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Geologic Framework and Hydrogeologic Characteristics of the Edwards Aquifer, Uvalde County, Texas

Water-Resources Investigations Report 03–4010

U.S. Department of the Interior
U.S. Geological Survey

Cover:

Sabinal River, Uvalde County, looking south at the Devils River Formation/Glen Rose Limestone contact; hills are Devils River, exposed rock is Glen Rose.

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By Allan K. Clark

U.S. GEOLOGICAL SURVEY
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(Plate is in pocket)

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VERTICAL DATUM

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

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Abstract

The Edwards aquifer in Uvalde County is composed of Lower Cretaceous carbonate (mostly dolomitic limestone) strata of the Devils River Formation in the Devils River trend and of the West Nueces, McKnight, and Salmon Peak Formations in the Maverick basin. Rocks in the Devils River trend are divided at the bottom of the Devils River Formation into the (informal) basal nodular unit. Maverick basin rocks are divided (informally) into the basal nodular unit of the West Nueces Formation; into lower, middle, and upper units of the McKnight Formation; and into lower and upper units of the Salmon Peak Formation. The Edwards aquifer overlies the (Lower Cretaceous) Glen Rose Limestone, which composes the lower confining unit of the Edwards aquifer. The Edwards aquifer is overlain by the (Upper Cretaceous) Del Rio Clay, the basal formation of the upper confining unit. Upper Cretaceous and (or) Lower Tertiary igneous rocks intrude all stratigraphic units that compose the Edwards aquifer, particularly in the southern part of the study area.

The Balcones fault zone and the Uvalde salient are the principal structural features in the study area. The fault zone comprises mostly en echelon, high-angle, and down-to-the-southeast normal faults that trend mostly from southwest to northeast. The Uvalde salient—resulting apparently from a combination of crustal uplift, diverse faulting, and igneous activity—elevates the Edwards aquifer to the surface across the central part of Uvalde County. Downfaulted blocks associated with six primary faults—Cooks, Black Mountain, Blue Mountain, Uvalde, Agape, and Connor—juxtapose the Salmon Peak Formation (Lower Cretaceous) in central parts of the study area against Upper Cretaceous strata in the southeastern part.

The carbonate rocks of the Devils River trend and the Maverick basin are products of assorted tectonic and depositional conditions that affected the depth and circulation of the Cretaceous seas. The Devils River Formation formed in a fringing carbonate bank—the Devils River trend—in mostly open shallow marine environments of relatively high wave and current energy. The West Nueces, McKnight, and Salmon Peak Formations resulted mostly from partly restricted to open marine, tidal-flat, and restricted deep-basinal environments in the Maverick basin.

The porosity of the Edwards aquifer results from depositional and diagenetic effects along specific lithostratigraphic horizons (fabric selective) and from structural and solutional features that can occur in any lithostratigraphic horizon (non-fabric selective). In addition to porosity depending upon the effects of fracturing and the dissolution of chemically unstable (soluble) minerals and fossils, the resultant permeability depends on the size, shape, and distribution of the porosity as well as the interconnection among the pores. Upper parts of the Devils River Formation and the upper unit of the Salmon Peak Formation compose some of the most porous and permeable rocks in Uvalde County.

INTRODUCTION

The Edwards aquifer, in carbonate (mostly dolomitic limestone) strata of Early Cretaceous age, is one of the most permeable and productive aquifers in the

