Report 296

Carbonate Geology and Hydrology of the Edwards Aquifer in the San Antonio Area, Texas

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TEXAS WATER DEVELOPMENT BOARD

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CARBONATE GEOLOGY AND HYDROLOGY OF THE EDWARDS AQUIFER IN THE SAN ANTONIO AREA, TEXAS

By
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ABSTRACT

Regional differences in the porosity and permeability of the Edwards aquifer are related to three major depositional areas, the Maverick basin, the Devils River trend, and the San Marcos platform, that existed during Early Cretaceous time. The rocks of the Maverick basin are predominantly deep basinal deposits of dense, homogeneous mudstones of low primary porosity. Permeability is principally associated with cavernous voids in the upper part of the Salmon Peak Formation in the Maverick basin. The rocks of the Devils River trend are a complex of marine and supratidal deposits in the lower part and reefal or inter-reefal deposits in the upper part. Permeable zones, which occur in the upper part of the trend, are associated with collapse breccias and rudist reefs. The rocks of the San Marcos platform predominantly are micrites that locally contain collapse breccias, honeycombed, burrowed mudstones, and rudist reef deposits that are well leached and very permeable. The rocks of the San Marcos platform form the most transmissive part of the Edwards aquifer in the San Antonio area. Karstification of the rocks on the San Marcos platform during Cretaceous time enhanced the permeability of the aquifer.

Permeability of the Edwards aquifer is greatest in particular strata (lithofacies) which have been leached in the freshwater zone. Ground water moves along vertical or steeply inclined fractures that are passageways by which water can enter permeable strata. Water moves from the fractures into beds formed by collapse breccias, burrowed wackestones, and rudist grainstones that have significant secondary porosity and permeability. Water has selectively dissolved sedimentary features within those rocks to increase the size of the openings and the degree of interconnection between pore voids.

Recognition of the hydrostratigraphic subdivisions provides a basis for defining the nonhomogeneity of the aquifer and determining its storage characteristics. The aquifer is considered to be a faulted and multilayered aquifer in which lateral circulation is mainly through very permeable, hydrostratigraphic subdivisions that are hydraulically connected at places by openings associated with steep-angle, normal faults. The Edwards aquifer is vertically displaced for its entire thickness at places along major northeastward trending faults. At these places, ground-water circulation is diverted either southwest or northeast.

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CARBONATE GEOLOGY AND HYDROLOGY OF THE EDWARDS AQUIFER IN THE SAN ANTONIO AREA, TEXAS

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INTRODUCTION

Purpose and Scope of This Report

The Edwards Limestone contains one of the most highly permeable and productive aquifers in Texas, and a knowledge of the nature of its pore system is useful for interpretations of the aquifer's hydrogeologic constants. For a better understanding of the porosity system, it is necessary to become knowledgeable of the geologic controls on porosity development and the diagenetic processes involved. Understanding the evolution of porosity from that of the depositional sediments to that of the consolidated carbonate rock can significantly contribute to the understanding of the porosity and permeability within the Edwards aquifer.

The purpose of this report is twofold: First, to describe the history of the carbonate sedimentary deposits and their subsequent diagenesis; and second, to use this knowledge to interpret the distribution of hydrogeologic characteristics of the aquifer and its confining units.

Definitions of Terms and Carbonate-Rock Classification Systems

Anisotropic—A formation is anisotropic if the hydraulic conductivity varies with the direction of measurement at a point within the formation.

Antithetic faults—Minor normal faults that are of the opposite orientation to the major fault with which they are associated.

Bioherm—A mound, dome, or small reef of rock built up by or composed almost exclusively of the remains of organisms (such as corals, algae, foraminifers, mollusks, or gastropods) and enclosed or surrounded by rock of different lithology.

Black rotund bodies (BRBs)—Small, 0.1 to 0.5 millimeters in diameter, spherical, dark colored textural features of unknown origin.

Cave popcorn—A rough, knobby secondary mineral deposit, usually of calcite, that is formed in a cave by action of water.

Collapse breccia—Formed where soluble material has been partly or wholly removed by solution, thereby allowing the overlying rock to settle and become fragmented.

Cone of depression—A depression in the potentiometric surface of a body of ground water that has the shape of an inverted cone and develops around a well from which water is being withdrawn. It defines the area of effect of a well.

Confined aquifer—An aquifer contained between two beds that retard but do not prevent the flow of water to or from an adjacent aquifer.

Conformable—An unbroken stratigraphic sequence in which the layers are formed one above the other in parallel order by regular, uninterrupted deposition under the same general conditions.

Dedolomitization—The replacement of dolomite by calcite in water with a very small magnesium to calcium ratio, which removes magnesium ions from the dolomite.

Diagenesis—All the chemical, physical, and biological changes, modifications, or transformations undergone by a sediment after its initial deposition, during and after lithification exclusive of surficial weathering and metamorphism.

Dolomitized—The process by which limestone is wholly or partly converted to dolomite or dolomitic limestone by the replacement of the original calcium carbonate (calcite) by magnesium carbonate, usually through the action of magnesium-bearing water.

En echelon faults—Faults that are in an overlapping or staggered arrangement.

Euxinic—An environment of slow circulation and stagnant or anaerobic conditions, characterized by a rock facies that includes black shales.

Evaporites—A nonclastic sedimentary rock composed primarily of minerals chemically precipitated from a saline solution that became concentrated by evaporation.

Fault scarp—A steep slope or cliff formed directly by movement along one side of a fault and representing the exposed surface of the fault before modification by erosion and weathering.

Fissile—Capable of being easily split along closely spaced planes.

Fore reef—The seaward side of a reef, commonly a steeply dipping slope with deposits of reef talus.

Graben—An elongate, relatively depressed crustal unit or block that is bounded by faults on its long sides.

Heterogeneity—Heterogeneity is said to exist if the hydraulic conductivity is dependent on position within an aquifer.

Homocline (regional)—A general term for a rock unit(s) in which the strata have the same dip.

Hydraulic conductivity—The volume of water at the prevailing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

Interreef—The area situated between reefs characterized by relatively nonfossiliferous rock.

Intraclast—A component of limestone representing a torn-up and reworked fragment of a penecontemporaneous sediment that has been eroded within the basin of deposition and redeposited there to form a new sediment. The fragment may range in size from fine sand to gravel.

Intrinsic permeability—A measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient. It is a property of the medium alone and is independent of the nature of the liquid and of the force field causing movement (Lohman and others, 1972).

Karstification—Action by water, mainly chemical but also mechanical, that produces features of a karst topography including caves, sink holes, and solution channels.

Lithofacies—The general aspect or appearance of the lithology of a sedimentary bed or formation considered as the expression of the local depositional environment.

Marl—Earthy and semifriable or crumbling unconsolidated deposits consisting chiefly of a mixture of clay and calcium carbonate in varying proportions formed under either marine or especially freshwater conditions.

Micrite—Semi-opaque crystalline matrix of limestones, consisting of chemically precipitated carbonate mud with crystals less than 4 microns in diameter and interpreted as lithified ooze.

Micritization—A process that causes a decrease in the size of carbonate grains, probably due to boring algae. Micrite envelopes commonly are developed on miliolids and clastic particles of shells. These envelopes were observed under magnification on many rock samples of the Edwards that were preserved in thin section slides. On some grains, the micrite envelope has extended throughout the entire particle, thereby destroying the internal features of the particle.

Potentiometric surface—A surface which represents the static head. As related to an aquifer, it is defined by the levels to which water will rise in tightly cased wells.

Primary porosity—The porosity that developed during the final stages of sedimentation or that was present within sedimentary particles at the time of deposition.

Rudist—A bivalve mollusk characterized by an inequivalve shell that lived attached to the substrate and formed mounds or reefs during the Cretaceous.

Supratidal—The ocean shore found just above the high-tide level.

Synthetic fault component—Minor normal faults that are of the same orientation as the major fault with which they are associated.

Talus (reef)—Fragmental material derived from the erosion of an organic reef.

Transgression—The spread or extension of the sea over land areas. A change that brings offshore, typically deep-water environments to areas formerly occupied by nearshore, typically shallow-water conditions.

Transmissivity—The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient.

Tectonic uplift—Regional uplift of the earth's surface resulting from gross movements of the Earth's crust.

Travertine—A hard dense, finely crystalline, compact or massive but often concretionary, limestone of white, tan, or cream color, commonly having a fibrous or concentric structure and splintery fracture.

Unconfined aquifer—An aquifer in which the water table forms the upper boundary.

Metric Conversions

For those readers interested in using the metric system, the inch-pound units of measurements used in this report may be converted to metric units by the following factors:

From English units	Multiply by	To obtain metric units
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
gallon per minute per foot [(gal/min)/ft]	0.207	liter per second per meter [(L/s)/m]
inch (in)	25.40	millimeter (mm)
mile (mi)	1.609	kilometer (km)
mile per day (mi/d)	1.609	kilometer per day (km/d)
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (kg/m^3)
pound per square inch (lb/in^2)	0.07031	kilogram per square centimeter (kg/cm^2)

From English units	Multiply by	To obtain metric units
square foot per pound (ft^2/lb)	0.204816	meter squared per kilogram (m^2/kg)
square inch per pound (in^2/lb)	0.00142243	meter squared per kilogram (m^2/kg)
square mile (mi^2)	2.590	square kilometer (km^2)

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level.

Location and Hydrogeologic Setting

The freshwater part of the Edwards aquifer in the San Antonio area is bounded by groundwater divides in Kinney County on the west and Hays County on the east, by the faulted outcrop of the aquifer on the north, and by the interface between freshwater and saline water (locally called the "bad-water" line) on the south (Figure 1). The area is about 180 miles long and varies in width from about 5 to 40 miles. The total area is about 3,200 square miles, of which about 2,000 square miles is within the freshwater zone of the artesian aquifer (Figure 1).

Recharge to the Edwards aquifer occurs in the area where the Edwards Limestone[1], or Group where it is divided, and equivalent rocks are exposed in the Balcones fault zone. Streams draining the Edwards Plateau lose all of their base flows and much of their storm runoffs by infiltration through porous and fractured limestone within the stream channels. These stream losses account for 60 to 80 percent of the recharge to the Edwards aquifer in the San Antonio area, and the rest of the recharge is derived from direct infiltration in the interstream areas.

The Balcones fault zone interrupts a regional homocline that dips gulfward from the Edwards Plateau toward the Gulf of Mexico and is a series of normal, en echelon, down-to-the-coast strike faults (Figure 2). In part, the fault zone is represented by prominent Gulf-facing scarps, that expose Lower Cretaceous rocks and mark the inner limit of Tertiary strata. Displacement on some individual faults exceeds 500 feet. The locations of the major faults in the Balcones fault zone are shown in Figure 3.

On a regional scale, the Balcones and Luling fault zones consist of series of grabens that attenuate by splaying out vertically. The half-graben represented by the Balcones fault zone is formed by faults dipping toward or into the normal faults of the opposite half-graben Luling fault zone. The faults of the Luling fault zone are inland-dipping, up-to-the-coast faults (Figure 4). Where inland-dipping faults have an opposite-facing complement, a graben is formed. These

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[1] The stratigraphic nomenclature used in this report was determined from several sources (Rose, 1972; Lozo and Smith, 1964; University of Texas, Bureau of Economic Geology, 1974; and Flawn and others, 1961) and may not necessarily follow the usage of the U.S. Geological Survey.

Carbonate-Rock Classification System of Dunham (1962)

Depositional texture recognizable					Depositional texture not recognizable
Original components not bound together during deposition				Original components were bound together during deposition... as shown by intergrown skeletal matter, lamination contrary to gravity, or sediment-floored cavities that are roofed over by organic or questionably organic matter and are too large to be interstices.	
Contains mud (particles of clay and fine silt size)			Lacks mud and is grain-supported		
Mud-supported		Grain-supported			
Less than 10 percent grains	More than 10 percent grains				Crystalline carbonate
Mudstone	Wackestone	Packstone	Grainstone	Boundstone	(Subdivide according to classifications designed to bear on physical texture or diagenesis.)

Carbonate-rock classification system of Folk (1962)

	More than 2/3 lime mud matrix				Subequal spar and lime mud	More than 2/3 spar cement		
Percent allochems	0-1 percent	1-10 percent	10-50 percent	More than 50 percent		Sorting poor	Sorting good	Rounded and abraded
Representative rock terms	Micrite and dismicrite	Fossiliferous micrite	Sparse biomicrite	Packed biomicrite	Poorly-washed biosparite	Unsorted biosparite	Sorted biosparite	Rounded biosparite
1959 terminology	Micrite and dismicrite	Fossiliferous micrite	Biomicrite		Biosparite			
Terrigenous analogues	Claystone		Sandy claystone	Clayey or immature sandstone		Submature sandstone	Mature sandstone	Supermature sandstone

grabens are believed to be an expression of an antithetic fault system in which the coastward-dipping faults are the synthetic component that terminates at depth against the inland-dipping, up-to-the-coast faults (Walthal and Walper, 1967, p. 107). The depth at which the graben terminates is dependent upon the width of the graben and the inclination of the fault zones.

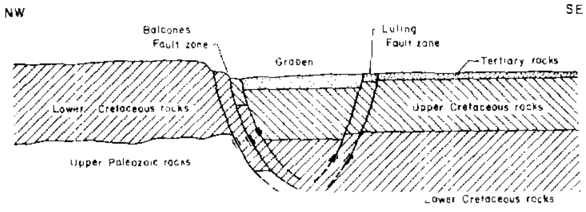


Figure 4.—Conceptual Section Showing the Regional Graben Formed by the Balcones and Luling Fault Zones in Bexar County

A geologic map of the hydrologic basin in the San Antonio area is given in Figure 5. Descriptions of the lithologic and hydrogeologic characteristics of the stratigraphic units within each of the four depositional provinces (the Central Texas platform, the Maverick basin, the Devils River trend, and the San Marcos platform) are given in Table 1. The locations of these depositional provinces are shown in Figure 6.

Previous Investigations

The U.S. Geological Survey has been collecting hydrologic and geologic data in the San Antonio area on a continuing basis since the 1930's. Reports of previous investigations include: Arnow (1959); Bennett and Sayre (1962); DeCook (1963); Garza (1962, 1966); George (1952); Holt (1959); Lang (1954); Livingston, Sayre, and White (1936); Petitt and George (1956); and Welder and Reeves (1962). These reports describe the general geology and hydrology of the area and discuss the availability of ground water. Reports prepared as a part of this study, which began in 1970, include: Maclay and Rettman (1972, 1973); Maclay, Rettman, and Small (1980); Maclay and Small (1976); Maclay, Small, and Rettman (1980, 1981); Pearson and Rettman (1976); Pearson, Rettman, and Wyerman (1975); Puente (1975, 1976, 1978); and Small and Maclay (1982). Other reports related to the geology and hydrology of limestone aquifers are listed in the section "Selected References."

METHODS OF INVESTIGATION

The initial phase in the investigation of the Edwards aquifer was to review all available reports on the geology of the Edwards Limestone or Edwards Group of Rose (1972) and equivalent rocks. Review of these reports indicated that although much new information was available, none of the recently obtained stratigraphic data had been related to the distribution of permeability and porosity in the Edwards aquifer.

The second phase was to conduct a test-drilling program to obtain cores from the Edwards aquifer for correlation with the Lower Cretaceous stratigraphic units in the Edwards Group as identified by Rose (1972) and for examination of the porosity and permeability characteristics of the rocks in these stratigraphic units. The cores were examined to determine the textures of the carbonates and their associated pore types; to determine the nature of the fractures, including the effects of dissolution; and to obtain evidence of paleokarstification. The Geological Survey cored eight test holes (Figure 1) through the entire thickness of the Edwards aquifer. The test-hole data are given in Small and Maclay (1982).

Table 1.--Summary of the Lithology and Water-Bearing Characteristics of the Hydrogeologic Units for Each of the Four Depositional Provinces Within the Hydrologic Basin [1]

(Function: AQ - aquifer; CB - confining bed)

Central Texas platform on the Edwards Plateau

System	Provincial series	Group	Formation	Function	Member or informal unit	Function	Thickness (feet)	Lithology	Hydrostratigraphy
Quaternary			Terrace deposits	Not saturated			30	Coarse limestone, gravel, sand, and silt.	Low terraces along stream deposits generally are unsaturated.
Cretaceous	Comanchean	Washita	Buda Limestone and Del Rio Clay	Not saturated			40-50	Dense, hard, nodular limestone in upper part and clay in lower part.	Deep water marine deposits. Little permeability.
		Edwards	Segovia	Not saturated			300-380	Limestone and dolomite: In upper part, cherty, miliolid, shell fragment rudistid limestone. In middle part, dolomite; porous, massive to thin bedded, cherty, collapse breccia. In lower part, miliolid limestone and marl and marly limestone.	Shallow water carbonates. Rocks in upper and middle parts contain cavernous porosity. Contains porous collapse breccias. Lowest unit has negligible permeability and forms a barrier to vertical flow of water in the formation.
			Fort Terrett	AQ	Kirschberg evaporite	Not saturated	40-80	Limestone: Dense, porcelaneous limestone, recrystallized limestone and travertine, collapse breccias.	Supratidal to tidal deposits. At least two vertical zones of collapse breccias within evaporitic rocks. Extensively leached. Significant porosity and permeability.
					Dolomitic	Not saturated	40-90	Dolomite; massive to thin bedded, fine to medium crystalline, homogeneous dolomite; scattered zone of chert and rudistid grainstone.	Intermittent tidal flat and emergent conditions. Permeable and porous unit, but not saturated at most locations.
					Burrowed	AQ	70-90	Limestone; massive cherty, honeycombed, burrowed, nonargillaceous, also contains thin beds of dolomite.	Tidal to intertidal deposits. Dolomitization of burrow fillings and later leaching produced honeycomb porosity. Permeable main water-bearing unit.
					Basal nodular bed	CB	30-50	Limestone; hard, dense, clayey, nodular, mottled, stylolitic, some marl.	Subtidal deposits, little porosity and permeability.
		Trinity	Glen Rose	CB	Upper part of Glen Rose	CB	400	Limestone, dolomite, shale and marl. Upper 160 feet is marl, grainstone, and dolomite and grading upward into sugary-textured, argillaceous dolomite. Middle part consists of about 70 feet of marl and evaporite beds. Lower part is about 170 feet that consists of a lower evaporite bed and an overlying massive, rudistid limestone.	Tidal and shallow water deposits. Little permeability overall. Evaporites are leached and porous near the land surface. Commonly, they form the most permeable zones in the upper unit. In the deeper subsurface, they are not leached and are almost impermeable.
				AQ	Lower part of Glen Rose	AQ	300	Limestone and some marl. More marly in the upper part. Massive rudistid reefal limestone in the lower part.	Marine deposits. Honeycomb rock in lower part is locally very permeable.
	Comanchean and Coahuilan		"Basement sands" Includes Pearsall (Hensell sand member), Sligo, and Hosston Formations	AQ			150-500	Mostly sandstone; calcareous, fine to medium grained (Hensell sand) in upper part. Massive limestone in middle part. Marl and sand in lower part.	Mostly shoreline deposits. Units contain beds of permeable sandstone and limestone in middle and upper parts. These permeable beds are interbedded with units that have negligible permeability.
Pre-Cretaceous								Shale, limestone, sand, and underlying granite and gneiss.	Well indurated Paleozoic rocks in Blanco and Val Verde Counties. Permeable units in Paleozoic elsewhere. The unit forms the base of the ground-water reservoir.

