GEOLOGIC FRAMEWORK OF THE EDWARDS AQUIFER AND UPPER CONFINING UNIT, AND HYDROGEOLOGIC CHARACTERISTICS OF THE EDWARDS AQUIFER, SOUTH-CENTRAL UVALDE COUNTY, TEXAS

U.S. GEOLOGICAL SURVEY
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Prepared in cooperation with the
SAN ANTONIO WATER SYSTEM

Cover photograph: Buda Limestone outcrop at Toadstool Waterhole on the Frio River, Uvalde County, Texas. Photograph by Allan K. Clark, August 1993.

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FIGURE

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Geologic Framework of the Edwards Aquifer and Upper Confining Unit, and Hydrogeologic Characteristics of the Edwards Aquifer, South-Central Uvalde County, Texas

By Allan K. Clark *and* Ted A. Small

Abstract

The stratigraphic units of the Edwards aquifer in south-central Uvalde County generally are porous and permeable. The stratigraphic units that compose the Edwards aquifer in south-central Uvalde County are the Devils River Formation in the Devils River trend; and the West Nueces, McKnight, and Salmon Peak Formations in the Maverick Basin. The Balcones fault zone is the principal structural feature in Uvalde County; however, the displacement along the fault zone is less in Uvalde County than in adjacent Medina and Bexar Counties to the east. The Uvalde Salient is a structural high in south-central Uvalde County, and consists of several closely connected crustal uplifts that bring Edwards aquifer strata to the surface generally forming prominent hills. The crustal uplifts forming this structural high are the remnants of intrusive and extrusive magnatic activity. Six primary faults—Cooks, Black Mountain, Blue Mountain, Uvalde, Agape, and Connor—cross the length of the study area from the southwest to the northeast juxtaposing the Lower Cretaceous Salmon Peak Formation at the surface in the northwestern part of the study area against Upper Cretaceous formations in the central part of the study area. In the study area, the porosity of the rocks in the Edwards aquifer is related to depositional or diagenetic elements along specific stratigraphic horizons (fabric selective) and to dissolution and structural elements that can occur in any lithostratigraphic horizon (not fabric selective). Permeability depends on the physical properties of the rock such as size, shape, distribution of pores, and fissuring and dissolution. The middle 185 feet of the lower part of the Devils River Formation, the upper part of the Devils River Formation, and the upper unit of the Salmon Peak Formation probably are the most porous and permeable stratigraphic zones of the Edwards aquifer in south-central Uvalde County.

INTRODUCTION

The Edwards aquifer is one of the most permeable and productive carbonate aquifers in the Nation. The dissolution-modified, faulted limestone aquifer is the sole source of public water supply for the city of Uvalde and is the major source of water for Uvalde County (fig. 1). In addition, the Edwards aquifer provides large quantities of water to agriculture, industry, and major springs. In Uvalde County, the Edwards aquifer comprises rocks of Lower Cretaceous age of the Devils River Formation (Lozo and Smith, 1964) in the Devils River trend depositional province; and equivalent rocks of the West Nueces, McKnight, and Salmon Peak Formations in the Maverick Basin depositional province (Lozo and Smith, 1964). In the southeastern part of Uvalde County, the lateral continuity of these formations is disrupted by Balcones faulting and by a structural high that brings Lower Cretaceous strata to the surface juxtaposed against Upper Cretaceous strata. This structural high, known as the Uvalde Salient (Welder and Reeves, 1962), is associated with late Cretaceous and early Tertiary igneous activity.

Streams cross the Edwards aquifer outcrop (the recharge zone) in the Balcones fault zone (fig. 1) and lose much, if not all, of their flow to faults, fractures, sinkholes, and caves in the outcrop. After entering the aquifer, the water moves east to points of discharge in Medina and Bexar Counties (mostly irrigation and municipal wells) and then northeast, parallel or almost parallel to the northeast-trending Balcones faults into

