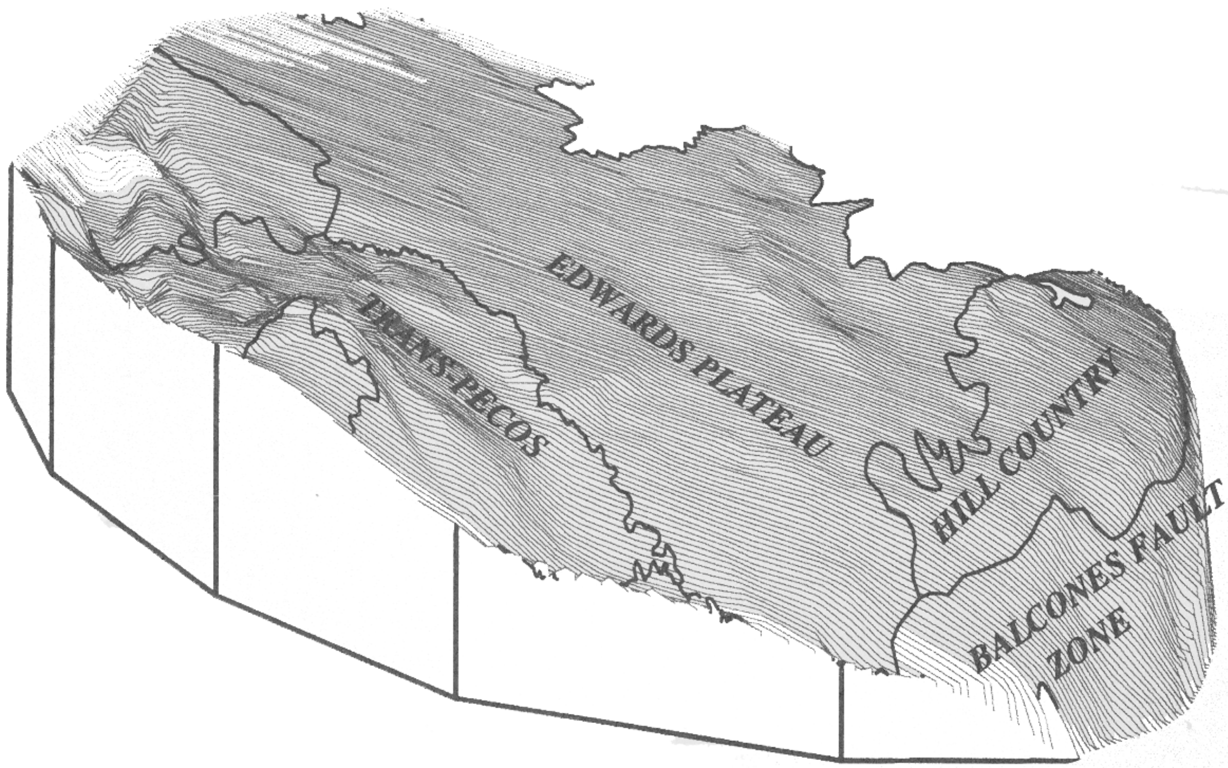
Configuration of the Base of the Edwards-Trinity Aquifer System and Hydrogeology of the Underlying Pre-Cretaceous Rocks, West-Central Texas

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 91–4071



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By Rene' A. Barker and Ann F. Ardis

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CONTENTS

ILLUSTRATIONS
[Plate is in pocket]

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
darcy	0.835	meter per day
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per mile (ft/mi)	0.1894	meter per kilometer
foot squared per day (ft^2/d)	0.0929	meter squared per day
gallon per minute (gal/min)	0.06309	liter per second
mile (mi)	1.609	kilometer
millidarcy	0.0000835	meter per day
square mile (mi^2)	2.590	square kilometer

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

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CONFIGURATION OF THE BASE OF THE EDWARDS-TRINITY AQUIFER SYSTEM AND HYDROGEOLOGY OF THE UNDERLYING PRE-CRETACEOUS ROCKS, WEST-CENTRAL TEXAS

By Rene' A. Barker and Ann F. Ardis

ABSTRACT

The Edwards-Trinity aquifer system is underlain by an extensive complex of rocks, ranging from Late Cambrian through Late Triassic in age, that are typically about 10 to perhaps 1,000 times less permeable than those composing the aquifer system. The Cretaceous rocks of the aquifer system are separated from the pre-Cretaceous rocks by an unconformity that spans about 60 million years of erosion during the Jurassic Period. The upper surface of the pre-Cretaceous rock complex forms the base of the Edwards-Trinity aquifer system. The configuration of the base reflects the original topography of the eroded pre-Cretaceous land surface plus the effects of subsequent deformation.

The most permeable pre-Cretaceous rocks are in the eastern half of the study area where they compose the Hickory aquifer (in Upper Cambrian rocks), Ellenburger-San Saba aquifer (Upper Cambrian-Lower Ordovician), and Marble Falls aquifer (Lower Pennsylvanian). These aquifers are hydraulically connected to the northeastern fringe of the Edwards-Trinity aquifer system, as their up-turned margins crop out around the flanks of the breached Llano uplift. The Rustler aquifer in rocks of Late Permian age underlies parts of the Trans-Pecos region, where it yields small amounts of greatly mineralized water for industrial and agricultural purposes. The Dockum aquifer in rocks of Late Triassic age directly underlies the Edwards-Trinity aquifer system in western parts of the study area, and locally increases the saturated thickness of the ground-water-flow system by an average of about 200 feet. Despite these notable exceptions, the collective effect of the pre-Cretaceous rocks is that of a barrier to ground-water flow, which limits the exchange of water across the base of the Edwards-Trinity aquifer system.

INTRODUCTION

The study of the Edwards-Trinity aquifer system by the U.S. Geological Survey is part of a nationwide Regional Aquifer-Systems Analysis (RASA) program. Since 1978, the RASA program has investigated more than 20 regional aquifer systems that individually provide significant amounts of ground water to large parts of the country. The overall objectives of each RASA study are to: (1) Describe the ground-water-flow system as it existed before development and as it exists today; (2) evaluate the changes that occurred between the predevelopment period and the present; (3) integrate the results of previous studies concerning particular aspects of the flow system or local areas within it; and (4) provide some capability for evaluating the effects of future ground-water development.

The ground-water-flow system of an area cannot be described without assessing the hydrogeologic boundaries of that system. An extensive complex of Paleozoic and Triassic rocks underlies west-central Texas. These pre-Cretaceous rocks are generally, but not everywhere, less permeable than the overlying Cretaceous rocks that compose the Edwards-Trinity aquifer system. The base of the Edwards-Trinity aquifer system is herein defined as the upper surface of the pre-Cretaceous rock complex upon which the rocks of the aquifer system rest.

Purpose and Scope

The purpose of this report is to: (1) Summarize the geologic history of the pre-Cretaceous rocks that underlie and, thus, affect the hydrogeology of the Edwards-Trinity aquifer system; (2) delineate the configuration of the base of the aquifer system (the upper surface of the pre-Cretaceous rocks); and (3) describe the hydrogeology of the pre-Cretaceous rocks, particularly with respect to their effect on the aquifer system.

The scope of this report is limited primarily to interpretation of information resulting from previous studies of pre-Cretaceous rocks in the study area. Previously completed fieldwork and publications served as the basis for the contents of this report. Hydrogeologic terminology used herein was determined from several sources such as the Bureau of Economic Geology of the University of Texas at Austin, the American Association of Petroleum Geologists, and the Texas Water Development Board; thus, some of the terminology may not conform to usage of the U.S. Geological Survey.

Location of Study Area

The study area of the Edwards-Trinity RASA extends approximately from Atascosa County on the southeast to Culberson County on the northwest and from the Rio Grande on the southwest to the Colorado River on the northeast (fig. 1). The Edwards-Trinity aquifer system of west-central Texas spans about 42,000 mi^2 in an area that includes four geographic subareas: The Balcones fault zone; the Hill Country; the Edwards Plateau; and the Trans-Pecos.

Previous Investigations and Methods of Present Study

The hydrogeologic data in this report originated primarily from the results of previous investigations. The data used to contour the configuration of the base of the Edwards-Trinity aquifer system were obtained from the sources listed on plate 1. The geologic ages of the rocks that constitute the base were determined from stratigraphic sections and geologic maps in reports listed under "Selected References."