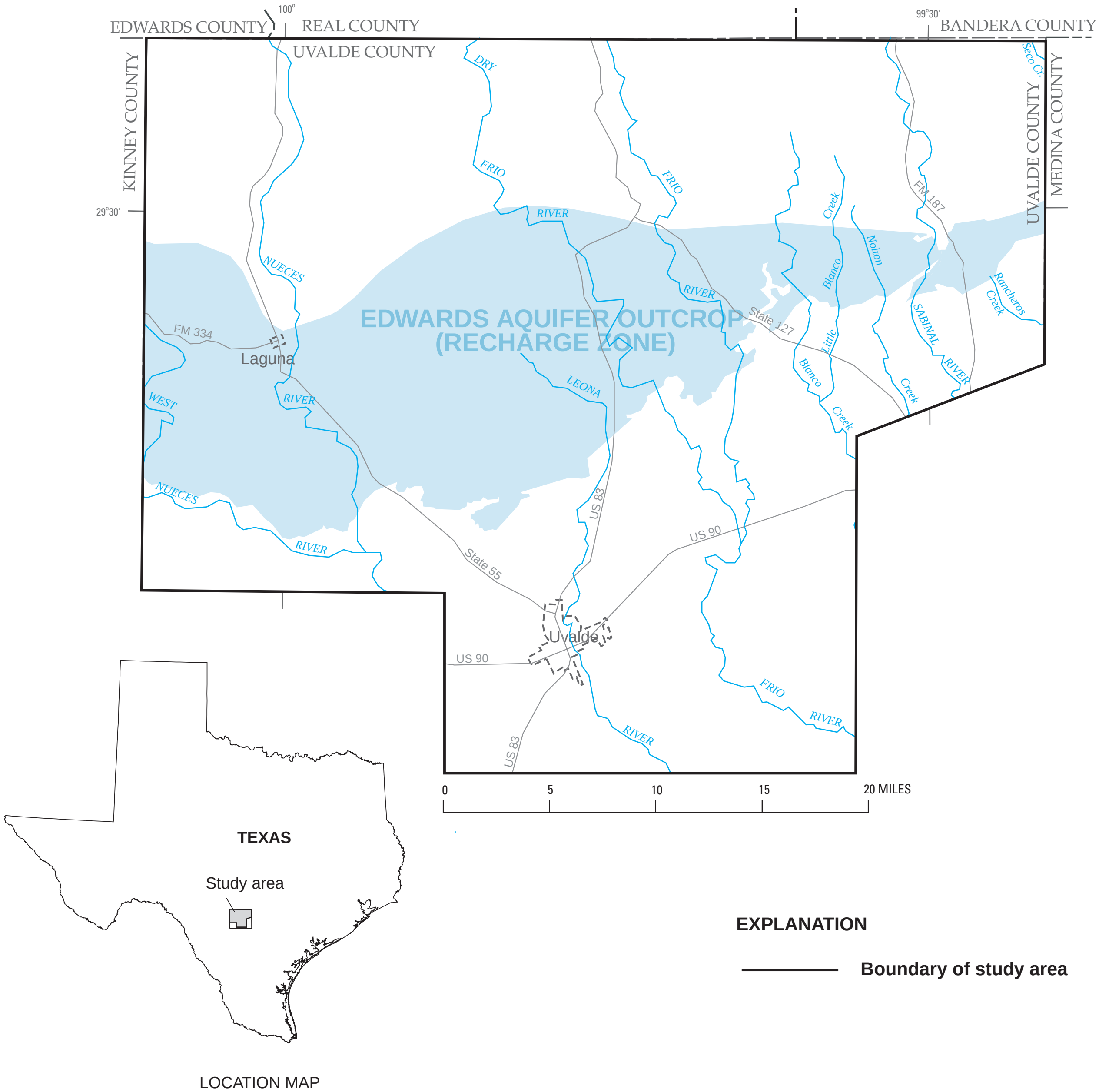

Figure 1. Location of study area.

Nation. In the study area (fig. 1), the aquifer crops out in a band (recharge zone) about 2 to 17 miles (mi) wide that runs from southwest to northeast across the northern and central parts of Uvalde County. This faulted, fractured, and diagenetically modified aquifer is the major source of water for agriculture in the county as well as the sole source of public water supply for the city of Uvalde. Recharge to the aquifer in Uvalde County has averaged nearly 300,000 acre-feet per year (acre-ft/yr) since 1934, or about 45 percent of the total recharge to the entire Edwards aquifer (Slattery and Thomas, 2001).