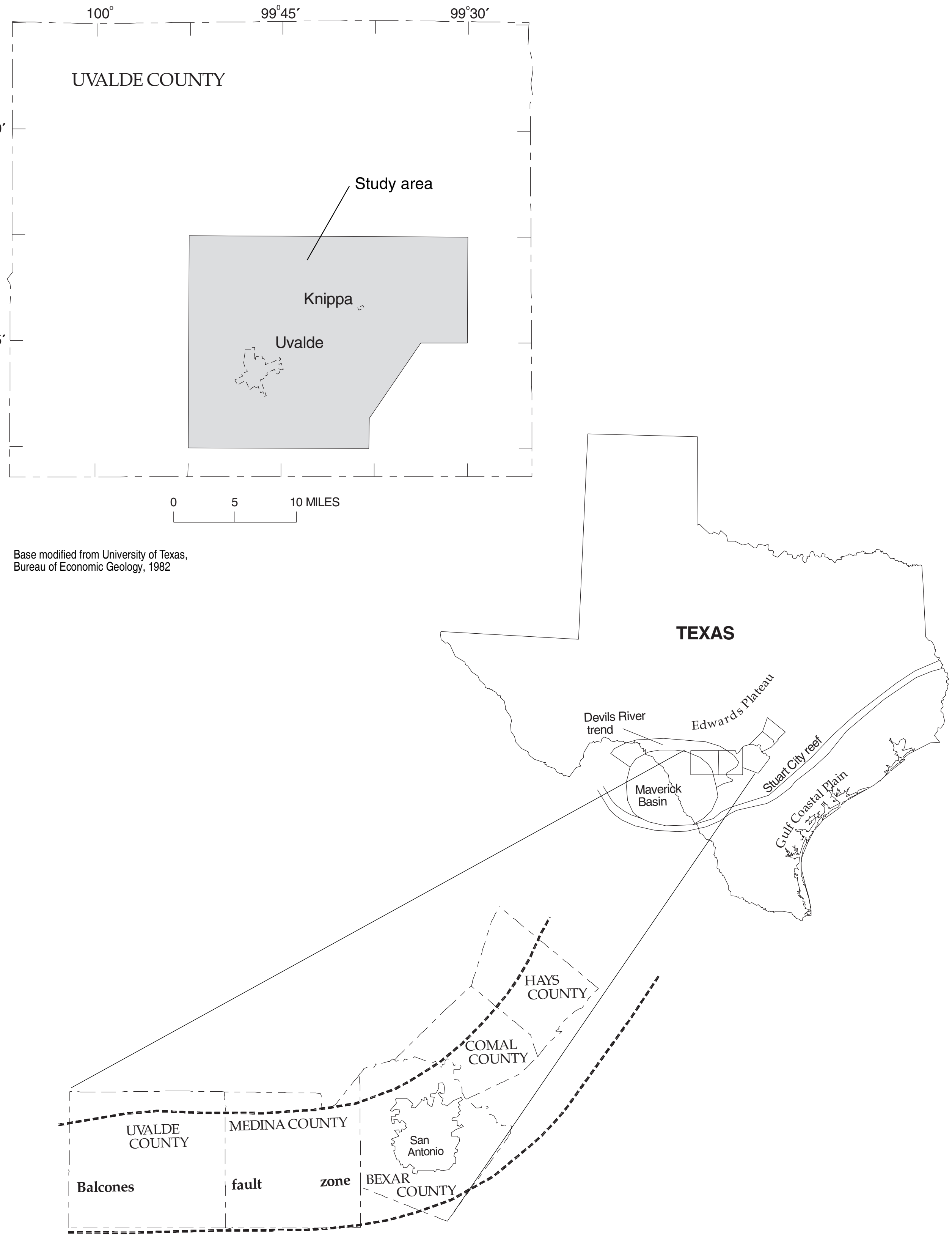

Figure 1. Location of study area and depositional provinces.

Comal and Hays Counties, where it is discharged by wells and springs.

The U.S. Geological Survey, in cooperation with the San Antonio Water System, mapped the Edwards aquifer outcrop and upper confining unit in south-central Uvalde County and described the hydrogeologic characteristics (porosity and permeability) of the Edwards aquifer to document conditions pertinent to the movement of ground water. This report describes the geologic framework of the Edwards aquifer and the upper confining unit, and the hydrogeologic characteristics of the Edwards aquifer in south-central Uvalde County. This report also delineates the surficial extent of igneous rocks present in the study area.

Methods of Investigation

The stratigraphic nomenclature and descriptions of Lozo and Smith (1964) were used to map the Edwards aquifer outcrop and upper confining unit in the Devils River trend (table 1) and the Maverick Basin (table 2). The carbonate-rock classification system of Dunham (1962) was used for the lithologic descriptions. The sedimentary carbonate classification system of Choquette and Pray (1970) was used to determine the porosity type. The stratigraphic units of the Edwards aquifer outcrop and upper confining unit in south-central Uvalde County are shown on plate 1. Pliocene- and Pleistocene-age rocks and recent alluvium were not mapped.

Recent aerial photographs were used to locate roads and excavations that could provide outcrop exposures for field examination. In addition, stratigraphic information was ascertained by inspection of surficial expressions and features as indicated by the following examples: The upper one-half of the Salmon Peak Formation can be identified on aerial photographs by a pattern of concentric rings of sparse vegetation growing on the differentially weathered limestone. Igneous outcrop can be recognized on aerial photographs as dark, semicircular patches.

Well logs and geologic map data were compiled and used in mapping the stratigraphic units of the Edwards aquifer and upper confining unit in the study area. The thicknesses of the stratigraphic units that compose the Edwards aquifer were determined from well logs in and adjacent to the aquifer in south-central Uvalde County.

Faults were identified in the field by stratigraphic displacement and characteristics related to faulting, such as juxtaposition of unlike formations, zones of fault gouge composed of soils that greatly resemble caliche, or relatively thick, sometimes vein-like masses of euhedral to subhedral calcite crystals. Steeply inclined strata, uncommon in the relatively flat-lying Edwards aquifer outcrop, typically represent drag-folding related to faulting.

Acknowledgments

Special thanks are extended to Bill Story and the Uvalde County Tax Assessors Office for the use of their aerial photographs. Also, thanks are extended to the owners and operators of the Agape Ranch and Vulcan Materials in Knippa who allowed repeated access to their property. In addition, the authors express thanks to H.H. Toone who provided access to Tower Mountain.

GEOLOGIC FRAMEWORK

General Features

The Balcones fault zone (fig. 1) is the principal structural feature in Uvalde County (Welder and Reeves, 1962). However, the displacement along the fault zone is less in Uvalde County than in Medina and Bexar Counties. Balcones faults are en echelon, high-angle, normal, and generally downthrown to the southeast in this area; however, a few faults are downthrown to the northwest. Balcones faults are nearly vertical (George, 1952), and some completely offset the rocks of the Edwards aquifer (Maclay and Small, 1984). Associated with the northeast-trending Balcones faults are faults that strike primarily northwest. Many of the faults show no surface expression because they are covered by thick sequences of Tertiary gravels and can be identified only from well logs. Displacement on most faults in the study area is difficult to determine; an exception is the Connor fault (pl. 1), which has a displacement greater than 500 feet (ft). A regional dip of about 3 degrees to the south and southeast for Cretaceous strata in Uvalde County was reported by Welder and Reeves (1962).

