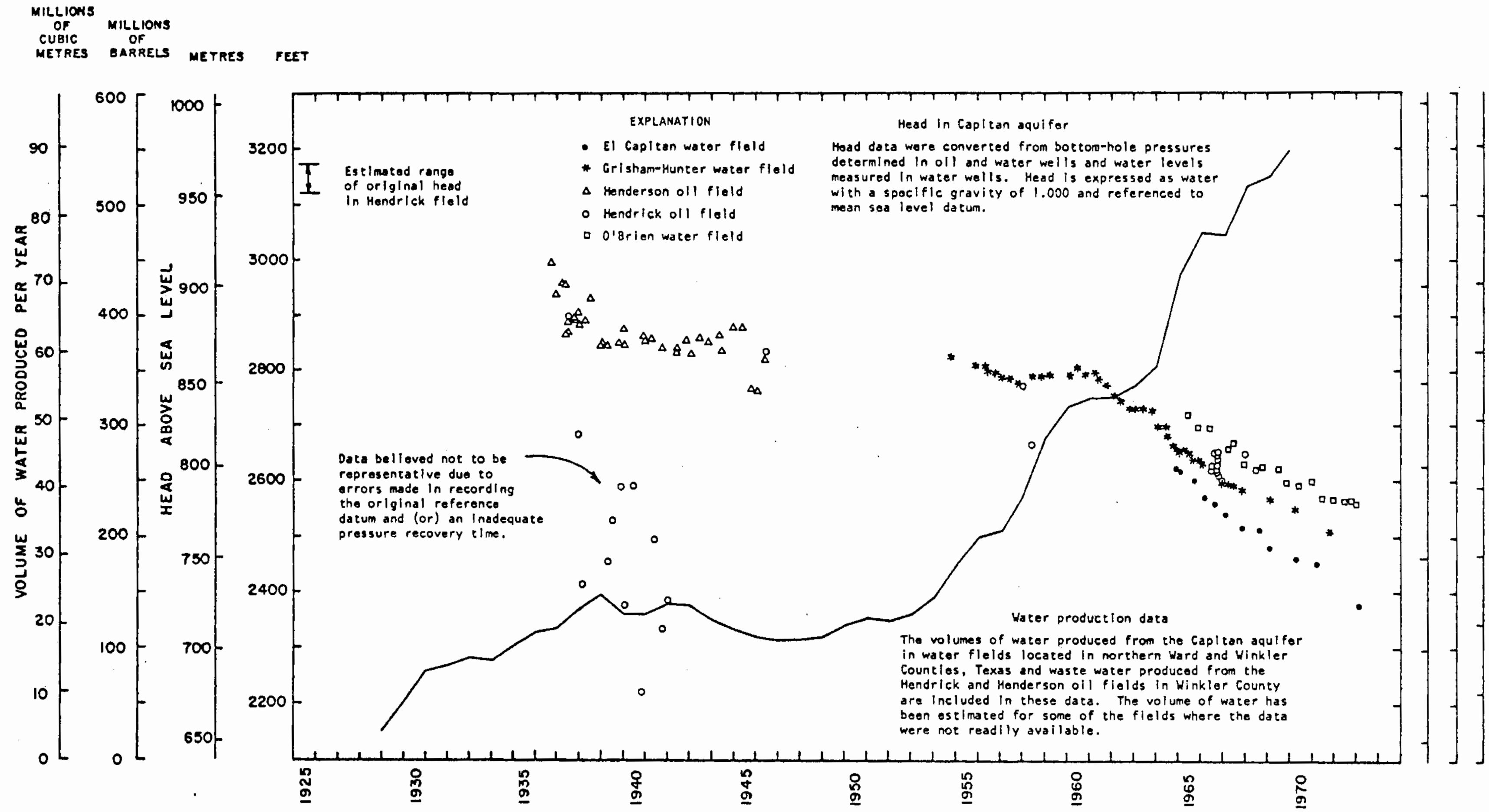


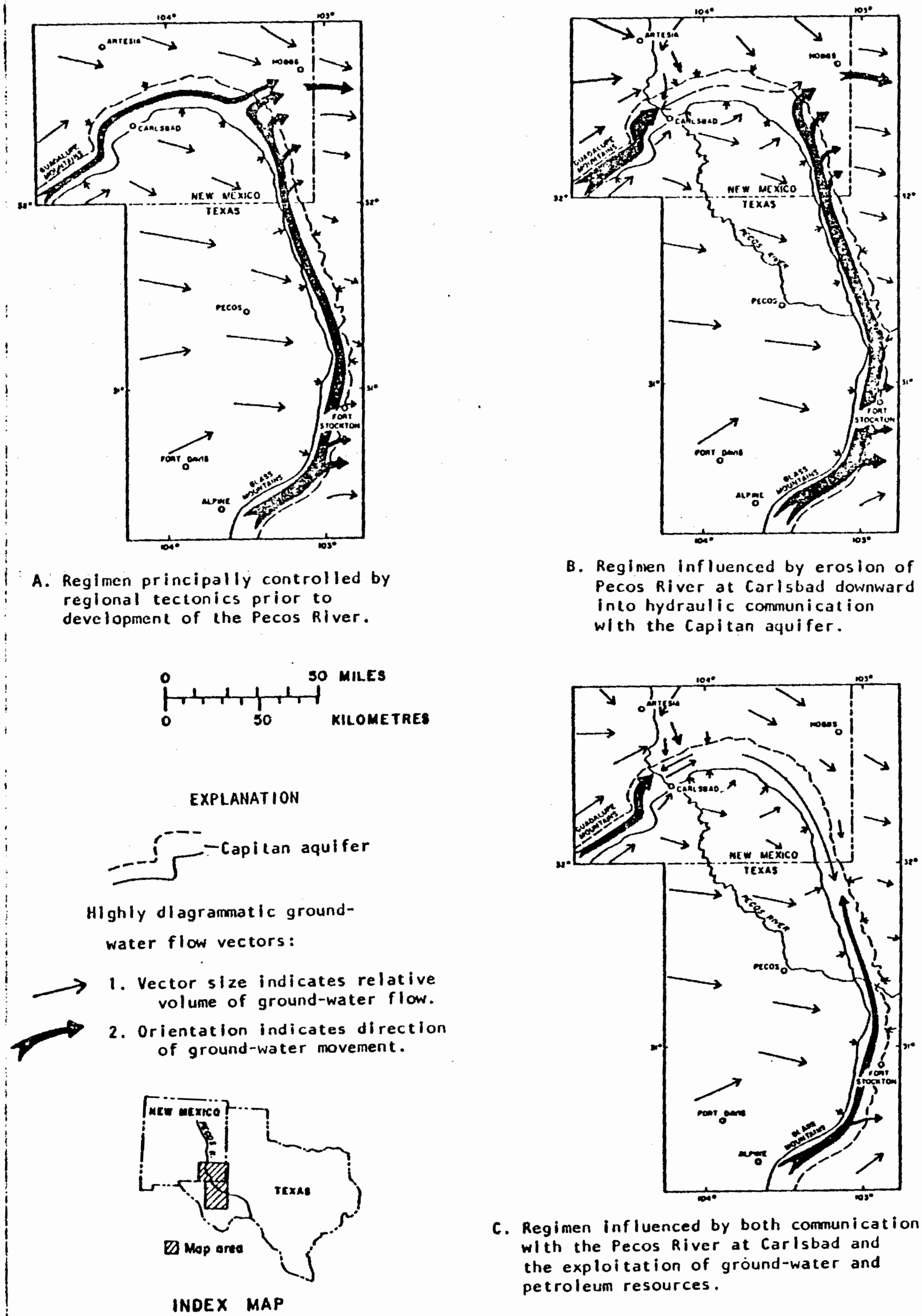
Figure 34.--Graph showing relationships between head and the production of ground water in Ward and Winkler Counties, Texas.

An average hydraulic gradient of approximately 10 feet per mile (2 m/km) has been induced in the potentiometric surface of the Capitan aquifer between Kermit and the boundary between Eddy and Lea Counties. The gradient is about 25 feet per mile (5 m/km) near the Eddy-Lea County boundary but diminishes very rapidly to about 6 feet per mile (1.2 m/km) along the western margin of the Central Basin platform in southern Lea County, New Mexico. The average hydraulic gradient between Kermit and the Pecos-Brewster County boundary is about 7.5 feet per mile (1.4 m/km).

The water produced from the Capitan aquifer probably was derived primarily from storage under water-table conditions in the Glass Mountains and, secondarily, from a decrease in artesian pressure in Pecos, Ward, and Winkler Counties, Texas, and southern Lea County, New Mexico.

Evolution of ground-water regimens

During the latter part of the Cenozoic Era the movement of ground water through the rocks of Permian Guadalupian age in southeastern New Mexico and western Texas has been controlled or influenced by the following: (1) the regional and local tectonics; (2) the evolution of the landscape; (3) the relative transmissivities of the various aquifers; (4) the amount of recharge; and (5) the exploitation of the petroleum and ground-water resources in the last 5 decades (fig. 35).



A. Regimen principally controlled by regional tectonics prior to development of the Pecos River.

B. Regimen influenced by erosion of Pecos River at Carlsbad downward into hydraulic communication with the Capitan aquifer.

C. Regimen influenced by both communication with the Pecos River at Carlsbad and the exploitation of ground-water and petroleum resources.

Figure 35.--Diagrammatic maps depicting the evolution of ground-water regimens in strata of Permian Guadalupian age in southeastern New Mexico and western Texas.

Regimen principally controlled by regional tectonics

The flow of ground water through the shelf, basin, and Capitan aquifers after the uplift of the Guadalupe and Glass Mountains but prior to the excavation of the Pecos River valley at Carlsbad is shown diagrammatically in figure 35 "A". The three aquifer systems were recharged by water originating as rain or snowfall on the outcrops along the western margin of the Delaware basin. Evidence of major surface drainage within the Trans-Pecos area of southeastern New Mexico and western Texas has not been reported.

Ground water moved generally eastward and southeastward through the shelf and basin aquifers under a gradient of probably only a few feet per mile toward natural discharge areas along streams draining to the ancestral Gulf of Mexico. Water entering the Capitan aquifer in the Guadalupe Mountains moved slowly northeastward and then eastward along the northern margin of the Delaware basin to a point southwest of present day Hobbs. Here it joined and commingled with a relatively larger volume of ground water moving northward from the Glass Mountains along the eastern margin of the Delaware basin. From this confluence, the ground water was discharged from the Capitan aquifer into the San Andres Limestone, where it then moved eastward across the Central Basin platform and Midland basin eventually to discharge into streams draining to the Gulf of Mexico.

Regimen influenced by erosion of Pecos River at Carlsbad

Some time after deposition of the Pliocene Ogallala Formation, perhaps early in Pleistocene time, the headward cutting of Pecos River extended westward across the Delaware basin to the exposed soluble Ochoan beds. It then turned northward following this natural weakness in the sedimentary rocks to pirate the streams draining to the east from the Sacramento and Guadalupe Mountains (Plummer, 1932; Bretz and Horberg, 1949b; and Thornbury, 1965). As the excavation of the Pecos River valley progressed, the hydraulic comunication with formations of Guadalupian age gradually increased until the Pecos River functioned as an upgradient drain. Eventually, the hydraulic gradients in the shelf, basin, and Capitan aquifer were reversed along the eastern side of the Pecos River valley, and ground water that formerly flowed eastward was diverted westward as spring flow into the Pecos River (fig. 35 "B"). Water recharged to the same aquifers in the Guadalupe Mountains began to follow the shorter path to springs in the Pecos River. Many of the solution features observed in the Guadalupian age sedimentary rocks west of the Pecos River near Carlsbad probably were initiated during this period.