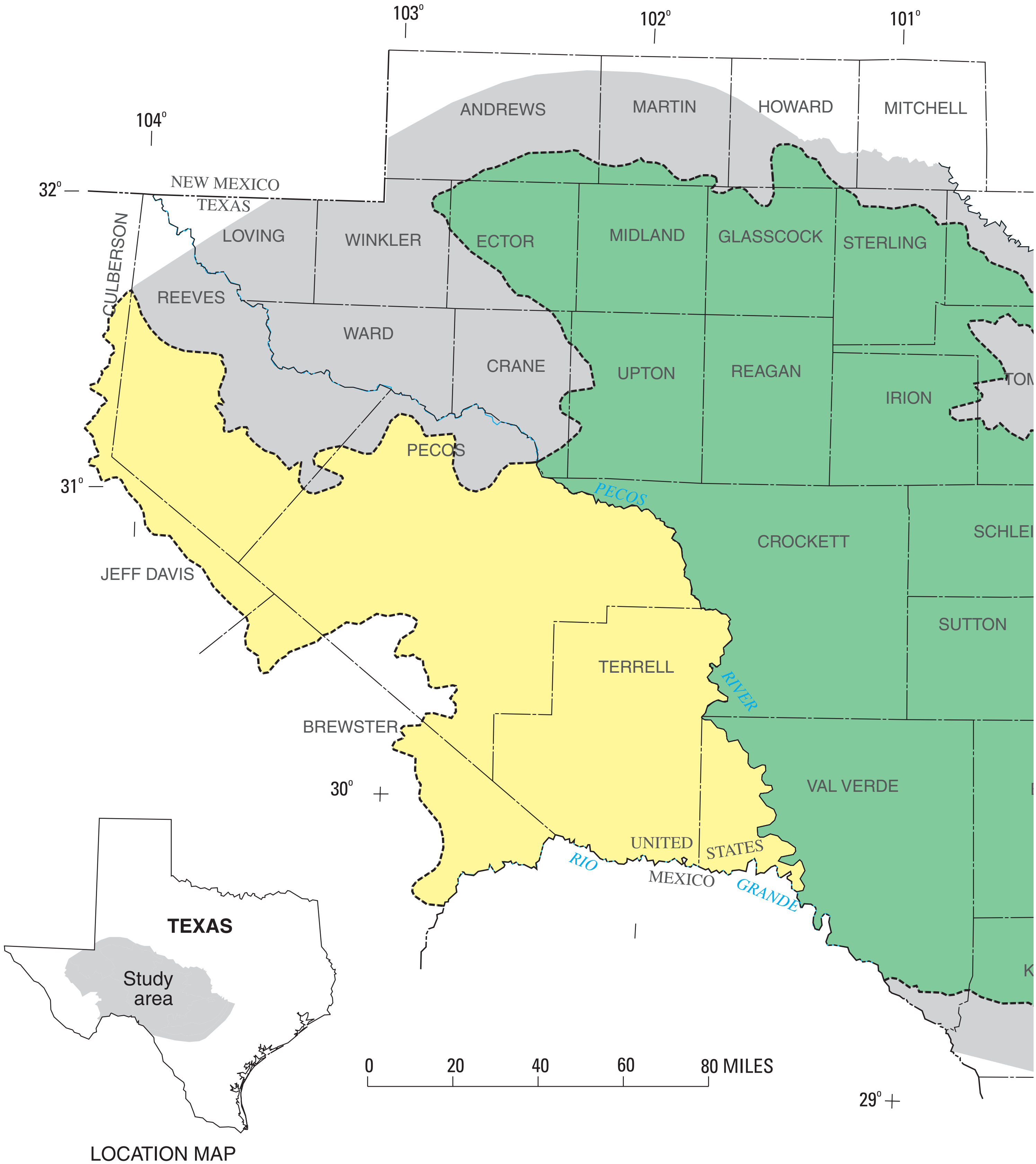
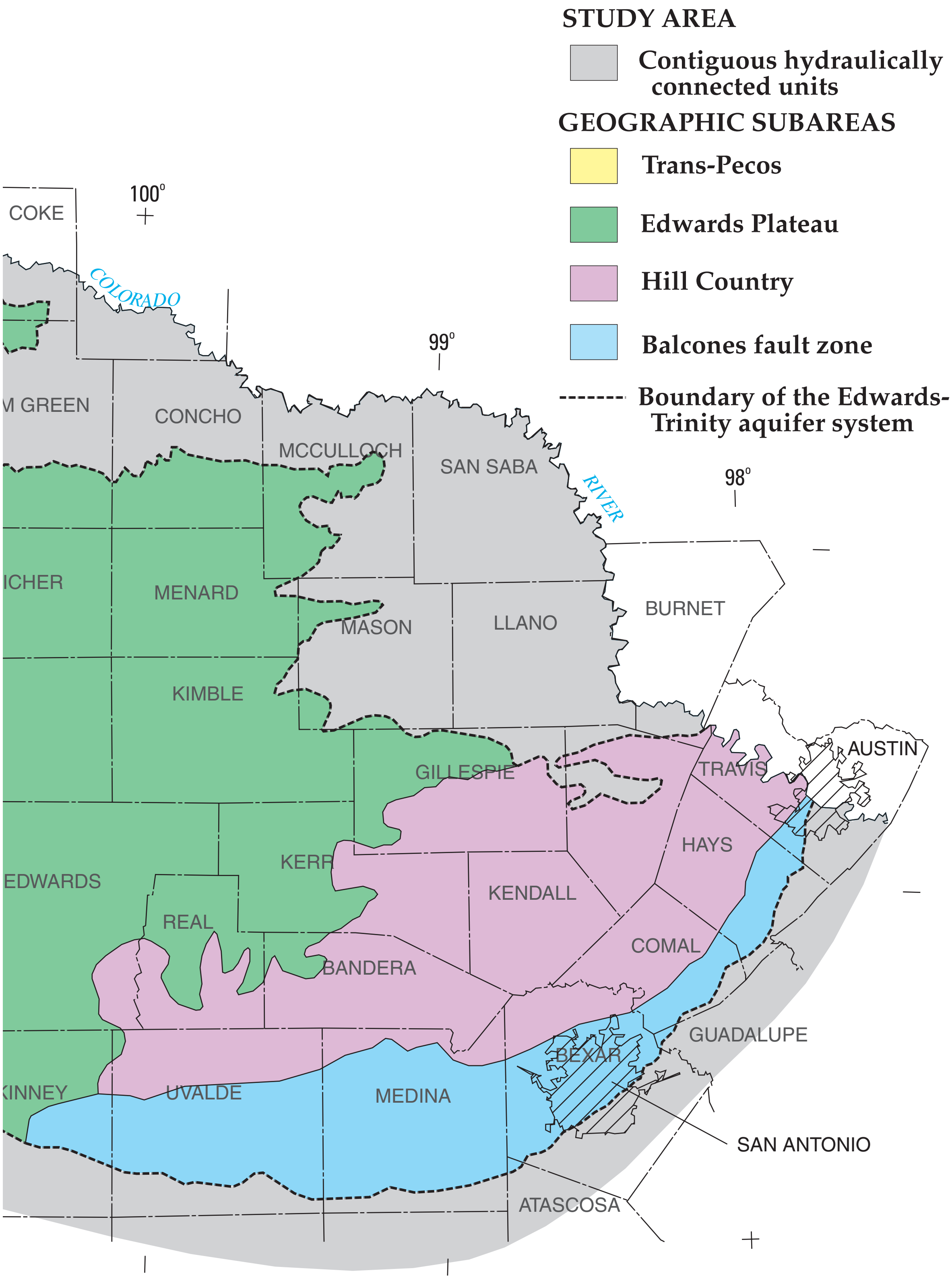


Figure 1. Study area and geographic subareas of the Edwards-Trinity aquifer system.



STUDY AREA
Contiguous hydraulically connected units
GEOGRAPHIC SUBAREAS
Trans-Pecos
Edwards Plateau
Hill Country
Balcones fault zone
Boundary of the Edwards-Trinity aquifer system
100°
99°
98°
COKE
COLORADO
RIVER
M GREEN
CONCHO
MCCULLOCH
SAN SABA
ICHER
MENARD
MASON
LLANO
BURNET
KIMBLE
GILLESPIE
TRAVIS
AUSTIN
HAYS
EDWARDS
KERR
KENDALL
REAL
COMAL
BANDERA
BEXAR
GUADALUPE
KINNEY
UVALDE
MEDINA
SAN ANTONIO
ATASCOSA

Although none of the previous studies dealt with the entire RASA study area (fig. 1), the results of previous work were integrated into a master data base that spans nearly the entire area of RASA interest. Where the results of previous work overlapped, the contributing data were checked for consistency and were revised if necessary. Where differences among the data were small, the inconsistencies were usually remedied by numerically averaging the available data. In the few cases where discrepancies were large (for example, as a result of differing stratigraphic picks, well locations, or datum altitudes), the inappropriate data were identified and discarded."

Edwards-Trinity Aquifer System

The Edwards-Trinity aquifer system (table 1) is in Cretaceous rocks that underlie about 42,000 mi^2 of west-central Texas. Gently dipping strata of the aquifer system thin northwestward atop massive pre-Cretaceous rocks (table 2) that form the base of the system. Lower Trinity rocks of the aquifer system grade upward--from predominately terrigenous clastic sediments in the east and fluvial-deltaic (terrestrial) deposits in the west--into supratidal and lagoonal evaporites, dolomitic intertidal deposits, and shallow marine and reefal carbonates of upper Trinity, Fredericksburg, and Washita strata. Although the gulfward-thickening wedge of Edwards-Trinity strata is not fully saturated nor consistently permeable in all directions, the rocks are enough alike hydrologically to collectively define a regional aquifer system. The permeability of the aquifer system results mostly from tectonic fractures and secondary porosity caused by the selective leaching of evaporites and soluble carbonate constituents. Although transmissivity values average less than 10,000 ft^2/d over 90 percent of the study area, they exceed 100,000 ft^2/d over most of the Edwards aquifer in the Balcones fault zone. The Hammett Shale, which blankets the Hill Country and easternmost parts of the Edwards Plateau, comprises one of two confining units. Where not exposed in the outcrop or covered with alluvium, the rocks of the aquifer system are overlain directly by either the Del Rio Clay or the Buda Limestone, both of which are relatively impermeable and form the lower part of the Navarro-Del Rio confining unit in the Balcones fault zone.

GEOLOGIC HISTORY OF THE PRE-CRETACEOUS ROCKS

The Edwards-Trinity aquifer system is underlain by a complex of Paleozoic (Upper Cambrian through Permian) and Mesozoic (Upper Triassic) rocks. The upper surface of this complex is the base of the Edwards-Trinity aquifer system, and aquifers in these pre-Cretaceous rocks interact hydraulically with parts of the Edwards-Trinity aquifer system. The depositional and tectonic origins of the pre-Cretaceous rocks are summarized below.

Paleozoic Era

The geologic history of west-central Texas during the Paleozoic Era was dominated by: (1) The Ouachita geosyncline (Flawn and others, 1961), which bordered a southern segment of the ancestral North American continent; (2) land masses to the south and east of the geosyncline; and (3) shallow inland seas across the stable continental foreland, north and west of the geosyncline. The location of the Ouachita geosyncline (Nicholas and Rozendal, 1975, fig. 5) was generally coincident with that of the Ouachita structural belt (fig. 2). From what is now southeastern Oklahoma, the Ouachita geosyncline trended southwesterly toward the Llano uplift where it curved westward, against the southern edge of the Devils River uplift, into the Marathon-Solitario uplift region of southwest Texas and northern Mexico. The Llano and Devils River uplifts were resistant promontories of crystalline Precambrian rock on the southern perimeter of the ancestral North American Craton (Flawn, 1956, p. 25).