In the northern part of the study area, Balcones faults have formed part of an escarpment that separates the Gulf Coastal Plain from the Edwards Plateau (fig. 1). This escarpment roughly parallels the Cooks fault (pl. 1) in the study area. Geomorphic expression of faulting on the upthrown fault blocks is indicated on topographic maps by the branching of subsequent valleys normal to the consequent valleys, forming a "T-square" morphology of the valleys. The formation of

Table 1. Summary of the lithologic and hydrologic properties of the stratigraphic units of the Devils River trend, south-central Uvalde County, Texas

[Groups and formations modified from Welder and Reeves (1962), Lozo and Smith (1964), Rose (1972), Humphreys (1984), Miller (1984), and Ewing and Barker (1986); lithology modified from Dunham (1962); and porosity type modified from Choquette and Pray (1970). CU, confining unit; *, not exposed in the study area; AQ, aquifer]

System	Hydro-geologic unit	Group or formation	Hydro-logic function	Thick-ness (feet)	Lithology	Field identification	Cavern develop-ment	Porosity/ permeability type
Tertiary	Upper confining unit	Indio Formation	CU	150–200	Light-gray to buff sandstone and sandy shale	Dark-brown sandstone, with abundant bog iron ore	None	Low porosity/low permeability
		Kincaid Formation	CU	15	Clay, siltstone; fine-grained sandstone and limestone	*	*	Low porosity/low permeability
Upper Cretaceous		Escondido Formation	CU	285	Fine-grained sandstone, with interbedded shale, clay, and pyroclastic material	Brown, fine-grained sandstone, locally fossiliferous	None	Low porosity/low permeability
		Anacacho Limestone	CU	Greater than 470	Massive mudstone to packstone, with interbedded bentonitic clay	White to gray packstone, with thick sequences of bentonitic clays	None	Low porosity/low permeability
		Austin Group	CU	300	Massive, chalky to marly, fossiliferous mudstone	White, chalky limestone; *Gryphaea aucella*	None	Low to moderate porosity and permeability
		Eagle Ford Group	CU	130–150	Brown, flaggy, sandy shale and argillaceous limestone	Thin flagstones; petroliferous	None	Primary porosity lost/low permeability
		Buda Limestone	CU	70–90	Buff to light-gray, dense mudstone	Porcelaneous limestone	Minor surface karst	Low porosity/low permeability
		Del Rio Clay	CU	90–110	Blue-green to yellow-brown clay	Fossiliferous; *Ilymatogyra arietina*	None	None; primary upper confining unit
Lower Cretaceous	Edwards aquifer	Devils River Formation, upper part	AQ	250	Light-gray wackestone to *miliolid* grainstone; chert	Fossiliferous; *Caprinid*	Probably extensive cave develop-ment	Both fabric and not fabric/one of the most porous and permeable
		Devils River Formation, lower part	AQ	350	Light-gray, dense, shaly, nodular mudstone grading to a burrowed mudstone to wackestone; mudstone and collapsed breccia on top	*	*	Mostly not fabric, low to high porosity/ low to high permeability
	Lower confining unit	Upper member of the Glen Rose Limestone	CU; evaporite beds AQ	350–500	Yellowish tan, thinly bedded limestone and marl	*	*	Some water production at evaporite beds/relatively impermeable

the consequent valleys resulted from the drop in base level of the downthrown block, which initiated headward erosion on the escarpment. The development of the subsequent valleys possibly is the result of faults structurally weakening the consequent valley slopes creating the T-square pattern normal to the natural course of headward erosion (Thornbury, 1962).

The structural high known as the Uvalde Salient in south-central Uvalde County causes the strata composing the Edwards aquifer to rise from about 900 ft below land surface to the surface in a distance of about 8 miles (mi) and then to drop to about 300 ft below land surface within another 6 mi (Welder and Reeves, 1962). According to Welder and Reeves (1962, p. 31), this

Table 2. Summary of the lithologic and hydrologic properties of the stratigraphic units of the Maverick Basin, south-central Uvalde County, Texas

[Groups and formations modified from Welder and Reeves (1962), Lozo and Smith (1964), Rose (1972), Humphreys (1984), Miller (1984), and Ewing and Barker (1986); lithology modified from Dunham (1962); and porosity type modified from Choquette and Pray (1970). CU, confining unit; *, not exposed in the study area; AQ, aquifer]

System	Hydro-geologic unit	Group or formation		Hydro-logic function	Thick-ness (feet)	Lithology	Field identification	Cavern develop-ment	Porosity/ permeability type
Tertiary	Upper confining unit	Indio Formation		CU	150–200	Light-gray to buff sandstone and sandy shale	Dark-brown sandstone, with abundant bog iron ore	None	Low porosity/ low permeability
		Kincaid Formation		CU	15	Clay, siltstone; fine-grained sandstone and limestone	*	*	Low porosity/ low permeability
Upper Cretaceous		Escondido Formation		CU	285	Fine-grained sandstone, with interbedded shale, clay, and pyroclastic material	Brown, fine-grained sandstone, locally fossiliferous	None	Low porosity/ low permeability
		Anacacho Limestone		CU	Greater than 470	Massive mudstone to packstone, with interbedded bentonitic clay	White to gray packstone, with thick sequences of bentonitic clays	None	Low porosity/low permeability
		Austin Group		CU	300	Massive, chalky to marly, fossiliferous mudstone	White, chalky limestone, with locally abundant *Gryphaea aucella*	None	Low to moderate porosity and permeability
		Eagle Ford Group		CU	130–150	Brown, flaggy, sandy shale and argillaceous limestone	Thin flagstones; petroliferous	None	Primary porosity lost/low permeability
		Buda Limestone		CU	70–90	Buff to light-gray, dense mudstone	Porcelaneous limestone	Minor surface karst	Low porosity/low permeability
		Del Rio Clay		CU	90–110	Blue-green to yellow-brown clay	Fossiliferous; *Ilymatogyra arietina*	None	None; primary upper confining unit
Lower Cretaceous	Edwards aquifer	Salmon Peak Formation	Upper unit	AQ	75	Grainstone that grades to mudstone	Light-gray mudstone, with abundant fossil fragments	Minor karst	Both fabric and not fabric, low to high porosity/low to moderate permeability
			Lower unit	AQ	310	Thick, massive lime mudstone; chert	Massive, gray mudstone	Minor karst	Mostly not fabric; low porosity/low permeability
		McKnight Formation	Upper member	CU	Greater than 45	Thinly bedded wackestone to grainstone	*	*	Mostly not fabric; low porosity/low permeability
			Middle member	CU	20	Dark, fissile, carbonaceous lime mudstone	*	*	Mostly not fabric; low porosity/low permeability
			Lower member	CU	95–100	Thinly bedded lime mudstone to grainstone, with evaporite collapse	*	*	Mostly not fabric; low porosity/low permeability
		West Nueces Formation	Unit B	CU	150	Fossiliferous grainstone to wackestone	*	*	Mostly not fabric; low porosity/low permeability
			Unit A	CU	50	White, medium to thick-bedded mudstone to packstone	*	*	Mostly not fabric; low porosity/low permeability
			Burrowed member	CU	30–40	Fossiliferous lime mudstone to packstone	*	*	Mostly not fabric; low porosity/low permeability
			Basal nodular member	CU	60–70	Nodular lime mudstone	*	*	Mostly not fabric; low porosity/low permeability
	Lower confining unit	Upper member of the Glen Rose Limestone		CU; evaporite beds AQ	350–500	Yellowish tan, thinly bedded limestone and marl	*	*	Some water production at evaporite beds/relatively impermeable