Movement of water eastward into the Capitan aquifer from the Guadalupe Mountains toward Hobbs was decreased by the lowering of the hydraulic head along the Pecos River. At the same time, a trough in the potentiometric surface of the shelf and basin aquifers began to develop east of Carlsbad, and water began to drain into the Capitan from the surrounding sedimentary rocks. Meanwhile, ground water continued to move northward from the Glass Mountains in the Capitan aquifer toward a point of discharge into the San Andres Limestone southwest of Hobbs. This part of the aquifer was unaffected by the cutting of the Pecos River valley across the Delaware basin and the Central Basin platform.

Regimen influenced by exploitation of ground-water and petroleum resources

Regionally, the movement of ground water in the shelf and basin aquifers east of the Pecos River at Carlsbad has changed very little as a result of the exploitation of ground water and petroleum during a period of approximately 50 years (fig. 35, "C"). Locally, however, the movement of ground water within these same aquifers is controlled by the effects of the numerous producing oil fields in the area.

The shape of the regional potentiometric surface representative of the hydraulic head in the Capitan aquifer east of the Pecos River at Carlsbad has been changed significantly in response to withdrawal of both ground water and petroleum during the past 50 years. The westward movement of saline water from the Capitan aquifer in Eddy County east of Carlsbad into the Pecos River has been greatly diminished or eliminated by a reduction in hydraulic head.

Similarly, the movement of water in the San Andres Limestone and Artesia Group eastward across the northern part of the Central Basin platform from New Mexico into Texas has been decreased. Eventually, the movement of water probably will be reversed. Water may be diverted from the San Andres Limestone and Artesia Group westward from Texas back toward Hobbs and then into the Capitan aquifer along the western margin of the Central Basin platform. The effects of exploitation of the ground-water and petroleum resources will continue to be the dominant factor influencing the movement of ground water in the Capitan aquifer for many years into the future.

Response of the Capitan aquifer to stresses

Water-level records

Water-level instrumentation

The 12 observation wells located on figure 24 are equipped with float-operated recorders. Eleven of the observation wells are equipped with graphic recorders. A continuous record of the water level is available on paper-strip charts for these wells. One water-level measurement per day is read from the strip chart, recorded for each of these wells, and encoded on forms from which tabulating cards are punched. City of Carlsbad Test Well 3 is equipped with a digital recorder. Values representing the level of the water in this well are punched into a paper tape at 15-minute intervals. The water-level data contained on the punched paper tape are then transferred to magnetic tape for further processing by digital computer.

The depth to water from the land surface at the observation wells varies from approximately 20 to 1,200 feet (6 to 365 metres). Crooked holes in several of the wells cause the float line to foul on the casing. The "stair steps" on the hydrographs recorded on Southwest Jal Unit 1, Hackberry Deep Unit 1, and occasionally on other wells, are due to fouling of the float line (fig. 24; and table 9).

Oil influx into observation wells

Oil from much deeper reservoirs began to seep through the cement plugs and to accumulate at the top of the water in the Yates State 1 well shortly after the well was completed in the Capitan aquifer. A wire-line bridge plug was set at the base of the intermediate casing during December 1971 and it effectively controlled the influx of oil (fig. 24 and table 9).

Oil began to flow into the well column of the Hackberry Deep Unit 1 during the summer of 1969. A wire-line bridge plug has not been installed in this well to control the influx of oil. Water-level measurements and hydrographs plotted from these data have been adjusted for the accumulation of oil at the top of the well column following a procedure developed by Hiss (1973).

Hydrographs

As discussed previously in this report, the water levels in observation wells must be adjusted to represent head measurements for a fluid of a common density and referenced to a common datum before head comparisons can be made. These adjustments of head data are made to account for the variation of the density of the water found in both the aquifer and the well-fluid columns. However, the changes in the unadjusted water levels can be used for general comparison of trends established in the aquifer.

Water levels measured for each of the 12 observation wells, plus one additional well temporarily loaned to the USGS and the stage of Lake Tansill (Tansill Dam), are plotted in figure 24. Abrupt changes in the hydrograph traces (as shown during 1967 in the Middleton Federal B 1 observation well, for example,) are the result of (1) corrections for original errors in measurement; (2) measurements made with different instruments that do not provide a common reading; (3) changes in the fluid-column density caused by swabbing or bailing the well; and (4) fouling of the float line. Descriptions of the adjustments, mechanical failures, and other events are described in narrative comments and by well-status designations keyed by numerical and alphabetical codes or indexes, respectively, to tables (fig. 24; and table 9).

None of the changes made to the measurements recorded in the observation wells have affected the major long-term trends shown in the hydrographs.

Response of the Capitan aquifer to seasonal variations in the Pecos River valley at Carlsbad

The demand for water for irrigation and municipal use is highest in the spring and summer seasons in the Pecos River valley near Carlsbad. Much of the water available to recharge the Capitan aquifer and replenish the flow of the Pecos River occurs as precipitation from thunderstorms during the late summer and early fall. Significant periodic declines in the potentiometric surface during the spring and summer, and rises in late summer, fall, and winter result from the two nonsynchronous events as shown in the hydrographs from the six observation wells located nearest to the Pecos River at Carlsbad (fig. 24). The magnitude of fluctuations appear to be closely related to the amount of precipitation received in the Carlsbad area, the stage of the Pecos River, and the general demand for water. Rainfall in the Pecos River watershed was particularly heavy during August 1966, early July 1967, late August and early September 1968, September and October of 1969 and 1970, and September 1972.

A major flood on the Pecos River occurred at Carlsbad coincidental with the prolonged period of heavy rainfall during August 1966 (Denis, 1968). The response of the potentiometric surface to this event is illustrated in the hydrographs of the water levels measured in the City of Carlsbad Wells 10 and 13, North Cedar Hills Unit 1, and City of Carlsbad Test Well 3. The flood is also strikingly recorded by the crest-stage gage at Tansill Dam.

The seasonal variations in the potentiometric surface of the Capitan aquifer in the Carlsbad area are transmitted to all the Capitan aquifer observation wells in Eddy County. The magnitude of the seasonal variations in head observed in the Hackberry Deep Unit 1 well located approximately 23 miles northeast of Carlsbad is much smaller than the head changes noted in the wells nearer to the Pecos River (figs. 24 and 25; table 8).

Response of the Capitan aquifer to pumpage in Lea County, New Mexico, and Ward and Winkler Counties, Texas

The head of the Capitan aquifer in each of 5 observation wells in southern Lea County has decreased at a remarkably consistent rate of 1.25 to 1.75 feet per month (0.38 to 0.53 m/month) over a period of about 6 years (figs. 24 and 25; and table 8).

A decrease in the rate of decline of water levels starting in the early part of 1969 was observed in the Southwest Jal Unit 1, Federal Davison 1, Eugene Coates 3, North Custer Mountain 1, and South Wilson Deep Unit 1 wells in Lea County. This change in the rate of decline was sensed first in March and April 1969 in the three southernmost wells in the observation-well network, and subsequently, a few months later in the two wells farther to the north. This change in the rate of decline is not perceptible in the Middleton Federal B 1 well on the western boundary of southern Lea County or in any of the wells in Eddy County (fig. 24).

An increase in the rate of decline was observed in the water levels beginning in October and November 1969 in the Southwest Jal Unit 1 and Federal Davison 1 wells, in February 1970 in the North Custer Mountain Unit 1 well, and in January 1970 in the South Wilson Deep Unit 1 well.

Conversations with oil industry personnel suggested that the changes in the rate of decline corresponded to a decrease and a subsequent increase in the rate of withdrawal of water from the Capitan aquifer in several of the large water fields in southeastern New Mexico and Ward and Winkler Counties, Texas. However, production data received from the same sources do not confirm this inferred cause of the fluctuations in head.

Comparison of the hydrographs for the Eugene Coates 3 well, completed in the Seven Rivers Formation, and the nearby Federal Davison 1 well, completed in the Capitan aquifer, confirms the measurable hydraulic communication between these formations in this area.

The long-term effect of withdrawal of oil, gas, and water from the Capitan aquifer and other associated reservoirs in measurable hydraulic communication on the potentiometric surface over a period of several decades can be seen by comparing the predevelopment potentiometric surface map to the postdevelopment map (figs. 22 and 23). The cause and effect relationships between the production of fluids and decline in head are substantiated by (1) the changes in head observed over a period of about six years in the wells in the Capitan aquifer observation-well network and (2) the relationships between volume of water produced and the decline in head over a period of about 45 years in the vicinity of the Hendrick field, Winkler County, Texas (figs. 24, 25, and 34).

Significance of the differences in response

The hydrographs may be separated into two groups with distinctly different trends. One group is composed of six of the observation wells located in Eddy County, where the water levels appear to respond primarily to climatic conditions and the withdrawal of water for municipal, industrial, agricultural, and other uses in the Pecos River valley. Net changes of less than 10 feet (3 metres) have been observed in these wells during a period of 6 years. The average monthly rate of change during the period of record is less than 0.05 foot (0.015 metre) per month (fig. 24; and table 8).

The other group includes one well in eastern Eddy County and five wells in southern Lea County, where water levels in individual wells have declined from 80 to 126 feet (24 to 38 metres). Decline rates of about 1 to 2 feet (0.3 to 0.6 metres) per month have been observed during the 6-year period, 1967-72, inclusive (fig. 24). The average rate of decline of about 2.5 feet (0.8 metres) per month in the Eugene Coates 3 well is not included in these computations. The water levels in the observation wells located in Lea County are declining primarily in response to withdrawal of water from the Capitan aquifer in Lea County, New Mexico, and Ward and Winkler Counties, Texas. The production of fluids from adjacent formations of Guadalupian age that are in measurable hydraulic communication with the Capitan aquifer also contributes to the decline in water levels.

The two distinct groups of wells, although completed in the same aquifer, appear to be separated by a hydraulic discontinuity in the vicinity of the Eddy-Lea County boundary. The degree of the apparent discontinuity is unknown. The effects of natural and artifically induced stresses recorded in the observation wells are among the geologic and hydrologic evidence pointing to a sharp reduction in the transmissivity in this area.

Withdrawal of fluids from aquifers of Guadalupian age

Oil and gas production

History

Descriptions of the exploration for oil and gas and the development of individual oil and gas fields in southeastern New Mexico and western Texas are available in Warner, 1939, p. 310-339; Ackers, DeChicchis, and Smith, 1930; DeFord and Wahlstrom, 1932; Winchester, 1933; Carpenter and Hill, 1936; Bates, 1942b; Fancher, Whiting, and Cretsinger, 1954; Helmig, 1956; Nutter, 1965; and in many other publications of the American Association of Petroleum Geologists, Roswell and West Texas Geological Societies, Lea County Operators Committee, New Mexico Oil and Gas Engineering Committee, New Mexico State Bureau of Mines and Mineral Resources, the Bureau of Economic Geology of the University of Texas, and the U.S. Bureau of Mines.