[1] Stratigraphy as described by Rose, 1972.

Table 1.--Summary of the Lithology and Water-Bearing Characteristics of the Hydrogeologic Units for Each of the Four Depositional Provinces Within the Hydrologic Basin--Continued

Maverick basin

System	Provincial series	Group	Formation	Function	Member or informal unit	Function	Thickness (feet)	Lithology	Hydrostratigraphy
Quaternary and Tertiary			Alluvial fan and fluviatile terrace deposits			AQ where saturated	6-80	Gravel, sand, silt, and clay. Coarser nearer the base and toward the Balcones fault escarpment.	Alluvial fans extending from the Balcones fault escarpment. Associated fluviatile deposits.
Cretaceous	Gulfian		Anacacho Limestone	CB			500	Limestone and marl; contains bentonite, chalky, and massive bedded.	Little permeability.
		Austin	Undivided	CB			600	Chalk and marl; chalk mostly microgranular calcite, bentonite seams, glauconitic.	Little to moderate permeability.
			Igneous rocks					Basalt.	Intrusive sills, lacoliths, and volcanic necks. Negligible permeability.
		Eagle Ford	Undivided	CB			250	Shale, siltstone, and limestone; flaggy limestone beds are interbedded with carbonaceous shale.	Little permeability.
	Comanchean	Washita	Buda Limestone	CB			100	Limestone; fine grained, bioclastic, glauconitic, hard, massive, nodular, argillaceous toward top.	Little permeability.
			Del Rio Clay	CB			120	Clay and shale; calcareous and gypsiferous, some thin beds of siltstone.	Negligible permeability.
			Salmon Peak Formation	AQ			380	Limestone; upper 80 feet contains reef talus grainstones and caprinid boundstones, crossbedding of grainstones; the lower 300 feet is a uniform dense carbonate mudstone.	Deep water deposits except toward the top. Upper part is moderately to very permeable. Lower part is almost impermeable except where fractured.
			McKnight	CB			150	Limestone and shale; upper 55 feet is a mudstone containing thin zones of collapse breccias; middle 24 feet is shaly, lime mudstone; lower part is limestone containing collapse breccias in upper part.	Deep basinal, euxinic deposits. Little permeability.
			West Nueces	CB			140	Limestone; upper 80 feet is largely a massive unit of miliolid and mollusc-bearing grainstone; lower 60 feet is a nodular, dense mudstone.	Upper part is moderately permeable. Lower part is almost impermeable.
		Trinity	Glen Rose	CB	Upper member		1,000-1,500	Limestone, dolomite, and marl; limestone is fine grained, hard to soft, marly; dolomite is porous and finely crystallized.	Little permeability.
					Lower member			Limestone and some marl. Massive bedded.	More permeable toward base of unit.
			Pearsall	CB			400	Sandstone, limestone, and shale.	Little permeability.
	Coahuilan		Sligo	CB			200	Limestone and some shale.	Little to moderate permeability.
			Hosston				900	Sandstone and shale.	Moderate to little permeability.
Pre-Cretaceous								Sandstone and limestone.	Little permeability.

Table 1.--Summary of the Lithology and Water-Bearing Characteristics of the Hydrogeologic Units for Each of the Four Depositional Provinces Within the Hydrologic Basin--Continued

Devils River trend

System	Provincial series	Group	Formation	Function	Member or informal unit	Function	Thickness (feet)	Lithology	Hydrostratigraphy
Quaternary			Alluvial and terrace deposits	AQ where saturated			0-40	Gravel, sand, and silt.	Unit occurs along stream courses of major drainage. Deposits are intermittently partly saturated. Not an important source of water.
Cretaceous	Gulfian	Austin	Undivided	AQ			200	Chalk, marl, and hard limestone; mostly a mudstone.	Little to moderate permeability.
		Eagle Ford	Undivided	CB			250	Shale and flaggy limestone.	Little permeability.
	Comanchean	Washita	Buda Limestone	CB			50	Limestone; dense, micritic limestone, and marly, nodular limestone.	Little permeability.
			Del Rio Clay	CB			100	Shale and thin beds of sandy limestone.	Little permeability.
		Fredericksburg	Devils River Limestone	AQ			450-700	Limestone and dolomite; hard, miliolid, pellet, rudistic, shell-fragment grainstone and mudstone; locally dolomitized, brecciated; rudistids common toward the top; nodular, argillaceous limestone toward the base.	Shallow water and supratidal unit. Exposed in the Devils River trend. Unit constitutes a low barrier reef that surrounded the Maverick basin on the north. Very permeable and porous unit particularly in the middle and upper parts. A major aquifer.
		Trinity	Glen Rose	CB	Upper part of Glen Rose	CB	1,500	Limestone and marl.	Relatively impermeable in upper part and permeable in the lower part.
					Lower part of Glen Rose	AQ		Massive limestone.	
			Pearsall	CB			400	Sandstone, limestone, and shale.	Relatively impermeable unit.
	Coahuilan	Sligo and Hosston Formations	CB				500-1,000	Limestone in upper part and sandstone and shale in lower part.	Variable permeability. Unit is relatively impermeable overall.
Paleozoic rock								Sandstone, slate, and shale.	Relatively impermeable.

Table 1.--Summary of the Lithology and Water-Bearing Characteristics of the Hydrogeologic Units for Each of the Four Depositional Provinces Within the Hydrologic Basin--Continued

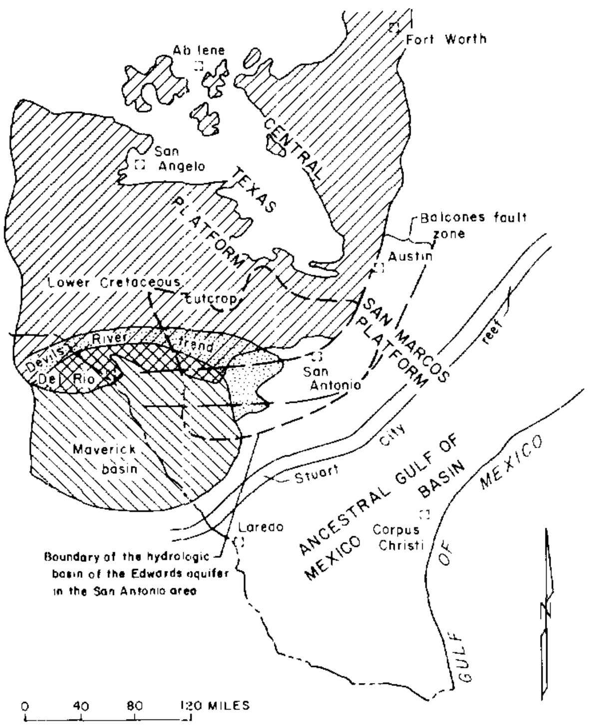
San Marcos platform in the Balcones fault zone

System	Provincial series	Group	Formation	Function	Member or informal unit	Function	Thickness (feet)	Lithology	Hydrostratigraphy
Quaternary			Alluvium	AQ			45	Silt, sand, gravel.	Flood plain; aquifers in hydraulic connection with streams.
			Terrace deposits	Not saturated			30	Coarse gravel, sand, and silt.	High terrace bordering streams and surficial deposits on high interstream areas in Balcones fault zone.
Tertiary	Eocene	Claiborne	Reklaw	CB			200	Sand, sandstone, and clay; lignitic, friable to highly indurated sandstone.	Deltaic and swamp deposits. Leaky confining bed confining the Carrizo aquifer below.
			Carrizo Sand	AQ			200-800	Sandstone; medium to very coarse, friable, thick bedded, few clay beds, ferruginous.	Very permeable aquifer formed by deltaic and shoreline deposits.
	Eocene and Paleocene	Wilcox and Midway		CB		CB	500-1,000	Clay, siltstone, and fine grained sandstone; lignitic, iron-bearing.	Leaky confining bed formed by deltaic and marine shoreline.
					Wills Point	CB	500	Clay and sand.	
Cretaceous	Gulfian	Navarro				CB	500	Marl, clay, and sand in upper part; chalky limestone and marl in lower part.	Deeper water marine deposits. Major barrier to vertical cross-formational flow separating Cretaceous aquifer from Tertiary aquifers.
		Taylor	Pecan Gap Anacacho Limestone	CB			300-500		
		Austin	Undivided	AQ			200-350	Chalk, marl, and hard limestone. Chalk is largely a carbonate mudstone(?).	Minor aquifer that is locally interconnected with the Edwards aquifer by openings along some faults.
		Eagle Ford	Undivided	CB			50	Shale, siltstone, and limestone; flaggy limestone and shale in upper part; siltstone and very fine sandstone in lower part.	Barrier to vertical cross-formational flow.
	Comanchean	Washita	Buda Limestone and Del Rio Clay	CB			100-200	Dense, hard, nodular limestone in the upper part and clay in lower part. Thickens to the west.	Fractured limestone in the Buda is locally water yielding and supplies small quantities of water to wells. Del Rio Clay has negligible permeability.
			Georgetown Limestone (unit is within the Edwards aquifer)	CB			20-60	Dense, argillaceous limestone; contains pyrite.	Deep water limestone with negligible porosity and little permeability.
		Edwards	Person (Edwards aquifer)	AQ	Marine	AQ	90-150	Limestone and dolomite; honeycombed limestone interbedded with chalky, porous limestone and massive, recrystallized limestone.	Reefal limestone and carbonates deposit under normal open marine conditions. Zones with significant porosity and permeability are laterally extensive. Karstified unit.
					Leached and collapsed members	AQ	60-90	Limestone and dolomite. Recrystallized limestone occurs predominantly in the freshwater zone of the Edwards aquifer. Dolomite occurs in the saline zone.	Tidal and supratidal deposits, conforming porous beds of collapse breccias and burrowed biomicrites. Zones of honeycombed porosity are laterally extensive.
					Regional dense bed	CB	20-30	Dense, argillaceous limestone.	Deep water limestone. Negligible permeability and porosity. Laterally extensive bed that is a barrier vertical flow in the Edwards aquifer.
			Kainer (Edwards aquifer)	AQ	Grainstone	AQ	50-60	Limestone, hard, miliolid grainstone with associated beds of marly mudstones and wackestones.	Shallow water, lagoonal sediments deposited in a moderately high energy environment. A cavernous, honeycombed layer commonly occurs near the middle of the subdivision. Interparticle porosity is locally significant.
					Dolomitic (includes Kirschberg evaporite)	AQ	150-200	Limestone, calcified dolomite, and dolomite. Leached, evaporitic rocks with breccias toward top. Dolomite occurs principally in the saline zone of the aquifer.	Supratidal deposits toward top. Mostly tidal to subtidal deposits below. Very porous and permeable zones formed by boxwork porosity in breccias or by burrowed zones.
					Basal Nodular Bed	CB	40-70	Limestone, hard, dense, clayey; nodular, mottled, stylolitic.	Subtidal deposits. Negligible porosity and permeability.

Table 1.--Summary of the Lithology and Water-Bearing Characteristics of the Hydrogeologic Units for Each of the Four Depositional Provinces Within the Hydrologic Basin--Continued

San Marcos platform in the Balcones fault zone--Continued

System	Provincial series	Group	Formation	Function	Member or informal unit	Function	Thickness (feet)	Lithology	Hydrostratigraphy
Cretaceous	Comanchean	Trinity	Glen Rose	CB	Upper part of Glen Rose	CB	300-400	Limestone, dolomite, shale and marl. Alternating beds of carbonates and marls. Evaporites and dolomites toward top variable bedding.	Supratidal and shoreline deposits toward top. Tidal to subtidal deposits below. Unit has little vertical permeability but has moderate lateral permeability.
					Lower part of Glen Rose	AQ	200-250	Massive limestone with few thin beds of marl.	Marine deposits - caprinid reef zones and porous and permeable honeycomb porosity near the base.
			Pearsall (Travis Peak in outcrop)	CB	Bexar	CB	300	Limestone and shale.	Shoreline deposits, relatively impermeable unit in the Balcones fault zone.
					Cow Creek Limestone member	AQ		Limestone and dolomite. Grainstone, packstone, and coquinoid beds.	Moderately permeable unit in Comal County.
					Pine Island Shale member	CB		Shale and argillaceous limestone.	Little permeability.
	Coahuilan	Nuevo Leon and Durango of Mexico	Sligo and Hosston Formations	CB			800-1,500	Limestone, shale, and sandstone.	Sandstone in lower part is moderately permeable.
Pre-Cretaceous								Slate, phylite, locally sedimentary rocks in grabens.	Basement rocks. No circulating ground water.



Modified from Rose (1972)

Figure 6.—Depositional Provinces of the Edwards Limestone and Equivalent Rock

The third phase was to log the test holes and all available wells to obtain geophysical data for correlation with lithologic data and laboratory data. Laboratory studies of the core samples included determination of pore-size distribution, grain density, mineralogy, formation-resistivity factor, and petrography. These data were used to calibrate and interpret the geophysical logs (Maclay, Small, and Rettman, 1981.)

The fourth phase was to develop a concept of the stratification of the aquifer and the distribution of the porosity and permeability by identifying and delineating hydrostratigraphic units. The internal boundaries in the aquifer, which cause discontinuities of permeability, were located by constructing systematically spaced, geologic sections drawn perpendicular to the strikes of the major faults in the area. The hydrologic, hydrochemical, and geologic data were used to interpret the rate and direction of ground-water movement within the aquifer.

STRATIGRAPHY OF ROCKS IN THE EDWARDS AQUIFER

The porosity and permeability of the Edwards aquifer is related to stratigraphy and to selective leaching of particular strata. Ground water moves along vertical or steeply inclined fractures that are passageways by which the water can enter the permeable strata. Water moves from the fractures into collapse breccias, burrowed wackestones, and rudist grainstones that have relatively large intrinsic permeability. Ground water has dissolved the pore walls within these rocks to create highly permeable strata. Therefore, laterally extensive beds (lithofacies) having cavernous or honeycombed porosity occur at stratigraphically-controlled intervals within the freshwater zone of the aquifer.

Depositional Provinces

The carbonate stratigraphy and associated rock types of the Edwards Limestone or its equivalents are related to major depositional provinces that persisted during Early Cretaceous time. Significant major differences in rock types and their associated porosity characteristics exist among and within each province.

The Maverick basin sediments consisted of predominantly deep basinal deposits of dense, homogeneous mudstones with little primary porosity (carbonate classification system of Dunham, 1962). The depositional province was confined between the Stuart City reef to the south and tidal flats or shallow water to the north and east (Smith, 1974, p. 17). Lagoonal evaporites and euxinic shales initially accumulated in the center of the Maverick basin and then spread laterally. Subtidal to supratidal, shallow-water limestones, dolomites, and evaporites accumulated to the north at the same time. The Maverick basin became an open marine, deep-water embayment when a transgression breached the Stuart City reef. The advance of this transgression is marked by a basal conglomeratic bed with slight to moderate permeability deposited on the euxinic shales. A pelagic mudstone with little permeability accumulated above the basal conglomeratic bed. Permeable, rudist-talus grainstones developed on the lime mudstones during a marine regression. The Maverick basin became extinct when a transgression inundated the Stuart City reef and deposited the sediments of the Del Rio Clay on the grainstones in the basin.

The Devils River trend is a complex deposit consisting of marine and supratidal deposits in the lower part and of reefal or inter-reefal deposits in the upper part. Permeable zones are associated with collapse breccias and rudist reefs in the upper part. The Devils River trend represents a shoal area that separated the Maverick basin in the south from the Central Texas platform in the north. The reef along the northern rim of the Maverick basin was an area of high wave action, particularly toward the latter stages of the basin. Rudist-coral reefs and associated reef talus accumulated on a base formed of sediments similar to those of the Maverick basin. The reefs were intermittently exposed, and dolomitization occurred at those times. The permeable zones occurred in some reef-talus deposits and in leached sediments.