Although clastic sedimentation prevailed during the entire history of the geosyncline, deposition in the foreland area was mainly organic or chemical and only partly clastic until Late Permian time (Sellards and Baker, 1935, p. 18). Intermittent tectonic pulses throughout the Paleozoic maintained prominent land areas near the southern and eastern margins of the geosyncline that supplied the subsiding trough with

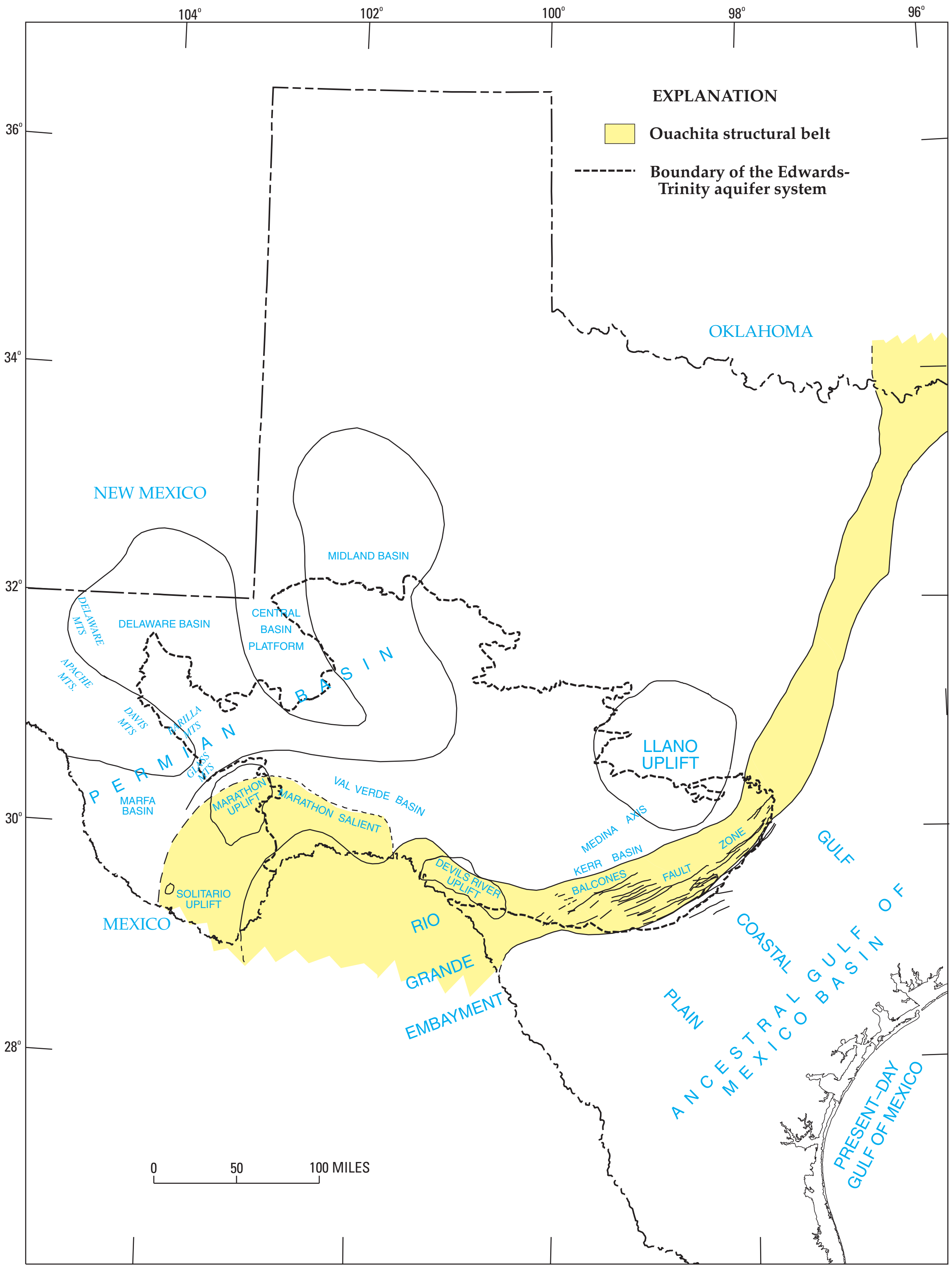


Figure 2. Paleogeographic and structural features in west-central Texas and parts of adjacent states and northern Mexico.

Table 1.—Generalized correlation chart of the rocks that compose the Edwards-Trinity aquifer system

[Hydrogeologic terminology modified from Imlay, 1945; Lozo and Stricklin, 1956; Forgotson, 1957; Brand and Deford, 1958; Stricklin and others, 1971; Rose, 1972; Loucks, 1977; and Smith and Brown, 1983]

EDWARDS AQUIFER
TRINITY AQUIFER
EDWARDS-TRINITY AQUIFER
NAVARRO-DEL RIO CONFINING UNIT
HAMMETT CONFINING UNIT
ROCKS ABSENT

ERATHEM	SYSTEM		PROVINCIAL STAGE	STRATIGRAPHIC UNIT: Trans-Pecos	Edwards Plateau: Northwestern	Edwards Plateau: Southeastern	Hill Country	Balcones fault zone
MESOZOIC	CRETACEOUS	UPPER	Gulfian	(Rocks absent) Boquillas Formation Buda Limestone Del Rio Clay	(Rocks absent) Buda Limestone Del Rio Clay	(Rocks absent) Anacacho Limestone Austin Group Eagle Ford Group Buda Limestone Del Rio Clay	(Rocks absent)	Navarro Group Taylor Group Austin Group Eagle Ford Group Buda Limestone Del Rio Clay
		LOWER	Washitan	Boracho Formation	Fort Lancaster Formation	Edwards Group: Segovia Formation	(Rocks absent)	Georgetown Formation Edwards Group: Person Formation
			Fredericks-burgian	Finlay Formation	Fort Terrett Formation	Edwards Group: Fort Terrett Formation	(Rocks absent)	Edwards Group: Kainer Formation
			Trinitian	Glen Rose Formation Basal Cretaceous sand	Basal Cretaceous sand	Glen Rose Limestone Hensel Sand Cow Creek Limestone Hammett Shale Basal Cretaceous sand	Glen Rose Limestone Hensel Sand Cow Creek Limestone Hammett Shale Sycamore Sand / Sligo Formation Hosston Formation	Glen Rose Limestone Pearsall Formation: Bexar Shale Member, Cow Creek Limestone Member, Pine Island Shale Member Sligo Formation Hosston Formation
				(Rocks absent)	(Rocks absent)	(Rocks absent)		

Table 2. Generalized correlation chart of the pre-Cretaceous rocks that form the base of the Edwards-Trinity aquifer system

(Hydrogeologic terminology based on usage of the Texas Water Development Board and the Bureau of Economic Geology, University of Texas at Austin)

<table>
<tr><th>ERA-THEM</th><th>SYSTEM</th><th>SERIES OR GROUP</th><th colspan="2">STRATIGRAPHIC UNIT</th><th>HYDROGEOLOGIC UNIT</th></tr>
<tr><td rowspan="3">MESOZOIC</td><td rowspan="3">Triassic</td><td rowspan="3">Dockum Group</td><td colspan="2">Upper</td><td>Confining unit</td></tr>
<tr><td colspan="2">Middle</td><td>Dockum aquifer</td></tr>
<tr><td colspan="2">Lower</td><td rowspan="2">Confining units</td></tr>
<tr><td rowspan="20">PALEOZOIC</td><td rowspan="7">Permian</td><td rowspan="4">Ochoan</td><td colspan="2">Dewey Lake Red Beds</td></tr>
<tr><td colspan="2">Rustler Formation</td><td>Rustler aquifer</td></tr>
<tr><td colspan="2">Salado Formation</td><td rowspan="8">Mostly confining units</td></tr>
<tr><td colspan="2">Castile Formation</td></tr>
<tr><td>Guadalupian</td><td colspan="2" rowspan="3">Undivided</td></tr>
<tr><td>Leonardian</td></tr>
<tr><td>Wolfcampian</td></tr>
<tr><td rowspan="4">Pennsylvanian</td><td>Cisco Group</td><td colspan="2" rowspan="3">Undivided</td></tr>
<tr><td>Canyon Group</td></tr>
<tr><td>Strawn Group</td></tr>
<tr><td>Bend Group</td><td colspan="2">Marble Falls Limestone</td><td>Marble Falls aquifer</td></tr>
<tr><td>Mississippian</td><td colspan="3">Undivided</td><td rowspan="4">Mostly confining units</td></tr>
<tr><td>Devonian</td><td colspan="3">Undivided</td></tr>
<tr><td>Silurian</td><td colspan="3">Undivided</td></tr>
<tr><td rowspan="2">Ordovician</td><td colspan="3">Undivided</td></tr>
<tr><td>Ellenburger Group</td><td colspan="2">Undivided</td><td rowspan="2">Ellenburger - San Saba aquifer</td></tr>
<tr><td rowspan="4">Cambrian</td><td rowspan="4">Upper</td><td rowspan="2">Wilberns Formation</td><td>San Saba Limestone Member</td></tr>
<tr><td>Undivided</td><td rowspan="2">Mostly confining units</td></tr>
<tr><td rowspan="2">Riley Formation</td><td>Undivided</td></tr>
<tr><td>Hickory Sandstone Member</td><td>Hickory aquifer</td></tr>
<tr><td colspan="5">Precambrian rocks, undifferentiated</td><td></td></tr>
</table>

sediment. According to Flawn and others (1961, p. 30), most of the middle and upper Paleozoic detritus resulted from the erosion of previously deposited sediment of the geosyncline, which was uplifted by preliminary bursts of orogenic activity prior to the climactic late Paleozoic orogeny.

The broad foreland area, north and west of the geosyncline, fluctuated between emergent periods of erosion and submergent periods of deposition during the early and middle Paleozoic. Following about 400 million years of erosion during the late Precambrian and Early Cambrian (Flawn, 1956, p. 68-71), the Hickory Sandstone Member of the Riley Formation was deposited in the Llano area upon an unevenly eroded surface of Precambrian igneous, meta-igneous, and metasedimentary rocks (Barnes and others, 1972). This was followed by the deposition of more than 2,500 ft of mostly marine sediments, including the San Saba Limestone Member of the Wilberns Formation (Upper Cambrian) and the cherty, dolomitic Ellenburger Group of Ordovician age. After about 1,000 ft of Silurian and Devonian marine strata were deposited in west Texas (Wilson and Majewske, 1960, p. 65-86), the central Texas area was inundated at least twice by Mississippian seas; however, relatively little sediment accumulated. Following uplift and erosion of the Mississippian strata in the Llano area, the Marble Falls Limestone of Early Pennsylvanian age was deposited. The pace of both deposition and tectonic activity increased substantially during the Pennsylvanian Period.