A few oil seeps and shows of oil encountered while drilling water wells indicated the presence of oil and gas in western Texas and southeastern New Mexico prior to the end of the nineteenth century. About 1900, an oil well was completed at a depth of 1,200 feet (365 metres) approximately 13 miles (21 kilometres) northwest of Fort Stockton, Tex. One well drilled to a depth of about 900 feet (275 metres) in Permian rocks in the Pecos River valley near Artesia, N. Mex. in 1909 apparently yielded a few barrels of oil per day for more than a decade (Nutter, 1965).

These were significant and encouraging finds, nevertheless, a number of test wells were drilled sporadically within the study area without commercial success until the discovery of the Artesia field located east of Carlsbad in 1923. Subsequently, the Wheat field in Loving County, Texas was discovered in 1925, and the Hendrick field near Kermit, Texas was found shortly thereafter in the summer of 1926.

After these prolific discoveries, interest in the exploration and development of the oil and gas reserves intensified rapidly. As a result, most of the major oil fields producing from rocks of Permian Guadalupian age were discovered prior to 1940. The majority of the pool extensions and development wells were completed and some of the secondary recovery projects were initiated by 1950. Several of the older oil fields of importance within the project area are listed in table 12, along with the year the field was discovered (Nutter, 1965; and Herald, 1957). The vast majority of the fields are located on either the western margin of the Central Basin platform or the Artesia-Vacuum arch on the Northwestern shelf (fig. 19).

Table 12.--Some of the first significant oil and gas fields discovered in southeastern New Mexico and western Texas

State	County	Field	Year of discovery
New Mexico	Eddy	Artesia	1923
		Getty	1927
	Lea	Maljamar	1926
		Rhodes	1927
		Hobbs	1928
		Wilson (West Eunice)	1928
		Eaves	1928
		Jal	1929
		Eunice	1929
		Vacuum	1929
		Langlie	1929
		Cooper	1929
Texas	Loving	Wheat	1925
	Winkler	Hendrick	1926
		Scarborough	1927
		Kermit (Bolin)	1928
		Leck	1928
	Ward	Shipley	1928
		North Ward	1929
		South Ward	1929
	Pecos	Yates	1926
		Pecos Valley (Low gravity)	1927
		Pecos Valley (High gravity)	1928

Sources of production data

New Mexico

The first records of the production of oil, gas, and waste water in Lea County were assembled for proration purposes and were made available to the public by the Hobbs Pool Operators Committee in 1932. This committee was succeeded by the Lea County Operators Committee in 1935 and the New Mexico Oil and Gas Engineering Committee in 1950. Statistical information supplied by oil companies are now tabulated by the New Mexico Oil Conservation Commission and published and distributed by the New Mexico Oil and Gas Engineering Committee in monthly and annual reports.

Complete statistical summaries containing the volume of oil, gas, waste water, and injected water have been available for Lea County since 1935. Similar records for Eddy County were first made available to the public in 1942 and are difficult to obtain prior to that date. Accurate volumes of the petroleum produced are determined by either gauging the oil stock tanks or by measuring the oil or gas as it passes through meters into a pipeline. Until the enactment of stringent laws to control pollution in recent years, waste water produced with oil was most often separated from the oil and gas and then disposed of in pits without volumetric determination.

Many operators reportedly calculate the volume of produced waste water from water to oil ratios determined by frequent sampling of the oil-water mixture. However, the volume of waste water reported by the operators to the regulatory agencies may be based only on visual estimates and may be unreliable. Gas flared or released at the wellhead may also be estimated or determined from gas-oil ratios.

The volume of water injected into underground reservoirs for waste disposal or pressure maintenance is reported to the regulatory agencies and published in monthly reports. The water produced from aquifers within the Lea County and Capitan underground water basins and the water injected into reservoirs in partially depleted oil-bearing reservoirs for pressure maintenance purposes is reported to the New Mexico State Engineer.

Texas

The volume of oil, gas, and condensate produced in Loving, Pecos, Reeves, Ward, Winkler, and other counties in Texas are compiled by the Oil and Gas Division of the Railroad Commission of Texas and published annually. This information is also available from private companies that specialize in the collection, tabulation, publication, and distribution of oil field scout reports and statistical data.

The volume of waste water produced as a by-product of oil production is not assembled by the Railroad Commission of Texas. Surveys of oil field brine production and disposal were made during 1961 and 1967 by the Texas Water Commission and the Texas Water Pollution Control Board (1963 and 1969). Some information describing the volumes of waste water produced in individual fields or oil-water ratios have been published in areal studies (Garza and Wesselman, 1959; White, 1971; Armstrong and McMillion, 1961; and Carpenter and Hill, 1936). Production statistics for a large part of the Hendrick field were obtained from private sources.

In order to supplement the meager information available concerning the volume of produced waste water, individual oil companies were canvassed by mail and asked to supply historical oil-water ratios for a number of fields in which they operated producing leases. The oil-water trends established from data obtained in this survey were then combined with published oil-production data and used to compute the amount of waste water produced from oil fields in the five Texas counties.

Large volumes of ground water are being produced from the Cenozoic, Rustler, Santa Rosa, and Capitan aquifers and used as injection water (Guyton, 1965). Some of the statistical data needed to determine the total amount of water produced from these water fields was derived from the biennial reports published by the Texas Petroleum Research Committee (1952-1968). However, most of the needed information was acquired directly from the individual companies engaged in suppling water for secondary recovery projects.

Volume of oil, gas, and water removed or injected

Computation of volumes

The total volume of oil, gas, water, and condensate that had been produced or injected into an individual oil, gas, or water field each year were extracted from all the available statistical reports and encoded for further processing with a digital computer. The volume of waste water produced in each of the oil fields in Texas was computed using the oil-water ratios obtained from the oil industry. Various summary reports were then prepared using these data (figs. 36-38; and table 13).

Within each state, a number of oil fields have been combined, separate pools have been created within fields, names changed, and field boundaries altered throughout the past 45 years. Consequently, it is often difficult to compute the total volume of fluid produced from any one geographic area. The changes appear to be confined to within county boundaries, probably due to considerations of tax liabilities. Therefore, the production totals for each county should be reasonably accurate.

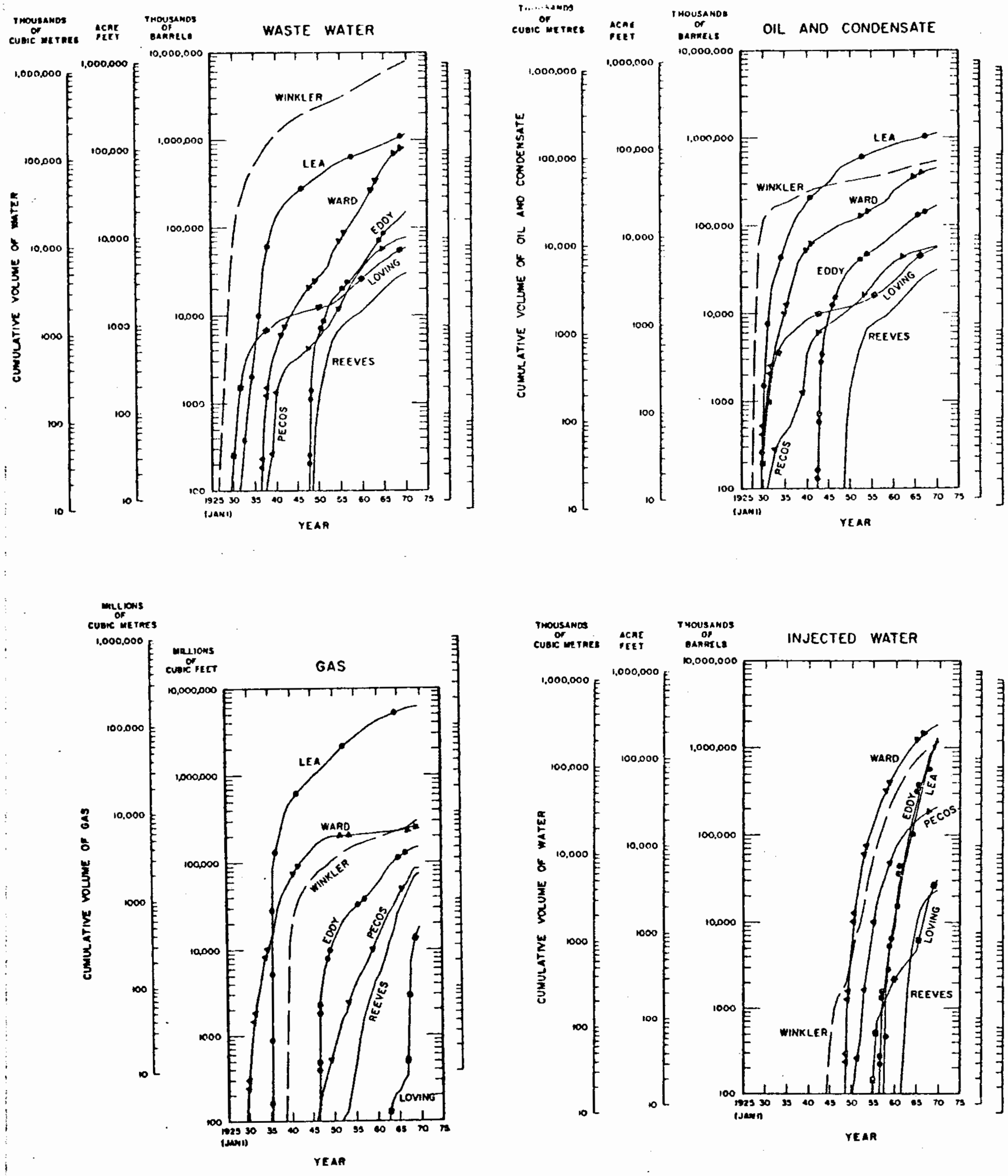


Figure 36.--Graph showing volume, by county, of fluid produced from or injected into oil fields completed in formations of Permian Guadalupian age in Eddy and Lea Counties, New Mexico, and Loving, Pecos, Reeves, Ward, and Winkler Counties, Texas. Volumes were determined under surface conditions, i.e., stock-tank barrels or cubic feet under one atmosphere of pressure.