structural high consists of several closely connected crustal uplifts where rocks of the Edwards aquifer and other formations are at the surface and generally form prominent hills. These uplifts are associated with extrusive and intrusive igneous rocks that extend from Blue Mountain (pl. 1) southwestward through Uvalde to Rocky Hill, eastward to Frio Mountain, and northeastward to about FM 2730. The Uvalde volcanoes roughly form the axis of the Uvalde Salient and were termed "The Frio River Line" by Ewing and Barker (1986). These extrusive rocks are the remnants of submarine and subaerial volcanoes (Ewing and Barker, 1986) and unroofed laccoliths (Welder and Reeves, 1962). It is uncertain whether the igneous rocks are connected in the subsurface.

Prominent hills near Uvalde and Knippa are composed of either Salmon Peak Limestone or basaltic rocks. Surrounding these hills are Upper Cretaceous formations that lie at lower elevations. Crossing the structural high is a series of faults older than those commonly associated with the Balcones fault zone that attenuate to the southwest and northeast. These faults are complex locally, often showing little relief or surface expression, and typically covered by Tertiary and Quaternary gravels. These faults are the result of uplift associated with the emplacement of magma during the late Cretaceous (Ewing and Barker, 1986), which was modified by Balcones faulting during the Miocene age (Maclay and Land, 1988).

In the central part of the study area, strata generally dips 2 to 7 degrees to the east and west away from the structural high. In most cases, these dips were determined from well logs because of lack of exposure. Six primary faults—Cooks, Black Mountain, Blue Mountain, Uvalde, Agape, and Connor (pl. 1)—strike southwest to northeast and cross almost the length of the study area, resulting in the Lower Cretaceous Salmon Peak Formation at the surface in the northwestern part of the study area juxtaposed against Upper Cretaceous formations in the central part of the study area.

Stratigraphy

The Devils River Formation (Lozo and Smith, 1964) (table 1) is about 600 ft thick (Miller, 1984) in the Devils River trend in south-central Uvalde County. The Devils River Formation is divided informally into lower and upper parts. The lower Devils River Formation is about 350 ft thick but is not exposed in the study area. According to Miller (1984), the lower Devils River Formation consists of light-gray, dense, shaly, nodular mudstone that grades to a burrowed mudstone to wackestone; mudstone and collapsed breccia are on top. The upper Devils River Formation is about 250 ft thick and consists of light-gray wackestone to *miliolid* grainstone. Rudists, shell fragments, chert nodules, and thin chert beds are scattered throughout. *Caprinid* fossils are common locally at the northern edge of the study area.

The Maverick Basin rocks that compose the Edwards aquifer (table 2) range in thickness from about 185 to 860 ft thick in south-central Uvalde County. The West Nueces Formation (Lozo and Smith, 1964) is the lowermost formation of the Edwards aquifer and comprises four informal members (Miller, 1984). The lowermost unit, the basal nodular member, is about 60 to 70 ft thick and consists of nodular lime mudstone. The next higher member, the 30- to 40-ft-thick burrowed member, is mostly fossiliferous lime mudstone to packstone. Unit A, which overlies the burrowed member, is about 50 ft thick and consists of medium- to thick-bedded mudstone to packstone. Unit B, the uppermost member of the West Nueces Formation, is about 150 ft thick and primarily is fossiliferous grainstone to wackestone. The West Nueces Formation is not exposed in the study area.

Miller (1984, p. 9) divided the McKnight Formation, which overlies the West Nueces Formation, into three informal members (table 2). The lower member is about 95 to 100 ft thick and consists of thinly bedded lime mudstone to grainstone. The middle member is about 20 ft thick and consists of dark, fissile, carbonaceous lime mudstone. The upper member is greater than 45 ft thick and consists of thinly bedded wackestone to grainstone. The McKnight Formation, like the West Nueces Formation, is not exposed in the study area.

The Salmon Peak Formation (Lozo and Smith, 1964), which overlies the McKnight Formation, is about 385 ft thick and is divided informally into lower and upper units. The lower unit consists of thick, massive lime mudstone. In the upper 165 ft of the lower unit, chert beds are common and grainstone is abundant. The upper unit of the Salmon Peak Formation is about 75 ft thick and consists of grainstone that grades to mudstone (Humphreys, 1984).