In Uvalde County, the Edwards aquifer is composed of the Devils River Formation in the Devils River trend and of the West Nueces, McKnight, and Salmon Peak Formations in the Maverick basin (pl. 1). The distribution and lateral continuity of these strata are affected by faults of the Balcones fault zone and a structural high (Uvalde salient) that juxtapose Lower Cretaceous rocks against Upper Cretaceous rocks at the surface in the central part of the study area. The Uvalde salient is believed to result in part from large-scale faulting associated with Late Cretaceous to perhaps Early Tertiary igneous activity. Additionally, all units of the Edwards aquifer contain extrusive and intrusive igneous rocks, particularly in the southern part of the study area.

The U.S. Geological Survey (USGS), in cooperation with the Edwards Aquifer Authority, mapped the Edwards aquifer outcrop in Uvalde County, adjacent areas to the north that contain remnants of the rocks that compose the Edwards aquifer, and adjacent areas to the south that include the Uvalde salient and igneous rocks. The mapping was done to obtain information that would contribute to a better understanding of the geologic framework and hydrogeologic characteristics in Uvalde County.

This report describes the geologic framework and hydrogeologic characteristics of the Edwards aquifer on the basis of field mapping. Description of the geologic framework includes the uppermost part of the lower confining unit and the lowermost part of the upper confining unit of the Edwards aquifer in Uvalde County. The report also describes igneous rocks that potentially impede flow in the aquifer, as well as the surficial distribution of these rocks. The stratigraphic units of the Edwards aquifer are shown on a map, and their lithologic and hydrogeologic properties summarized in tables.

Methods of Investigation

The stratigraphic nomenclature and lithologic descriptions of Lozo and Smith (1964) were used to map the Edwards aquifer outcrop and adjacent areas in the Devils River trend (table 1) and in the Maverick basin (table 2) of Uvalde County. Dunham (1962) was used to describe carbonate lithology. Choquette and Pray (1970) was used to determine porosity type. Rose (1972) and Maclay and Small (1984) were used to separate the basal nodular unit from the overlying, undivided part of the Devils River Formation in the Devils River trend and from the overlying, undivided part of the West Nueces Formation in the Maverick basin.

Well logs and geologic data supplemented the results of field mapping. The thicknesses of the stratigraphic units were determined using well logs from the recharge zone and from the downdip, confined part of the Edwards aquifer. Aerial photographs were used to help identify minor faults and to aid in mapping the geology of inaccessible areas. Igneous outcrops were recognized from aerial photographs as dark, semicircular patches. Distinct marker beds, such as the basal nodular unit and the middle unit of the McKnight Formation were used as stratigraphic identifiers where possible.

Faults were identified in the field through the observation of (1) stratigraphic displacements, (2) juxtapositioning of unlike formations, and (3) zones of fault gouge (caliche-like soils), and (or) relatively thick, sometimes vein-like masses of euhedral to subhedral calcite crystals. Steeply inclined strata, uncommon in the relatively flat-lying outcrop of the Edwards aquifer, typically were found to represent drag-folding related to faulting. Where the faults are obscured and difficult to identify in the field, some—especially those in the western part of the study area—could be mapped from aerial photographs that regularly showed the offset of vegetation patterns related to distinct soil and (or) rock types.

Previous Work

Previous mapping of the Lower Cretaceous rocks in Uvalde County was done mostly at group and (or) formational levels. In addition to mapping the Glen Rose Limestone, Sayre (1936) separated the Edwards Limestone and Georgetown Formation into single units. William F. Guyton and Associates (1955) described characteristics of the “Edwards Limestone reservoir” in the San Antonio area and mapped the distribution of “Edwards and associated limestones.” Holt (1959) indicated that rocks now mapped as part of the Edwards Group (Rose, 1972) were not as widespread as previously believed. For rocks in Uvalde County equivalent to those on the Edwards Plateau, Welder and Reeves (1962) reported a regional dip across the Balcones fault zone of about 100 feet per mile (ft/mi) toward the south or southeast. Lozo and Smith (1964) restricted the extent of the Devils River Formation (Udden, 1907) of the Devils River trend and redefined the stratigraphy of the West Nueces, McKnight, and Salmon Peak Formations of the Maverick basin. Barnes (1977, 1983) mapped the distribution of rocks composing the Edwards aquifer and the approximate location of the facies transition between the San Marcos platform and the Devils River trend (Rose, 1972). Miller (1983) mapped a similar transition between the Devils River trend and the Maverick basin, in addition to identifying the basal nodular unit at the bottom of the Devils River