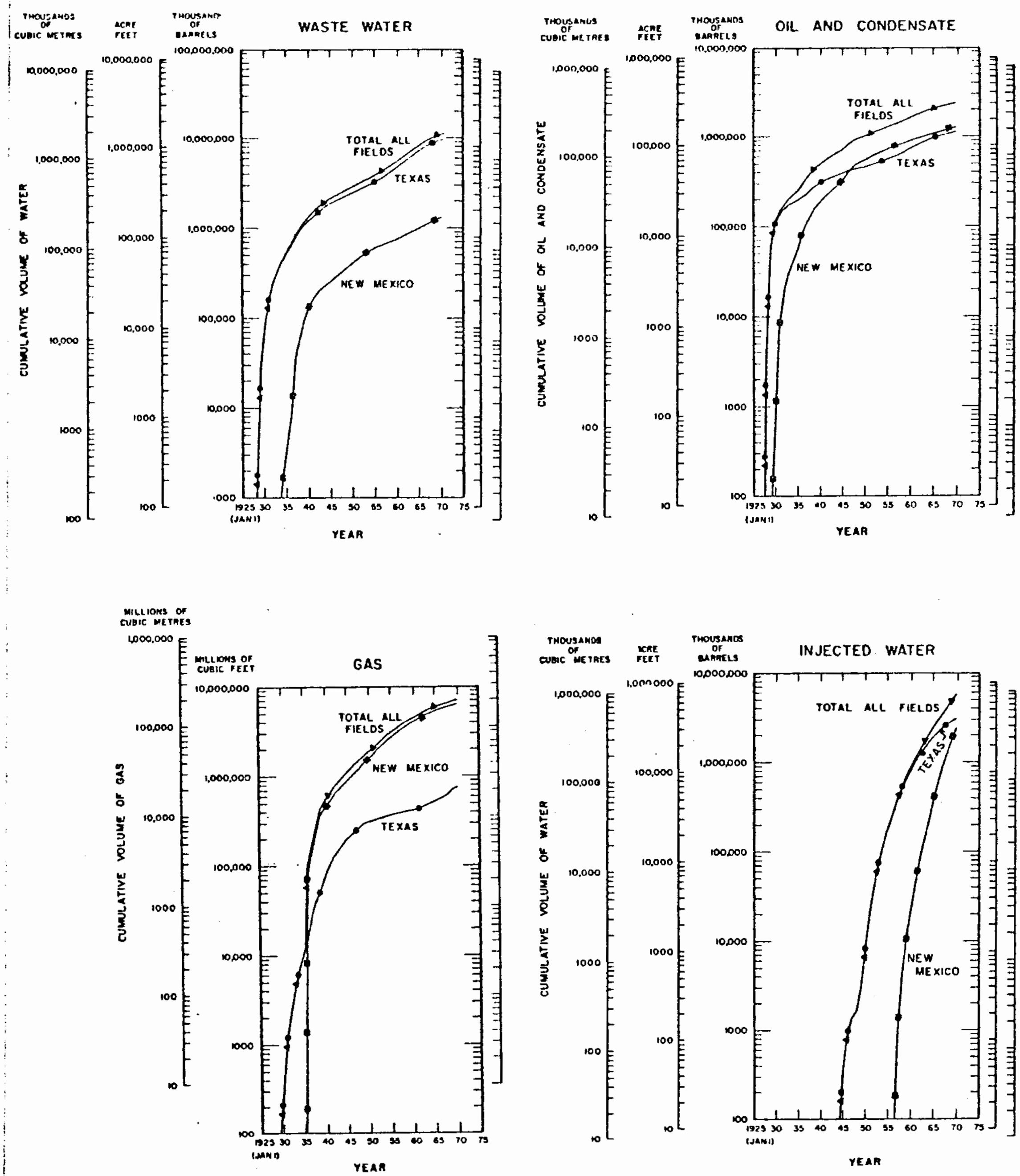


Figure 37.--Graph showing volume, by state, of fluid produced from or injected into oil fields completed in formations of Permian Guadalupian age in Eddy and Lea Counties, New Mexico, and Loving, Pecos, Reeves, Ward, and Winkler Counties, Texas. Volumes were determined under surface conditions, i.e., stock-tank barrels or cubic feet under one atmosphere of pressure.

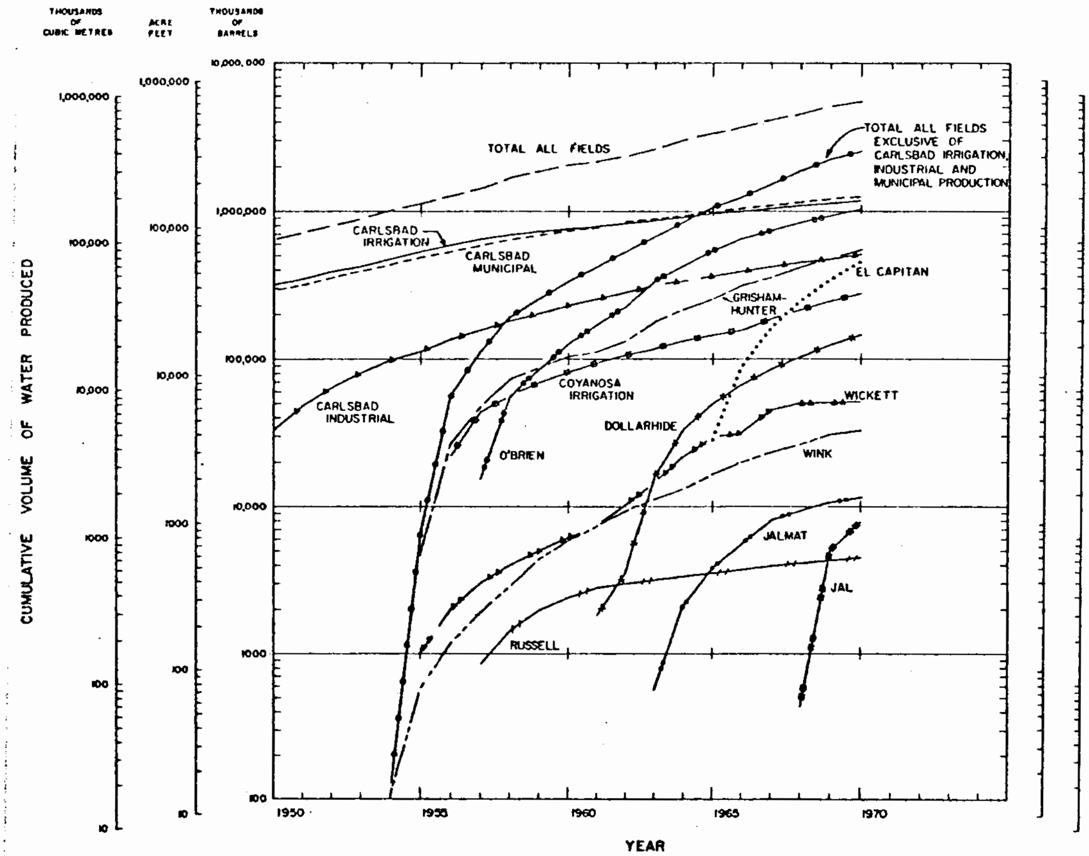


Figure 38.--Graph showing volume of water produced from principal water fields completed in the Capitan aquifer in southeastern New Mexico and western Texas.

Table 13.--Volume of fluid produced from or injected into formations of Permian Guadalupian age in Lea and Eddy Counties, New Mexico, and Loving, Pecos, Reeves, Ward, and Winkler Counties, Texas 1/

County	1920-29 Cumulative	1930-39 Cumulative	1940-49 Cumulative	1950-59 Cumulative	1960-69 Cumulative
New Mexico					
Eddy County					
Water					
Industrial (Capitan aquifer)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	4.4 (33.8; 5.4) 4.4 (33.8; 5.4)	25.2 (196 ; 31) 29.6 (230 ; 37)	35.8 (278 ; 44) 65.4 (508 ; 81)
Irrigation (Capitan aquifer)	4.5 (34.7; 5.5) 4.5 (34.7; 5.5)	9.8 (76.3; 12) 14.3 (111 ; 18)	26.5 (206 ; 33) 40.8 (317 ; --)	57.2 (444 ; 71) 98.0 (761 ; 121)	52.7 (409 ; 65) 151 (1,170 ; 186)
Municipal (Capitan aquifer)	5.1 (39.8; 6.3) 5.1 (39.8; 6.3)	9.2 (71.2; 11) 14.3 (111 ; 18)	23.2 (180 ; 50) 37.5 (291 ; 46)	56.7 (440 ; 70) 94.2 (731 ; 116)	68.1 (529 ; 84) 162 (1,260 ; 200)
Petroleum waste	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	.8 (6.2; 1.0) .8 (6.2; 1.0)	4.2 (32.7; 5.2) 5.0 (38.9; 6.2)	14.6 (113 ; 18) 19.6 (152 ; 24)
Secondary recovery					
Produced (Capitan aquifer)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	.3 (2.4; .38) .3 (2.4; .38)	.3 (2.2; .35) .6 (4.6; .73)
Injected	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	.6 (4.0; .64) .6 (4.0; .64)	145 (1,130 ; 180) 146 (1,200 ; 191)
Petroleum	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	4.2 (32.2; 5.1) 4.2 (32.2; 5.1)	6.1 (47.2; 7.5) 10.2 (79.4; 13)	10.9 (85 ; 14) 21.1 (164 ; 26)
Gas	-- --	-- --	11.2 (0.32) 11.2 (.32)	40.1 (1.1) 51.3 (1.4)	98.9 (2.8) 150 (4.2)

Table 13.--Volume of fluid produced from or injected into formations of Permian Guadalupian age in Lea and Eddy Counties, New Mexico, and Loving, Pecos, Reeves, Ward, and Winkler Counties, Texas - Continued

County	1920-29 Cumulative	1930-39 Cumulative	1940-49 Cumulative	1950-59 Cumulative	1960-69 Cumulative
New Mexico - Continued					
Southern Lea County					
Water					
Petroleum waste	-- (-- ; --) -- (-- ; --)	17.0 (132 ; 21) 17.0 (132 ; 21)	33.9 (263 ; 42) 50.9 (395 ; 63)	41.4 (321 ; 51) 92.3 (716 ; 114)	58.7 (456 ; 72) 151 (1,170 ; 186)
Secondary recovery					
Produced (Capitan aquifer)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	2.8 (21.5; 3.4) 2.8 (21.5; 3.4)
Injected	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	1.3 (9.9; 1.6) 1.3 (9.9; 1.6)	161 (1,250 ; 199) 162 (1,260 ; 200)
Petroleum	0.13 (1.01; 0.16) .13 (1.01; .16)	23.8 (185 ; 29) 23.9 (186 ; 30)	43.6 (338 ; 54) 67.5 (524 ; 83)	38.5 (299 ; 48) 106 (823 ; 131)	38.3 (297 ; 47) 144 (1,120 ; 178)
Gas	-- --	377 (10.7) 377 (10.7)	1,180 (33.4) 1,560 (44.2)	2,380 (67.4) 3,940 (112)	2,190 (62) 6,130 (174)
Texas					
Loving County					
Water					
Petroleum waste	.03 (.25; .04) .03 (.25; .04)	1.06 (8.2; 1.3) 1.1 (8.4; 1.3)	.5 (3.2 ; .58) 1.6 (12.1 ; 1.9)	1.9 (14.9; 2.4) 3.5 (27.0; 4.3)	4.1 (32.1; 5.1) 7.6 (59.1; 9.4)
Secondary recovery					
Produced (Capitan aquifer)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)

Table 13.--Volume of fluid produced from or injected into formations of Permian Guadalupian age in Lea and Eddy Counties, New Mexico, and Loving, Pecos, Reeves, Ward, and Winkler Counties, Texas - Continued