During the Ouachita orogeny, which climaxed between Late Pennsylvanian and Early Permian time, geosynclinal deposits several thousands of feet thick were overwhelmed by uplift and intense deformation as part of a tectonic upheaval that progressed westward from northeast Texas to the Trans-Pecos (Flawn and others, 1961, p. 186-188). The geosynclinal facies were folded, sheared, and thrust faulted into a late Paleozoic mountain range that extended from eastern Mississippi, through the Ouachita Mountains of Arkansas and Oklahoma, to the Marathon-Solitario region of Texas. The interior sediments of the geosyncline underwent various degrees of metamorphism--producing slate, phyllite, and metaquartzite--as blocks of early Paleozoic rocks were thrust northward across younger strata. The Llano and Devils River uplifts became resistant buttresses against which the Ouachita facies were thrust from the south, shearing and folding intervening rocks of the foreland. A very complex foreland structure resulted (Webster, 1980; Calhoun and Webster, 1983), creating petroleum traps that help provide one of the most productive oil and gas provinces in the world.

During the waning stages of the Ouachita orogeny, three distinct but interconnected basins developed within a broad shallow seaway in west Texas (King, 1942). These basins, individually called the Marfa, Delaware, and Midland basins, are collectively known as the Permian Basin (fig. 2). The basins were fringed by barrier reefs and separated by carbonate platforms. Until sediment filled the basins toward the end of Permian time, conditions that were unique to the basins, the intervening platforms, and the fringing reefs produced different kinds of rocks. The basins were the centers of deep-water marine (mainly clastic) deposition, collecting black shales first and calcareous sandstones later. The reefs provided environments wherein dolomite and limestone formed, while layers of gypsiferous shale and bedded gypsum accumulated in lagoons behind the reefs. The warm, shallow-water environment of the platforms produced dolomitic limestones, while evaporites and onshore red beds formed along the landward edges of the basins. From a widespread beginning, the seas of the west-Texas Permian Basin withdrew and expanded cyclically over time, becoming progressively more restricted.

The depositional regime of west Texas experienced a profound change during the Late Permian (King, 1942, p. 758-763). Under conditions of extreme aridity, the seaways shrank and the basins became saltier; red beds, evaporites, and dolomitic limestones encroached upon the basins. In response to regional upwarping, the sea level eventually fell below the basin rims, exposing the fringing reefs and leaving the interbasin platforms emergent. Under the intense aridity, detrital influx to the basins was minimal, and each basin became a giant evaporating pan, not unlike the Dead Sea of the present day. The predominate sediments were gypsum, anhydrite, halite, and potash of the Castile and Salado Formations--which, in the Delaware basin, are more than 4,000 ft thick (Jones, 1953, p. 40). Following differential uplift and erosion near the end of the Permian Period, fresher water conditions returned and the thin Rustler Formation of principally reddish sand, anhydrite, and dolomitic limestone was deposited. As the connection with the open sea continued to improve, the super-saline waters disappeared and fine-grained clastic sediments washed in from surrounding high ground and blanketed the underlying evaporitic strata with the Dewey Lake Red Beds. The Permian sea withdrew southward as the region once again was uplifted at the close of the Paleozoic Era.

Mesozoic Era

The retreat of the Permian sea was followed by a long interval of nondeposition, local warping, and erosion during Early and Middle Triassic time. The humidity probably increased relative to that of the Late Permian, as the climate fluctuated between pluvial intervals and moderate aridity. While uplift continued in the Llano area, and erosion planed down the central basin platform (fig. 2), a closed continental basin formed in west Texas. This basin was partly filled during the Late Triassic with easily erodible Paleozoic sediments that were reworked and deposited as red beds under fluvial, deltaic, and lacustrine conditions (McGowen and others, 1979). These Triassic red beds--known today as the Dockum Group--exhibit many facies, ranging from mudstones to conglomerates, but are predominately variegated shales and quartzose siltstones and sandstones.

Most of west-central Texas was emergent during the Jurassic (60 million years), during which time the study area was eroded to a rolling peneplain characterized by broad river valleys and low ridges of resistant rocks. This peneplained surface, upon which the Cretaceous rocks eventually were deposited, was named the Wichita paleoplain by Hill (1901, p. 384). The pre-Cretaceous landmass slumped toward the ancestral Gulf of Mexico basin (fig. 2), causing a reversal in the direction of surface drainage. The reversal in drainage, which may have begun during the Permian, was completed by the end of the Jurassic so that the earlier pattern of northwestward drainage toward inland seas was superceded by southeastward drainage into a westward-advancing Cretaceous sea (Sellards and others, 1933, p. 24).

The ancestral Ouachita Mountains were denuded to the roots by erosion, as the remnants in central Texas sank beneath the transgressing Cretaceous sea (Flawn and others, 1961, p. 189-190). Surface remnants of this once-prominent mountain range are visible today in west-central Arkansas, southeastern Oklahoma, and in the Marathon-Solitario uplift region of southwest Texas (Nicholas and Rozendal, 1975). The mostly buried foundation of the Ouachita Mountains is marked by the Ouachita structural belt (fig. 2).

The early Mesozoic collapse of the Ouachita structural belt in central Texas accompanied the opening of the Gulf of Mexico. The area of greatest subsidence corresponds to the present Gulf Coastal Plain (fig. 2). Flawn (1964, p. 274) suggested that the ancestral Gulf of Mexico basin developed from a fundamental weakness or lack of stability in the Ouachita structural belt.

Geologists have recognized for a number of years that the Balcones fault zone is linked to features of the underlying Ouachita structural belt. R.W. Maclay (U.S. Geological Survey, written commun., 1989) attributes the nearly vertical planes of normal (down-to-the-gulf) faulting within the fault zone to surfaces created earlier by wrench faulting in the Ouachita structural belt. Sellards and Baker (1935, p. 57-62) suggested that tectonic adjustments to tensional forces across the Ouachita structure during the late Mesozoic established the pattern for Balcones faulting (of Cretaceous strata) during the Cenozoic. Flawn (1956, p. 32) surmised that the southern margin of the ancient North American Craton was the fundamental control for all Ouachita and Balcones structures.

CONFIGURATION OF THE BASE OF THE EDWARDS-TRINITY AQUIFER SYSTEM

The contour map on plate 1 illustrates the relief on the base of the Edwards-Trinity aquifer system. The configuration of the base results from the erosional topography of the pre-Cretaceous land surface (Wichita paleoplain), plus the effects of subsequent deformation. The surface upon which the Edwards-

Trinity rocks were deposited was considerably flatter than the present-day base. In addition to trends inherent from the Wichita paleoplain, the base manifests the superimposed effects of subsidence, uplift, folding, faulting, and structural collapse caused by the dissolution of underlying carbonate constituents and evaporite minerals.

Depending on the density of control and the amount of relief on the base, the contours on plate 1 depict intervals of 100, 200, or 500 ft. The contours were drawn to show regional trends; local features IY be obscured. For example, sharp, local fault displacements on the base are not obvious on plate 1. Altitudes on the base range from about 5,000 ft below sea level on the Ouachita structural belt in southern Medina County to more than 4,000 ft above sea level on the northern flank of the Marathon uplift in southern Pecos and northern Brewster Counties. Regionally, the base is characterized by: (1) A steeply plunging southeastern margin that conforms to the Balcones fault zone; (2) a moderately inclined band that wraps around the Hill Country to the southern part of the Edwards Plateau from the southeastern flank of the Llano uplift; (3) a broad platform with a gentle southward tilt in the northern Edwards Plateau; and (4) a variable, rugged configuration in the Trans-Pecos.

Balcones Fault Zone

The base of the Edwards-Trinity aquifer system in the Balcones fault zone (fig. 1) is the top of sunken, partly metamorphosed remnants of the ancient Ouachita Mountains. Flawn and others (1961, p. 13) have separated these pre-Cretaceous rocks into the foreland facies and Ouachita facies (fig. 3) of the Ouachita structural belt (fig. 2). Paleozoic rocks north and west of the structural belt are informally termed "foreland rocks."

Plate 1 shows that the base of the aquifer system in the Balcones fault zone descends steeply lard the Gulf of Mexico at slopes averaging about 175 ft/mi. The gulfward plunge of the base results 11 both subsidence toward the ancestral Gulf of Mexico basin during late Paleozoic and Mesozoic time j down-to-the-gulf fault displacements atop the Ouachita structural belt during late Mesozoic(?) and Cenozoic time. The base, between altitudes of about 2,500 ft below sea level and about sea level, is overlain by the Balcones fault system (fig. 2), a zone of en echelon normal faults. In addition to cutting through rocks of the Edwards-Trinity aquifer system (fig. 3), some of the Balcones faults appear to extend into rocks of the Ouachita structural belt (Flawn and others, 1961, pl. 2; Maclay and Small, 1986, fig. 2).

Because the base in the Balcones fault zone is generalized with 500-ft contours, the displacement caused by individual faults is masked on plate 1. Although the total throw of Balcones faulting (of Cretaceous strata) was estimated by Weeks (1945, p. 1,734) to be about 1,200 ft near San Antonio and about 900 ft near Austin, the amount of vertical fault displacement within the pre-Cretaceous rocks is unknown. Fault displacements within the Cretaceous rocks above the base greatly affect ground-water conditions in the Edwards aquifer of the Balcones fault zone (Maclay and Small, 1986).