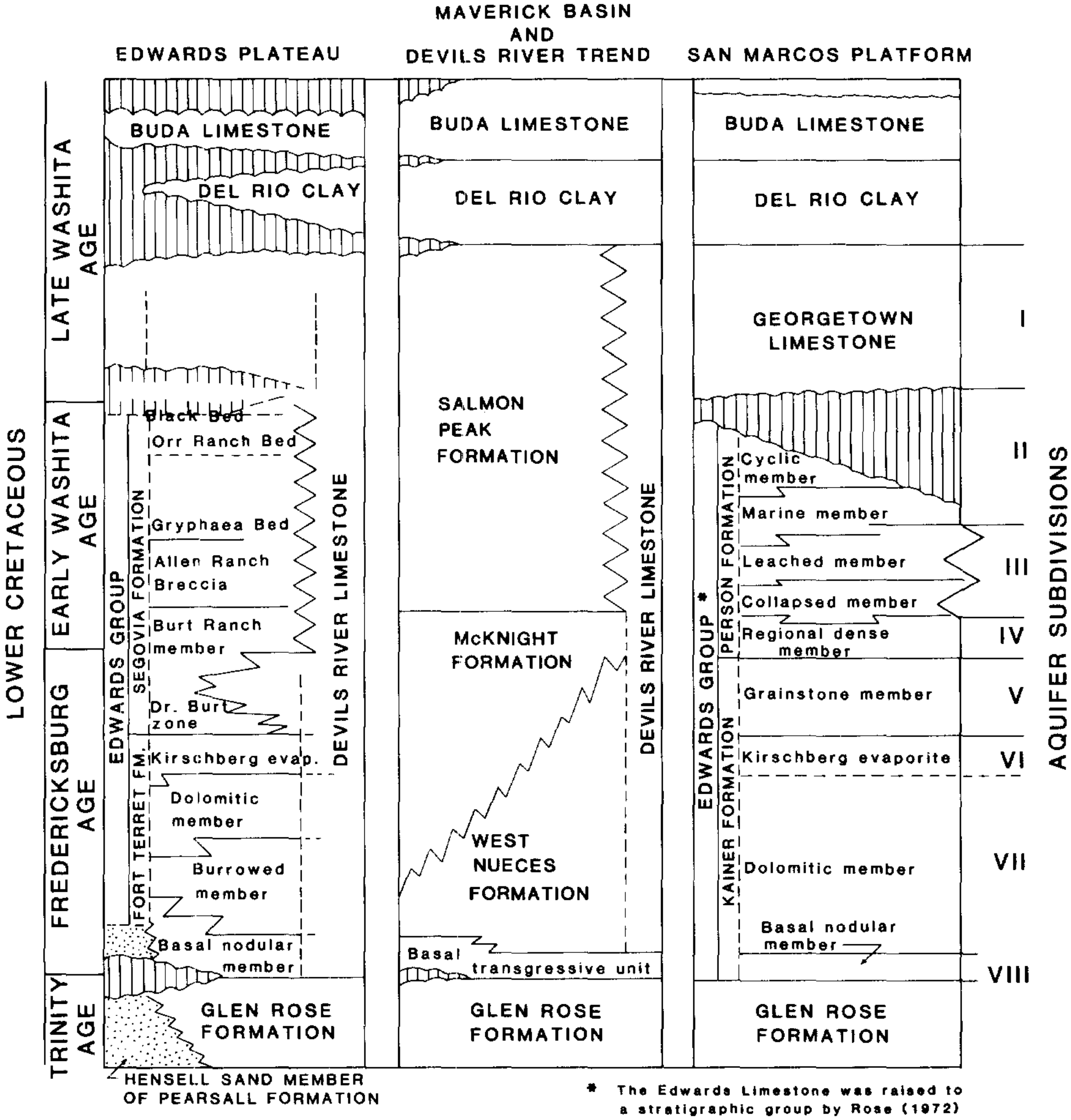
The sediments of the San Marcos platform consist mostly of micrites that locally contain collapse breccias, honeycombed structures, burrowed mudstones, and rudist reef materials. These sedimentary features within the micrites are the most highly leached and permeable part of the Edwards aquifer in the Balcones fault zone. The depositional environment varied from open marine to arid, hot, supratidal flats (Rose, 1972). Areally extensive, thin- to medium-bedded strata of pelleted and intraclastic micrites accumulated to 500 feet. These sediments were leached during Cretaceous time. Anhydrite or gypsum evaporitic deposits accumulated in laterally continuous beds and isolated lenses within micritic sediments. Collapse breccias with significant permeability resulted from dissolution of the evaporites.

Deposition at the top of the Edwards Group was interrupted by a period of subaerial erosion and karstification on the San Marcos platform (Rose, 1972). Following erosion, the Edwards Group was deeply buried by marine, transgressive sediments during Late Cretaceous time.

Extensive Late Cretaceous and early Tertiary continental uplift and erosion removed much of the Upper Cretaceous deposits from the Edwards Plateau. The Edwards Group was exposed in the recharge area of the Edwards aquifer on the San Marcos plateau, but remained covered by Upper Cretaceous deposits in the confined zone of the aquifer.

Stratigraphic Units

Regional stratigraphic studies of the Edwards Limestone or Group and equivalent rocks in South Texas by Tucker (1962), Winter (1962), Lozo and Smith (1964), Fisher and Rodda (1969), and Rose (1972) have resulted in a much better understanding of the regional stratigraphy and have resolved problems of stratigraphic nomenclature and correlation. This report principally uses the nomenclature proposed by Lozo and Smith (1964) and by Rose (1972), which is consistent with the usage on the Geologic Atlas of Texas published by the University of Texas, Bureau of Economic Geology (see "Selected References"). The Edwards aquifer in the San Antonio area is composed of carbonate rocks of the Edwards Group of Rose (1972) and the Georgetown and Devils River Limestones and the Salmon Peak, McKnight, and West Nueces Formations of Lozo and Smith (1964). The correlations of stratigraphic units of the Lower Cretaceous Series in South Texas are shown in Figure 7. A regional stratigraphic section that extends across the Maverick basin and the Devils River trend to the San Marcos platform is shown in Figure 8.



* The Edwards Limestone was raised to a stratigraphic group by Rose (1972)

Modified from Rose (1972)

Figure 7.—Correlation of Stratigraphic Units of the Lower Cretaceous Series in South Texas

The basal stratigraphic formation of the Edwards Group of Rose (1972) on the San Marcos platform is the Kainer Formation of Rose (1972), which is about 250 feet thick. This formation consists of three members as identified by Rose (1972). The basal nodular member is a marine deposit consisting of massive, nodular wackestones. The dolomitic member consists mostly of intertidal and tidal, burrowed and dolomitized wackestones with significant permeability. The upper part of the dolomitic member contains leached evaporitic deposits of the Kirschberg evaporite. The uppermost member of the Kainer Formation is the grainstone member, which is a shallow marine deposit that marks the beginning of another cycle of sedimentation started by a transgressing sea. This member consists of well-cemented, miliolid grainstones with lesser quantities of mudstone.

The upper stratigraphic unit of the Edwards Group on the San Marcos platform is the Person Formation of Rose (1972), which is about 180 feet thick. Rose (1972) identified five informal members in the subsurface of South Texas. The basal member is a laterally extensive marine deposit consisting of dense, shaly mudstone known as the regional dense member. It is easily recognized in the test-hole cores by its lithology and on the geophysical logs by distinct shifts in the log traces. The overlying members, the collapsed member and leached member, consist of intertidal to supratidal deposits. These members contain permeable units that are formed by collapse breccias and by dolomitized and burrowed wackestones. The uppermost member that can be identified in the test-hole cores is the marine member, which consists of rudist-bearing wackestones and packstones and shell-fragment grainstone. The cyclic member, which could not be identified in the test-hole cores, may be wholly or partly eroded.

The Devils River Limestone of the Devils River trend is about 450 feet thick. It is a complex of reefal and inter-reefal deposits in the upper part and marine to supratidal deposits in the lower part. The lithofacies grade upward from about 70 feet of nodular, dense, shaly limestone above the contact with the Glen Rose Formation, to about 180 feet of tidal and marine wackestone and mudstone containing burrowed or honeycombed beds. Above these rocks are about 40 feet of mudstones and permeable collapse breccias. The upper 160 feet represent shallow marine deposits consisting of biohermal rudist mounds, talus grainstones, and inter-reefal wackestones.

In the Maverick basin, the formations stratigraphically equivalent to the Edwards Group of Rose (1972) are, ascending, the West Nueces, McKnight, and Salmon Peak Formations of Lozo and Smith (1964). The West Nueces Formation in Uvalde County consists of nodular, shaly limestone about 60 feet thick in the lower part and pelleted, shell-fragment wackestone and some grainstones in the upper 80 feet. The upper part contains beds of dolomitized, burrowed wackestones that are leached and form honeycombed rock in some places.

The McKnight Formation consists of an upper and a lower thin-bedded limestone separated by a black, fissile, clayey, lime mudstone about 25 feet thick. The lower limestone unit, about 70 feet thick, consists of relatively impermeable fecal-pellet mudstones and shell-fragment grainstones containing zones of interbedded collapse breccias. The upper limestone, which is about 55 feet thick, consists mostly of thin-bedded mudstones and associated evaporites. The Salmon Peak Formation consists of about 300 feet of dense, massive, lime mudstone containing chert in the lower part and about 75 feet of layered to crossbedded, rounded shell-fragment, permeable grainstones in the upper part.

DIAGENESIS OF THE EDWARDS AQUIFER

Diagenesis is defined by Gary, McAfee, and Wolf (1977) as "... all the chemical, physical, and biologic changes, modifications, or transformations undergone by a sediment after its initial deposition, and during and after its lithification, exclusive of surficial weathering and metamorphism." Knowledge of the process and products of carbonate diagenesis that have occurred or are occurring in the varied lithofacies in the Edwards aquifer is essential for the interpretation and prediction of permeability and porosity. Recrystallization of rocks in the Edwards aquifer resulted in a net overall decrease in total porosity in the freshwater zone of the aquifer and greatly modified and increased the pore sizes and interconnections (permeability) in some lithofacies. Consequently, permeability has been greatly enhanced as a result of diagenesis.

Because of the complexity of carbonate diagenesis, a discussion as related to the Edwards aquifer can only be abbreviated in order to remain within the scope of this report. (An annotated list of pertinent papers on carbonate diagenesis, particularly those relating to genesis of porosity, is given in Table 2.) The information contained in these studies provided the criteria and general knowledge necessary to interpret the test-hole cores and surface exposures of rock in the Edwards aquifer.

The rocks in the freshwater and saline-water zones of the Edwards aquifer were deposited in similar environments and underwent similar early diagenetic processes, including dolomitization, micritization, and selective leaching of fossils. However, because of different late diagenetic histories, a distinct change in the texture and composition of the rocks occurs from the freshwater zone to the saline-water zone. This change is the result of the diagenesis produced by circulating freshwater.

The rocks in the saline-water zone are mostly dolomitic, medium to dark gray or brown, and contain unoxidized organic material, including petroleum and accessory minerals such as pyrite, gypsum, and celestite. The matrix of the rocks in the saline-water zone are more porous than the stratigraphically equivalent rocks in the freshwater zone; however, the voids are predominantly small interparticle, intraparticle, and intercrystalline pores. The permeability of the rocks is relatively small because of the small size of the interconnections between the pores. Pore types from the saline-water zone are related predominantly to fabric of the rock rather than to other features (Figure 9).

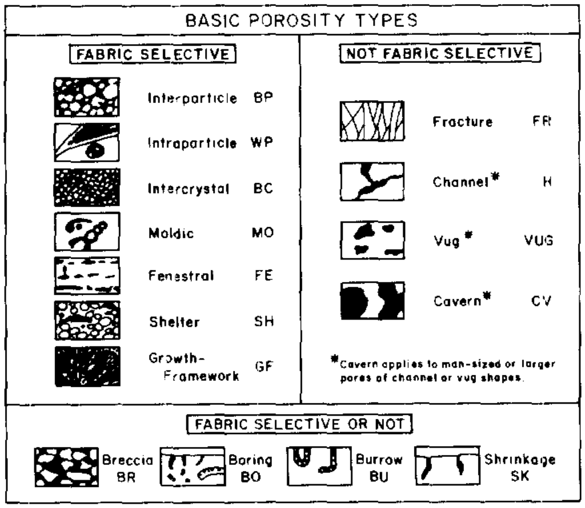


Figure 9.—Porosity-Classification System of Choquette and Pray (1970)

Dolomite crystals have different morphologies in the saline-water zone. Most dolomite was formed by replacement or recrystallization of micrites (micrites are very fine grained carbonate rocks such as mudstones, wackestones, and packstones). Large crystals (as much as several hundred

Table 2.--Annotated List of Sources of Information Relevant to the Diagenesis of Rocks in the Edwards Aquifer

Author	Information relevant to diagenesis of rocks in the Edwards aquifer
Bathhurst (1971)	A comprehensive work that includes information on: Mineralogic composition and leachability of marine invertebrates; discussions of diagenesis in a freshwater environment including recrystallization, calcitization (dedolomitization); diagenesis on the sea floor including micritization; discussion of cementation including illustrations of cements that indicate different depositional environments. Comment - This treatise was used extensively by writers to obtain background information for interpretation and identification of diagenetic products observed in samples taken from the Edwards.
Beales and Oldershaw (1969)	Evaporitic conditions commonly accompany the evolution of reef-bank environments. Resulting evaporites enhance the porosity and permeability of the reef. Breccia moldic porosity is recognized to be of great importance. Comment - The development of short-duration, interreefal and intrareefal or intraflat evaporites in an environment of migrating, extremely shallow, supratidal or shoal-restricted lagoons and saline flats, indicates a genetic model for the widespread bedded breccias, such as those occurring in the Kirschberg member of the Kainer Formation and Person Formation of Edwards Group. Breccia moldic porosity occurs in the upper part of the Devils River Limestone.
Choquette and Pray (1970)	The genesis and geometry of pore systems in carbonate rocks is described, and a classification system for identification of pores of different origins is introduced. Most porosity in carbonates can be related to sedimentary or diagenetic components that constitute the rock texture. Textural related porosity generally is primary or formed in early post-depositional time. Comment - The concepts and the classification system presented in the paper were extensively applied to investigation of the Edwards core.
Fisher and Rodda (1969)	Identifies two types of dolomite, stratal and massive, occurring within the Edwards aquifer. Stratal dolomite is deposited in supratidal flats; massive dolomite to reflux of saline fluids through shallow beach barriers. Criteria for identifying these types of dolomite are given. Massive dolomites are relatively homogeneous and consist mainly of euhedral crystals of dolomite. They are moderately to very porous and slightly to moderately permeable. Stratal dolomite consists mostly of extremely fine subhedral crystals of dolomite.
Folk (1965)	Classic paper on carbonate recrystallization. Recrystallization (neomorphism) is recognized to include: Grain growth (very pervasive) in the freshwater zone of the Edwards aquifer; replacement; and inversion. Discusses formation of microspar in micrites. Illustrations of different carbonate cement types--equant, fibrous, and bladed, and their environmental significance. Comment - Edwards aquifer is extensively neomorphosed in the freshwater zone. Carbonate cements typically are equant in the freshwater zone.
Folk and Land (1975)	Mg/Ca ratio and salinity: Two controls over crystallization of dolomite. Micritic dolomite forms at high salinity and a high ratio of Mg/Ca, blocky calcite forms at low salinity and a low ratio of Mg/Ca. At a reduced salinity and Mg/Ca approaching 1, large limpid crystals of both calcite and dolomite can form. Comment - These minerals and their morphologies occur in the Edwards aquifer. Limpid dolomite crystals occur near the bad-water line. Micritic dolomite is associated with supratidal deposits.
Freeze and Cherry (1979)	Identified incongruent dissolution as a significant geologic process in carbonate rocks. If calcite and dolomite occur within the same hydrogeologic system, these minerals may dissolve simultaneously or sequentially. Incongruent dissolution occurs when one or more of the dissolution products occur as a solid. Comment - The coexisting processes of dolomite dissolution and calcite precipitation may have produced porous, honeycombed rock. Incongruent dissolution of dolomite from the dolomitized burrows could produce the pores and provide the carbonate for cementation by calcite within the rock matrix. When ground water dissolves calcite to equilibrium first and then encounters dolomite further down the flow line, dolomite dissolves regardless of temperature. Comment - This process may be producing the very permeable zone in the freshwater zone of the Edwards aquifer near the "bad-water" line.

Table 2.--Annotated List of Sources of Information Relevant to the Diagenesis of Rocks in the Edwards Aquifer--Continued

Author	Information relevant to diagenesis of rocks in the Edwards aquifer
Longman (1980)	An excellent summary of carbonate diagenesis that indicates the types and textures of cements and the porosity produced in major diagenetic environments. Criteria for recognizing marine and freshwater diagenetic environments are presented. Comment - The criteria presented were used to interpret megascopic and microscopic observations of lithologies in the Edwards aquifer.
Palciauskas and Domenico (1976)	The process of dissolution as a system determined by dispersion, convection, and chemical reactions is examined. The distance to attainment of saturation with respect to individual minerals increases with increasing rates of dispersion and velocity of ground water and decreases with increasing rates of reaction. A greater quantity of material is dissolved with high-flow rates than with low-flow rates. Comment - It is suggested that in the Edwards aquifer more material will be removed from very permeable rock where ground-water velocities are higher, than from small interconnected openings in the rock matrix. A feed-back process is formed where the permeable zones become increasingly more permeable at the expense of decreasing permeability within the matrix.
Runnells (1969)	Mixing of natural waters can result in dissolution. For example, the solubility of calcite is a nonlinear function of the partial pressure of carbon dioxide gas in the coexisting vapor phase. Physical mixing of waters results in a linear proportional relationship between the constituents of the mixture. Therefore, mixing of two waters both saturated with respect to calcite but each in contact with different partial pressures of carbon dioxide, would result in dissolution of additional calcite. Comment - Surface water that enters the Edwards aquifer commonly is saturated with respect to calcite. When calcite-saturated surface water at atmospheric pressure is mixed with ground water at or near saturation with respect to calcite and in contact with carbon dioxide at a higher partial pressure, additional dissolution of calcite can occur.
Shinn, Ginsburg, and Lloyd (1965)	The formation of dolomite on exposed, supratidal mud flats in the Bahama Islands is discussed. Dolomite forms where tidal flooding and storm sedimentation is followed by many days of subaerial exposure. Comment - Supratidal evaporites in Edwards aquifer are interpreted to have formed under similar conditions.

microns in diameter) of clear, euhedral (nearly perfect development of crystal faces) crystals occur in some massive dolomite beds. Other types of dolomite include: Dolomitic rhombs with distinct zoning bands paralleling the crystal faces; turbid, "dusty looking," fine grained dolomite; and dolomite rhombs having hollow centers. The latter two types are associated with supratidal features (Ruth Dieke, U.S. Geological Survey, oral commun., 1979). Dolomite in micrite ranges from scattered "floating" rhombs to tightly packed rhombs with little or none of the original carbonate mud remaining.

The rocks in the freshwater zone are calcitic, light buff to white, strongly recrystallized, and dense. These rocks contain little pyrite and no gypsum. Oxidized iron gives a rusty-orange tinge to many rocks in the freshwater zone, particularly in those parts of the aquifer where water circulation is relatively rapid. In parts of the aquifer where water circulation is relatively slow, the color of the rocks is typically a darker gray or brown.

Recrystallization of the rocks of the Edwards aquifer principally is by dedolomitization, which is caused by extensive freshwater flushing that removes magnesium from the dolomitic rock and replaces it with calcium. Dedolomitization results in the conversion of dolomite to a dense limestone that may contain permeable zones of breccia-moldic porosity. A photograph of solutioned rock from the freshwater zone and its diagenetic features is shown in Figure 10.

The pores and pore systems of the Edwards aquifer are physically and genetically complex. The geometry of the pores varies widely, partly because of the wide range in the size and shape,

Figure 10.—Diagenetic Features of Representative Rocks From the Edwards Aquifer

packing, and dissolution of the original sedimentary particles, and partly because of the size and shape of the pores within the sedimentary particles. The porosity of typical lithofacies of rocks in the Edwards aquifer is summarized in Table 3.