County	1920-29 Cumulative	1930-39 Cumulative	1940-49 Cumulative	1950-59 Cumulative	1960-69 Cumulative
Texas - Continued					
Loving County - Continued					
Water - Continued					
Secondary recovery					
Injected	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	0.3 (2.2; 0.35) .3 (2.2; .35)	3.45 (26.8 ; 4.3) 3.73 (29.0 ; 4.6)
Petroleum	0.03 (0.32; 0.05) .03 (.32; .05)	1.06 (8.2; 1.3) 1.1 (8.6; 1.4)	0.5 (3.5; 0.56) 1.6 (12.1; 1.9)	1.4 (11.2: 1.8) 3.0 (23.3; 3.7)	4.12 (32.0 ; 5.0) 7.12 (55.3 ; 8.8)
Gas	-- --	-- --	-- --	.01 (.0003) .01 (.0003)	18.0 (.51) 18.0 (.51)
Pecos County					
Water					
Irrigation (Capitan aquifer)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	10.5 (81.4 ; 12.9) 10.5 (81.4 ; 12.9)	25.2 (196 ; 31.2) 35.7 (277 ; 44.0)
Irrigation (San Andres Formation)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	14.9 (116 ; 18.4) 14.9 (116 ; 18.4)	82.7 (642 ; 102) 97.6 (758 ; 121)	90.4 (702 ; 112) 188 (1,460 ; 232)
Petroleum waste	-- (-- ; --) -- (-- ; --)	.18 (1.4; .22) .18 (1.4; .22)	.56 (4.4; .69) .74 (5.8; .92)	4.0 (30.9 ; 4.9) 4.7 (36.7 ; 5.8)	5.3 (40.9 ; 6.5) 10.0 (77.6 ; 12.3)
Secondary recovery					
Produced (Capitan aquifer)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)
Injected	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	.01 (.03; .005) .01 (.03; .005)	8.2 (63.5 ; 10.1) 8.2 (63.5 ; 10.1)	18.6 (145 ; 23.0) 26.8 (208 ; 33.0)

Table 13.--Volume of fluid produced from or injected into formations of Permian Guadalupian age in Lea and Eddy Counties, New Mexico, and Loving, Pecos, Reeves, Ward, and Winkler Counties, Texas - Continued

County	1920-29 Cumulative	1930-39 Cumulative	1940-49 Cumulative	1950-59 Cumulative	1960-69 Cumulative
Texas - Continued					
Pecos County - Continued					
Petroleum	0.01 (0.04; 0.01) .01 (.04; .01)	0.44 (3.4; 0.54) .44 (3.4; .55)	1.1 (8.1; 1.2) 1.5 (11.5; 1.8)	3.5 (36.8; 4.3) 4.9 (38.3; 6.1)	2.4 (18.9 ; 3.0) 7.4 (57.2 ; 9.1)
Gas	-- --	-- --	.7 (.02) .7 (.02)	12.0 (.34) 12.7 (.36)	71.8 (2.03) 84.5 (2.39)
Reeves County					
Water					
Petroleum waste	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	.17 (1.3; .21) .17 (1.3; .21)	1.3 (10.4; 1.6) 1.5 (11.7; 1.9)	2.4 (18.5 ; 2.9) 3.9 (30.2 ; 4.8)
Secondary recovery					
Produced (Capitan aquifer)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)
Injected	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	3.0 (23.2 ; 3.7) 3.0 (23.2 ; 3.7)
Petroleum	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	.18 (1.4; .22) .18 (1.4; .22)	1.3 (9.8; 1.6) 1.4 (11.2; 1.8)	2.5 (19.6 ; 3.1) 4.0 (30.8 ; 4.9)
Gas					
Produced	-- --	-- --	.04 (.0012) .04 (.0012)	2.0 (.057) 2.0 (.057)	71.7 (2.03) 73.7 (2.09)
Injected	-- --	-- --	-- --	99 (2.8) 99 (2.8)	-- -- 99 (2.8)

Table 13.--Volume of fluid produced from or injected into formations of Permian Guadalupian age in Lea and Eddy Counties, New Mexico, and Loving, Pecos, Reeves, Ward, and Winkler Counties, Texas - Continued

County	1920-29 Cumulative	1930-39 Cumulative	1940-49 Cumulative	1950-59 Cumularive	1960-69 Cumulative
Texas					
Ward County					
Water					
Petroleum waste	-- (-- ; --) -- (-- ; --)	0.55 (4.2; 0.67) .55 (4.2; .67)	3.0 (23.5; 3.7) 3.6 (27.7; 4.4)	21.0 (163 ; 25.9) 24.6 (191 ; 30.4)	84.4 (655 ; 104) 109 (846 ; 135)
Secondary recovery					
Produced (Capitan aquifer)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	17.2 (133 ; 21.1) 17.2 (133 ; 21.1)	123 (956 ; 152) 140 (1,090 ; 173)
Injected	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	.57 (4.4; .70) .57 (4.4; .70)	64.0 (497 ; 79.0) 64.5 (501 ; 79.7)	169 (1,310 ; 208) 233 (1,810 ; 288)
Petroleum	0.06 (0.44; 0.07) .06 (.44; .07)	7.1 (55.0; 8.7) 7.1 (55.4; 8.8)	7.4 (57.6; 9.2) 14.6 (113 ; 18.0)	17.3 (134 ; 21.3) 31.8 (247 ; 39.3)	25.4 (197 ; 31.3) 57.2 (444 ; 70.6)
Gas					
Produced	.30 (.01) .30 (.01)	61.7 (1.75) 62.0 (1.76)	144 (4.1) 206 (5.8)	8.7 (.25) 215 (6.1)	46.0 (1.3) 265 (7.5)
Injected	-- --	-- --	6.1 (.17) 6.1 (.17)	1.7 (.05) 7.9 (.22)	-- 7.9 (.22)

Table 13.--Volume of fluid produced from or injected into formations of Permian Guadalupian age in Lea and Eddy Counties, New Mexico, and Loving, Pecos, Reeves, Ward, and Winkler Counties, Texas - Concluded

County	1920-29 Cumulative	1930-39 Cumulative	1940-49 Cumulative	1950-59 Cumulative	1960-69 Cumulative
Texas					
Winkler County					
Water					
Petroleum waste	9.8 (75.7 ; 12.0) 9.8 (75.7 ; 12.0)	141 (1,090 ; 173) 151 (1,170 ; 186)	156 (1,210 ; 192) 307 (2,380 ; 378)	234 (1,810; 288) 541 (4,190; 666)	357 (2,770; 440) 898 (6,970; 1,108)
Secondary recovery					
Produced (Capitan aquifer)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	14.2 (110; 17.5) 14.2 (110; 17.5)	139 (1,080; 172) 153 (1,190; 189)
Injected	-- (-- ; --) -- (-- ; --)	-- (-- ; --) -- (-- ; --)	.49 (3.8; .60) .49 (3.8; .60)	35.0 (272; 43.2) 35.5 (276; 43.9)	114 (884; 141) 149 (1,160; 184)
Petroleum	14.6 (113 ; 18.0) 14.6 (113 ; 18.0)	16.5(128 ; 20.3) 31.1(241 ; 38.3)	10.9 (85 ; 13.5) 42.0 (326 ; 51.8)	11.1 (86; 13.7) 53.1 (412; 65.5)	16.1 (125; 19.9) 69.2 (537; 85.4)
Gas					
Produced	-- --	12.7 (.36) 12.7 (.36)	93.9 (2.7) 107 (3.0)	80.7 (2.3) 188 (5.3)	116 (3.3) 304 (8.6)
Injected	-- --	-- --	.83 (.024) .83 (.024)	14.7 (.42) 15.5 (.44)	34.7 (.98) 50.2 (1.4)

1/ Water and oil in thousands of acre-feet (millions of barrels; millions of cubic metres); gas in billions of cubic feet (billions of cubic metres). All volumes were determined at surface conditions.

Volume of oil and gas produced

The cumulative volumes of oil and gas produced in the seven counties within the project area are shown graphically in figures 36 and 37, and tabulated in table 13. The volume of oil produced in all seven counties has gradually and consistently increased during the past 20 to 30 years. The rate of increase in oil production is less in Winkler County after 1933 than in the other six counties.

A substantial part of the total amount of oil produced in Winkler County came from the Hendrick field. The maximum rate of oil production was reached early in the life of this field, followed by a very rapid decline (fig. 36). A total of approximately 310,400 acre-feet (2,410,000,000 barrels; 383,000,000 cubic metres) of oil has been produced in the seven counties in southeastern New Mexico and western Texas. Of this amount, 145,500 acre-feet (1,130,000,000 barrels; 180,000,000 cubic metres) or 47 percent of the total was produced from oil fields in Loving, Pecos, Reeves, Ward, and Winkler Counties, Texas; and the remainder, 165,000 acre-feet (1,280,000,000 barrels; 204,000,000 cubic metres), or 53 percent, was produced from oil fields in Eddy and Lea Counties, New Mexico. Oil was being produced at an average annual volume of 4,380 acre-feet (34,000,000 barrels; 5,400,000 cubic metres) and 5,150 acre-feet (40,000,000 barrels; 6,360,000 cubic metres) per year in the project area in Texas and New Mexico, respectively, during the period 1965-69.

Production of oil in secondary recovery projects

Oil has been produced continually from many of the oil fields in southeastern New Mexico and western Texas for more than 45 years. The original expelling force created by expansion of the gas dissolved in oil in many of the oil fields was depleted very rapidly before more than a minor fraction of the original oil in place in the reservoir was recovered. Substantial additional oil, frequently as much as had been produced by primary methods, has been produced from many of the fields by application of secondary recovery techniques to maintain, restore, or increase the pressures in the partly depleted reservoirs.

Waterflooding, a secondary recovery method involving the injection of water to increase reservoir pressure, has been particularly successful within the project area. Water is introduced under pressure through injection wells into the oil-bearing reservoir rock. The remaining oil is then displaced, theoretically pushed as a bank through the porous medium, toward the cones of lower pressure at the producing wells. Recovery of oil is enhanced if the rock surfaces are preferentially wet by the water as it displaces oil from oil-wet surfaces (Uren, 1939, p. 444; and Levorsen, 1967). The productive life of a field is often prolonged 5 to 10 or more years by waterflooding.

Gas injection secondary recovery projects were initiated in the Shipley field, Ward County in 1930 and in the Langlie-Mattix field, Lea County in 1941 (Fancher, Whiting, and Cretsinger, 1954; and Davis, 1942). Waterfloods were started on units in the Kermit field in Winkler County in 1943, the South Ward field in Ward County and the Pecos Valley Low and High-Gravity fields in Pecos County in 1949. By 1952, three gas-injection and 23 waterflood projects were active in Loving, Pecos, Reeves, Ward, and Winkler Counties, Texas. Fifteen years later, more than 250 secondary recovery projects, most of which were waterfloods, were operating in the same area (Texas Petroleum Research Committee, 1968).

The first waterflood in the New Mexico part of the study area was started in the Shugart field in 1952 (New Mexico Oil and Gas Association, 1966, p. 6). The number of waterfloods in operation in Eddy and Lea Counties rapidly increased to 24 in 1960, to 100 in 1965, and to approximately 185 by the latter part of 1969.

Fancher, Whiting, and Cretsinger (1954) estimated the remaining oil reserves in reservoirs of several geologic ages in Loving, Pecos, Reeves, Ward, and Winkler Counties, Texas, as of 1952, to be approximately 121,700 acre-feet (945,000,000 barrels; 150,000,000 cubic metres), recoverable by primary methods; and 98,700 acre-feet (766,000,000 barrels; 122,000,000 cubic metres), recoverable by secondary methods.

Water from the Capitan aquifer is being exported from Winkler County to Andrews and Ector Counties, Texas where it is injected into partly depleted reservoirs in a number of oil fields (Brackbill, and Gaines, 1964). Operators of waterfloods located in Crane and Gaines Counties reportedly are also potential users of water from the Capitan aquifer. Similar estimates of oil reserves for these four counties indicated that approximately 341,300 acre-feet (2,650,000,000 barrels; 421,000,000 cubic metres) and 304,400 acre-feet (2,363,000,000 barrels; 375,700,000 cubic metres) are recoverable by primary and secondary production methods, respectively.