Table 1. Summary of the lithologic and hydrologic properties of the stratigraphic units of the Devils River trend, 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; AQ, aquifer]

System	Hydro-geologic unit	Group, formation, or subunit		Hydro-logic function	Thick-ness[1] (feet)	Lithology	Field identification	Cavern development	Porosity/ permeability type
Upper Cretaceous	Upper confining unit	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; AQ where connected to Edwards by faults/ fractures	300	Massive, chalky to marly, fossiliferous mudstone	White, chalky limestone; *Gryphaea aucella*	Minor along fracture/faults	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, nodular	Minor surface karst	Low porosity/low permeability
		Del Rio Clay		CU	50–110	Blue-green to yellow-brown clay	Fossiliferous; *Ilymatogyra arietina*	None	Negligible; primary upper confining unit
Lower Cretaceous	Edwards aquifer	Devils River Formation	Undivided	AQ	520–600	*Miliolid*, shell-fragment wackestones and grainstones with abundant rudists and chert compose upper 250 feet. Recrystallized and brecciated mudstones near middle grade downward into medium-bedded wackestone to grainstone with gray, vuggy spar and chert. Sparry limestone and burrowed mudstones compose lower 120–180 feet.	Most fossils (caprinids, monopleurids, and requieniids) near top. Highly dissolutioned and brecciated, with vuggy porosity and most chert near middle. Relatively massive and burrowed, with little chert near base.	Most extensive near top, with some sinkhole development near middle and some cavern development associated with solutionally enlarged fractures near base	Both fabric and non-fabric selective, with most fabric selective near top and most non-fabric near base; upper parts most porous and permeable with decreasing porosity and permeability downward; small porosity and permeability related to enlarged fractures near base
			Basal nodular unit	CU; AQ where solutionally enhanced	20–70	Nodular, burrowed mudstone to wackestone *miliolids*, gastropods, and *Exogyra texana*	Nodular gray mudstone, black rotund bodies	Minor, primarily near contact with Glen Rose Limestone	Non-fabric selective
	Lower confining unit	Upper member of Glen Rose Limestone		CU; evaporite beds AQ	800+	Yellowish-tan, thinly bedded limestone and marl	Stairstep topography, tan mudstones, marly, thin-bedded, *Tylostoma* sp.	Minor, related to fractures, faults, and bedding planes	Mostly non-fabric selective porosity, with generally low permeability

[1] Where present.

Table 2. Summary of the lithologic and hydrologic properties of the stratigraphic units of the Maverick basin, 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; AQ, aquifer]