On the basis of the observation of the test-hole cores from the Edwards aquifer, most of the porosity is related to rock textures and sedimentary features rather than to fractures. Most fractures observed in the cores are only a few millimeters or less in width, steeply inclined to near vertical, and open or partly filled with spar or clear calcite. The individual fractures are spaced at vertical intervals ranging from 1 to 20 feet; however, most fractures are within a 10-foot vertical distance of each other.

Dissolution along bedding planes can be observed in the cores and at the outcrop. Some bedding planes are iron stained and show other evidence of ground-water circulation. Dissolution related to erosional surfaces is difficult to document; however, travertine and "cave popcorn," which is evidence of a vadose environment (in the unsaturated zone), have been observed in cores obtained from the confined zone of the aquifer in the eastern part of the San Antonio area. These deposits probably were formed under vadose conditions that existed in Early Cretaceous time before the rocks forming the Edwards aquifer were deeply buried by Upper Cretaceous deposits. A summary of the geologic processes in the development of the Edwards aquifer is given in Table 4.

HYDROLOGY OF THE EDWARDS AQUIFER

Hydrologic Boundaries

The Edwards aquifer in the San Antonio area consists of both unconfined and confined zones. The unconfined zone is almost entirely within the infiltration area as shown in Figure 1. In this area, the Edwards Group or its stratigraphic equivalents are exposed except along some streams where the rocks may be covered by permeable alluvial materials.

The lateral boundaries of the confined aquifer are the limits of the unconfined and the confined zones on the north; the ground-water divides on the west and on the east; and the "bad-water" line on the south (Figure 1). The northern boundary of the confined aquifer was mapped by using water-level data for February 1972 and a contour map of the base of the Del Rio Clay, the upper confining bed of the Edwards aquifer. The boundary was determined by locating points where the altitude of the top of the aquifer (base of the Del Rio Clay) equaled the altitude of the potentiometric head in the aquifer. Because the head reacts to changing hydrologic conditions, the northern boundary of the confined zone will laterally shift at some places if water levels change. The position of the future boundary will depend upon the configuration of the potentiometric surface, which is affected by pumping and recharge of the aquifer.

Most lateral shifts in the northern boundary can be expected to occur in Uvalde and Bexar Counties if and when water levels are significantly lowered. In these areas, water-level declines of 200 feet below the water level in February 1972 would cause a shift of several miles in the position of the northern boundary. The segments of the confined-unconfined aquifer boundary that are along major faults with large vertical displacement, such as Haby Crossing and Comal

Table 3.--Porosity of Typical Lithofacies of Rocks in the Edwards Aquifer

Carbonate facies	Sedimentary structures and depositional environment	Allochems or crystals	Matrix	Diagenesis	Porosity
Mudstone					
Dense, nonfossiliferous	Mudcracks, irregular lamination, stromatolitic, brecciated; supratidal.	Lithoclasts and algal fragments. Grains are isolated in mud matrix.	Carbonate mud is greater than 90 percent of the rock.	Commonly partly to completely dolomitized.	Little effective porosity except for some zones of leached collapse breccias. Porosity consists almost entirely of micropores that are poorly interconnected.
Pelletoidal, whole fossil, and shaly	Laminated, burrowed, churned, nodular, and dolomitized; tidal flat to lagoonal.	Whole fossil and fossil fragments. Grains are isolated in mud matrix.	Carbonate mud, may be pelleted.	Commonly partly dolomitized. May be chalky.	Effective porosity is dependent on leaching. Honeycombed rock is developed in some leached, mottled and burrowed zones. Nodular and pelleted zones generally are dense and nonporous. Large voids commonly are molds after megafossils. Porosity in chalks is due to micropores.
Wackestone					
Fossil fragment, rudistid, and whole fossil	Burrowed and churned; lagoonal.	Whole mollusk, miliolid, intraclasts. Algal grains are isolated in mud matrix.	Carbonate mud--may be pelleted, may be converted to microspar. Comprises more than one-half of the rock constituents.	Commonly partly dolomitized. May be chalky.	Effective porosity is dependent on the leaching of grains and the conversion of a significant part of the mud to large, euhedral dolomite rhombs. Pore types include molds, intercrystalline voids, and pinpoint vugs.
Packstone					
Fossil and fossil fragment, intraclastic	Moderately disturbed; lagoonal to open marine.	Fossils and intraclasts. Larger grains are touching.	Carbonate mud, generally comprises less than one-half of the rock constituents.	Commonly leached and dolomitized.	Effective porosity is significant where leaching and dolomitization has occurred. Pore types are vugs, interparticle, and moldic.
Grainstone					
Miliolid and fossil fragment	Cross bedded; shallow marine.	Miliolids and fossil talus. Grains are touching.	Spar.	Commonly tightly cemented.	Effective porosity is variable. Very porous where well leached. Some grainstones are leached to chalk, a very porous rock that will drain slowly.
Boundstone					
Algal and reefal	Sedimentary structure indicates growth position of organisms; patch reefs to algal flats.	Whole mollusk fossils, commonly large rudists, algal mats.	Carbonate mud.	Algal zones commonly dolomitized.	Variable effective porosity. Leached rudistid beds have little to moderate porosity, but significant permeability.
Dolomite	No trace of original texture when dolomitization is complete.	Dolomite rhombs, ranging from very fine-grained subhedral to coarsely crystalline euhedral.	--	Some dolomites are extensively leached.	Generally, the coarsely sucrosic dolomites have the greatest effective porosity. Porosity is increased by vugs. The fine grained dolomites have little effective porosity. These rocks occur principally in the saline zone of the aquifer.
Recrystallized limestone	No trace of original texture in matrix.	--	Spar.	--	Matrix has no effective porosity, but secondary vugs may be large and well connected. Boxwork porosity is developed in some evaporitic zones. These rocks occur in the freshwater zone of the Edwards aquifer.

Table 4.--Summary of Geologic Processes in the Development of Rocks in the Edwards Aquifer

Time	Stage or event	Geologic processes	Result
Early Cretaceous	Depositional - Accumulation of carbonate sediments mostly in shallow marine and tidal environments.	Shallow burial and intermittent periods of subaerial exposure. Cementation of some sediments.	Formation of lithofacies. Selective dissolution of shells containing aragonite or high magnesium calcite. Dissolution of evaporites. Formation of some collapse breccias.
Early Cretaceous	Erosional - Recession of the sea and uplift on the San Marcos platform.	Erosion and prolonged dissolution under subaerial conditions. Extensive removal of sediments in the eastern part of the San Antonio area.	Formation of a cavernous porosity system. Cementation of some grainstone by freshwater that is saturated with respect to calcite. Preferential leaching of some reefal rocks and dolomitized, burrowed tidal wackestone.
Middle to Late Cretaceous	Deep burial - Transgressions of continental seas across the Edwards outcrop.	Deep burial of the Edwards Limestone by clay, limestone, sandstone of Late Cretaceous age. Very slow circulation or near stagnant conditions. Saline water in the deeply buried deposits. High pressures resulted in many stylolites. Some compaction of some sediments.	Dormant stage of aquifer development. Formation of stylolites. Compaction is indicated by "squashed" intraclasts and miliolids in a few strata.
Late Cretaceous and early Tertiary	Exhumation - Differential uplift and erosion of the area that presently constitutes the Edwards Plateau.	Stripping of Upper Cretaceous sediments by streams that emptied into ancestral Gulf of Mexico. Formation of karstic plain where Edwards becomes exposed.	Dormant stage of aquifer development except where Edwards became exposed subaerially. In these areas, cavernous porosity began to develop in plains adjacent to major streams.
Miocene	Tensional stresses developed in rocks of Balcones fault zone resulting from subsidence in the Gulf of Mexico.	Normal, steep-angle faulting. Most intensive faulting occurs in eastern part of the San Antonio area.	A system of nearly vertical fractures is developed throughout the Balcones fault zone. Major displacements along major faults abut permeable strata of Edwards against relatively impermeable strata. Incisement of streams flowing normal to trend of major faults produces regional topographic lows near the Balcones fault escarpment.
Miocene to present	Tensional stresses continue but are attenuating.	Periodic movement along faults in the Balcones fault zone. Dissolution and cementation occurring simultaneously in the freshwater zone of the confined Edwards aquifer.	Establishment of the regional confined aquifer in the Balcones fault zone. Major artesian springs emerge at topographic low points in the eastern part of the San Antonio area. Drainages of ancestral springs are captured by a dominant spring. Internal boundaries, formed by faults, divert ground-water flow eastward. When a lower spring outlet forms in the valley of an incising stream, cavernous openings of former solution channels are drained and then exposed as caves at higher levels on the valley walls.

Springs faults, will not move laterally because the confined aquifer is at considerable depths below the potentiometric surface of the aquifer. Therefore, the aquifer will remain saturated even though the water levels may be lowered significantly.

The southern boundary, the "bad-water" line, is set where the concentration of 1,000 mg/L (milligrams per liter) of dissolved solids occurs in the aquifer. The concentrations of dissolved solids at given sampling points vary slightly with time, but the lateral position of the "bad-water" line has not significantly shifted. The geologic and hydrologic conditions near the southern boundary are not completely known. In general, the aquifer in the saline-water zone has considerably less capacity to transmit water than the aquifer in the freshwater zone because an integrated network of cavernous zones has not been developed by circulating freshwater. Faults have significantly disrupted the lateral continuity of the geologic formations at places in Bexar County. These factors serve to restrict lateral ground-water flow across the "bad-water" line.

The upper confining bed of the Edwards aquifer is the Del Rio Clay. The base of the Del Rio Clay was mapped by using data from geophysical logs and selected drillers' logs (Figure 11). This map represents the top of the Edwards aquifer. The Del Rio Clay conformably overlies the Georgetown Limestone on the San Marcos platform and overlies the Devils River Limestone and Salmon Peak Formation in the Maverick basin. It is predominantly a blue clay that ranges in thickness from about 30 feet in Hays County to about 120 feet in Uvalde County. Beds of nearly impermeable limestone, a few inches thick, are interspersed in the lower part of the unit. The upper part of the Del Rio Clay is slightly sandy, but the formation has negligible permeability.

The lower confining bed of the Edwards aquifer is the Glen Rose Formation, which conformably underlies the Edwards Limestone or Group. The Glen Rose Formation ranges in thickness from about 700 feet in Comal County to about 500 feet in Uvalde County. The formation consists of alternating beds of hard limestone, marls, and dolomites with some zones of evaporites. The Glen Rose Formation generally has little permeability, but yields small quantities of water from distinct lateral zones. Vertical movement is restricted by marls with negligible permeability.

Because of large displacements along faults, the Edwards aquifer is confined horizontally at places by the following stratigraphic units: the Austin Group, the Eagle Ford Group, the Buda Limestone, the Del Rio Clay, and the Glen Rose Formation. The lithology and water-bearing characteristics of these stratigraphic units are described in Table 1.

Heterogeneity of the Aquifer

The permeability of the Edwards aquifer is dependent on the position within the rocks of the aquifer. Therefore, the aquifer is heterogenous. The heterogeneity of the Edwards aquifer may be categorized into layered, discontinuous, and trending according to a classification suggested by Freeze and Cherry (1979, p. 30).

Layered Heterogeneity

Layered heterogeneity consists of individual beds or units that have different average hydraulic conductivities. However, each bed may have variable porosity. The Edwards aquifer on the San Marcos platform consists of eight hydrostratigraphic subdivisions (Figure 12 and Table 5). Very permeable zones are distributed erratically throughout subdivisions 2 and 7. The most permeable zones in these subdivisions occur in honeycombed rocks formed by large rudist molds, by irregular openings developed in burrowed tidal wackestones, and by moldic porosity developed in collapse breccias that formed in supratidal deposits. The most porous rocks are leached or incompletely cemented grainstones that occur mostly in subdivisions 3, 5, and 6. These porous rocks have high porosity, but relatively little permeability. Mercury-injection studies of the core samples indicate, however, that some of the water in the small pores within these rocks will drain slowly by gravity (Maclay and Small, 1976).

The lithofacies of subdivisions 1, 4, and 8 are nearly impermeable and have effective porosities of less than 10 percent. The hydrogeologic characteristics of the recrystallized rocks in subdivisions 2, 3, 6, and 7 are variable, ranging from predominantly nonporous, dense, calcitic, crystalline rocks to porous and permeable rocks having solution or sucrosic porosity. The relative permeabilities of these units were estimated on the basis of core observations, geophysical logs, and a few packer tests.

The layered heterogeneity of the Edwards aquifer within the Maverick basin is shown by the geophysical logs of test hole YP-69-42-709 drilled by the Texas Water Commission northwest of Uvalde (Figure 13). The Edwards aquifer in the Maverick basin consists of three hydrostratigraphic subdivisions. The upper subdivision (Salmon Peak Formation) is the most permeable. Cavernous porosity is indicated by increased hole diameter as detected by the caliper log in the upper part of subdivision 1.

The Edwards aquifer is separated into an upper zone and a lower zone in some places by subdivision 2 (the McKnight Formation) in the Maverick basin and by subdivision 4 (the regional dense member) on the San Marcos platform. These subdivisions have little or negligible permeability and lack open fractures. At other places, the aquifer is not hydraulically separated because faults have placed permeable beds of the lower zone adjacent to permeable beds of the upper zone.

The Sabinal test hole (YP-69-37-402) entirely penetrated the Devils River Formation. The geophysical logs and core-hole data did not indicate that the Devils River Formation could be readily subdivided into layered hydrogeologic units (Figure 14). However, the caliper log indicated cavernous porosity occurs in the upper part of the formation.

Discontinuous Heterogeneity

Discontinuous heterogeneity (Freeze and Cherry, p. 30, 1979) occurs in the Edwards aquifer where faults place rocks of significantly different permeabilities in laterally adjacent positions. This type of heterogeneity, which is very common in the Edwards aquifer, exerts a major control on the direction of ground-water flow. Where very permeable rocks, such as those of subdivision 6, are juxtaposed against relatively impermeable rocks, water movement is blocked by the barrier fault and is diverted to a direction approximately parallel to the fault. Along segments of some major faults, the full thickness of the aquifer is vertically displaced, so that lateral continuity is

Table 5.--Porosity, Permeability, and Lithology of the Hydrologic Subdivisions of the Edwards Aquifer in Bexar County

Subdivision [1]	Thickness (feet)	Total porosity [2] (percent)	Relative matrix permeability [3]	Fractures	Description of carbonate facies and pore types
1	20-40	<5	Negligible	Few, closed	Dense, shaly limestone; mudstone and wackestone; isolated fossil molds.
2	80-100	5-15	Little	Many, open	Hard, dense, recrystallized limestone; mudstone; rudistid biomicrite; some moldic porosity.
3	60-90	5-20	Little to large	Many, open	Recrystallized, leached limestone; burrowed mudstone and wackestone, highly leached in places; solution breccias, vuggy, honeycombed.
4	20-24	<5	Negligible	Closed	Dense, shaly to wispy limestone; mudstone; no open fractures.
5	50-60	5-15	Little to moderate	Few, open	Limestone; chalky to hard well cemented miliolid grainstone with associated beds of mudstones and wackestones; locally honeycombed in burrowed beds.
6	50-70	5-25	Little to very large	Undetermined	Limestone and leached evaporitic rocks with boxwork porosity; most porous subdivision.
7	110-150	5-20	Little to large	Many, open	Limestone, recrystallized from dolomite, honeycombed in a few burrowed beds; more cavernous in upper part.
8	40-60	<10	Little	Few, open	Dense, hard limestone; clayey mudstone to wackestone, nodular, wispy, stylolitic, mottled; isolated molds.

1/ Correlation with stratigraphic units shown in Figure 12.
2/ Based on visual examination of cores.
3/ Matrix permeability refers to permeability related to smaller interstices, which is the bulk of the rock, and not to the larger cavernous openings.

completely disrupted in the direction perpendicular to the fault. At other places, where several parallel faults occur in proximity, a series of partial barriers to lateral flow may restrict flow in the direction perpendicular to the strikes of the faults.

A series of hydrogeologic sections through the Edwards aquifer (Figure 15) were drawn to map the locations of internal barriers. Representative hydrogeologic sections taken from this series are shown in Figures 16a-f. The trace of the potentiometric surface along the sections is shown to indicate where the aquifer is completely or partly saturated. Location of the major internal barriers in the confined freshwater zone of the Edwards aquifer are shown in Figure 17. A major barrier is designated as a place of greater than 50 percent vertical displacement of the aquifer. Vertical displacement of 50 percent or greater will place the most permeable stratigraphic subdivisions on the one side of the fault plane against relatively impermeable strata on the other side.

Trending Heterogeneity

Trending heterogeneity (Freeze and Cherry, 1979) is caused by a gradational and regional change in the permeability of the aquifer. Trending heterogeneity occurs in the Edwards aquifer because of regional changes in carbonate deposition environments, location of paleokarst, characteristics of solution-channel networks, and the incidence and intensity of fractures.

Carbonate rocks deposited on the San Marcos platform and in the Devils River trend contain a much greater abundance of sedimentary features that contribute to the development of large secondary openings than the rocks in the Maverick basin. The reefs and supratidal flats on the San Marcos platform contained readily soluble evaporites that were exposed to leaching during intermittent periods of subaerial exposure and the consequent production of porous collapse breccias. The rocks of the Maverick basin are predominantly dense, homogeneous mudstones. Permeability within these rocks principally is dependent on solution openings developed along fractures or certain bedding planes.

Paleokarst is karstified rocks that have been buried by later sediments (Monroe, 1970). Karst is a terrain, generally underlain by limestone in which the topography, formed chiefly by dissolving rock, is characterized by closed depressions, subterranean drainage, and caves. According to Rose (1972), subaerial exposure and erosion occurred in the eastern part of the San Antonio area just before the transgression of the sea that deposited the dense, deepwater sediments of the Georgetown Limestone. During the extended periods of exposure and erosion, karstification occurred. Field evidence of this karstification includes reports by well drillers of caves in the downdip part of the aquifer within the saline-water zone and the occurrence of vadose deposits (cave popcorn and travertine) in cores obtained from the artesian zone. Other evidence of karstic cavernous porosity at depth within the confined zone of the aquifer in Bexar County is the occurrence of live blind catfish that have been netted from the discharge of flowing wells completed in the aquifer at depths greater than 1,000 feet (Longley, 1981; Longley and Karnei, 1978). These catfish require space of adequate size in order to survive. Karstification probably significantly increased the permeability of the carbonates in the eastern part of the San Antonio area.