Wells completed in the Capitan aquifer probably will be the source of much of the large quantity of water required for secondary recovery purposes. Other sources will be recycled waste water and new water pumped from the Santa Rosa, Rustler, San Andres, and Cenozoic aquifers. By the end of 1969, more than 416,000 acre-feet (3,230,000,000 barrels; 514,000,000 cubic metres) of water had been injected into reservoirs of several geologic ages in the five Texas counties within the project area.

The New Mexico Oil and Gas Association (1966) estimated reserves of recoverable oil in southeastern New Mexico during the next two decades to be: primary--23,200 acre-feet (180,000,000 barrels; 28,600,000 cubic metres); and secondary--77,300 acre-feet (600,000,000 barrels; 95,400,000 cubic metres). An estimated 979,000 acre-feet (7,600,000,000 barrels; 1,208,000,000 cubic metres) of water would have to be injected in waterfloods at an average rate of 45,600 acre-feet (354,000,000 barrels; 56,300,000 cubic metres) per year in order to produce the additional 600 million barrels (95,400,000 cubic metres) of oil recoverable by secondary methods. Approximately 45 percent of the required water would have to be new or "make-up" water, and the remainder would be recycled waste water.

Water is being pumped from the Ogallala, Rustler, Santa Rosa, San Andres, and Capitan aquifers in southeastern New Mexico for use in waterfloods. Yields from wells in the Ogallala, San Andres, and Capitan aquifers were considered by the New Mexico Oil and Gas Association to be adequate to support full-scale waterflood projects. More than 307,000 acre-feet (2,390,000,000 barrels; 380,000,000 cubic metres) of water have been injected into reservoirs of several different geologic ages in active waterfloods in southeastern New Mexico through the end of 1969. Approximately 73,300 acre-feet (569,000,000 barrels; 90,500,000 cubic metres) of water was injected in waterfloods during 1969. The volume of water being injected per year in Eddy and Lea Counties is increasing very rapidly (fig. 36).

Water production

Waste-water production in oil fields

Large amounts of waste water have been produced from the Artesia Group and San Andres Limestone in several of the oil fields located along the southern edge of the Northwestern shelf and western and northern margins of the Central Basin platform. Water-oil ratios during the life of production in these fields average 1.7:1 and 12:1 in Lea and Eddy Counties, respectively, and are much smaller than the water-oil ratio of 25:1 in the Hendrick field in Winkler County. The cumulative volumes of waste water and oil produced from several of these fields are given in table 14. The small fields in Eddy County and the Hobbs and Cooper-Jal (Jalmat) fields have strong water drives (Schuehle, 1942, p. 229; and Miller, and Bates, 1942, p. 201). A combination of solution gas and water-drive forces are probably active in the reservoirs in the other fields listed in table 10.

Until recently, most of the waste water was placed in earthen "evaporation" pits, where much of it seeped into the shallow aquifers (Nicholson and Clebsch, 1961, p. 102; Garza and Wesselman, 1962, p. 25; Gilkey and Stotelmeyer, 1965, p. 11-26; and White, 1971, p. 51). Nearly all of the waste water is now collected and transported by truck or pipeline systems to other storage areas, often in areas remote from the source. The waste water then is either injected into aquifers selected as waste repositories or into oil-bearing reservoirs as secondary recovery floodwater.

Table 14.--Selected oil fields in Lea and Eddy Counties, New Mexico, with relatively large water-oil ratios

County	Field and reservoir	Cumulative volume produced through 1969, in acre-feet (bbls; hm^3)		Water to oil ratio
		oil	water	
Eddy	Benson--Yates Formation	31.6 (245,000; 0.039)	197.1 (1,530,000; 0.243)	6.2:1
	Barber--Yates Formation	153.3 (1,190,000; .189)	1,494.1 (11,600,000; 1.843)	9.7:1
	Dos Hermanos--Yates and Seven Rivers Formation	149.4 (1,160,000; .184)	1,983.5 (15,400,000; 2.447)	13.3:1
	Getty--Yates Formation	172.6 (1,340,000; .213)	5,499.8 (42,700,000; 6.784)	31.9:1
	Magruder--Yates Formation	1.3 (10,300; .002)	30.0 (233,000; .370)	22.6:1
	PCA--Yates Formation	77.9 (605,000; .096)	378.7 (2,940,000; .467)	4.9:1
	Russell--Yates Formation	284.6 (2,210,000; .351)	678.8 (5,270,000; .837)	2.4:1
Lea	Eumont--Yates, Seven Rivers, and Queen Formations	3,838.2 (29,800,000; 4.734)	5,267.9 (40,900,000; 6.498)	1.4:1
	Eunice--Grayburg Formation and San Andres Limestone	14,296.8 (111,000,000; 17.635)	12,364.8 (96,000,000; 15.252)	.9:1
	Eunice South--Seven Rivers and Queen Formations	3,155.6 (24,500,000; 3.892)	3,954.2 (30,700,000; 4.878)	1.3:1

Table 14.--Selected oil fields in Lea and Eddy Counties, New Mexico, with relatively large water-oil ratios - Concluded

County	Field and reservoir	Cumulative volume produced through 1969, in acre-feet (bbls; hm^3)		Water to oil ratio
		oil	water	
Lea	Hobbs--Grayburg Formation and San Andres Limestone	25,760.0 (200,000,000; 31.775)	16,357.6 (127,000,000; 20.177)	0.6:1
	Jalmat--Yates, Seven Rivers and Tansill Formations (formerly Cooper--White Lime; Jal--White Lime; and Cooper-Jal--Yates and Seven Rivers Formations)	8,668.2 (67,300,000; 10.692)	51,004.8 (396,000,000; 62.914)	5.9:1
	Monument--Grayburg Formation and San Andres Limestone	10,870.7 (84,400,000; 13.409)	21,896.0 (170,000,000; 27.009)	2.0:1
	Wilson--Yates and Seven Rivers Formations	826.9 (6,420,000; 1.020)	1,841.8 (14,300,000; 2.272	2.2:1

Hendrick field

The discovery well in the Hendrick field, northeast of Wink in central Winkler County, one of the most prolific oil fields in western Texas, was completed in late 1926 (Carpenter and Hill, 1936, p. 123). Development of the field was rapid, and more than 600 wells had been drilled by early 1930 within an area encompassing approximately 10,000 acres. In May 1928, when the Hendrick field became the first field to be prorated in Texas, about 164 wells were producing more than 500,000 barrels (79,000 cubic metres) of oil and waste water per day. Sulfurous water ranging in amounts from 0.5 to 98 percent of the total fluid was produced in nearly half of these wells (Ackers, DeChicchis and Smith, 1930, p. 941). More than 130 million barrels (20,700,000 cubic metres) of oil had been produced by 1930, and water-oil ratios of as high as 16:1 were reported from estimated daily production records (Carpenter and Hill, 1936, p. 134). Data obtained from one of the largest operators in the Hendrick field indicate that waste water was being produced at sharply increasing rates and already constituted 95 percent of the total fluid produced in 1934. The ratio of water to oil gradually increased during the next ten years, until the percentage of waste water became a relatively constant 99 percent of all fluid produced from 1944 to 1960.

In 1957, only a very small fraction of the Hendrick field waste water was being recycled in waterflooding projects. Most of this waste water was placed in surface pits or in a communal disposal lake near Wink, Tex. (Garza and Wesselman, 1959, p. 45). As the number of waterflood projects increased in the sixties, more of this produced waste water was injected for secondary recovery purposes. Most of it continued to be disposed of in the usual manner, until laws were passed to preclude the disposal of brine effluent in earthen surface pits.

Extrapolation of the earliest available pressure data for the Hendrick field indicates an original bottom-hole pressure in excess of 1,350 psi (pounds per square inch), or about 3,120 feet of freshwater head above mean sea level. An original "rock pressure" of 1,300 pounds for the Hendrick field was reported in Ackers, DeChicchis, and Smith (1930 p. 923). The hydraulic head in the Hendrick field had declined to less than 2,500 feet above mean sea level by 1969. The slow but consistent decline in reservoir pressure in conjunction with the high water-oil ratio in the fluid produced indicates the field is being produced under strong water-drive reservoir conditions (fig. 34).

Approximately 32,000 acre-feet (250,000,000 barrels; 39,700,000 cubic metres) of oil and an estimated 810,000 acre-feet (6,300,000,000 barrels; 1,000,000,000 cubic metres) of water have been produced from the Hendrick field through 1969. An average of over 28,000 acre-feet (218,000,000 barrels; 34,700,000 cubic metres) of water per year was produced from the Hendrick field during the 5-year period, 1965-69. About 200 million, or about 80 percent, of the 250 million barrels (39,700,000 cubic metres) of oil recovered through 1969 had been produced by the end of 1939. More than 58 percent of the total waste water produced from Permian Guadalupian formations as a waste by-product of the exploitation of oil and gas within the project area was produced from the Hendrick field. About 10 percent of the total oil produced from the same formations in this seven-county area has been produced from the Hendrick field.

The quality of water produced from the nearby water fields completed in the Capitan aquifer is identical to that from the Hendrick field. The reservoir pressures in the same water fields and the Hendrick field are similar and are apparently declining at similar rates (fig. 34). Thus, the hydraulic communication between the reservoir in the Hendrick field and the Capitan aquifer appears to be excellent. Therefore, most of the water produced from the Seven Rivers and Yates Formations in this field, can be considered as having been produced from the Capitan aquifer.

Volume of waste water produced

A total of approximately 1,390,000 acre-feet (10,800,000,000 barrels; 1,720,000,000 cubic metres) of water has been produced as a waste by-product during the production of oil and gas in the seven-county area studied in southeastern New Mexico and western Texas. About 170,000 acre-feet (1,320,000,000 barrels; 210,000,000 cubic metres), or 12 percent, was produced in Eddy and Lea Counties and 1,220,000 acre-feet (9,440,000,000 barrels; 1,500,000,000 cubic metres), or 88 percent, was produced from oil fields in Loving, Pecos, Reeves, Ward, and Winkler Counties. Waste water was being produced at an annual average volume of 8,600 acre-feet (66,600,000 barrels; 10,600,000 cubic metres) and 54,400 acre-feet (422,000,000 barrels; 67,090,000 cubic metres) in the same counties in New Mexico and Texas, respectively, during the period 1965-69.

Production of water from the Capitan aquifer

Oil industry use

The Capitan aquifer is considered to be the prime source of the large quantities of water for the many secondary recovery projects now in operation or planned for the oil fields on the Northwestern shelf and Central Basin platform. The El Capitan, Grisham-Hunter, and O'Brien fields, largest of the nine water fields completed in the Capitan aquifer, are located in Winkler and Ward Counties (fig. 19).

Water produced from the Capitan aquifer in the Russell and Jalmat water field in New Mexico is injected into shallower reservoirs in the Artesia Group within the same local area. Water produced from the Capitan aquifer in the other seven principal water fields is transported through a network of pipelines for varying distances to other fields, where it is injected into reservoirs of several geologic ages (Brackbill and Gaines, 1964). Wells in the O'Brien field are completed in the lower part of the Capitan aquifer which, at this locality, includes carbonate banks or reefs in the upper part of the San Andres Limestone (fig. 7 E-E').