System	Hydrogeologic unit	Group, formation, or subunit	Hydrologic function	Thickness[1] (feet)	Lithology	Field identification	Cavern development	Porosity/ permeability type
Upper Cretaceous	Upper confining unit	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	50–110	Blue-green to yellow-brown clay	Fossiliferous; *Ilymatogyra arietina*	None	Negligible; primary upper confining unit
		West prong beds	CU	0–20	Reddish-brown, gray to light-tan, argillaceous limestone	*Waconella wacoensis*	None	Low porosity/low permeability
Lower Cretaceous	Edwards aquifer	Salmon Peak Formation: Upper unit	AQ	75	Mudstone that grades upward into grainstone	Light-gray mudstone, with abundant fossil fragments	Minor karst, associated with solutioning along fractures	Both fabric and nonfabric selective, low to high porosity/low to high permeability
		Salmon Peak Formation: Lower unit	AQ	310	Thick, massive lime mudstone, grainstone, and chert	Massive, gray mudstone	Minor karst, associated with solutioning along fractures	Mostly non-fabric selective; low porosity/low permeability
		McKnight Formation: Upper unit	AQ	100–160	Brownish, thin-bedded, pelleted, mudstone, wackestone, packstone, and grainstone	Brown, thin-bedded mudstone with collapse breccia	Negligible	Mostly fabric selective; high porosity and permeability where evaporite dissolution has occurred
		McKnight Formation: Middle unit	CU	40	Dark, laminated, fissile mudstone	Petroliferous odor, dark, laminated mudstone; vegetative band on aerial photo	None	Mostly non-fabric selective; low porosity/low permeability
		McKnight Formation: Lower unit	CU; AQ in evaporites	60–80	Thinly bedded *miliolid*, gryphaeid fragmented mudstone to grainstone	Thin-bedded mudstone to grainstone	Negligible	Mostly fabric selective; low to high porosity/low permeability
		West Nueces Formation: Undivided	CU	120–260	Gray, thick-bedded, burrowed, shell-fragment wackestone, packstone, and grainstone	Gray wackestone, *miliolids*, gastropods, and *Texigryphaea*	Minor, associated with fracture solutioning	Mostly non-fabric selective; low porosity/low permeability
		West Nueces Formation: Basal nodular unit	CU; AQ where solutionally enhanced	20–60	Nodular, burrowed mudstone to wackestone *miliolids*, gastropods, and *Exogyra texana*	Nodular gray mudstone, black rotund bodies	Minor, primarily near contact with Glen Rose Limestone	Mostly non-fabric selective; low porosity/low permeability
	Lower confining unit	Upper member of Glen Rose Limestone	CU; evaporite beds AQ	350–500	Yellowish-tan, thinly bedded limestone and marl	Tan argillaceous limestone	Minor, associated with fracture solutioning	Mostly non-fabric selective porosity, with generally low permeability

[1] Where present.

and West Nueces Formations and dividing the McKnight Formation into lower, middle, and upper subunits on the following USGS topographic maps: Chalk Bluff, Deep Creek, Lake Creek, Reagan Wells, Sevenmile Hill, and Sycamore Mountain quadrangles. Clark and Small (1997) mapped the Uvalde salient and faults associated with this structural high. Dr. Eddie Collins (University of Texas, Bureau of Economic Geology, oral commun., 2000) mapped geologic structure on the Trio, Flatrock Crossing, Comanche Waterhole, and Utopia quadrangles.

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GEOLOGIC FRAMEWORK

Geologic History

Lower Cretaceous rocks in the study area were deposited upon the Comanche shelf, a (continental) shelf-margin platform that was sheltered largely by the Stuart City reef from storm waves and deep ocean currents in the ancestral Gulf of Mexico (pl. 1). Subsidence across a tectonic hinge line (Smith, 1981, p. 4) that skirted the southern margin of this carbonate shelf kept parts of Kinney, Uvalde, and Medina Counties submerged within a semicircular depression known as the Maverick basin. Greater rates of subsidence south of this hinge line caused fundamental differences between the rocks deposited here and those deposited elsewhere over the relatively shallow Comanche shelf (Barker and Ardis, 1996, p. B23). Depositional environments inside the basin were effectively isolated from those elsewhere by an intervening zone of reef growth, known as the Devils River trend, that bounded the basin on the west, north, and east. This fringing bank of reefal rocks (Miller, 1984, p. 17–21) today composes the Devils River Formation. The persistently submerged Maverick basin, within which relatively restricted, basinal deposition occurred almost continuously during the Early Cretaceous, today contains the West Nueces, McKnight, and Salmon Peak Formations.