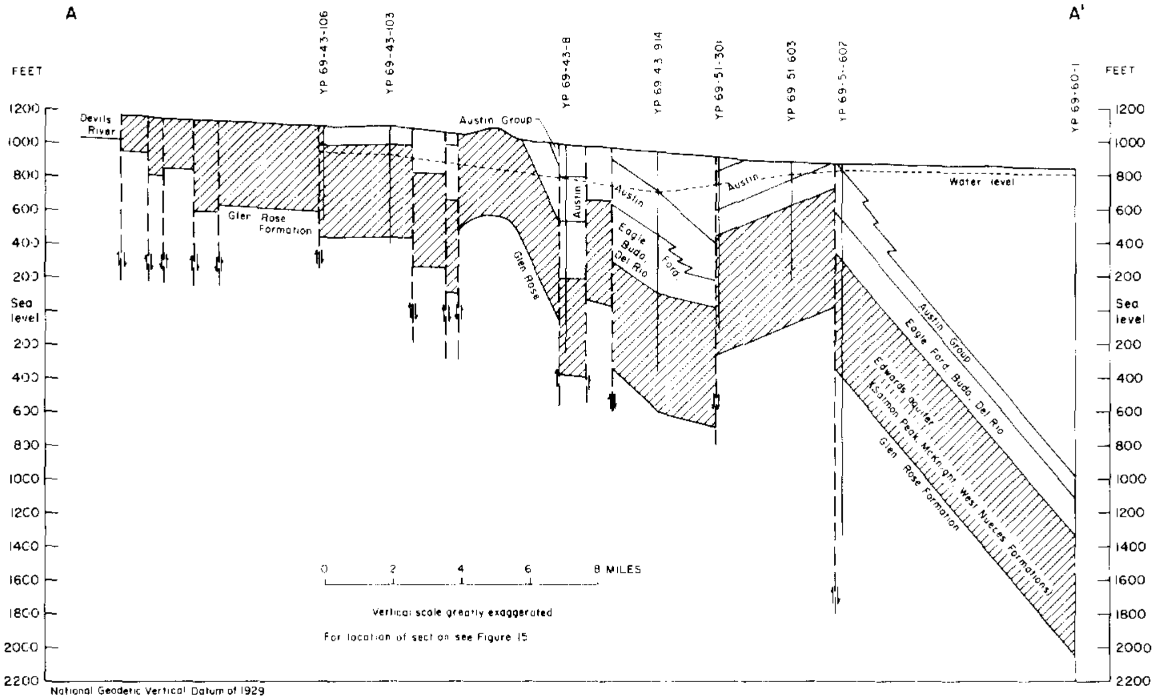


Figure 16a.—Hydrogeologic Section A-A' Through the Edwards Aquifer

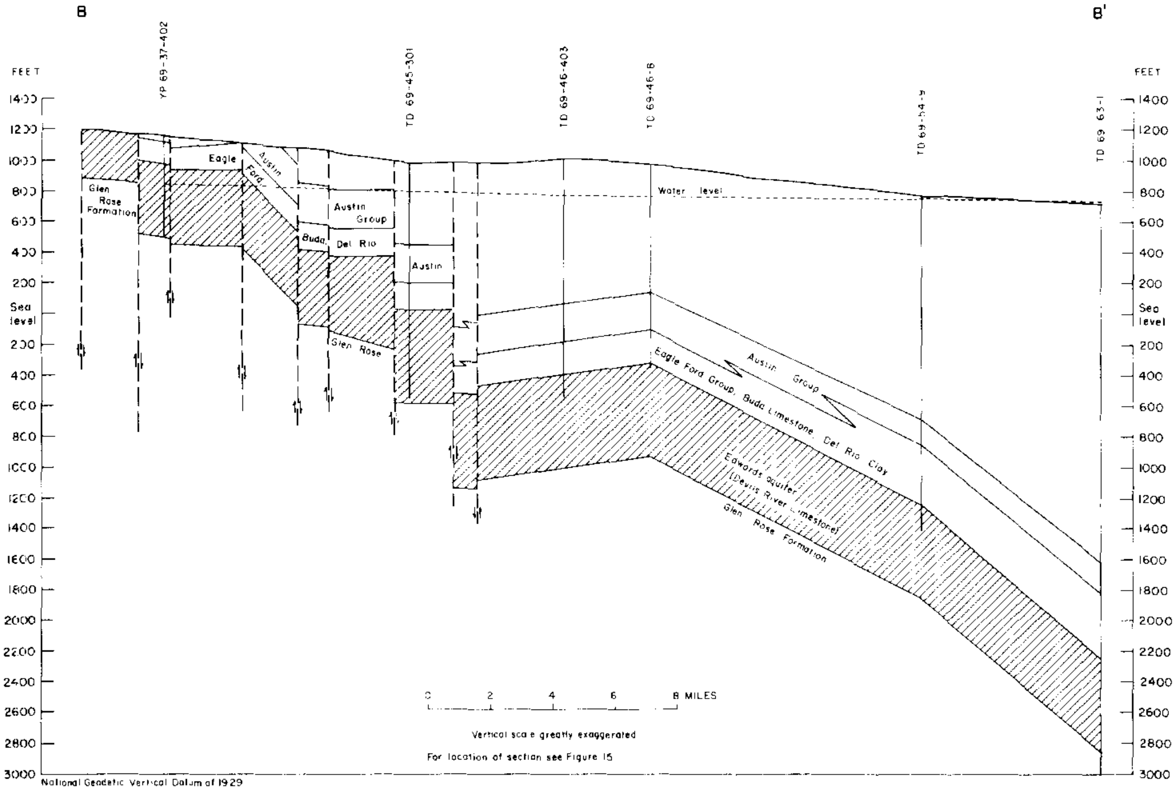


Figure 16b.—Hydrogeologic Section B-B' Through the Edwards Aquifer

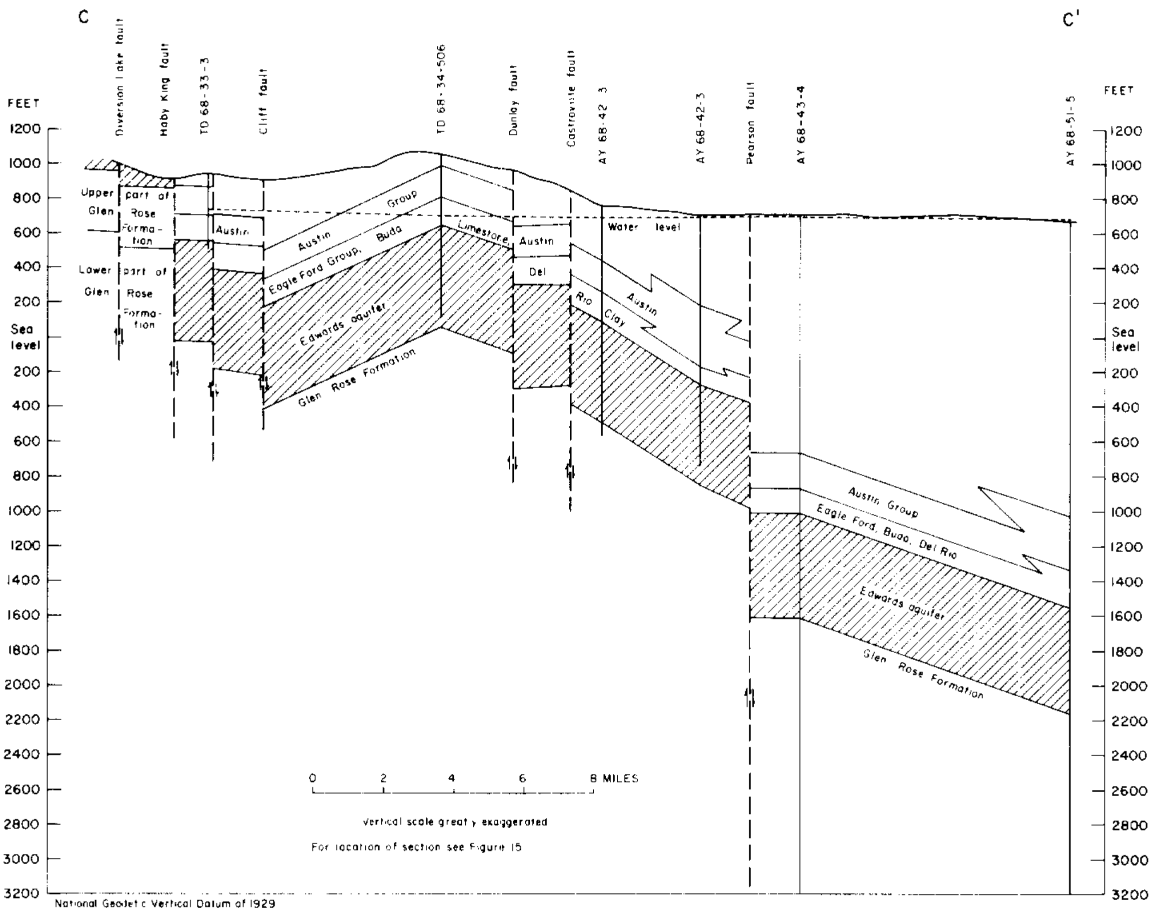
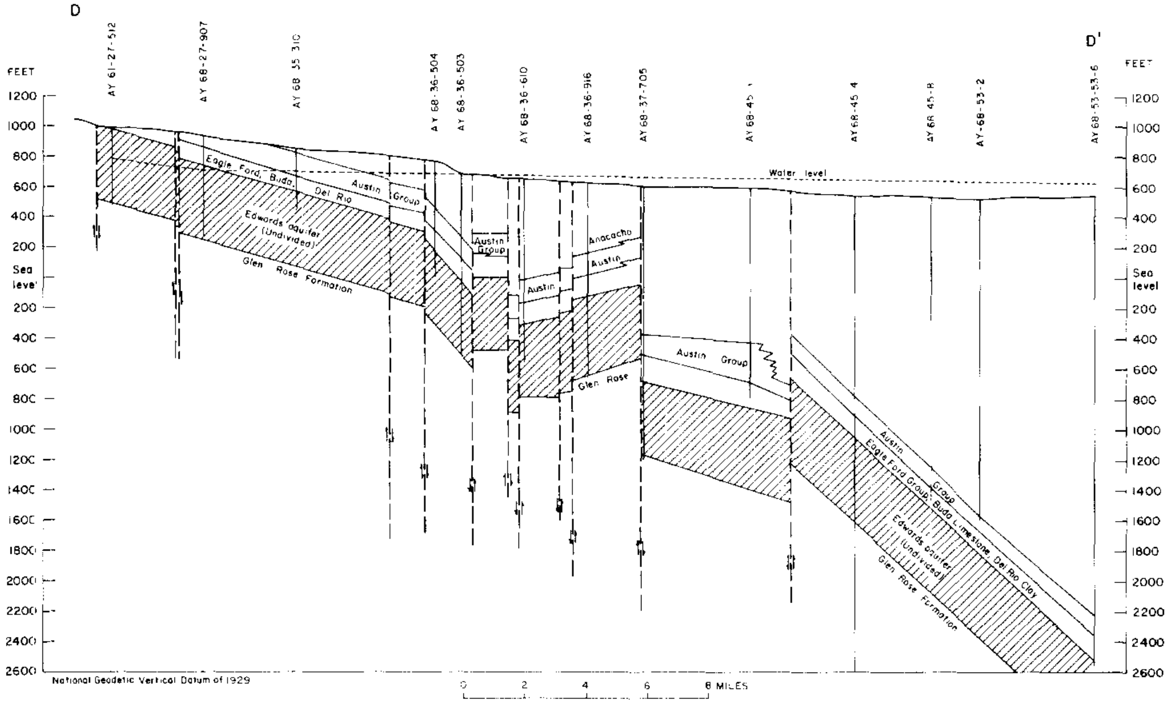


Figure 16c.—Hydrogeologic Section C-C′ Through the Edwards Aquifer

Recent work by Wermund, Cepeda, and Luttrell (1978) is an investigation of fractures on the southern Edwards Plateau and in the Balcones fault zone and shows the distribution, orientation, and magnitude of the fractures. Their study investigates the regional distribution and variations of fractures and faults. They identified lineations or fracture zones observed on aerial photographs as short and long lineations. Short lineations are as much as 2.8 miles long, and long lineations are as much as 99.4 miles long. They also investigated the distribution of caves and the orientation of cave passages for comparison with orientations of short and long lineations.

The orientations of the short-fracture zones are indicated by rosettes and the intensity of fracturing by the length of the arms of the rosettes in Figure 18. The dominant orientation of the short lineations are to the northeast and northwest. These orientations characterize the fractures both on the Edwards Plateau and in the Balcones fault zone. The incidence of short-fracture zones (the number of short fractures within a 7.5-minute quadrangle) also is shown in Figure 18. The distribution of the short lineations is not consistent, and there is no systematic increase or decrease in the number of fractures in relation to faulting in the Balcones fault zone. The largest number of fractures per quadrangle in the Balcones fault zone occurs in Medina and Uvalde Counties rather than in Bexar County, where fault displacement and intensity are greater.

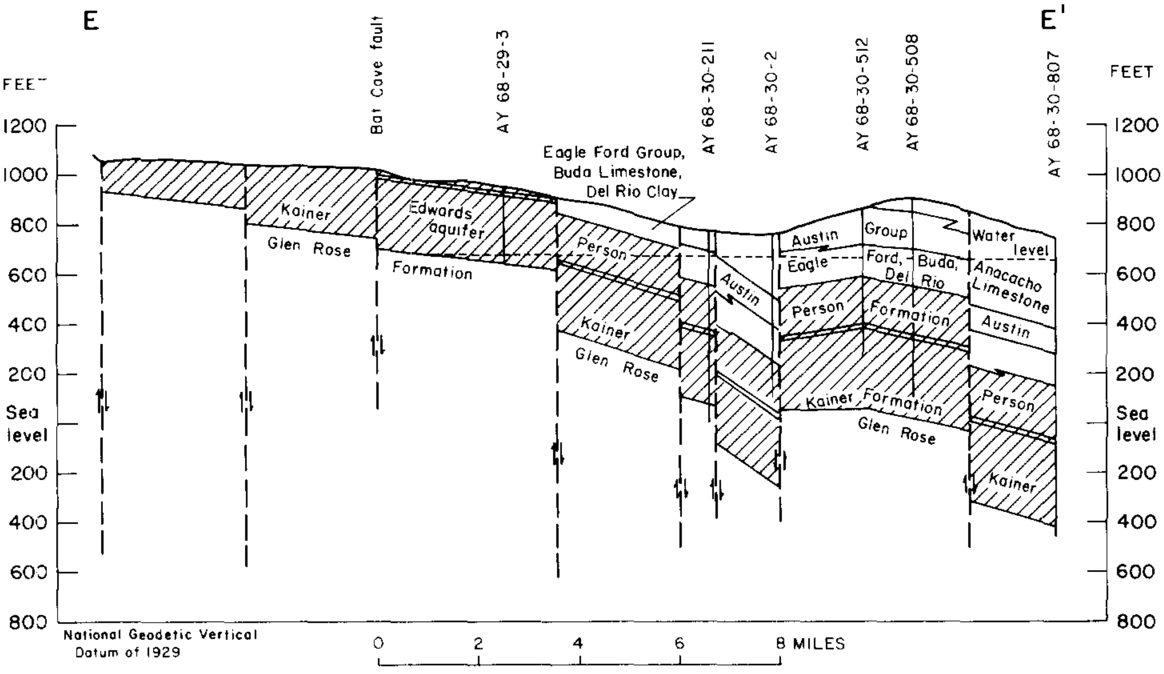


National Geodetic Vertical Datum of 1929

Vertical scale greatly exaggerated

For location of section see Figure 15

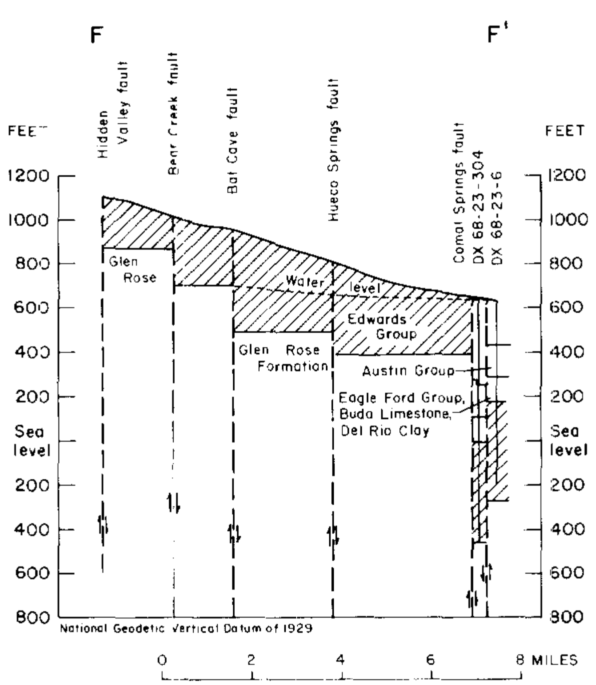
Figure 16d.—Hydrogeologic Section D-D' Through the Edwards Aquifer



National Geodetic Vertical Datum of 1929

For location of section see Figure 15

Figure 16e.—Hydrogeologic Section E-E' Through the Edwards Aquifer



For location of section see Figure 15

Figure 16f.—Hydrogeologic Section F-F' Through the Edwards Aquifer

The orientation and length of the long fractures and the distribution of caves and orientations of their passages are shown in Figure 19. The orientation of the long fractures is similar to that of the short fractures. In the vicinity of the Balcones fault zone, many long lineations represent single faults. The rosettes (Figure 19) indicate the distribution of the caves is controlled by the fracture systems. In the eastern part of the San Antonio area, the caves are partly alined with the major faults of the Balcones fault zone. The north-trending orientation of cave passages is suggested by Wermund, Cepeda, and Luttrell (1978) to indicate control by older fractures associated with the basement rocks.

The work by Wermund, Cepeda, and Luttrell (1978) indicates that fractures have affected the orientation of cave passages; however, the regionally significant permeability in the eastern part of the San Antonio area probably cannot be wholly attributed predominantly to dissolution along fracture openings because no regional trend of incidence of fractures is apparent. Fractures do have significant effect on the vertical circulation within the aquifer and provide part of the geologic conditions necessary for the development of greater transmissivity in the eastern part of the San Antonio area.

Anisotropy of the Aquifer

Anisotropy of an aquifer occurs when the permeability shows variations with the direction of measurements at any given point in a geologic formation (Freeze and Cherry, 1979, p. 32). Therefore, an anisotropic aquifer will have a dominant permeability in one or more directions depending upon geologic and hydrologic conditions.