Approximately 296,200 acre-feet (2,300,000,000 barrels; 366,000,000 cubic metres) of water have been produced from the Capitan aquifer in Eddy and Lea Counties, New Mexico and Ward and Winkler Counties, Texas, during the period 1954-69 for use in oil field secondary recovery projects (table 15 and fig. 38). Nearly 264,000 acre-feet (2,050,000,000 barrels; 326,000,000 cubic metres), or more than 89 percent, was produced from wells in the Capitan, Grisham-Hunter, and O'Brien fields. Approximatley 40,700 acre-feet (316,000,000 barrels; 50,200,000 cubic metres) of water were produced from all the nine fields completed in the Capitan aquifer during 1969. About 37,400 acre-feet (290,000,000 barrels; 46,000,000 cubic metres) of water were produced from the El Capitan, Grisham-Hunter and O'Brien fields during the same period.

The demand for water from the Capitan aquifer for secondary recovery purposes has increased at a rate of about 25 percent per year during 1965-69, inclusive (fig. 38). This trend of increasing withdrawal of water from the Capitan aquifer can be expected to continue as more secondary recovery projects are placed in operation. Oil-industry sources report that the peak demand for water can be expected during the period 1970-80.

Table 15.--Volume of water produced from the Capitan aquifer for use in oil field secondary recovery projects

State	County	Water field	Volume of water produced during 1969 in acre-feet (bbls; hm^3)	Cumulative volume of water produced to January 1, 1970 in acre-feet (bbls; hm^3)
New Mexico	Eddy	Russell	40.2 (312,000; 0.05)	591.2 (4,590,000; 0.73)
	Lea	Jalmat	124.2 (964,000; .15)	1,481.2 (11,500,000; 1.83)
		Jal	363.2 (2,820,000; .45)	1,007.2 (7,820,000; 1.24)
Texas	Winkler	Dollarhide	2,717.7 (21,100,000; 3.35)	18,676.0 (145,000,000; 23.04)
		El Capitan	14,425.6 (112,000,000; 17.79)	58,604.0 (455,000,000; 72.29)
		Grisham-Hunter	8,835.7 (68,600,000; 10.90)	71,355.2 (554,000,000; 88.02)
		Wink	199.6 (1,550,000; .25)	4,147.4 (32,200,000; 5.16)
	Ward	O'Brien	14,039.2 (109,000,000; 17.32)	133,952.0 (1,040,000,000; 165.23)
		Wickett	13.8 (107,000; .02)	6,646.1 (51,600,000; 8.20)

Municipal use

The municipal water supplies for the city of Carlsbad and the community of White City are obtained from wells completed in the Capitan aquifer (fig. 19; and Bjorklund and Motts, 1959; and Halpenny and Greene, 1966). A total of approximately 162,300 acre-feet (1,260,000,000 barrels; 200,000,000 cubic metres) of water have been produced from the Capitan aquifer in the Happy Valley and Dark Canyon municipal well fields located southwest of Carlsbad during a period of about 50 years. The annual average production during the 5-year period 1965-69 was 6,830 acre-feet (53,000,000 barrels; 8,400,000 cubic metres). Water with a chemical quality suitable for human consumption can be obtained from the Capitan aquifer in only two areas; one is an extensive area southwest of the Pecos River at Carlsbad, and the other is a less well defined area in the Glass Mountains southwest of Fort Stockton.

Irrigation

Water pumped from the Capitan aquifer is used to irrigate about 2,300 acres of farmland in the Pecos River valley in the immediate vicinity of Carlsbad (Bjorklund and Motts, 1959). Approximately 5,400 acre-feet (42,000,000 barrels; 6,700,000 cubic metres) of water per year is estimated to have been used for irrigation purposes during the period 1965-69. An estimated total of 150,700 acre-feet (1,170,000,000 barrels; 186,000,000 cubic metres) has been withdrawn from the Capitan aquifer within the Carlsbad area for irrigation of croplands during the past 50 years.

Water of marginal chemical quality for irrigation of crops is produced from one flowing well near Coyanosa in northern Pecos County. This well has been used to irrigate cotton and other crops tolerant to saline water (Armstrong and McMillion, 1961; and Guyton and Associates, 1958).

Use in potash refining plants

Water pumped from the Capitan aquifer at Carlsbad is transported by pipeline to a potash refining plant located about 18 miles (29 kilometres) east of Carlsbad. Approximately 3,740 acre-feet (29,000,000 barrels; 4,600,000 cubic metres) of water per year was used to refine potash ore during the period 1965-69. An estimated total of 65,400 acre-feet (508,000,000 barrels; 80,800,000 cubic metres) of water has been pumped from the Capitan aquifer during the past 23 years and used for this purpose.

Amount of water produced from the Capitan aquifer

The cumulative volume of water produced from the principal water fields completed in the Capitan aquifer in southeastern New Mexico and western Texas is shown in figure 38. With the exception of the Wickett water field in Ward County, Texas, increasing amounts of water are being produced from all of the larger water fields.

The demand on the Capitan aquifer system within the project area has increased at an annual average rate of 54,600 acre-feet (424,000,000 barrels; 67,400,000 cubic metres) during the period 1965-69. The demand on the Capitan aquifer east of the Pecos River valley at Carlsbad has increased at an annual average rate of 38,400 acre-feet (298,000,000 barrels; 47,000,000 cubic metres) during the same period.

Approximately 711,000 acre-feet (5,520,000,000 barrels; 878,000,000 cubic metres), 378,700 acre-feet (2,940,000,000 barrels; 467,000,000 cubic metres), and 332,300 acre-feet (2,580,000,000 barrels; 410,000,000 cubic metres) of water have been produced from the entire Capitan aquifer system, the Capitan aquifer in the Pecos River valley at Carlsbad, and the Capitan aquifer east of the Pecos River valley at Carlsbad, respectively. These figures exclude the 820,000 acre-feet (6,300,000,000 barrels; 1,002,000,000 cubic metres) of water produced with oil from the Hendrick field in Winkler County, Texas.

CONCLUSIONS

Permian Guadalupian age strata can be divided into three aquifers. The Capitan aquifer is a lithosome that includes the Capitan and Goat Seep Limestones and most or all of the Carlsbad facies of Meissner (1972). Some of the shelf-margin carbonate banks or stratigraphic reefs in the upper part of San Andres Limestone are included within the Capitan aquifer whenever they cannot be readily distinguished from the Goat Seep Limestone and Carlsbad facies. Saturated strata yielding significant quantities of water from the San Andres Limestone and the Bernal and Chalk Bluff facies of Meissner (1972) comprise the shelf aquifers. The contact between the Capitan and shelf aquifers is gradational and is difficult to discern with accuracy in some areas. Similarly, saturated strata yielding significant quantities of water from the Brushy Canyon, Cherry Canyon, and Bell Canyon Formations of the Delaware Mountain Group are referred to as the basin aquifers.

The Capitan aquifer extends approximately 200 miles (322 kilometres) in a continuous and unbroken arcuate strip parallel to the northern and eastern margins of the Delaware basin from the Guadalupe Mountains southwest of Carlsbad, N. Mex. to the Glass Mountains southwest of Fort Stockton, Tex. The width of the Capitan aquifer varies from 10 to more than 14 miles (16 to 23 kilometres) along the southern edge of the Northwestern shelf from the vicinity of Carlsbad to the central part of southern Lea County, New Mexico but seldom exceeds 11 miles (18 kilometres) along the western margin of the Central Basin platform. The thickness of the Capitan aquifer averages about 1,200 feet (365 metres) but a thickness of more than 2,300 feet (700 metres) was mapped in a small area east of Carlsbad. Depths to the top of the Capitan aquifer in New Mexico vary from not more than a few hundred feet in the Pecos River valley at Carlsbad to more than 4,300 feet (1,310 metres) in the western part of southern Lea County. Depths to the Capitan aquifer vary from less than 2,500 to more than 3,300 feet (760 to 1,005 metres) throughout Winkler, Ward and the northern part of Pecos Counties, Texas.

Submarine canyons and reentrants of Guadalupian and (or) earliest Ochoan age similar to those that have been mapped at surface exposures in the Guadalupe Mountains and Delaware basin by previous investigators have been located in the subsurface along the northern and eastern margins of the Delaware basin. The submarine canyons are filled with material with a relatively low hydraulic conductivity. The thickness, and correspondingly, the transmissivity of the Capitan aquifer are both reduced very significantly by local incision of the submarine canyons that are usually oriented transverse to the arcuate trend of the aquifer.

The location of the largest and most deeply incised submarine canyon, the West Laguna submarine canyon, coincides approximately with the positions of both the most rapid decline in the hydraulic head and the strongest eastward gradient in the present-day potentiometric surface near the boundary between Eddy and Lea Counties, New Mexico. The behavior of the hydraulic head in response to stresses and the shape of the potentiometric surface both confirm the existence of a zone with low transmissivity and restricted circulation in the Capitan aquifer.

New wells could not be drilled to evaluate the characteristics of the Capitan aquifer because of economic limitations. Aquifer performance tests were accomplished on two wells completed in the Capitan aquifer and one well producing from the San Andres Limestone in cooperation with oil companies. Limited additional information was obtained from the literature and from private sources. These data, albeit meager, suggest that the hydraulic conductivity of the Capitan aquifer along the northern margin of the Delaware basin ranges from about 1 to perhaps as much as 20 ft/day (0.3 to 7.6 m/day). Other limited information suggests that the hydraulic conductivity of the Capitan aquifer along the western margin of the Central Basin platform in Texas is similar. An average hydraulic conductivity for the Capitan aquifer of about 5 ft/day (1.5 m/day) would appear to be reasonable for most areas east of the Pecos River at Carlsbad and north of the Glass Mountains. The hydraulic conductivities of the shelf aquifers east of the Pecos River valley between Roswell and Carlsbad and the basin aquifers, are from one to two orders of magnitude lower than that of the Capitan aquifer. The transmissivity of the apparent restriction in the Capitan aquifer near the Eddy-Lea County boundary probably is similar to that of the shelf and basin aquifers.

Water containing a relatively low chloride-ion concentration is present in the Capitan aquifer throughout the region. Most of the shelf aquifers, in areas west of the Pecos River at Carlsbad, in zones near the Capitan aquifer along the margin of the Norwestern shelf and Central Basin platform, and in localities at the north and south ends of the Central Basin platform, also contain water with a relatively low chloride-ion concentration.

In sharp contrast, the rocks of Guadalupian age on the Northwestern shelf, east of Artesia, N. Mex., the medial part of the Central Basin platform, and in the Delaware basin, contain water with relatively high concentrations of chloride-ion.

Fingers of the best quality of water found in the Permian rocks extend into the Capitan aquifer from recharge areas in the Guadalupe and Glass Mountains. Isochlore patterns suggest that the bulk of the relatively good quality water found in the Capitan aquifer came from the Glass Mountains.

The saline-fresh water interface in the Capitan aquifer is located at an altitude of approximately 2,350 feet (715 metres) above sea level in the vicinity of Carlsbad, N. Mex. indicating that the fresh water in the Capitan aquifer west of the Pecos River in this area is only about 750 feet (230 metres) thick.

A series of linear lens-shaped depressions form a narrow trough extending northward from near Belding in southwestern Pecos County, Texas in an arcuate trend above and parallel to the Capitan aquifer to the vicinity of the San Simon Swale in southern Lea County, New Mexico. The trough was formed when halite was dissolved and removed from the Salado and Castile Formations by ground water moving northward from the Glass Mountains through fractures and joints in the adjacent and underlying Capitan and shelf aquifers. The Belding-San Simon trough is filled with collapsed Triassic and Cretaceous strata and younger alluvium and documents the relative age of the emplacement of water into the Capitan aquifer along the western margin of the Central Basin platform.