The upper confining unit of the Devils River (table 1) and Salmon Peak Formations (table 2) consists of the Upper Cretaceous Del Rio Clay, Buda Limestone, Eagle Ford Group, Austin Group, Anacacho Limestone, Escondido Formation, and the Tertiary Kincaid and

Indio Formations. Igneous rocks are present in all of the formations in the study area because of late Cretaceous and early Tertiary igneous activity (Getzendaner, 1931). The Del Rio Clay is about 90 to 110 ft thick and thickens to the west of the study area. The Del Rio Clay is a dark blue-green to yellow-brown clay with thin beds of impermeable limestone. Iron nodules and the fossil oyster *Ilymatogyra arietina*, formerly *Exogyra arietina* (Roemer), are abundant locally. Excellent exposures of the Del Rio Clay are found north of Uvalde adjacent to US 83 (pl. 1). In this area, *Ilymatogyra arietina* is abundant, and the contact between the Del Rio Clay and the overlying Buda Limestone is distinct and easily recognized.

The Buda Limestone overlies the Del Rio Clay and consists of buff to light-gray, dense mudstone, weathering from a smooth gray to a grayish-white, nodular surface (tables 1, 2). Bored rip-up clasts of Del Rio Clay can be found within the bottom few inches of the Buda Limestone north of Uvalde; however, these clasts are not common. Blocks of resistant Buda Limestone have slumped onto the slopes of the Del Rio Clay adjacent to US 83 north of Uvalde (pl. 1).

The Eagle Ford Group is about 130 to 150 ft thick (Welder and Reeves, 1962, p. 19) and consists of brown, flaggy, sandy shale and argillaceous limestone (tables 1, 2). Some of the freshly fractured flagstones emit a petroliferous odor. The best exposures of the Eagle Ford Group in south-central Uvalde County are found near Toadstool Waterhole (pl. 1).

The Austin Group overlies the Eagle Ford Group and consists of massive, chalky, locally marly, generally fossiliferous mudstone commonly containing the fossil oyster *Gryphaea aucella*. The Austin Group thickens from about 275 ft in the eastern part of the county to more than about 500 ft in the southwestern part of the county (Welder and Reeves, 1962, p. 20). Field observations indicate that Austin Group outcrops located near igneous bodies commonly are sandy with abundant fossil fragments, iron nodules, and fractures. These fractures usually contain void-filling calcite, sometimes in the form of dogtooth spar. The best exposure of the Austin Group in south-central Uvalde County is at Cypress Waterhole (pl. 1).

The Anacacho Limestone is greater than 470 ft thick and consists of massive mudstone to packstone with interbedded bentonitic clay (tables 1, 2). The Anacacho Limestone primarily crops out over most of the eastern one-half of the study area, and exposures can be found along the Frio River between Traprock and Black Waterhole (pl. 1).

The Escondido Formation overlies the Anacacho Limestone and consists of fine-grained sandstone, with interbedded shale, clay, and pyroclastic material (Welder and Reeves, 1962). The only exposures of the Escondido Formation are found in the eastern part of the study area (pl. 1).

The Kincaid Formation, about 15 ft thick (Welder and Reeves, 1962), overlies the Escondido Formation but is not exposed in the study area. The Kincaid Formation consists of clay, siltstone, and small amounts of fine-grained sandstone and limestone.

The nonmarine Indio Formation is exposed in the southern part of the study area and is composed of light-gray to buff sandstone and sandy shale. In some areas, the Indio Formation contains thin beds of lignite and bog iron ore (Welder and Reeves, 1962).

Igneous rocks are in all of the formations in the study area (and therefore are not included in tables 1 and 2). The late Cretaceous and early Tertiary igneous rocks consist of melilite-olivine nephelinite, nepheline basanite, olivine basalt, olivine nephelinite, and phonolite (Ewing and Barker, 1986). According to Welder and Reeves (1962), some of the igneous rocks and associated pyroclastics are known locally as "serpentine." The term serpentine refers to the soft, green-to-yellow clays associated with the diagenesis of pyroclastics and basalts. These soft, easily eroded tuffs are abundant along the Frio River from Black Waterhole to Connor Lane (pl. 1); they are commonly found in stream cuts.

Depositional History

The formations and members that compose the Edwards aquifer reflect a variety of depositional environments, tectonic sedimentary processes, reef deposition, and fluctuations of paleomarine waters. The rocks of the West Nueces, McKnight, and Salmon Peak Formations in the Maverick Basin were deposited in a marine basin; and the rocks that would become the Devils River Formation in the Devils River trend formed a fringing carbonate bank around the basin (fig. 1). The Devils River Formation is stratigraphically equivalent to the combined West Nueces, McKnight, and Salmon Peak Formations. The lateral transition between the Devils River Formation and the West Nueces, McKnight, and Salmon Peak Formations is gradational, with interfingering and prograding over areas in the basin.

According to Rose (1974, p. 17), the rocks of the subtidal West Nueces and McKnight Formations were deposited in the Maverick Basin, which was restricted between the Stuart City reef to the south and tidal flats or shallow water barriers on the other sides, and lagoonal evaporites and organic-rich euxenic shales accumulated. As these shales accumulated, the rocks of the intertidal and supratidal lower Devils River Formation were accumulating to the north and west. The Maverick Basin subsided to become a deep (100 to 600 ft), open-marine embayment in which rocks of the Salmon Peak Formation accumulated. At the same time, rocks of the upper Devils River Formation were deposited along what is now called the Devils River trend. The rocks of the upper Devils River Formation formed a carbonate bank composed of rudist bioherms and biostromes.