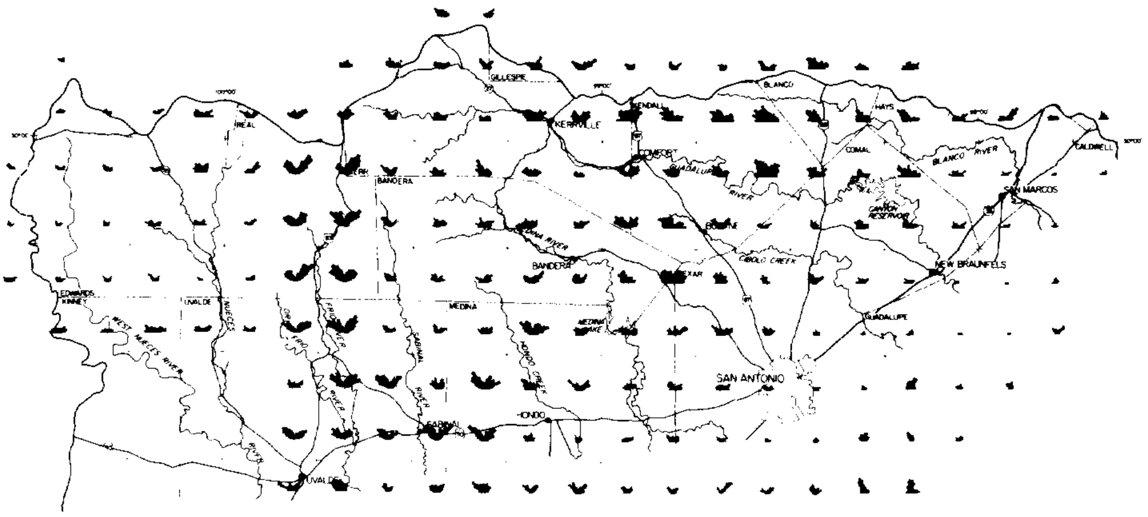
Anisotropic properties need to be quantified to solve problems at a scale of a well field. For problems at a regional scale, complete documentation of anisotropic properties generally is very difficult. Anisotropy in the Edwards aquifer varies significantly from place to place.

The hydrogeologic conditions that contribute to or affect the development of anisotropy in the Edwards aquifer in the San Antonio area are:

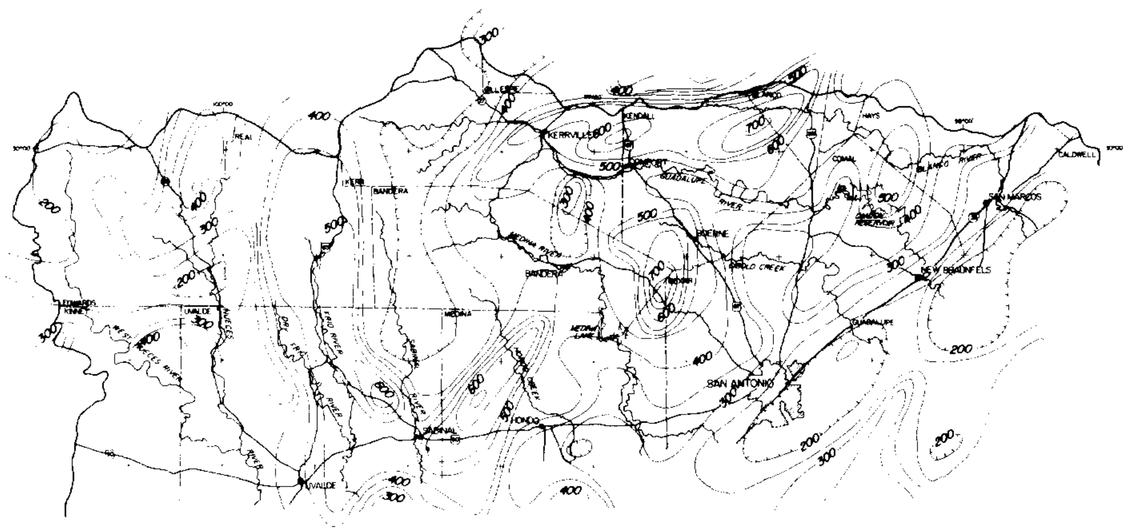
1. Tubular openings or solution channels probably exist in areas of homogeneous, dense, fractured limestone particularly in the western part of the San Antonio area. These tubular openings are alined along fractures and are oriented in the direction of ground-water flow.

2. Local anisotropy in the Edwards aquifer is not readily apparent from the pattern of the regional potentiometric maps (Maclay, Small, and Rettman, 1980, Figure 6). However, hydrogeologic conditions for its development exist, as for example, the occurrence of faults that completely displaced the aquifer on the upthrown fault block from the aquifer on the downthrown block.

3. Solution channels within the Edwards aquifer may be oriented parallel to the stream courses of certain recharging streams within the San Antonio area.



Orientation of short-fracture zones



Incidence of short-fracture zones

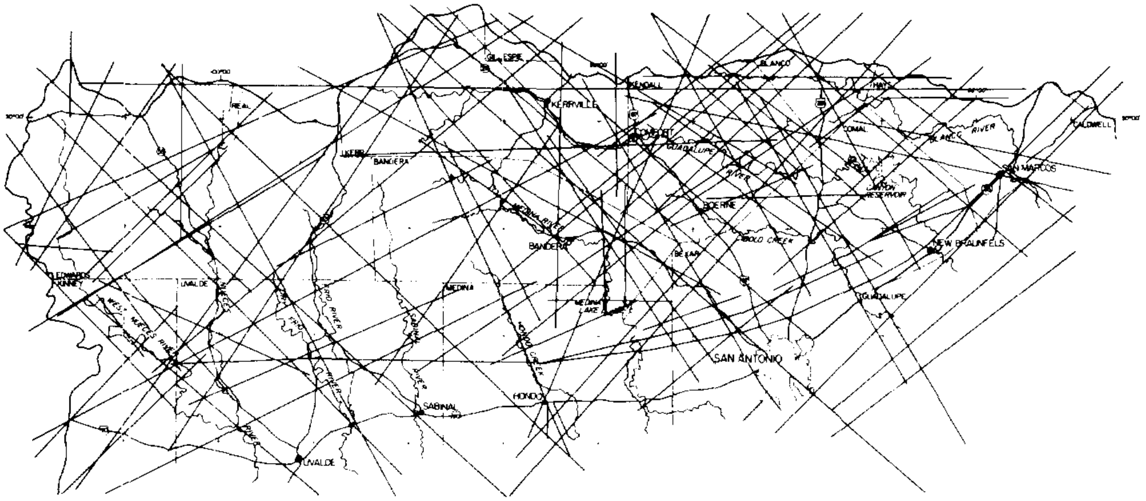
0 10 20 30 MILES

From Wermund and others, 1978

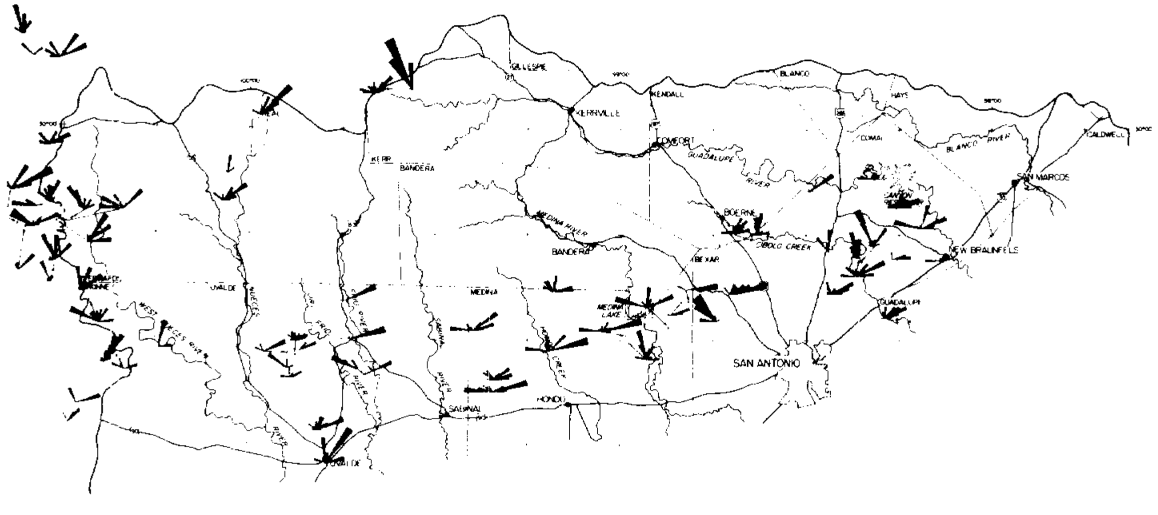
Figure 18.—Orientation and Incidence of Short Lineation Features on the Edwards Plateau and in the Balcones Fault Zone

4. A highly permeable belt of rocks exists along segments of the "bad water" line in areas where mixing of ground water of two different chemical types may increase the solution capacity of the water.

5. Vertical solution channels are well developed below segments of stream courses crossing the recharge area of the Edwards aquifer.



Orientation of long-fracture zones



Distribution and orientation of caves

From Wermund and others, 1978

Figure 19.—Orientation and Incidence of Long Lineation Features and the Distribution of Caves on the Edwards Plateau and in the Balcones Fault Zone

Hydrologic Properties

Transmissivity

Transmissivity is inherently a difficult property to quantify for solutioned and heterogeneous carbonate aquifers such as the Edwards because of the nonuniform distribution of permeability. Permeability and hydraulic conductivity are controlled effectively by the size of the interconnected voids in porous zones or along channels. The size of the interconnected voids that are effective for the transmission of ground water range by more than four to five orders of magnitude. Snow (1969) shows that intrinsic permeability is related to the third power of the fracture width.

In the Edwards aquifer, the observed voids range in size from less than 10 microns or 0.0004 inch, as determined from petrographic studies of thin sections of rock samples, to about 3 to 10 ft, as detected by caliper logs in a well bore or shown in maps of caves in Bexar County (Poole and Passmore, 1978). The lower limit of the size of openings that will transmit water by gravity drainage is about 10 microns or 0.0004 inch (Maclay and Small, 1976, p. 51).

Relatively small interconnected voids could account for significant permeability and transmissivity; however, fracture and solution openings commonly are open at one place whereas at other places, they are very restricted or closed. The passageways that transport most of the water are those that are interconnected and contain the largest openings at the points of constriction. The location of these constrictions practically are never known, but channels or zones that show evidence of solution enlargement indicate a less restricted pathway while a more restricted pathway is indicated by partial cementation of openings.

To apply the concept of transmissivity to mathematical analysis of regional ground-water flow using the ground-water flow equations, the aquifer needs to be considered a continuum rather than a system of specified individual channels. This assumption allows the size, configuration, and position of individual fractures and karstic cavities to be neglected and a statistically averaged value of transmissivity to be representative of these features. The statistical averaging of the effects of all interconnected openings is expressed by the magnitude of transmissivity. On a regional scale, the concept of a continuum is practical, and usually a realistic assumption can be made for solving some problems of ground-water flow.

In an attempt to quantify the magnitudes and distribution of the transmissivity, the area was subdivided into subareas (Figure 20) having different ranges in transmissivities. The estimated relative transmissivities were designated on a scale of 0 to 10, where 0 indicates the least transmissivity and 10 the greatest. Estimated values of transmissivities are suggested to range from about 200,000 ft^2/d for a ranking of 1 to about 2 million ft^2/d for a ranking of 10. These estimates are judgments made on the basis of a general knowledge of the geology, hydrology, and hydrochemistry of the aquifer and on other types of data such as: spacing of potentiometric contours; specific capacities of wells; flow-net analyses of particular areas; results of aquifer-performance tests; rate of pressure transmission through aquifers; correlation of water levels; springflow hydrographs; distribution of tritium within waters of the aquifer; saturation indices of water with respect to particular minerals; salinity; and the ratios of major ions in solution. (Most of these data have been presented in the following reports: Maclay, Rettman, and Small, 1980; Maclay and Small, 1976; Maclay, Small, and Rettman, 1980; Pearson and Rettman, 1976; Pearson, Rettman, and Wyerman, 1975; Puente, 1975, 1976, and 1978; and Small and Maclay, 1982.)

Subareas A through G (Figure 20) are mostly in the unconfined zone of the aquifer. The smaller values of transmissivity occur near the northern boundaries of the subareas, where the saturated thickness of the aquifer is relatively small. Locally, in the vicinity of recharging streams, the transmissivity may be considerably greater.

Subarea A is underlain mostly by the McKnight and West Nueces Formations, both of which contain rocks with relatively little intrinsic permeability. Fracture incidence is sparse. Yields of wells increase toward the east in the subarea.

Subarea B is underlain by the Devils River Limestone, which is very permeable in the upper part. The subarea is dissected by numerous faults and fractures; therefore, the lateral continuity of some strata is limited. The greatest transmissivities occur toward the southeast.

Subarea C is underlain mostly by the Devils River Limestone. The subarea is extensively faulted in the eastern part, and these faults restrict ground-water movement toward the southeast. Ground water moves mostly southwestward toward subarea K. Transmissivity may be greater locally within the graben that trends southwestward through the central part of the subarea.

Subarea D, which is underlain mostly by the lower part of the Kainer Formation of Rose (1972), is bordered on the south by Haby Crossing fault, which vertically displaces the entire thickness of the Edwards aquifer. Ground water is recharged to moderately permeable rocks in the interstream areas and is discharged to intermittent springs in the topographic lows. Probably only a small quantity of water recharged in this subarea moves to other subareas.

Subareas E and F are underlain mostly by the Kainer Formation, but the Person Formation of Rose (1972) is exposed toward the southeast. Faults, caves, and collapsed sink holes are common in these areas, particularly in northeast Bexar County and in Comal County. The rocks have the capability to transmit water at rapid rates; however, the saturated thickness is limited, thus resulting in lesser transmissivities. A perched water table occurs in the southwest part of subarea F. A graben that contains a full thickness of the Edwards Group of Rose (1972) extends from the vicinity of Cibolo Creek toward Hueco Springs. This graben, which contains rocks with significant transmissivity may be a ground-water drain.

In subarea G, most of the Edwards Group has been removed by erosion during post-Cretaceous time; consequently, the transmissivity is relatively small. In the eastern part of the subarea, the Edwards aquifer may be separated into an upper and lower unit by the regional dense member. The lower unit contains saline water. Natural sulfur deposits occur in this part of the aquifer in the vicinity of San Marcos. The salinity of water and the occurrence of sulfur indicate decreased circulation and reducing conditions in the lower part of the aquifer.

Subareas H through U are mostly in the confined freshwater zone of the aquifer. In general, the transmissivities are large and increase eastward through a central zone toward Comal Springs. Within this central zone, the velocity of pressure waves caused by pumping stresses are rapid, and water levels in widely dispersed observation wells show a significant degree of correlation (Maclay, Small, and Rettman, 1980).

In subarea H, water is transmitted mainly through the Salmon Peak Formation of Lozo and Smith (1964) which commonly is permeable near the top and near the bottom. Transmissivity in subarea H probably increases toward the east. Locally, greatest transmissivities probably occur near the Nueces River.

In subarea I, transmissivity probably increases northeastward. High transmissivities occur locally near Leona Springs, south of Uvalde. Wells having yields of several thousands of gallons per minute occur in the subarea.

Subarea J is a structurally complex area containing many local barriers and intrusive igneous rocks. Local transmissivity may be large, but the capability of the rocks as a whole to transmit water is small. A regional cone of depression is developed periodically in the subarea as a result of pumping of a few wells.

Subarea K is a large subarea with significant transmissivity that is underlain mostly by the Devils River Limestone. The temperature of the ground water increases only slightly with depth, indicating vertical circulation within the aquifer. Inflow from the major recharge areas to the west and north has forced freshwater southward within the aquifer. No major internal barriers occur in the western part of subarea K, and the correlation of water levels between widely spaced wells in this subarea is excellent.

Subarea L is underlain by the Devils River Limestone. The aquifer contains more mineralized water and the water has a greater variation in the major ions in solution than in subarea K (Maclay, Rettman, and Small, 1980). These facts indicate slower ground-water circulation and lesser transmissivity of the aquifer. Ground-water temperatures in the subarea are considerably higher than in subarea K.

Subarea M, which is underlain by the Edwards Group, receives little underflow from recharging streams to the north because of a ground-water barrier created by the Haby Crossing fault. The water types are more varied than in subareas K and N (Maclay, Rettman, and Small, 1980). The variation is particularly evident near the Haby Crossing fault, where underflow from the lower part of the Glen Rose is possible. Core-hole data from the Rio Medina test hole (TD-68-34-506) indicates that most ground-water circulation occurs in the upper part of the aquifer (Maclay and Small, 1976).

Subarea N, which is underlain by the Edwards Group, contains large-yield wells with large specific capacities, both of which indicate significant transmissivities. Wells that yield several thousand gallons per minute with only a few feet of drawdown may be drilled at most places in the subarea. Water levels fluctuate daily because of the extensive pumping in Bexar County. The water quality shows little variation and is very similar to that in the recharge area. A slight increase in mineralization of the water occurs near the "bad-water" line.

Subarea O probably receives considerable inflow from subarea E, while ground-water outflow is mostly toward the more transmissive subareas P and R. The rapid eastward flow of ground water in subarea O was documented by an environmental tracer, trichlorofluoromethane, CCl_3F (Thompson and Hayes, 1979). Water in some wells in this subarea becomes cloudy with suspended matter after intense storms, which indicates hydraulic continuity with the cavernous limestone in subarea E. The specific capacities of wells in this subarea exceed 2,000 (gal/min)/ft of drawdown.

Subarea P contains very cavernous limestones in the Person and Kainer Formations. The specific capacities of some wells in the subarea exceed 6,000 (gal/min)/ft of drawdown.

Subarea Q is an area of substantially lesser transmissivity than subareas P and R. The specific capacities of a few wells are greater than 1,000 (gal/min)/ft of drawdown. The hydrochemistry of the water in this subarea is more variable than in subareas P and R, which indicates slower ground-water circulation (Maclay, Rettman, and Small, 1980).

Subarea R is the most transmissive zone in the San Antonio area. Water flows through the confined aquifer along the Comal Springs fault on the downthrown side of the fault. Well yields are very large. Geophysical logs indicate that both the Person and Kainer Formations are very cavernous. Water is discharged to Comal Springs in New Braunfels by moving upward along the fault plane.

Subarea S probably is somewhat less transmissive than subarea R. Greatest transmissivity should occur near Comal Springs, and an aquifer test near Gruene indicated a large transmissivity (Maclay, Small, and Rettman, 1980). In this subarea, cross faults may divert water from the downthrown side of Comal Springs fault to the upthrown side.