Hill Country and Southern Edwards Plateau

The Edwards-Trinity aquifer system in the Hill Country and southern parts of the Edwards Plateau is underlain by a moderately steep band of pre-Cretaceous rocks updip of, and roughly conformable to, the Balcones fault zone. Between sea level and about 1,000 ft above sea level, the southward slope on base averages about 40 ft/mi--less than 25 percent of that in the fault zone. Flawn and others (1961, p. 19) suggest that this slope approximates that which existed across the entire eastern part of the Wichita paleoplain before gulfward downwarping and fault displacement steepened it over the Balcones It zone. Local aberrations in the configuration of the base also indicate smaller-scale warping and (or) fault displacements that trend north to south and northwest to southeast. Although features of this smaller size do not appear to significantly affect the regional hydrology of the overlying aquifer system, they could

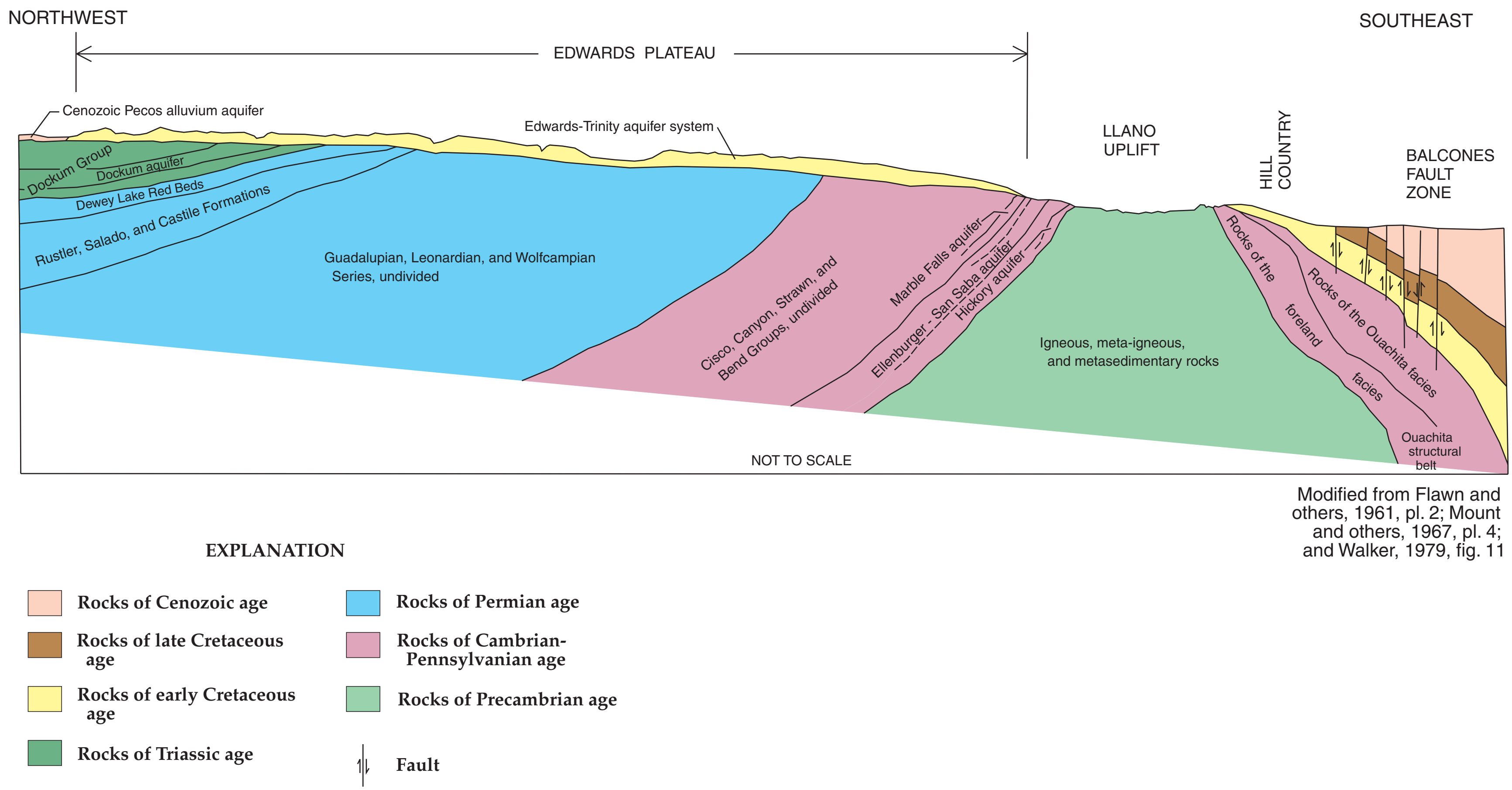


Figure 3. Generalized hydrogeologic section through the study area showing relation between the Edwards-Trinity aquifer system and the pre-Cretaceous rocks that form the base of the system.

indicate local increases or decreases in transmissivity resulting from the thickening, thinning, displacement of water-yielding zones in the Cretaceous rocks that compose the system. The steepening slope on the base across Val Verde County may be partly a result of downwarping on the northeastern flank of the Rio Grande embayment (Murray, 1961, p. 128-131). This downwarping would 'e occurred prior to or during deposition of the Lower Cretaceous Glen Rose Limestone (table 1), which nearly quadruples in thickness between northern and southern Val Verde County (Reeves and Small, 1973, p. 10).

Northern Edwards Plateau

In northern parts of the Edwards Plateau, between altitudes of about 1,000 and 3,000 lt, the regional slope on the base of the Edwards-Trinity aquifer system averages about 10ft/mi. The contour map of the base (pl. 1) indicates numerous positive and negative features in this area; some are too small in vertical or areal extent to be accurately defined with the 100-ft contour interval used for this area of the map. Most of the features are erosional scars carved into the pre-Cretaceous surface by wind and water. The areas of highest relief stood as islands in the Early Cretaceous sea; the lowest areas were the first to receive Cretaceous sediments, and they now contain the thickest accumulations. Some of the local relief in eastern parts of the area may have formed (or was accentuated) during the Miocene, when deformation along the Balcones fault zone probably re-elevated the Llano uplift (Barnes and others, 1972, p. 44). The regional southeastward slope of the Edwards Plateau is probably caused by a broad, gentle uplift and eastward tilting of the western landscape that occurred sometime (perhaps, off and on) during the Cenozoic Era (Sellards and Baker, 1935, p. 155).

Cartwright (1932, p. 694-699) noted some of the more prominent features of the base in his map of the pre-Cretaceous surface of the northeastern part of the Edwards Plateau; Rose (1972, figs. 4 and 5) have names to a few of the structures that he associated with relief in beds of the overlying Edwards Group (Fredericksburg-lower Washita rocks). The elongate high near the intersection of Kimble, Menard, Schleicher, and Sutton Counties--named the Roosevelt high by Rose--was attributed by Cartwright to the resistant nature of the underlying massive limestone of Lower Permian age. The dome-shaped feature on the base in north-central Gillespie County results from a Precambrian high at the head of the Medina axis (fig. 2)--a positive feature described by Rose (1972) as bearing southwesterly across central Kerr and northwestern Bandera Counties. The wide, southward plunging depression between the Roosevelt high and the Medina axis was designated by Rose (1972) as the Junction trough. Plate 1 indicates that, on the base, there is about 800 ft of relief between the Junction trough and the Roosevelt high, and about 500 ft of relief between this trough and the dome in north-central Gillespie County. Structure-contour maps drawn by Rose (1972, figs. 4 and 5) for the base of the Edwards Group, and for an horizon near the middle of the Edwards, show about 100 ft of relief between both the Junction trough and the Roosevelt high and the Junction trough and the dome in Gillespie County. These maps show that horizons within the rocks of the Edwards-Trinity aquifer system undulate less abruptly than does the base of the system.

Much of the local relief in the bedding of the Edwards-Trinity rocks results from differential compaction of the Cretaceous sediments as they adjusted to the topography of the pre-Cretaceous terrain. Collapse structures, resulting from the post-depositional or penecontemporaneous removal of evaporitic sediments, also are important factors, but only in small areas (Rose, 1972, p. 55-56). According to Cartwright (1932, p. 700), the plastic lime mud and marly clay of the Edwards-Trinity sediments adjusted "...in direction, though not in degree, to the slope of the surface on which they were deposited." As Cretaceous sediments accumulated upon the pre-Cretaceous surface of local erosional relief, the muds and clays compacted and the overlying beds settled. The areas of thickest deposition--corresponding to the areas of lowest elevation on the pre-Cretaceous surface--settled the most, thereby translating a subdued replica of the basal surface into overlying rocks of the Edwards-Trinity aquifer system.

Trans-Pecos

The Trans-Pecos is the most mountainous region in Texas. The base of the Edwards-Trinity aquifer system on the eastern flanks of mountains (in Brewster, Culberson, and Jeff Davis Counties) is ruggedly configured partly as a result of the active tectonic history of the region. The highest elevations in the study area are in southern Pecos and northern Brewster Counties on the eastern flank of the Marathon uplift (fig. 2), where Paleozoic rocks were intensely folded, overthrusted, and uplifted during the Ouachita orogeny. The Marathon area was beveled by erosion prior to being inundated by Cretaceous seas. Since the Early Cretaceous, the area was twice uplifted and eroded as a result of major late Mesozoic and Cenozoic deformations. Northwest of the Marathon uplift, the southwestern margin of the study area is bounded by the Glass, Davis, Barrilla, Apache, and Delaware Mountains (fig. 2). These elevated land masses and associated high-angle faults and tight folds--which today separate the mountains hydraulically from the Edwards-Trinity aquifer system--were formed mostly by Laramide and Basin and Range deformations during the Cenozoic (Henry and Price, 1985). Concurrently, toward the north, the base of the aquifer system was warped and faulted. Because of the structural complexity of the rocks underlying the mountain flanks, and the sparse control available at this time to define it, the configuration of the base is not mapped on plate 1 to the southwestern boundary of the study area.

From northern Terrell County, the base of the Edwards-Trinity aquifer system plunges southward at about 50 to 60 ft/mi, and the Glen Rose Limestone thickens greatly in this direction. The abrupt steepening of the base and thickening of the Glen Rose here resemble conditions in Val Verde County; these conditions undoubtedly relate to the structural history of the area. The southern part of Terrell County is underlain by the Marathon salient of the Ouachita structural belt (fig. 2), which sank from prominence following the Late Paleozoic orogeny. According to Murray (1961, p. 129), regional zones of weakness associated with the structural belt may have helped determine the size, shape, and form of the Rio Grande embayment. Jager (1942, p. 384) attributed the presence of the Glen Rose Limestone and the thickening of Cretaceous rocks in Terrell County to "...the steep slope into the Rio Grande embayment, the old floor of which sank rapidly during Cretaceous time." Jager (1942) also noted the "valley-like feature" along the Pecos River in northeastern Pecos and northwestern Crockett Counties (outlined by the 2,000-ft contour on pl. 1), which he noted might be due in large part to "salt solution."