During a marine transgression, subsidence of the Maverick Basin ceased and the Stuart City reef (fig. 1) was breached (Rose, 1974, p. 17). This breaching allowed for the deposition of the rocks of the Del Rio Clay (tables 1, 2), thus ending the deposition of the rocks of the Salmon Peak and upper Devils River Formations (Maclay and Small, 1984). The rocks of the Buda Limestone were deposited over the rocks of the Del Rio Clay following a marine regression/transgression episode. Deposition of the rocks of the Eagle Ford Group began with a drop in sea level, an increase in siliciclastic deposition, and the development of an anoxic environment (Trevino, 1988). Deposition of the rocks of the Eagle Ford Group ceased after a subsequent rise in sea level, and deposition of the rocks of the Austin Group, which occurred in an epicontinental sea, began (Frazier and Schwimmer, 1987).

The rocks of the Anacacho Limestone accumulated as patchy biostromes on bathymetric highs associated with the igneous intrusions, and also as atoll reefs or bank deposits around seamounts (Wilson, 1983), with interbedded sequences of pyroclastic ash (Welder and Reeves, 1962). After the rocks of the Anacacho Limestone were deposited, aerial exposure of the area caused a 10-million-year time gap in the geologic record (Ewing and Barker, 1986). Evidence of this time gap can be found in western Uvalde County, where the Escondido Formation unconformably overlies the Austin Group. The Indio Formation, which overlies the unexposed Kincaid Formation, was deposited in a nonmarine environment.

Late Cretaceous igneous activity in the area caused uplift that resulted in subaerial exposure during the middle period of Upper Cretaceous time (Ewing and Barker, 1986). This igneous activity is believed to be the result of late Cretaceous compressional forces that reactivated weak zones in the Ouachita thrust belt (Wilson, 1977) and (or) a change in mantle convection regimes (Ewing and Barker, 1986). Igneous activity was both intrusive (laccoliths, dikes, and possibly sills) and extrusive (submarine and subaerial volcanoes), and led to the formation of pyroclastics and possibly lava flows (Ewing and Barker, 1986). Excellent exposures of extrusive igneous rocks can be found at Black Waterhole and Traprock (pl. 1). Igneous rocks are believed to form the core of many of the Lower Cretaceous exposures in the study area, such as Frio Hill and Salt Mountain. Many wells in the county penetrate basalt and serpentine (Welder and Reeves, 1962, p. 31). Taylor Mountain is an example of a Lower Cretaceous complex that has been eroded down to the igneous core.

HYDROGEOLOGIC CHARACTERISTICS

Major factors controlling porosity and permeability in the Edwards aquifer in the study area are faulting, stratification, karstification, and igneous rocks. Zones of faulted, fractured, and dissolutioned limestone, along with layers of burrowed, honeycombed, and occasionally cavernous limestone are common in the Edwards aquifer. Possible barriers to flow within the study area might be the result of complex faulting and igneous bodies. The complex faulting in the area suggests that impermeable material might be in fault contact with rocks of the Edwards aquifer in some places, blocking or retarding eastward flow (Welder and Reeves, 1962, p. 41). Maclay and Land (1988, p. A20) reported that the study area is intensively faulted and contains many poorly permeable, intrusive igneous rocks. The lateral continuity of the Edwards aquifer is disrupted by the many faults that strike in different directions and form numerous barriers to ground-water flow. These geologic factors have reduced the capacity of the aquifer to transmit water. A break in the hydraulic continuity could occur along the southern edge of the study area at the Connor fault (pl. 1). In this area, faulting has uplifted the Del Rio Clay against the Indio Formation (Welder and Reeves, 1962).

Igneous rocks might act as barriers to ground-water flow by filling primary voids with secondary minerals, thus decreasing permeability. Porosity and permeability decrease with time, and porosity might decrease to less than 1 percent (Erdelyi and Galfi, 1988). Also, dikes and sills generally have a porosity of less than 5 percent; thus, these features could impede the vertical and horizontal movement of ground water. Permeability in igneous rocks tends to be localized, resulting primarily from other primary and secondary structures within the rock such as joints caused by cooling and intersecting vesicles (Davis and DeWiest, 1966). According to Todd (1959), subsurface igneous bodies can be highly impermeable. Pumping in the study area occasionally creates a regional cone of depression that is believed to be directly related to the presence of igneous rocks. In the study area, local transmissivity can be large, but the capacity of the rocks as a whole to transmit water is small (Maclay and Small, 1984, p. 66). Evidence of low porosity and permeability can be seen at the Black Waterhole (pl. 1) and at many other waterholes along the lower Frio River within the study area; the areas with low porosity and permeability generally are underlain by either basalt or pyroclastics. Northeast of Black Waterhole, exposures of basalt (informally called "Gaging station basalt" on plate 1) show well-developed columnar joints that have been infilled with secondary calcite. Small baked zones associated with igneous bodies in the study area (F.A. Welder, U.S. Geological Survey, written commun., 1957) might have partially reduced the primary porosity of the formation penetrated. Faulting and fracturing are associated with the emplacement and subsequent contraction of the igneous bodies; however, such faulting and fracturing is not evident in the field because of alluvial cover. Austin Group outcrops containing stress fractures overlain by pyroclastics lie between Black Waterhole and the Gaging station basalt. Between the Black Waterhole and the Cypress Waterhole (pl. 1) are several areas of outcrop also containing stress fractures that generally have been filled partly or completely by secondary mineralization. This secondary mineralization primarily is calcite; but iron oxide staining can be found along fractures, which indicates that igneous bodies influenced porosity and permeability in nearby formations.

According to Choquette and Pray (1970, p. 212), porosity in sedimentary carbonates is either fabric selective or not fabric selective. Fabric selective porosity is related directly to the depositional or diagenetic fabric elements of a sediment and typically is controlled by lithostratigraphic horizon. Not fabric selective porosity is not related to depositional or diagenetic fabric elements of a sediment and can exist in any lithostratigraphic horizon.