Subarea T probably is very transmissive. It is adjacent to the Hueco Springs and San Marcos faults and extends from Comal County into Hays County. Large-capacity wells have been drilled near these faults. Ground water in this subarea moves to San Marcos Springs, and the greatest transmissivity occurs in the vicinity of San Marcos Springs.

Subarea U probably is much less transmissive than subarea T. The water is more mineralized, indicating slower ground-water circulation. Cross faults restrict circulation in the vicinity of Kyle.

The saline-water zone of the aquifer is hydraulically connected with the freshwater zone; however, the saline-water zone has a much lesser transmissivity. The geologic conditions that cause this change in hydraulic connection are fault barriers and much lesser permeabilities of the rocks in the saline zone. In Bexar County, the response of water levels in the saline-water zone is delayed by several days from the time of significant changes in water levels in the freshwater zone. This fact indicates that hydraulic connection between the freshwater and saline-water zones is restricted in Bexar County. In the western part of the San Antonio area, hydraulic connection between the saline-water and freshwater zones is better developed because of less fault displacement. In Hays and Comal Counties, very highly mineralized water occurs in the saline-water zones immediately adjacent to the "bad-water" line, which indicates that circulation is slow.

Storage Coefficients

In the confined zone of the Edwards aquifer, the water derived from storage comes from expansion of the water and compression of the framework of the aquifer. The storage coefficient for the confined zone can be computed from the equation given by Jacob (1950):

$$S = abc \quad (d + e/b), \tag{1}$$

where a = specific weight of water (62.4 lb/ft^3),

b = porosity of the aquifer (dimensionless),

c = thickness of the aquifer (feet),

d = compressibility of water, which is 3.3×10^{-6} in^2/lb or 2.29×10^{-8} ft^2/lb, and

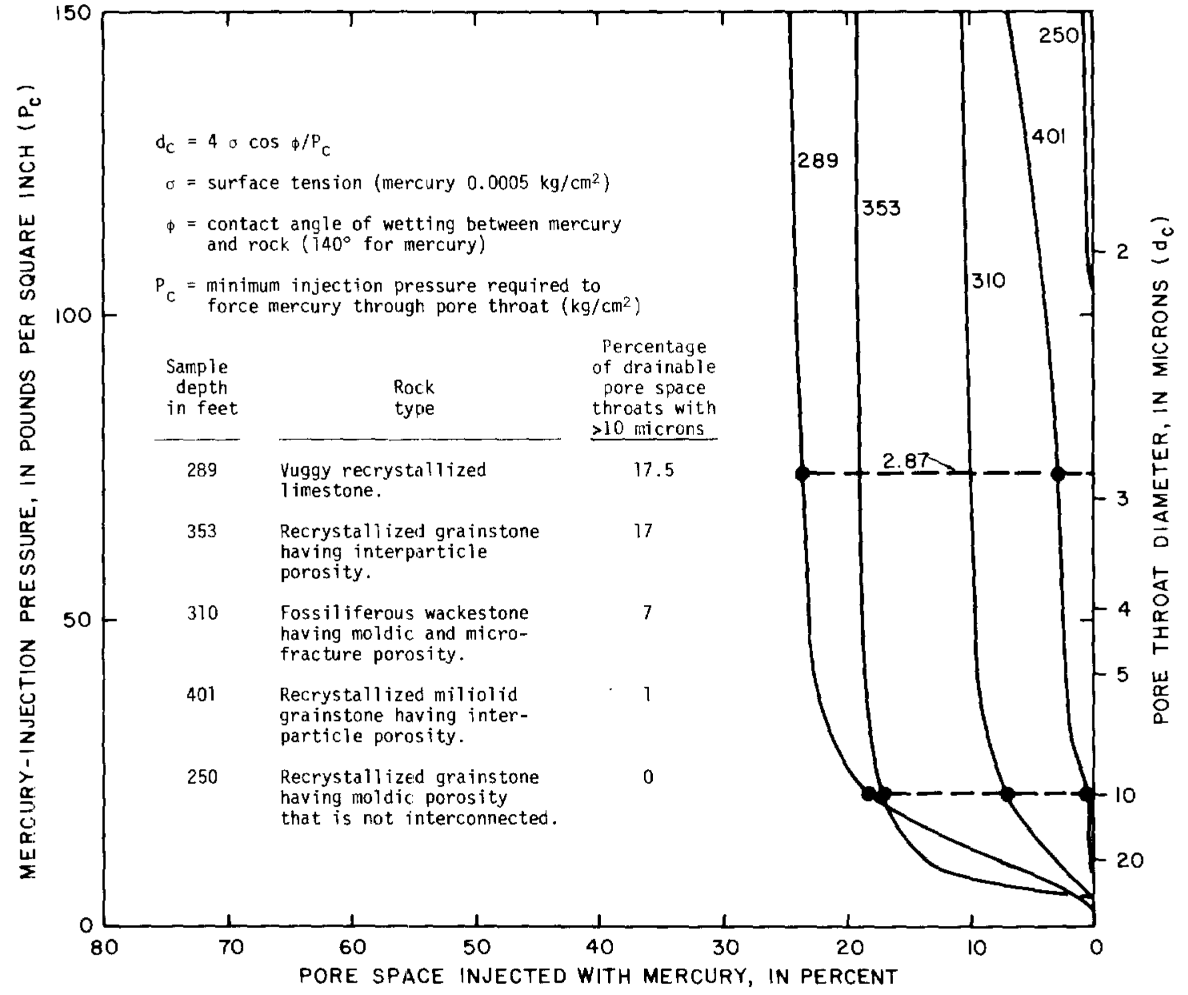
e = compressibility of the limestone aquifer skeleton, which is 1.00×10^{-7} in^2/lb or 6.95×10^{-10} ft^2/lb (Birch and others, 1942)

Assuming a porosity of about 20 percent, which is a conservative estimate based on measurements by neutron logs, and an aquifer thickness of 500 feet, the storage coefficient is calculated to be 1.6×10^{-4}. The storage coefficient will vary depending upon the porosity and the thickness of the aquifer; but it probably ranges from about 1×10^{-4} to 1×10^{-5}.

The storage characteristics of the rocks were investigated by analyses of the test-hole cores to determine pore-size distribution, permeability, and total porosity. These data are available in the geologic-data report that supplements this report (Maclay, Small, and Rettman, 1981). Porosity values determined from geophysical logs need to be interpreted to estimate the storage capacity. Porosity values obtained from geophysical logs are considerably greater than the effective porosity or the specific yield because geophysical tools sense all porosity, including unconnected pores and micropores. The fraction of the pore space occupied by micropores is large for most rock textures. Although a small fraction of the water within rock pores of most unfractured micrites will drain by gravity, fracturing increases the drainability (specific yield). Indications of effective porosity within micrites include observations of staining in rocks and the S shape (delayed-drainage type) of time-drawdown curves of an aquifer test in cavernous, but micritic, rocks at Gruene (Maclay, Small, and Rettman, 1981). A review of the theoretical background for aquifer tests in rocks having dual porosity systems by Babushkin and others (1975) shows the physical and mathematical basis for the S shape of the time-drawdown curve.

The drainable porosity, which is nearly equivalent to the specific yield, was defined by Maclay and Small (1976) as the porosity developed by pores that are interconnected by pore throats larger than 10 microns (0.0004 inch) in diameter. Any pores connected by pore throats larger than 2.87 microns (0.0001 inch) in diameter could slowly drain water by gravity; however, pore throats must be considerably greater than 2.87 microns (0.0001 inch) in diameter for the water to drain quickly. Estimates of the drainable porosity of representative rocks that were obtained from the unconfined zone of the Edwards aquifer at the Lockhill test hole (AY-68-28-404) ranged from 0 to 17.5 percent (Figure 21). Details of the test procedures and the results of other rock-sample tests are given by Maclay and Small (1976).

The rocks with fractures and solution channels may have a specific yield of about 1 percent while the micrites with texture-related porosity may have a specific yield of several percent. Therefore, the capacity of the Edwards aquifer to store water is determined largely by percentage



$d_c = 4\ \sigma \cos \phi / P_c$

σ = surface tension (mercury 0.0005 kg/cm^2)

ϕ = contact angle of wetting between mercury and rock (140° for mercury)

P_c = minimum injection pressure required to force mercury through pore throat (kg/cm^2)

Sample depth in feet	Rock type	Percentage of drainable pore space throats with >10 microns
289	Vuggy recrystallized limestone.	17.5
353	Recrystallized grainstone having interparticle porosity.	17
310	Fossiliferous wackestone having moldic and micro-fracture porosity.	7
401	Recrystallized miliolid grainstone having inter-particle porosity.	1
250	Recrystallized grainstone having moldic porosity that is not interconnected.	0

Figure 21.—Estimates of Drainable Pore Space in Different Rock Types in the Lockhill Test Hole (AY-68-28-404)

of voids within the rock matrix, while the capacity to transmit water is determined by the characteristics of fractures and solution-channel systems.

An estimate of the regional specific yield in the unconfined zone of the Edwards aquifer was made by Maclay and Rettman (1973) using records of annual recharge and discharge and observing water levels in 10 wells. The estimate of the regional specific yield was about 3 percent for the test range of water levels. This value may or may not be representative in the confined zone or for stages other than the test range. A summary of estimates of specific yield or drainable porosity is given in Table 6.

Estimates of specific yield for the confined zone cannot be determined directly because the aquifer is saturated. However, the rocks in the confined zone are stratigraphically and lithologically similar to those in the unconfined zone, for which the regional specific yield has been estimated. It should be noted that the complete geologic section forming the Edwards aquifer was tested. Because of the dip of the aquifer, all the geologic strata occur at different places near the water table in the unconfined area.

Table 6.--Summary of Estimates of Specific Yield or Drainable Porosity of the Edwards Aquifer

Method of estimate	Specific yield (percent)	Remarks
1. Regional specific yield. (Based on the annual water balance and the changes in stage in the aquifer.)	3	Annual estimates vary from less than 1 to more than 4 percent.
2. Estimates of drainable porosity for the entire thickness of the aquifer on the basis of visual examination of cores.		Much of the observable porosity is poorly connected or not connected. Only a fraction will drain by gravity. Porosity consists of relatively small-size openings between the allochems or dolomite crystals. Visual openings in the rocks in the freshwater zone are, in general, of a large size.
A. Test holes completed in saline-water zone:		
Randolph	6	
San Marcos	6	
Devine	14	
B. Test holes completed in freshwater zone:		
Feathercrest	10	
Lockhill	8	
Castle Hills	10	
Rio Medina	12	
Sabinal	8	
3. Estimates of drainable porosity on the basis of laboratory and geophysical data.		Neutron porosity was multiplied by a porosity factor, which is a decimal fraction representing the number of voids connected by pore-throat diameters of more than 10 microns (0.0004 inch).
Test holes completed in freshwater zone:		
Feathercrest	2.0	
Lockhill	1.7	
Castle Hills	2.0	
Rio Medina	2.5	
Sabinal	2.1	

The volume of water in storage in the confined freshwater zone of the aquifer, which has an area of 1,500 mi^2, is estimated to be 19.5 million acre-feet. This estimated volume is based on an estimated average specific yield of 4 percent and an aquifer thickness of 500 feet. This is a very large volume of water; but, only a small fraction of this volume can be recovered economically because of adverse conditions, such as major water-level declines, greater cost of pumping, and local invasion of saline water. Some of these adverse conditions could occur gradually and could be difficult to detect within a short period of time.

Hydrologic Balance

The hydrologic balance is represented by an equation which states that inflow equals outflow, plus or minus change in storage for a designated period. In the Edwards aquifer, inflow is equivalent to recharge; outflow is the summation of pumpage and spring flow; and the change in storage is indicated by changes in water levels of wells. Water levels in index well AY-68-37-203, which is located at Fort Sam Houston in San Antonio, are used to indicate the relative volume of water in storage. Monthly or yearly average water levels in this well correlate closely with other monthly or yearly average water levels in wells distributed throughout the Edwards aquifer (Puente, 1976). The relation of water levels in downtown San Antonio to changes in the annual water balance for the Edwards aquifer is shown in Figure 22.

Annual pumpage has more than tripled since 1934, but water levels have also risen to record highs. The explanation of this apparent anomaly is that during this period, recharge has been substantially greater than normal. The intermittent, rapid lowering of water levels during the summer in index well AY-68-37-203 during the 1960's and 1970's is the result of greater daily pumping rates by wells in the Bexar County area. Transient pressure waves resulting from changes in pumping rates are transmitted and attenuated quickly through the zone of the confined aquifer.

Application of the hydrologic budget equation to the Edwards aquifer provides only a general approximation of the hydrologic regime. It does not account for areal variations in recharge, aquifer characteristics, and discharge. The average annual hydrologic budget does not indicate short-term transient effects which may be quite significant in individual wells.

The recharge component of the hydrologic balance has been estimated for 1934-78 and is tabulated in Table 7. The method of calculating annual recharge is based on data collected from a network of streamflow-gaging stations and on assumptions related to applying the runoff characteristics from gaged areas to ungaged areas. The basic approach is the continuity equation in which recharge within a stream basin is the difference between measured streamflow upstream and downstream from the infiltration area of the aquifer plus the estimated inflow from the interstream areas within the infiltration area. Details of the procedures for calculating recharge are given by Puente (1978).

The calculated discharge by county during 1934-76 is given in Table 8. Pumpage data are obtained from large users, which include municipalities, water districts, and industries. Springflow is measured regularly at Comal Springs and San Marcos Springs. Other springs are measured periodically.

Table 7.--Calculated Annual Recharge to the Edwards Aquifer by Basin, 1934-78
(Data in thousands of acre-feet)

Calendar year	Nueces-West Nueces River basin	Frio-Dry Frio River basin1/	Sabinal River basin1/	Area between Sabinal River and Medina River basins1/	Medina Lake	Area between Cibolo Creek and Medina River basins1/	Cibolo-Dry Comal Creek basin	Blanco River basin1/	Total
1934	8.6	27.9	7.5	19.9	46.5	21.0	28.4	19.8	179.6
1935	411.3	192.3	56.6	166.2	71.1	138.2	182.7	39.8	1,258.2
1936	176.5	157.4	43.5	142.9	91.6	108.9	146.1	42.7	909.6
1937	28.8	75.7	21.5	61.3	80.5	47.8	63.9	21.2	400.7
1938	63.5	69.3	20.9	54.1	65.5	46.2	76.8	36.4	432.7
1939	227.0	49.5	17.0	33.1	42.4	9.3	9.6	11.1	399.0
1940	50.4	60.3	23.8	56.6	38.8	29.3	30.8	18.8	308.8
1941	89.9	151.8	50.6	139.0	54.1	116.3	191.2	57.8	850.7
1942	103.5	95.1	34.0	84.4	51.7	66.9	93.6	28.6	557.8
1943	36.5	42.3	11.1	33.8	41.5	29.5	58.3	20.1	273.1
1944	64.1	76.0	24.8	74.3	50.5	72.5	152.5	46.2	560.9
1945	47.3	71.1	30.8	78.6	54.8	79.6	129.9	35.7	527.8
1946	80.9	54.2	16.5	52.0	51.4	105.1	155.3	40.7	556.1
1947	72.4	77.7	16.7	45.2	44.0	55.5	79.5	31.6	422.6
1948	41.1	25.6	26.0	20.2	14.8	17.5	19.9	13.2	178.3
1949	166.0	86.1	31.5	70.3	33.0	41.8	55.9	23.5	508.1
1950	41.5	35.5	13.3	27.0	23.6	17.3	24.6	17.4	200.2
1951	18.3	28.4	7.3	26.4	21.1	15.3	12.5	10.6	139.9
1952	27.9	15.7	3.2	30.2	25.4	50.1	102.3	20.7	275.5
1953	21.4	15.1	3.2	4.4	36.2	20.1	42.3	24.9	167.6
1954	61.3	31.6	7.1	11.9	25.3	4.2	10.0	10.7	162.1
1955	128.0	22.1	.6	7.7	16.5	4.3	3.3	9.5	192.0
1956	15.6	4.2	1.6	3.6	6.3	2.0	2.2	8.2	43.7
1957	108.6	133.6	65.4	129.5	55.6	175.6	397.9	76.4	1,142.6
1958	266.7	300.0	223.8	294.9	95.5	190.9	268.7	70.7	1,711.2
1959	109.6	158.9	61.6	96.7	94.7	57.4	77.9	33.6	690.4
1960	88.7	128.1	64.9	127.0	104.0	89.7	160.0	62.4	824.8
1961	85.2	151.3	57.4	105.4	88.3	69.3	110.8	49.4	717.1
1962	47.4	46.6	4.3	23.5	57.3	16.7	24.7	18.9	239.4
1963	39.7	27.0	5.0	10.3	41.9	9.3	21.3	16.2	170.7
1964	126.1	57.1	16.3	61.3	43.3	35.8	51.1	22.2	413.2
1965	97.9	83.0	23.2	104.0	54.6	78.8	115.3	66.7	623.5
1966	169.2	134.0	37.7	78.2	50.5	44.5	66.5	34.6	615.2
1967	82.2	137.9	30.4	64.8	44.7	30.2	57.3	19.0	466.5
1968	130.8	176.0	66.4	198.7	59.9	83.1	120.5	49.3	884.7
1969	119.7	113.8	30.7	84.2	55.4	60.2	99.9	46.6	610.5
1970	112.6	141.9	35.4	81.6	68.0	68.8	113.8	39.5	661.6
1971	263.4	212.4	39.2	155.6	68.7	81.4	82.4	22.2	925.3
1972	108.4	144.6	49.0	154.6	87.9	74.3	104.2	33.4	756.4
1973	190.6	256.9	123.9	286.4	97.6	237.2	211.7	82.2	1,486.5
1974	91.1	135.7	36.1	115.3	96.2	68.1	76.9	39.1	658.5
1975	71.8	143.6	47.9	195.9	93.4	138.8	195.7	85.9	973.0
1976	150.7	238.6	68.2	182.0	94.5	47.9	54.3	57.9	894.1
1977	102.9	193.0	62.7	159.5	77.7	97.9	191.6	66.7	952.0
1978	69.8	73.1	30.9	103.7	76.7	49.6	72.4	26.3	502.5
Average	102.6	103.4	36.7	90.1	57.6	64.5	96.6	35.7	587.2

1/ Includes recharge from gaged and ungaged areas within the basin.