The removal of soluble halite, gypsum, and anhydrite from the Castile, Salado, and Rustler Formations of Late Permian age has profoundly altered the base of the Edwards-Trinity aquifer system in parts of the Trans-Pecos. The dissolution may have begun as early as Late Permian or Triassic time and probably has continued into the Cenozoic Era. The source and course of the freshwater that dissolved the soluble strata is debatable (Adams, 1944; Maley and Huffington, 1953; and Wessel, 1988); the conditions probably varied from time to time and from place to place. Nevertheless, large solution cavities developed in the subsurface as the salts and evaporites were carried away by undersaturated ground water. As overlying Permian, Triassic, and Cretaceous strata collapsed, an elongate complex of troughs formed, which stretches from northern Pecos County to southeastern New Mexico (Ashworth, 1990, fig. 5). The troughs were subsequently filled with approximately 1,900 ft of alluvium derived from the trough margins and mountains to the south.

The Cenozoic alluvium, as it is known in west Texas, extends into large parts of Crane, Loving, Pecos, Reeves, Ward, and Winkler Counties where the older Edwards-Trinity rocks have been eroded from the area. The alluvium is predominately an unconsolidated to semi-consolidated mixture of gravel, sand, silt, clay, and caliche. Where it is relatively permeable and important as a source of ground water, the unit comprises the Cenozoic Pecos alluvium aquifer (Ashworth, 1990, p. 12). Because the Cenozoic Pecos alluvium aquifer is contiguous and hydraulically connected to the Edwards-Trinity aquifer system, the base of the alluvium is included on plate 1 where the Edwards-Trinity rocks are missing.

HYDROGEOLOGY OF THE PRE-CRETACEOUS ROCKS

The pre-Cretaceous rock complex that underlies the Edwards-Trinity aquifer system typically is a barrier to ground-water flow, thus limiting the exchange of water between the pre-Cretaceous rocks and the aquifer system. Nevertheless, a few Paleozoic formations and one Triassic unit are permeable over large enough parts of the study area to be considered "minor" aquifers by the Texas Water Development Board (1990, p. 1-6). In most places, the Edwards-Trinity aquifer system is more permeable than the underlying pre-Cretaceous rocks, and the aquifer system generally contains water that is less expensive to pump and is suitable for more uses without treatment. In some places outside the area underlain by the Edwards-Trinity aquifer system, or near the thin, unsaturated fringes of the system, the pre-Cretaceous rocks are the sole or primary source of ground water. Where the rocks of the Edwards-Trinity system are present and are saturated, however, the pre-Cretaceous strata are generally less important sources of ground water because they are deeper and typically contain water with larger concentrations of dissolved minerals.

The ages of the rocks that directly underlie the Edwards- Trinity aquifer system--and selected contiguous rocks that are hydraulically connected to the system--are indicated on plate 1 and in figure 3. Hydrogeologic aspects of the pre-Cretaceous rocks are discussed below, starting in the eastern part of the study area with the oldest rocks and progressing westward toward the youngest.

Cambrian through Pennsylvanian Rocks

The southern and eastern parts of the Edwards-Trinity aquifer system are underlain directly by rocks ranging in age from Cambrian through Pennsylvanian whose hydrogeologic characteristics vary considerably. Rocks belonging to the Ouachita facies (fig. 3) of the Ouachita structural belt (figs. 2 and 3) generally are metamorphosed and (or) sheared and locally crystalline (Flawn and others, 1961, p. 121-124); these Cambrian through Pennsylvanian rocks are virtually impermeable. Although the Cambrian through Pennsylvanian rocks of the foreland facies generally are deformed structurally, they are only slightly metamorphosed and thus, may be permeable locally. The extent of deformation and degree of metamorphism in the foreland rocks generally decrease with distance from the Ouachita structural belt (Flawn and others, 1961).

The most permeable strata of Cambrian through Pennsylvanian age are within the: (1) Hickory Sandstone Member of the Riley Formation (Upper Cambrian); (2) San Saba Limestone Member of the Wilberns Formation (Upper Cambrian); (3) Ellenburger Group (Lower Ordovician); and (4) Marble Falls Limestone (Lower Pennsylvanian). These rocks are important aquifers in the northeastern part of the study area where the Edwards- Trinity strata have been removed by erosion and upturned edges of the aquifers are exposed in broken, arcuate bands around the granitic core of the now-breached Llano uplift (fig. 3; pl. 1). Locally, the Hickory Sandstone Member and the Marble Falls Limestone each yield more than 1,000 gal/min to individual wells; the Ellenburger Group and San Saba Limestone Member, combined, yield as much as 1,000 gal/min to individual wells (Muller and Price, 1979, p. 54).

Because the permeability of the Cambrian and Ordovician rocks generally is restricted to scattered fracture zones and an irregular distribution of solution cavities, the availability of ground water from these rocks varies greatly. The Hickory aquifer, consisting principally of sand, fractured sandstone, and zones of dissolved carbonate cement in the Hickory Sandstone (Pettigrew, 1991), furnishes most of the ground water for the Llano uplift area of central Texas (Muller and Price, 1987, p. 54). Because the Ellenburger Group and the San Saba Limestone are adjacent and hydraulically similar, they are generally combined for hydrologic purposes into the Ellenburger-San Saba aquifer. The strata composing the Hickory and Ellenburger-San Saba aquifers dip at slopes generally exceeding 100 ft/mi beneath the Edwards-Trinity Aquifer system in Blanco, Concho, Gillespie, Kimble, and Menard Counties. The Hickory and Ellenburger-San Saba aquifers become less accessible, and their waters more saline, away from the Llano uplift.

Follett (1973, p. 17) found that the rock units between the Hickory and Ellenburger-San Saba aquifers in northwest Blanco County yield very small to small quantities of freshwater, and reported that '...individually they are relatively insignificant in regard to the hydrology of the area." Although this description by Follett (1973) is believed to apply generally throughout the study area, Mason (1961, p. 26) deduced from water-quality similarities in southern McCulloch County that most Cambrian rocks there probably are connected hydraulically. Alexander and Patman (1969, p. 26) reported that a similar situation may exist in Kimble County. Mason (1961) also noted that in many places the hydraulic head is greater in the Hickory aquifer than in the overlying Cambrian and Ordovician rocks. Because of the noted head differences and the fact that the few wells in the intervening Cambrian rocks are limited to very small yields (less than 10 gal/min) for domestic and stock purposes, the rocks between the Hickory and Ellenburger-San Saba aquifers are considered to be mostly confining units in this report (table 2).

The Silurian, Devonian, and Mississippian rock units are relatively thin in the study area, and they generally are buried too deep to have been explored for potential sources of ground water. The clastic Silurian, Devonian, and Mississippian deposits are composed mostly of dark petroliferous and pyritiferous shales (University of Texas, Bureau of Economic Geology, 1981), and the calcareous rocks are typically siliceous or cherty as the result of cementation and recrystallization (Barnes and others, 1972, p. 30-37). Because of their generally fine-grained and (or) dense nature, the Silurian, Devonian, and Mississippian rocks are assumed herein to comprise mostly confining units (table 2) and to have only negligible hydrologic effects on the Edwards-Trinity aquifer system.

Except where the Marble Falls Limestone of Early Pennsylvanian age is permeable by virtue of solution cavities and fractures in and near its outcrop area (pl. 1), the Pennsylvanian rocks are relatively impermeable. Where the Marble Falls Limestone is permeable, contains freshwater, and is accessible to water-supply wells, it composes the Marble Falls aquifer (Muller and Price, 1979, p. 54). Pennsylvanian rocks that are stratigraphically above the Marble Falls aquifer are considered herein (table 2) to compose mostly confining units.

Because the intervening Middle and Upper Pennsylvanian and Permian rocks are mostly confining units (table 2) that total hundreds of feet in thickness, there is little potential for hydraulic interaction between the Cambrian through Pennsylvanian rocks and the Cretaceous rocks of the Edwards-Trinity aquifer system. However, exceptions to this generalization occur on the flanks of the Llano uplift near the northeastern fringe of the Edwards-Trinity aquifer system (fig. 2).

A potentiometric-surface map of the study area by Kuniansky (1990) shows that the Edwards-Trinity aquifer system is hydraulically continuous with Cambrian through Pennsylvanian rocks in Blanco, Gillespie, Llano, Mason, McCulloch, and San Saba Counties (fig. 1). The internal, deeply eroded part of the Llano uplift forms a topographic basin of low relief (fig. 3). The potentiometric data (Kuniansky, 1990) indicate that ground water discharging laterally from the northeastern fringe of the Edwards-Trinity aquifer system joins the shallow ground-water-flow regime of the breached Llano uplift. The shallow flow regime of this area includes the outcrop areas of the Hickory, Ellenburger-San Saba, and Marble Falls aquifers (pl. 1).

As the result of late Paleozoic to early Mesozoic faulting and erosion, the Hensel Sand of Cretaceous age (table 1) rests directly on Cambrian and Ordovician rocks in eastern Kimble County and parts of Gillespie County (Mount, 1963, fig. 3). The Hensel Sand forms the lower part of the Edwards-Trinity aquifer system in these areas. Here, the Paleozoic rocks are hydraulically connected to the Hensel Sand, which may receive some recharge through upward leakage of ground water from the underlying Hickory and Ellenburger-San Saba aquifers (Mount and others, 1967, p. 63).

Permian and Triassic Rocks

The central, northern, and western parts of the Edwards-Trinity aquifer system are underlain directly by Permian and Triassic rocks (fig. 3; pl. 1) that in most places are relatively impermeable, but, in some places, offer potential for secondary sources of ground water. Where permeable Permian or Triassic rocks directly underlie the Edwards-Trinity aquifer system, small amounts of water may migrate along circuitous flowpaths between these pre-Cretaceous rocks and the Cretaceous rocks of the aquifer system. The known sources of ground water from the Permian and Triassic rocks and the exchange of water across the base of the aquifer system are discussed below.