Choquette and Pray (1970, p. 222) designated seven types of carbonate porosity that are "extremely common and volumetrically important." Five of these (interparticle, intraparticle, intercrystalline, moldic, and fenestral) generally are fabric selective, and two (fracture and vuggy) are not fabric selective. According to Choquette and Pray (1970, p. 223–224), breccia porosity is a type of interparticle porosity and can be either fabric selective or not fabric selective. Other types of porosity in the Edwards aquifer are channel and cavern, both of which are not fabric selective; and burrow, which can be either fabric selective or not fabric selective. Choquette and Pray (1970, p. 250) noted that vugs and channels are similar in that neither is fabric selective. Vugs and channels differ in shape; "vug" is used to describe the more equidimensional pores; whereas "channel" is used to describe markedly elongated pores or irregular openings with a marked elongation in one or two dimensions.

According to Ford and Williams (1989, p. 130), permeability depends on the physical properties of the rock, particularly size, shape, and distribution of pores, and fissuring and dissolution. Ford and Williams (1989, p. 150) further state that, a consequence of the effects of fissuring and differential solution, permeability might be greater in some directions and stratigraphic horizons than in others.

The Devils River Formation in the Devils River trend (table 1) is one of the most porous and permeable stratigraphic units of the Edwards aquifer in south-central Uvalde County. The lowermost 45 ft of the lower part of the Devils River Formation has very low porosity (less than 3 percent) and permeability (Sieh, 1975). The next 50 ft of strata has about 8 percent fracture, intercrystalline, and vuggy porosity. The middle 185 ft of the lower part of the Devils River Formation probably is the most porous and permeable section of that unit, with breccia, cavern, fracture, and vuggy porosity, ranging from low (less than 3 percent) to high (15 percent). The uppermost 70 ft of the lower part of the Devils River Formation consists of rocks with less than 3 percent fracture, moldic, and vuggy porosity. The upper part of the Devils River Formation consists of rocks with low (less than 3 percent) to high (15 percent) cavernous, moldic, fracture, and vuggy porosity (Sieh, 1975). Outcrops of the upper part of the formation in the study area show predominantly fracture, moldic, cavern, and breccia porosity, which indicates that the upper part of the Devils River probably is one of the more permeable units in the study area.

In the Maverick Basin (table 2), the West Nueces Formation contains low, moldic porosity (5 to 10 percent) (Hovorka and others, 1993) and little to no permeability. Fractures within this formation have been filled with secondary calcite (Small and Maclay, 1982). The McKnight Formation contains mainly vuggy and breccia porosity, with a few fractures. The McKnight Formation also has little to no permeability, with predominantly low porosity (less than 3 percent); however, the breccia porosity in this formation might be as high as 25 percent (Small and Maclay, 1982). The Salmon Peak Formation is the uppermost stratigraphic unit of the Edwards aquifer in the Maverick Basin and probably is the most porous and permeable. The lowermost 250 ft of the lower unit of the Salmon Peak Formation has low fracture and vuggy porosity (less than 3 percent) and low permeability (Small and Maclay, 1982). Porosity and permeability in the upper unit of the Salmon Peak Formation ranges from very low (less than 1 percent) to very high (25 percent) (Sieh, 1975). The upper unit of the formation probably is one of the more porous and permeable in the study area. In the northern part of the study area, the porosity types are interparticle, moldic, fenestral, fracture, breccia, vuggy, and cavern. South of Black Mountain fault, the outcrop has predominantly fracture, breccia, interparticle, moldic, and cavern porosity.

SUMMARY

The Edwards aquifer, sole source of public water supply for the city of Uvalde, is the major source of water for Uvalde County. In addition, the Edwards aquifer provides large quantities of water to agriculture, industry, and major springs. The aquifer primarily consists of dissolution-modified, faulted limestone. In Uvalde County, the Edwards aquifer comprises rocks of Lower Cretaceous age of the Devils River Formation (Devils River trend depositional province); and the West Nueces, McKnight, and Salmon Peak Formations (Maverick Basin depositional province).

Normally, most recharge to the Edwards aquifer occurs in basins west of Bexar County. Streams cross Edwards aquifer outcrops (the recharge zone) in the Balcones fault zone and lose much, if not all, of their flow to faults, fractures, sinkholes, and caves in the outcrop. After entering the aquifer, the water moves east to points of discharge in Medina and Bexar Counties (mostly irrigation and municipal wells) and then northeast, parallel or almost parallel to the northeast-trending Balcones faults into Comal and Hays Counties, where it is discharged by wells and springs.

The Balcones fault zone is the principal structural feature in Uvalde County; however, the displacement along the fault zone is less in Uvalde County than in Medina and Bexar Counties. The Uvalde Salient is a structural high in south-central Uvalde County and consists of several closely connected crustal uplifts that bring Edwards aquifer rocks to the surface in the form of prominent hills. The basalts that form the axis of the Uvalde Salient are remnants of intrusive and extrusive magnatic activity. The six primary faults in south-central Uvalde County are Cooks, Black Mountain, Blue Mountain, Uvalde, Agape, and Connor. These faults strike southwest to northeast and cross almost the length of the study area, resulting in the Lower Cretaceous Salmon Peak Formation at the surface in the northwestern part of the study area juxtaposed against Upper Cretaceous formations in the central part of the study area.

The formations and members that compose the Edwards aquifer reflect a variety of depositional environments, tectonic sedimentary processes, reef deposition, and fluctuations of paleomarine waters. The rocks of the West Nueces, McKnight, and Salmon Peak Formations were deposited in a marine basin; and the rocks of the Devils River Formation formed a fringing carbonate bank around the basin. The Devils River Formation in the Devils River trend is stratigraphically equivalent to the combined West Nueces, McKnight, and Salmon Peak Formations in the Maverick Basin.