Table 8.--Calculated Annual Discharge From the Edwards Aquifer by County, 1934-78
(Data in thousands of acre-feet)

Year	Spring and well discharge					Total	Total spring discharge	Total well discharge
	Kinney-Uvalde Counties	Medina County	Bexar County	Comal County	Hays County			
1934	12.6	1.3	109.3	229.1	85.6	437.9	336.0	101.9
1935	12.2	1.5	171.8	237.2	96.9	519.6	415.9	103.7
1936	26.6	1.5	215.2	261.7	93.2	598.2	485.5	112.7
1937	28.3	1.5	201.8	252.5	87.1	571.2	451.0	120.2
1938	25.2	1.6	187.6	250.0	93.4	557.8	437.7	120.1
1939	18.2	1.6	122.5	219.4	71.1	432.8	313.9	118.9
1940	16.1	1.6	116.7	203.8	78.4	416.6	296.5	120.1
1941	17.9	1.6	197.4	250.0	134.3	601.2	464.4	136.8
1942	22.5	1.7	203.2	255.1	112.2	594.7	450.1	144.6
1943	19.2	1.7	172.0	249.2	97.2	539.3	390.2	149.1
1944	11.6	1.7	166.3	252.5	135.3	567.4	420.1	147.3
1945	12.4	1.7	199.8	263.1	137.8	614.8	461.5	153.3
1946	6.2	1.7	180.1	261.9	134.0	583.9	428.9	155.0
1947	13.8	2.0	193.3	256.8	127.6	593.5	426.5	167.0
1948	9.2	1.9	159.2	203.0	77.3	450.6	281.9	168.7
1949	13.2	2.0	165.3	209.5	89.8	479.8	300.4	179.4
1950	17.8	2.2	177.3	191.1	78.3	466.7	272.9	193.8
1951	16.9	2.2	186.9	150.5	69.1	425.6	215.9	209.7
1952	22.7	3.1	187.1	133.2	78.8	424.9	209.5	215.4
1953	27.5	4.0	193.7	141.7	101.4	468.3	238.5	229.8
1954	26.6	6.3	208.9	101.0	81.5	424.3	178.1	246.2
1955	28.3	11.1	215.2	70.1	64.1	388.8	127.8	261.0
1956	59.6	17.7	229.6	33.6	50.4	390.9	69.8	321.1
1957	29.0	11.9	189.4	113.2	113.0	456.5	219.2	237.3
1958	23.7	6.6	199.5	231.8	155.9	617.5	398.2	219.3
1959	43.0	8.3	217.5	231.7	118.5	619.0	384.5	234.5
1960	53.7	7.6	215.4	235.2	143.5	655.4	428.3	227.1
1961	56.5	6.4	230.3	249.5	140.8	683.5	455.3	228.2
1962	64.6	8.1	220.0	197.5	98.8	589.0	321.1	267.9
1963	51.4	9.7	217.3	155.7	81.9	516.0	239.6	276.4
1964	49.3	8.6	201.0	141.8	73.3	474.0	213.8	260.2
1965	46.8	10.0	201.1	194.7	126.3	578.9	322.8	256.1
1966	48.5	10.4	198.0	198.9	15.4	571.2	315.3	255.9
1967	81.1	15.2	239.7	139.1	82.3	557.4	216.1	341.3
1968	58.0	9.9	207.1	238.2	146.8	660.0	408.3	251.7
1969	88.5	13.6	216.3	218.2	122.1	658.7	351.2	307.5
1970	100.9	16.5	230.6	229.2	149.9	727.1	397.7	329.4
1971	117.0	32.4	262.8	168.2	99.1	679.5	272.7	406.8
1972	112.6	28.8	247.7	234.3	123.7	747.1	375.8	371.3
1973	96.5	14.9	273.0	289.3	164.3	838.0	527.6	310.4
1974	133.3	28.6	272.1	286.1	141.1	861.2	483.8	377.4
1975	112.0	22.6	259.0	296.0	178.6	868.2	540.4	327.8
1976	136.4	19.4	253.2	279.7	164.7	853.4	503.9	349.5
1977	156.5	19.9	317.5	295.0	172.0	960.9	580.3	380.6
1978	154.3	38.7	269.5	245.7	99.1	807.3	375.5	431.8

The record high and low water levels in selected observation wells in the Edwards aquifer are given in Table 9. Water-level maps for the Edwards aquifer have been prepared for 23 different dates from 1934 to 1976 (Maclay, Small, and Rettman, 1980).

Ground-Water Circulation and Rate of Movement

The regional direction of ground-water flow in the Edwards aquifer is determined primarily by altitude, whereas, local direction of flow is determined largely by local characteristics of the aquifer framework. The regional direction of ground-water flow, as interpreted from all available data, is shown in Figure 23.

Recharge occurs primarily along the stream beds of the major streams crossing the outcrop of the rocks forming the Edwards aquifer. Part of this recharge is derived from the base flow and part is derived from the flood flow, which begins in the upper reaches and may include the entire reach during intense storms. A small quantity of the recharge occurs in the interstream areas by direct infiltration. The top of the saturated zone generally is several hundred feet below the land surface throughout most of the recharge area; therefore, recharge is limited by the ability of the limestone to transmit water downward. Only a very small part of the recharge occurs as underflow from the Edwards Plateau, primarily in northeastern Kinney County.

In general, the slope of the water-level surface in the recharge area is toward the confined zone. The slope of the potentiometric surface within the confined freshwater zone declines toward the major springs in the eastern part of the San Antonio area. The slight slope of that potentiometric surface is indicative of the capacity of the rocks to transmit the large volumes of water from the recharge area in the western part of the San Antonio area.

In eastern Kinney and western Uvalde Counties, ground water moves toward Leona Springs, south of Uvalde. Ground water moves southeastward from central Uvalde County in the area between Laguna and the Dry Frio River toward the confined zone of the aquifer in eastern Uvalde and western Medina Counties. In southeastern Uvalde County, ground water moves toward a large cone of depression south of U.S. Highway 90. This cone of depression is intermittently developed by pumping for irrigation. The area where the cone develops is intensively faulted and contains many impermeable intrusive igneous rocks. The lateral continuity of the permeable strata is disrupted by the many faults that strike in different directions and form numerous barriers to ground-water flow. These geologic factors have lessened the capacity of the aquifer to transmit water through this area.

In northern Medina County, the direction of ground-water flow is affected primarily by parallel northeastward-striking faults that divert the flow toward the southwest. The steep regional slope of the potentiometric surface toward the southeast is the result of these faults being local barriers to southeastward flow. The altitudes of the water levels change abruptly across segments of the major faults in northern Medina County (Holt, 1959). Ground water was traced by a dye for a distance of several miles parallel to the Medina Lake fault southwest of Medina Lake (C. L. R. Holt, Jr., U.S. Geological Survey, retired, oral commun., 1976). Investigations of the concentrations of tritium, an environmental tracer, support the interpretation that water moves toward the southwest in northern Medina County (Pearson, Rettman, and Wyerman, 1975).

Table 9.--Annual High and Low Water Levels and Record High and Low Water Levels in Selected Observation Wells in the Edwards Aquifer, 1975-78

(Levels are in feet above National Geodetic Vertical Datum of 1929)

Well	1975		1976		1977		1978		Record high	Record low	Period of record
	High	Low	High	Low	High	Low	High	Low			
YP-69-50-302 1/ H-5-1 (Uvalde County)	881.48	879.45	884.98	876.02	886.26	881.36	882.61	875.67	886.26 May 1977	811.0 Apr. 1957	1929-32 1934-78
TD-68-41-301 1/ J-1-82 (Medina County)	720.79	707.46	732.32	694.84	737.78	715.65	722.36	681.62	737.78 May 1977	622.3 Aug. 1956	1950-78
AY-68-37-203 1/ 2/ J-17 (Bexar County)	686.99	671.99	693.09	663.76	695.95	675.63	684.11	650.13	696.5 Oct. 1973	3/ 612.5 Aug. 1956	1932-78 4/
DX-68-23-302 1/ G-49 (Comal County)	628.50	626.50	629.38	625.76	630.15	627.61	628.05	624.52	630.17 Apr. 1977	613.3 Aug. 1956	1948-78
LR-67-01-304 1/ H-23 (Hays County)	589.85	571.42	584.55	571.20	587.95	567.80	572.00	540.40	593.8 Mar. 1968	540.4 July 1978	1937-78

1/ New State well number replaces old well number.
2/ Replaces well 26 and reflects the same water level; composite record of wells 26 and AY-68-37-203.
3/ Record low for well 26.
4/ Composite record of wells 26 and AY-68-37-203.

The Haby Crossing fault in northeast Medina County and northwestern Bexar County vertically separates the Edwards aquifer in the recharge area from the Edwards aquifer in the confined zone (Figure 3). Consequently, ground water cannot readily move from the recharge area directly into the confined zone in this area.

In northwestern Medina County, ground water moves into the confined zone from the major sources of recharge, which are to the northwest in Uvalde County and the northeast in Medina County. This large recharge forces the water to move far southward into the confined zone. No major fault barriers occur within the confined zone to obstruct the southward movement of ground water in this area.

In southern Medina County, ground water moves eastward toward Bexar County. At places along segments of the Dunlay, Castroville, and Pearson faults, the aquifer is completely or almost completely displaced vertically, which restricts or prevents ground-water circulation perpendicular to the faults. Most of the ground-water flow from Medina County into Bexar County probably occurs south of the Castroville fault. The chemistry of the water south of the Castroville fault typically is similar to that of the main zone of circulation, whereas the chemistry of the water to the north is different from that of the main zone of circulation (Maclay, Rettman, and Small, 1980).

In northeast Bexar County, water moves southward or southeastward from the unconfined zone toward the confined zone of the aquifer. In the vicinity of Cibolo Creek, water may move from Bexar County through the unconfined zone into Comal County.

In the confined zone in Bexar County, ground water generally moves northeastward toward the "neck" of the aquifer in the vicinity of Selma. When water levels are high, however, ground water is diverted locally toward San Pedro Springs and San Antonio Springs, which are intermittent and artesian. These springs occur along a fault that marks the southeast boundary of a horst that probably diverts ground-water flow locally to the northeast and to the southeast.

In northwestern Comal County, water in the unconfined zone moves toward Hueco Springs from the area northwest of the Hueco Springs fault. A narrow and complexly faulted graben that extends northeastward from the vicinity of Bracken to Hunter may act as a ground-water drain that collects water northwest of the Hueco Springs fault. In the area between the Hueco Springs fault and Comal Springs fault, ground water is diverted northeastward; however, some flow is discharged locally at Comal Springs.

The confined freshwater zone of the Edwards aquifer in Comal County occupies a narrow band that extends along the Comal Springs fault from the downthrown side of Comal Springs fault to the "bad-water" line. A substantial flow of ground water moves northeastward through the confined aquifer toward Comal Springs. Along most of the length of Comal Springs fault between Bexar County and Comal Springs, the confined part of the aquifer is vertically separated from the unconfined aquifer on the upthrown side of the fault. Therefore, water from the unconfined zone cannot move directly into the confined zone. However, near Bracken, the confined and unconfined zones of the Edwards aquifer are not completely separated, and water may move from either zone into the other zone.

Most of the flow of Comal Springs is sustained by underflow along the downthrown side of Comal Springs fault. This conclusion is supported by tritium studies and other hydrochemical data. The concentrations and ratios of the major dissolved constituents in the springflow remain markedly constant and are very similar to the concentrations in water in the confined aquifer in Bexar County.

In southern Hays County, substantial water flow moves northeastward through the confined aquifer within a narrow strip between the Hueco Springs and Comal Springs faults and discharges at San Marcos Springs. Part of the flow of San Marcos Springs also is sustained by water moving southeastward from the recharge area in southern Hays County. In northeastern Hays County, a poorly-defined ground-water divide separates the Edwards aquifer in the San Antonio area from the Edwards aquifer to the northeast.

The rate of ground-water movement in a cavernous carbonate aquifer is rapid in comparison to the rate of movement in a sandstone aquifer. Velocities as fast as 0.5 mi/d were measured in carbonate aquifers of Ordovician age in the Ozark region of Missouri (Skelton and Miller, 1979). In comparison, ground-water velocities in sandstone aquifers commonly are only a few centimeters per day.

Ground-water velocities in the Edwards aquifer have been estimated or measured by several different methods. A gross estimate can be made for the confined freshwater zone on the basis of the estimated total volume of water stored in the confined zone of the aquifer, which is 19.5 million acre-feet, and the approximate average annual recharge of 550,000 acre-feet. The residence time for water in the confined zone is about 35 years. The average distance an increment of water from the confined aquifer west of Comal Springs would travel through the confined aquifer to Comal Springs during the 35 years is about 65 miles. Based on these values, the estimated ground-water velocity is about 27 ft/d.

The distribution of trichlorofluoromethane, that served as a ground-water tracer in the eastern part of the San Antonio area, has been investigated by Thompson and Hayes (1979). They identified a plume of ground water containing trichlorofluoromethane that extends about 46 miles from north San Antonio to San Marcos. Trichlorofluoromethane, which is a manmade compound used for industrial purposes, was first produced commercially in 1931. Therefore, the tracer has moved from its source to the sink in no more than 45 years, which is an average minimum velocity of 14.4 ft/d. It is far more likely, however, that the tracer was first introduced into the ground water during the past 10 to 15 years when use of the compound became more prevalent.

On the basis of tritium concentrations, Pearson (1973) estimated the residence time for water in the freshwater zone of the Edwards aquifer to be greater than 20 years, and on the basis of carbon-14 data, estimated the residence time of waters in the saline-water zone to be greater than several tens of thousands of years. Estimates of ground-water velocities, using Rhodamine WT dye, were made at several well sites within Bexar County. These estimates range from 2 to 31 ft/d at the sites (Maclay, Small, and Rettman, 1981).

SUMMARY OF CONCLUSIONS

1. The permeability of the Edwards aquifer in the San Antonio area is related directly to particular strata (lithofacies) and to the leaching of these strata in the freshwater zone of the aquifer. Ground water has moved along vertical or steeply inclined, open fractures that act as passageways by which water can enter the permeable strata. Water moves from the fractures into collapse breccias, burrowed wackestones, and rudist grainstones that have significant intrinsic permeability. Ground water has dissolved the pore walls within these rocks to create a very permeable strata; therefore, laterally extensive beds having cavernous or honeycomb porosity occur at stratigraphically controlled intervals within the freshwater zone of the Edwards aquifer.

2. The character of the lithofacies and their lateral extent in the Edwards aquifer were determined by the dominant processes of sedimentation acting in three major and significantly different depositional regions, which persisted throughout an extended period of Early Cretaceous time. The depositional environment of the San Marcos platform varied from open marine seas to arid, hot, supratidal flats. Areally extensive, thin-to-medium bedded strata consisting predominantly of pelleted and intraclastic micrites that contained permeable, dolomitized sediments accumulated to a thickness of about 500 feet. These sediments were partly leached during Cretaceous time.

3. Recrystallization of the rocks of the Edwards aquifer has resulted in a net decrease in total porosity in the freshwater zone of the aquifer, but has greatly modified and increased the pore sizes and interconnections in some lithofacies; consequently, permeability has been greatly enhanced.

4. The texture and composition of the rocks in the freshwater zone are very different from the texture and composition of the rocks in the saline-water zone because of diagenesis produced by circulating freshwater. Rocks in the saline-water zone typically are mostly dolomitic and medium to dark gray or brown. They contain unoxidized organic material including petroleum and accessory minerals, such as pyrite, gypsum, and celestite. The matrix of the rocks in the saline-water zone is more porous than that of stratigraphically equivalent rocks in the freshwater zone. However, the voids are predominantly small interparticle, intraparticle, and intercrystalline pores. The permeability of the rocks is relatively small because of the small size of the interconnections between the pores.

Rocks in the freshwater zone typically are calcitic, light buff to white, mostly recrystallized, and dense. They contain little pyrite and no gypsum. In parts of the aquifer where ground-water circulation is relatively slow or negligible, the rock typically is a darker gray or brown. These rocks contain permeable zones formed by solutioning of breccia, moldic, and honeycomb porosity.

5. The Edwards aquifer on the San Marcos platform consists of eight hydrostratigraphic subdivisions (layered heterogeneity). Very permeable zones occur in the upper part of subdivision 2, in the lower part of subdivision 3, in dispersed zones in subdivision 6, and in the upper part of subdivision 7. The Maverick basin consists of three hydrostratigraphic subdivisions. The Salmon Peak, the uppermost subdivision, is the most permeable.

The aquifer is separated into an upper and lower zone by subdivision 4 (regional dense member of the Kainer Formation) on the San Marcos platform and by subdivision 2 (McKnight Formation) in the Maverick basin. These subdivisions, which have negligible permeability, hydraulically separate the aquifer in those areas where the vertical displacements along faults have not positioned the permeable zones against more permeable zones.

6. Discontinuous heterogeneity occurs in the Edwards aquifer where faults place rocks of significantly different permeabilities next to each other. This type of heterogeneity, which is very common, exerts a major control on the direction of ground-water flow.

7. Trending heterogeneity is caused by a gradational change in permeability on a regional scale. Trending heterogeneity occurs in the Edwards aquifer because of regional changes in carbonate depositional environments, location of paleokarst, and characteristics of solution-channel networks near springs issuing from carbonate rocks.

8. Regional anisotropy in the Edwards aquifer is difficult to determine from the available data; however, hydrogeologic conditions for development of anisotropy occur in some places. No single value or direction can realistically represent anisotropic characteristics for the entire aquifer because the conditions vary significantly from place to place.

9. In the San Antonio area, the estimated relative transmissivities are based on the geology, hydrology, and hydrochemistry of the Edwards aquifer subarea. The transmissivities are estimated to range from a negligible value in parts of the recharge area to about 2 million ft^2/d for the most permeable subarea in the confined zone of the aquifer.

10. The storage coefficient in the confined zone varies with the porosity and thickness of the aquifer; however, the order of magnitude probably ranges from about 1×10^{-4} to 1×10^{-5}.

11. On the basis of hydrologic data, regional specific yield in the unconfined zone is about 3 percent. An estimate of drainable porosity for the full thickness of the aquifer is about 2 percent based upon geophysical and laboratory data. The estimate of drainable porosity on the basis of visual observation of test-hole cores is about 10 percent. Much of the observable porosity apparently is poorly connected or not connected.

12. The general direction of ground-water flow is from the Edwards Plateau to the Balcones fault zone and from there to a major discharge area in the eastern part of the San Antonio area. Faults significantly affect the local direction of ground-water flow.

13. An estimate of the average ground-water velocity within the confined freshwater zone is about 27 ft/d. Estimates of ground-water velocities made at well sites range from 2 to 31 ft/d.

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