The majority of Wolfcampian and Leonardian (Lower Permian) and Guadalupian (Upper Permian) rocks in the study area are strongly indurated, fine-grained marine deposits that (relative to the permeability of the overlying Cretaceous rocks) compose mostly confining units (table 2). Mount and others (1967, p. 79) characterized the Lower Permian rocks of the northern Edwards Plateau as "...either too tight to yield water to wells or else they yield only small amounts of mineralized water." However, the sandy characteristics of some Leonardian and Guadalupian strata indicate that they "...may contain small amounts of fresh to slightly-saline water..." to supplement the water supply in parts of Coke, Irion, Schleicher, and Tom Green Counties (Walker, 1979, p. 46). The potential also exists for Lower Permian rocks that form the elongate high on the base of the aquifer system near the common corner of Kimble, Menard, Schleicher, and Sutton Counties (pl. 1) to receive minor amounts of downward leakage from the Edwards-Trinity aquifer system (Mount and others, 1967, fig. 9).

The Ochoan (Upper Permian) strata of the Permian Basin are composed mostly of terrestrial red beds that are relatively impermeable. However, the Rustler Formation is a marginal source of highly mineralized water that is used by industry and agriculture in parts of the Trans-Pecos. The generally large and highly variable concentrations of calcium, sodium, sulfate, and chloride make the water unsuitable for drinking and most other domestic uses. Transmissivity and storage-coefficient values in the Rustler are believed to be low, and well yields generally are much less than 1,000 gal/min (Muller and Price, 1979, p. 57). Nevertheless, the Rustler Formation is permeable enough to provide or augment the water supply for irrigation, livestock, and secondary oil recovery in most of Reeves County and in western parts of Loving, Pecos, and Ward Counties. Where the Rustler Formation yields ground water to wells, it is known as the Rustler aquifer (Ashworth, 1990, p. 6).

The lower, middle, and upper parts of the Upper Triassic Dockum Group in west Texas were referenced by many authors for many years as the Tecovas, Santa Rosa, and Chinle "formations," respectively (Jones, 1953, p. 41). However, the stratigraphic relations among the Santa Rosa Sandstone and Chinle Formation of the Colorado Plateau and the Triassic rocks of west Texas are uncertain, and they are currently being debated (Chatterjee, 1987, p. 139-149). Therefore, a general subdivision of the Dockum Group (lower, middle, and upper) is used herein (table 2).

The Dockum Group (McGowen and others, 1979) is a terrigenous red-bed facies of fluvial, deltaic, 3.nd lacustrine environments that is composed mostly of reddish-brown to gray sandstone, sand, 5il1stone, and shale. Because the lower and upper parts of the Dockum Group contain the largest percentages of siltstone and shale, they are relatively impermeable. The middle part of the Dockum, however, is sandy locally. Where the middle Dockum unit is accessible to water-supply wells and composed principally of sand that is saturated, it comprises the Dockum aquifer (Texas Water Development Board, 1990). In the west Texas area, and in most of the hydrogeologic literature, the Dockum aquifer has been known as the Santa Rosa aquifer.

The Dockum aquifer is an important source of irrigation and livestock water and a less important, source of domestic and municipal water in northwestern parts of the Edwards Plateau, in most of Winkler and Ward Counties, and in eastern parts of Loving and Reeves Counties (Mount and others, 1967; White, 1968; Ashworth, 1990). Water pumped from the Dockum aquifer varies considerably in quantity and quality with respect to area; however, well yields rarely exceed a few hundred gallons per minute and the water typically contains large concentrations of sodium, sulfate, and fluoride. Hydraulic interaction with the Edwards-Trinity system is limited to areas where the upper Dockum unit is absent. The upper Dockum unit typically consists of shale and lenticular beds of siltstone that confine ground water in the underlying Dockum aquifer. Where the upper Dockum unit is absent, sands of the Dockum aquifer are directly overlain by basal sands of the Edwards-Trinity aquifer system (fig. 3). Where the Dockum and Edwards-Trinity aquifers abut, the effective depth of the ground-water-flow system may extend to the lower Dockum unit, or--where the lower Dockum unit is missing--to the Dewey Lake Red Beds of Ochoan Late Permian) age.

Areas where the Dockum aquifer is known to merge hydraulically with the Edwards-Trinity aquifer system are indicated on plate 1. In these areas, the saturated thickness of the regional flow system may increase by as much as 400 ft (Ogilbee and others, 1962, pls. 5-7; Walker, 1979, fig. 13); however, the average increase in saturation is probably about 200 ft.

Although the Dockum aquifer is known to directly underlie the Edwards-Trinity aquifer system in eastern Reeves and western Crockett Counties, the extent and hydraulic characteristics of the middle Dockum unit are uncertain across central Pecos County. Over most of Pecos County, the Edwards-Trinity system is underlain directly by Permian and Triassic red beds that have not been differentiated. The uppermost Permian strata, composed primarily of Dewey Lake Red Beds, are red shales and siltstones cemented with gypsum and calcite. The Dewey Lake unit resembles the lowermost Triassic strata, the lower Dockum unit, which is composed also of strongly oxidized terrestrial sediment; the lower Dockum unit primarily is a reworked remnant of the Dewey Lake Red Beds. Although the thickness of the undifferentiated red-bed interval in Pecos County ranges from 0 to about 1,500 ft, no part stands out as an especially noteworthy water-yielding unit. According to Armstrong and McMillion (1961, p. 37), the red beds of Permian and Triassic age in this area yield "...small amounts of water at various locations." If the middle Dockum unit exists in Pecos County, it is apparently less permeable than the Dockum aquifer of adjacent counties. For these reasons, the possibility of hydraulic contact between the Dockum aquifer (middle Dockum unit) and the Edwards-Trinity aquifer across central Pecos County is uncertain and, thus, is noted by question marks on plate 1.

The wide extent and typically low permeability of the Permian and Triassic red beds generally buffer the Edwards-Trinity aquifer system from the deeper, salt-laden sediments of the Permian Basin. The collective thickness of the Dewey Lake and lower Dockum confining units generally exceeds a few hundred feet over most of the Trans-Pecos and northwestern Edwards Plateau. However, where these units are absent in northeastern Pecos County (pl. 1), there is potential for water-quality degradation in the Edwards-Trinity aquifer system by upward leakage of brackish water from the underlying Salado and Rustler Formations.

The Permian and Triassic red beds are thin or missing in an area just south of the Pecos River in northeastern Pecos County (Armstrong and McMillion, 1961, pl. 7). Here, as shown on plate 1, the Rustler Formation (or the Salado Formation, where the Rustler is missing) directly underlies the Edwards-Trinity aquifer system. The Rustler Formation is composed predominately of anhydrite and dolomite, with minor amounts of salt and limestone. The Salado Formation is composed principally of halite, with small amounts of anhydrite, dolomite, and potash minerals (Jones, 1953, p. 40-41). The concentration of dissolved solids in water from the Rustler Formation commonly ranges between about 2,000 and about 6,000 mg/L (Muller and Price, 1979, p. 57). Although hydrostatic pressures in the Rustler Formation have declined since development began, many of the first wells completed in this unit flowed at land surface (Knowles and Lang, 1947, p. 7-8; Armstrong and McMillion, 1961, p. 34-36). When measured in February 1987, water levels in two wells completed in the Rustler aquifer of west-central Pecos County were about 40 ft higher than those in nearby wells finished in the Edwards-Trinity aquifer system (T.A. Small, U.S. Geological Survey, written commun., 1989). According to Small, the dissolved solids and hydrostatic pressure of water in the Salado Formation are probably as great or greater than in the Rustler Formation.

The concentration of chemical constituents in water samples from the overlying part of the Edwards-Trinity aquifer system during 1969-75 averaged 1,750 mg/L for dissolved solids, 625 mg/L for sulfate, and 320 mg/L for chloride (Rees and Buckner, 1980, fig. 6). These relatively large concentrations may indicate upward leakage of brackish ground water from the Salado and Rustler Formations.

Hydraulic Characteristics

Transmissivity and storage-coefficient data are sparse for the Paleozoic and Triassic rocks. Conditions that determine the hydraulic properties of these rocks are extremely variable and the opportunities to test for these properties have been limited. Aquifer tests on the Hickory aquifer conducted at 14 sites in Gillespie, Mason, and McCulloch Counties yielded transmissivity values that range from about 500 to about 4,850 ft^2/d and average about 3,250 ft^2/d (Mason, 1961; Mount, 1963; Myers, 1969). Where the Hickory aquifer is confined, storage-coefficient values range from about 1×10^{-5} to about 1×10^{-4}. Mount (1963, p. 20) determined that the transmissivity of the Ellenburger Group in one area of southeastern Gillespie County ranges from about 10,000 to about 13,500 ft^2/d. Aquifer-test data are not available for the total thickness of the Ellenburger-San Saba aquifer, nor for the Marble Falls aquifer in the study area. A 21-hour aquifer test in Ward County indicated a transmissivity value of about 2,900 ft^2/d for the Rustler aquifer (White, 1971, p. 28). Aquifer-test data are not available for the Dockum aquifer in Upper Triassic rocks of the study area. However, Mount and others (1967, p. 54) reported that the transmissivity of the "upper sands of the Santa Rosa aquifer" in Upper Triassic rocks north of the study area (in Scurry County) ranges from about 200 to about 800 ft^2/d and averages about 500 ft^2/d; the associated values of storage coefficient average about 2×10^{-3}. An aquifer test in Upton County on the upper Dockum (confining) unit yielded a transmissivity value of about 50 ft^2/d for the "Chinle equivalent," as the strata were called at that time (White, 1968, p. 22).

The transmissivity and storage-coefficient values listed above apply to local conditions that were found to yield ground water to wells. These data probably reflect "better-than-average" conditions near successful wells, rather than average conditions that might provide "dry holes" or less successful wells. Although the results of aquifer tests on successful wells in water-scarce areas are usually reported, such is not the case with disappointing results.