Twelve observation wells have been completed in the Capitan aquifer in Eddy and southern Lea Counties, New Mexico in order to monitor the effects of fluid production from this aquifer and other aquifers in measurable hydraulic communication. Very small net changes in the water levels, generally due to climatic and water-use conditions in the Pecos River valley, have been noted in six of the seven wells in Eddy County over a 3-to 6-year period. However, the water levels in one well in extreme eastern Eddy County and five wells in southern Lea County have declined from about 23 to 126 feet (7 to 38 metres) at rates of 0.32 to 1.70 feet per month (0.098 to 0.52 m/month) during the period 1967 through 1972. This decline is due to (1) the withdrawal of water from the Capitan aquifer in Lea County, New Mexico and Ward and Winkler Counties, Texas to supply water for use in the secondary recovery of oil, and (2) the production of petroleum and associated waste water from formations of Permian Guadalupian age that are in measurable hydraulic communication with the Capitan aquifer in this same area.

Ground water in the Capitan aquifer in both Texas and New Mexico is being diverted to a "regional center of pumping" just to the west of Kermit, Texas, where the potentiometric surface has been lowered approximately 700 feet (215 metres) in response to withdrawal of water and petroleum from the Capitan and associated aquifers during a period of about 45 years. The water table in the Capitan aquifer in the Glass Mountains has declined about 300 feet (90 metres) during the same period and the head has been lowered approximately 150 feet (45 metres) in the vicinity of a former ground-water divide near the boundary between Eddy and Lea Counties, New Mexico.

The deeply incised submarine canyons in eastern Eddy County, New Mexico form a hydraulic restriction that effectively controls movement of water in the aquifer from the Pecos River at Carlsbad eastward under present day conditions. However, movement of much greater volumes of water from the Pecos River into the Capitan aquifer may occur at an unknown future time if the differential in head across the restriction becomes large enough.

RECOMMENDATIONS

The following recommendations are made as a result of this study: (1) surveillance of the water-level changes in the Capitan aquifer should be continued by maintaining and operating the Capitan aquifer observation-well network indefinitely; (2) the observation-well network should be augmented by acquiring and completing one additional well in a location 5 to 8 miles (8 to 13 kilometres) west of the boundary between Eddy and Lea Counties, New Mexico, and near the south edge of the Capitan aquifer; (3) geologic and hydrologic studies should be continued in an effort to determine, quantitatively, the aquifer characteristics of the apparent restriction to movement of ground water in the Capitan aquifer in eastern Eddy County; (4) the amount of water being withdrawn from the Capitan and other aquifers in measurable hydraulic communication with this aquifer in Lea County, New Mexico and Winkler and Ward Counties, Texas, should be recorded. The reliability of the data now in the files should be evaluated to eliminate errors made by estimating production; and (5) computations should be made, preferably using a numerical model, to determine the magnitude of any significant diversion of water from the Pecos River at Carlsbad that could possibly result at some time in the future as the stresses are increased by continued withdrawal of water.

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Case Nos. 24278, 24277, 24123, 23775, 23614-23617, and 24018-24027
OCD Exhibit No. 5C

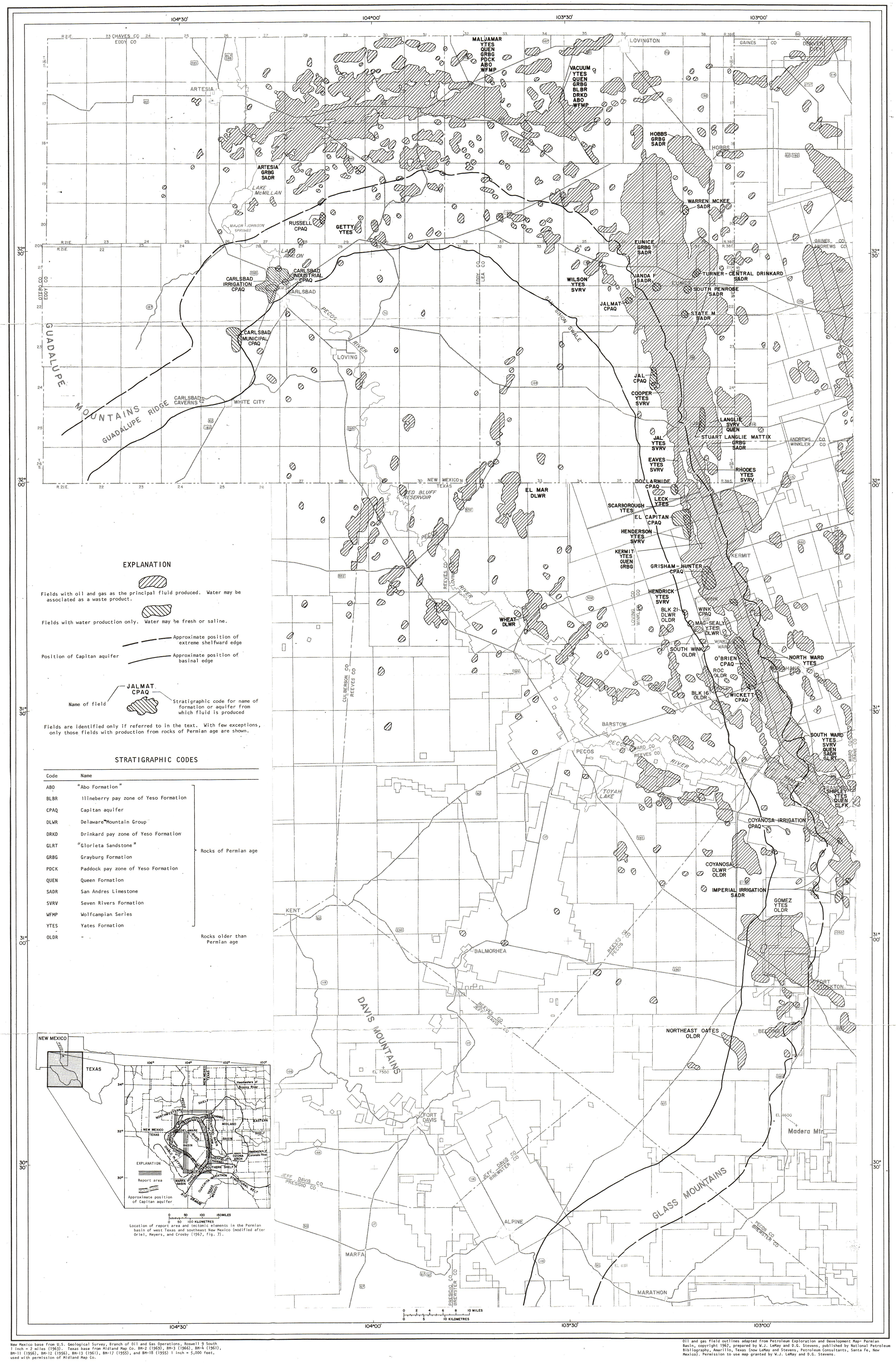

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FIGURE 19-- MAP SHOWING LOCATION OF OIL, GAS, AND WATER FIELDS WITH PRODUCTION FROM ROCKS OF PERMIAN AGE IN THE DELAWARE BASIN AND SURROUNDING AREAS

Case Nos. 24278, 24277, 24123, 23775, 23614-23617, and 24018-24027
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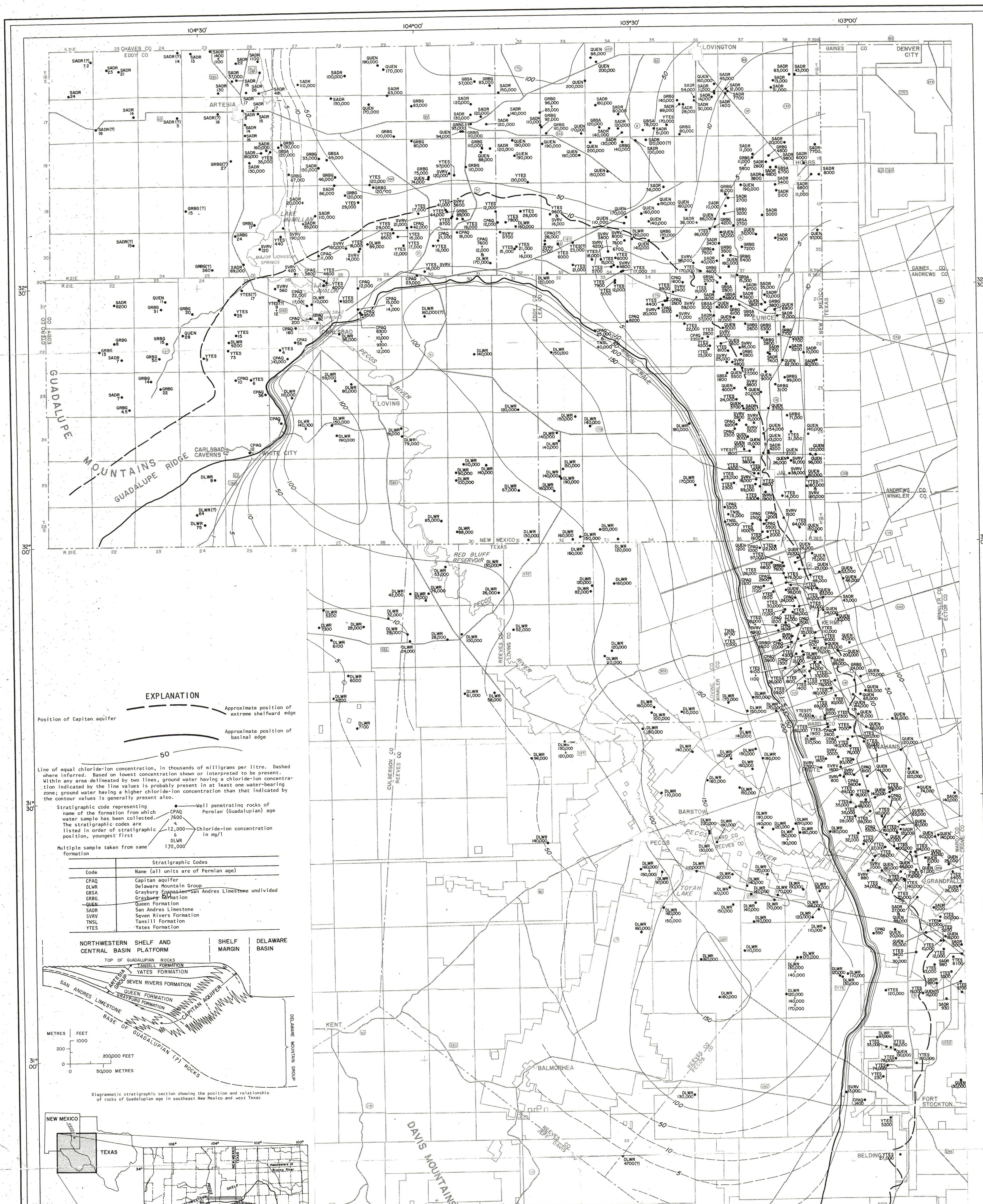

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FIGURE 26-- MAP SHOWING THE CHLORIDE-ION CONCENTRATION IN PERMIAN GUADALUPIAN AGE SEDIMENTARY ROCKS