The major factors controlling porosity and permeability in the Edwards aquifer in the study area are faulting, stratification, karstification, and igneous rocks. Zones of faulted, fractured, and dissolutioned limestone, along with layers of burrowed, honeycombed, and occasionally cavernous limestone, are common in the Edwards aquifer. Igneous rocks might act as barriers to ground-water flow by filling primary voids with secondary minerals, thus decreasing permeability. Small baked zones associated with igneous bodies might have partially reduced the primary porosity of the formation penetrated.

The two types of porosity in the Edwards aquifer are fabric selective, which is related to the depositional or diagenetic elements of a sediment and typically is controlled by lithostratigraphic horizon; and not fabric selective, which can exist in any lithostratigraphic horizon. Permeability in the study area depends on the physical properties of the rock such as size, shape, and distribution of pores, and fissuring and dissolution. The middle 185 ft of the lower part of the Devils River Formation, the upper part of the Devils River Formation, and the upper unit of the Salmon Peak Formation probably are the most porous and permeable stratigraphic zones of the Edwards aquifer in south-central Uvalde County.

REFERENCES CITED

Choquette, P.W., and Pray, L.C., 1970, Geologic nomenclature and classification of porosity in sedimentary carbonates: American Association of Petroleum Geologists Bulletin, v. 54, no. 2, p. 207–250.

Davis, S.N., and DeWiest, R.J.M., 1966, Hydrogeology: New York, Wiley, 333 p.

Dunham, R.J., 1962, Classification of carbonate rocks according to depositional texture, *in* Classification of Carbonate Rocks Symposium: American Association of Petroleum Geologists Memoir 1, p. 108–121.

Erdelyi, Mihaly, and Galfi, Janos, 1988, Surface and subsurface mapping in hydrogeology: New York, Wiley, p. 234–237.

Ewing, T.E., and Barker, D.S., 1986, Late Cretaceous igneous rocks of the Uvalde area, southwest Texas: San Antonio, South Texas Geological Society Guidebook, p. 1–5.

Ford, D.C., and Williams, P.W., 1989, Karst geomorphology and hydrology: London, Chapman and Hall, 601 p.

Frazier, W.J., and Schwimmer, D.R., 1987, Regional stratigraphy of North America: New York, Plenum Press, p. 406–407.

George, W.O., 1952, Geology and ground-water resources of Comal County, Texas: U.S. Geological Survey Water-Supply Paper 1138, 126 p.

Getzendaner, F.M., 1931, Mineral resources of Texas, Uvalde County: Austin, University of Texas, Bureau of Economic Geology Mineral Resources Pamphlet, p. 93–111.

Hovorka, S.D., Ruppel, S.C., Dutton, A.R., and Yeh, Joseph, 1993, Edwards aquifer storage assessment, Kinney County to Hays County, Texas: San Antonio, Edwards Underground Water District, 109 p.

Humphreys, C.H., 1984, Stratigraphy of the lower Cretaceous (Albian) Salmon Peak Formation of the Maverick Basin, south Texas, *in* Stratigraphy and structure of the Maverick Basin and Devils River trend, lower Cretaceous, southwest Texas: San Antonio Geological Society, p. 34–59.

Lozo, F.E., Jr., and Smith, C.I., 1964, Revision of Comanche Cretaceous stratigraphic nomenclature, southern Edwards Plateau, Southwest Texas: Gulf Coast Association of Geological Societies Transactions, v. 14, p. 285–306.

Maclay, R.W., and Land, L.F., 1988, Simulation of flow in the Edwards aquifer, San Antonio region, Texas, and refinement of storage and flow concepts: U.S. Geological Survey Water-Supply Paper 2336–A, p. A5–A20.

Maclay, R.W., and Small, T.A., 1984, Carbonate geology and hydrology of the Edwards aquifer in the San Antonio area, Texas: U.S. Geological Survey Open-File Report 83–537, 72 p.

Miller, B.C., 1984, Physical stratigraphy and facies analysis, lower Cretaceous, Maverick Basin and Devils River trend, Uvalde and Real Counties, Texas, *in* Stratigraphy and structure of the Maverick Basin and Devils River trend, lower Cretaceous, southwest Texas: San Antonio Geological Society, p. 3–33.

Rose, P.R., 1972, Edwards Group, surface and subsurface, central Texas: Austin, University of Texas, Bureau of Economic Geology Report of Investigations 74, 34 p.

_____ed., 1974, Stratigraphy of the Edwards Group and equivalents, eastern Edwards Plateau, Texas: San Antonio, South Texas Geological Society Guidebook, 120 p.

Sieh, T.W., 1975, Edwards (Balcones fault zone) aquifer test well drilling investigation: Texas Water Development Board, fig. 15.

Small, T.A., and Maclay, R.W., 1982, Test-hole data for the Edwards aquifer in the San Antonio area, Texas: Texas Department of Water Resources Limited Publication 171, p. 137–153.

Thornbury, W.D., 1962, Principles of geomorphology: New York, Wiley, 617 p.

Todd, D.K., 1959, Ground water hydrology: New York, Wiley, p. 41.

Trevino, R.H., 1988, Facies and depositional environments of the Boquillas Formation, upper Cretaceous of southwest Texas: Arlington, Tex., University of Texas at Arlington, M.A. thesis, p. 54–63.

University of Texas, Bureau of Economic Geology, 1982, Geologic atlas of Texas, San Antonio sheet: Austin, scale 1:250,000.

Welder, F.A., and Reeves, R.D., 1962, Geology and ground-water resources of Uvalde County, Texas: Texas Water Commission Bulletin 6212, p. 8–215.

Wilson, Douglas, 1983, Paleoenvironments of the upper Cretaceous Anacacho Formation in southwestern Texas: South Texas Geological Society Bulletin, v. 24, no. 2, p. 22–28.

Wilson, W.F., 1977, Relict tectonism in south Texas: South Texas Geological Society Bulletin, v. 17, no. 5, p. 23–25.