Hydraulic-conductivity data for relatively deep Paleozoic rocks are available from core sampling and production tests conducted by the petroleum industry and summarized by the Texas Water Development Board (1972, p. 6-9). For Cambrian through Pennsylvanian rocks of central Texas, hydraulic-conductivity values range from 0.1 to 600 millidarcies (2.74×10^{-4} to 1.64 ft/d). Hydraulic-conductivity values measured in the Wolfcampian (Lower Permian) rocks of west-central Texas range from 1 millidarcy to "more than 1 darcy" (2.74×10^{-3} to more than 2.74 ft/d). For Guadalupian (Upper Permian) rocks of west Texas, the hydraulic-conductivity values range from 1 to 500 millidarcies (2.74×10^{-3} to 1.37 ft/d). Although these hydraulic-conductivity data typify the capacity of production zones in petroleum reservoirs, they are extremely small by water-well standards. By comparison, the hydraulic conductivity of water-yielding Edwards-Trinity strata probably averages about 10 ft/d in the western part of the study area and about 1,000 ft/d in the Balcones fault zone. Although some of the Paleozoic rocks are permeable enough for petroleum extraction, few of the Paleozoic units constitute reliable aquifers.

The scarcity of hydraulic data for the pre-Cretaceous rocks precludes mapping the distribution of transmissivity or hydraulic conductivity; however, a general assessment can be made regarding their permeability relative to that of the Edwards-Trinity aquifer system. The results of computer-model analyses, aquifer tests, and geologic observation indicate that transmissivity values range from less than 100 to about 50,000 ft^2/d and average less than 10,000 ft^2/d over the Hill Country, Edwards Plateau, and Trans-Pecos. Maclay and Land (1988, p. A26) indicated that transmissivity values in the Edwards aquifer of the Balcones fault zone range from about 10,000 to more than 1,000,000 ft^2/d; Maclay and Small [1986, fig. 20) indicate an average transmissivity value of about 750,000 ft^2/d for the San Antonio area. The saturated thickness of the aquifer system ranges from less than 10ft in western parts of the study 3rea to more than 1,000 ft in the Balcones fault zone and probably averages about 500 It, overall. Based on the available hydraulic data and the known depositional, structural, and diagenetic differences between the pre-Cretaceous and Cretaceous rocks, it can be generalized that the aquifer system is underlain by rocks that are typically 10 to perhaps 1,000 times less permeable than those of the aquifer system.

Hydraulic-head and hydraulic-conductivity data are not available to quantify the magnitude of ground-water flow across the base of the Edwards-Trinity aquifer system. However, the rates of vertical ground-water flow between the pre-Cretaceous rocks of the base and the Cretaceous rocks of the aquifer system are considered very small or negligible, compared to the rates of lateral flow within the system.

Permeability differences between the rocks of the Edwards-Trinity aquifer system and the pre-Cretaceous rocks that underlie it result from depositional, structural, and diagenetic differences between the pre-Cretaceous and Cretaceous rocks. Whereas the bulk of Upper Cambrian through Lower Permian rocks originated in basinal or geosynclinal environments, most of the Edwards-Trinity strata reflect characteristics of a shallow carbonate shelf (Rose, 1972, p. 62-71). The pre-Cretaceous rocks are structurally more complex than those of the overlying aquifer system (Sellards and Baker, 1935). Folds and faults within the Paleozoic rocks have compartmentalized fluid flow, creating petroleum traps and restricting ground-water circulation. The major structure affecting the aquifer system is the Balcones fault zone, and this zone is characterized by porous fractured rock and a honeycombed and cavernous pattern of secondary permeability (Maclay and Small, 1986). LeGrand and Stringfield (1966) showed that secondary (post-depositional) permeability values in carbonate rocks increase with the dynamics of freshwater circulation and attain maximum values within the zone of water-level fluctuation. A relatively shallow water table has probably persisted since the Edwards-Trinity sediments were subaerially exposed; this condition, coupled with a surficial influx of carbon dioxide-enriched meteoric water, has favored a near-surface pattern of permeability development (Abbott, 1975, p. 255-260).

Because compaction, cementation, and recrystallization of calcareous sediments progress with time, and each of these processes generally reduces or obliterates the primary porosity, the permeability of carbonate rocks typically decreases with geologic age (Jakucs, 1977, p. 69, fig. 16). The permeability of some Cretaceous rocks of the Edwards-Trinity system has increased locally over time, as the result of tectonic fracturing and a dynamic freshwater-flow regime that aided the porosity-enhancing process of dissolution. In contrast, it seems that the effects of compaction, cementation, and recrystallization resulting from deep burial and late diagenesis have combined to retard the overall permeability in the underlying pre-Cretaceous rocks.

SUMMARY

The Edwards- Trinity aquifer system is composed of Cretaceous rocks that are underlain by an extensive complex of Cambrian through Triassic rocks. The upper surface of the pre-Cretaceous complex forms the base of the aquifer system. The incongruent contact between the pre-Cretaceous rocks and those of the aquifer system marks a major unconformity, spanning about 60 million years of erosion during the Jurassic Period. As the result of relatively advanced stages of compaction, cementation, and recrystallization resulting from deep burial and late diagenesis, the pre-Cretaceous rocks typically are about 10 to perhaps 1,000 times less permeable than the Cretaceous rocks of the aquifer system.

The configuration of the base results from the erosional topography of the pre-Cretaceous land surface, plus the effects of subsequent structural deformation. In addition to relief inherent from the original (much flatter) surface, the present surface exhibits the effects of subsidence, uplift, folding, faulting, and structural collapse caused by the dissolution of underlying carbonate rocks. From about 5,000 ft below sea level on the sunken Ouachita structural belt at the southern edge of the Balcones fault zone, the base rises to more than 4,000 ft above sea level on the northern flank of the Marathon uplift in the Trans-Pecos. Regionally, the base is characterized by: (1) A steeply plunging southeastern margin over the Balcones fault zone; (2) a moderately inclined band that wraps around the Hill Country into the southern Edwards Plateau; (3) a broad platform with a gentle southward slope in the northern Edwards Plateau; and (4) a variable, rugged configuration in the Trans-Pecos. Slopes on this surface range from an average of about 10 ft/mi in northern parts of the Edwards Plateau to an average of about 175 ft/mi across the Balcones fault zone.

Permeable pre-Cretaceous rocks (of Late Cambrian through Early Pennsylvanian age) are exposed on the flanks of the breached Llano uplift where rocks of the Edwards-Trinity aquifer system are missing. Water discharging laterally from the northeastern fringe of the Edwards-Trinity aquifer system merges with the shallow flow regime of the Llano uplift where the Hickory, Ellenburger-San Saba, and Marble Falls aquifers crop out. Under ideal conditions, these aquifers locally yield 1,000 gal/min or more to individual wells.

The Rustler aquifer in Upper Permian rocks is a marginal source of greatly mineralized water, which is used for industrial and agricultural purposes in parts of the Trans-Pecos. Upward leakage of brackish ground water from the Rustler Formation or the underlying Salado Formation, or both, may have contributed to the degradation of water quality in the Edwards-Trinity aquifer system of northeastern Pecos County.

The middle unit of the Dockum Group of Triassic age is locally sandy; where it is permeable and saturated, it is known as the Dockum aquifer. The Dockum aquifer is used as a source of water for livestock, domestic, and municipal supply in parts of the Edwards Plateau and Trans-Pecos; well yields are generally limited to a few hundred gallons per minute. Where the upper Dockum unit is absent, the Dockum aquifer directly underlies the Edwards-Trinity aquifer system and may increase the saturated thickness of the regional ground-water-flow system by an average of about 200 ft.

Paleozoic rocks in eastern Kimble County and parts of Gillespie County are hydraulically connected to the Hensel Sand of the Edwards-Trinity aquifer system. Here, the Hensel Sand may receive some recharge through the upward leakage of ground water from the Hickory and Ellenburger-San Saba aquifers. Subcrops of sandy and dolomitic middle Permian rocks in northern parts of the Edwards Plateau may contain small amounts of fresh to slightly-saline water to supplement local water supplies in an area generally dominated by the Edwards-Trinity aquifer system. The potential exists for minor amounts of downward leakage from the aquifer system to Lower Permian rocks that form a prominent Paleozoic high near the common corner of Kimble, Menard, Schleicher, and Sutton Counties.

The conditions that determine the hydraulic properties of the pre-Cretaceous rocks vary greatly, and the opportunities to test for these properties have been rare. Extremely limited hydraulic data indicate an average transmissivity value of about 3,250 ft^2/d for the Hickory aquifer and local transmissivity values of: (1) about 10,000 to 13,500 ft^2/d for the Ellenburger Group; (2) about 2,900 ft^2/d for the Rustler aquifer; (3) about 200 to about 800 ft^2/d for the Dockum aquifer; and (4) about 50 ft^2/d for the upper (confining) unit of the Dockum Group. Storage-coefficient data indicate values ranging from about 1×10^{-5} to about 1×10^{-4} for the Hickory aquifer and about 2×10^{-3} for the Dockum aquifer. Aquifer-test data are not available for the Marble Falls aquifer or the total thickness of the Ellenburger-San Saba aquifer, and the transmissivity and storage-coefficient values given for the Dockum aquifer come from Scurry County, north of the study area.

Hydraulic-head and hydraulic-conductivity data are not available to quantify the magnitude of ground-water flow across the base of the aquifer system. However, the rates of vertical exchange between the pre-Cretaceous rocks of the base and the Cretaceous rocks of the aquifer system are very small or negligible relative to the rates of lateral flow within the aquifer system.

With the exception of conditions near the Llano uplift and in subcrops of the Rustler and Dockum aquifers in western parts of the study area, there is little indication that an appreciable amount of leakage occurs between the Edwards- Trinity aquifer system and the underlying pre-Cretaceous rocks. The aquifer system generally is isolated from the permeable pre-Cretaceous rocks by intervening strata of relatively low permeability. Depositional, structural, and diagenetic information about the rocks--together with observations of the occurrence, availability, and movement of ground water in the study area--indicate that the pre-Cretaceous rocks collectively form a barrier to ground-water flow, which generally limits the exchange of water across the base of the aquifer system.

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