The West Nueces Formation and the lowermost part of the McKnight Formation formed during relatively early stages of the Maverick basin when the area was characterized by partly restricted to open-marine environments and normal salinities. Evaporite-dominated deposits near the top of the lower McKnight formed on a broad tidal mudflat (Miller, 1984, p. 30). Gypsiferous deposits prograded northward toward the Devils River trend as water depths increased abruptly inside the basin in response to accelerated rates of subsidence south of the tectonic hinge line (Dr. Charles Smith, University of Texas at Arlington [retired], oral commun., 1989). As subsidence continued, the circulation of seawater deteriorated basinward into extremely restricted to euxinic conditions near the bottom. A thin-bedded, finely laminated sequence of deep-water mudstone resulted that today comprises middle parts of the McKnight Formation (characterized by anhydrite-rich, dark organic shales and petroliferous limestones). As water depths subsequently decreased, argillaceous mudstone accumulated in slightly fresher water to form upper parts of the McKnight Formation. The McKnight Formation later was covered with more than 300 feet (ft) of dense, thick-bedded to massive lime mudstone that today composes the lower two-thirds of the Salmon Peak Formation (Humphreys, 1984). The lower few hundred feet of the Salmon Peak Formation, which mostly was deposited as a pelagic lime mudstone, formed in an open to partly restricted embayment of relatively low (wave and current) energy (Dr. Charles Smith, University of Texas at Arlington [retired], oral commun., 1989). The upper Salmon Peak formed as the Stuart City reef began to disintegrate, which improved the connection between the basin and open sea, and reworked grainstone and wackestone deposits prograded southward from the Devils River trend.

Concurrent with deposition inside the Maverick basin, the Devils River trend—a bank of now partly to completely dolomitized *miliolid*, shell-fragment, and rudist-bearing limestone—formed around the western, northern, and eastern margins of the basin (Lozo and Smith, 1964, p. 291–297). Nodular, burrowed, dolomitic, and evaporitic rock sequences that today compose lower parts of the Devils River Formation were deposited in partly restricted tidal flat environments somewhat similar to those elsewhere on the Comanche shelf (Miller, 1984). Upper parts of the Devils River Formation formed in much different (mostly open shallow marine) environments of moderate to high energy and relatively unrestricted circulation that enhanced the growth of rudist bioherms and biostromes.

Following tectonic uplift and erosion atop the Comanche shelf near the end of Early Cretaceous time, south-central Texas was once again submerged during a major marine transgression. By the beginning of Late Cretaceous time, the Maverick basin was no longer subsiding, and the Stuart City reef had been breached (Rose, 1974, p. 17). The growth of carbonate-producing organisms in environments no longer sheltered by the Stuart City reef was impeded by the influx of fine-grained terrigenous sediments (Dr. Charles Smith, University of Texas at Arlington [retired], oral commun., 1989). All previous depositional environments associated with the Devils River trend and Maverick basin were superseded as south-central Texas was blanketed by the Del Rio Clay.

Additional subaerial exposure and erosion in the study area resulted from structural uplift associated with Late Mesozoic to Early Cenozoic igneous activity. The igneous activity is believed to have resulted from changes in mantle convection regimes (Ewing and Barker, 1986) and (or) from compressional forces associated with the Laramide orogenic activity (Ewing, 1991, p. 24); either could have reactivated zones of weakness in the underlying Ouachita structural belt (Wilson, 1977).

The igneous invasions into the study area were both extrusive (submarine and possible subaerial volcanoes) and intrusive (dikes, sills, stocks, plugs, and possibly laccoliths) and might have accompanied pyroclastic events and (or) lava flows (Ewing and Barker, 1986). All stratigraphic units that compose the Edwards aquifer in the area are intruded by mostly basaltic igneous rocks.

Structural Features

The Balcones fault zone (pl. 1), aligned from southwest to northeast across the study area, is the principal structural feature in Uvalde County. As elsewhere in the Balcones fault zone, most of the faults are high-angle, en echelon, normal faults, and are vertical or nearly so (George, 1952) and downthrown to the southeast (fig. 2).

Although most of the faults in Uvalde County are genetically similar to those in Medina County (Holt, 1959) and in Bexar County (Arnow, 1959, p. 20), the individual fault displacements typically are less in Uvalde County, where the maximum displacement across the entire zone is about 700 ft (Welder and Reeves, 1962, p. 31). Many of the relatively minor faults, with displacements of 20 ft or less, are difficult to identify in the field. Some, however, can be observed as linear trends on aerial photographs. Those with no surface expression, perhaps because they are covered by Tertiary and Quaternary gravels, are identifiable only from well logs. Some structures are actually shatter zones—not the single, sharp breaks implied by individual lines on a map.

Downthrown blocks along six primary faults—Cooks, Black Mountain, Blue Mountain, Uvalde, Agape, and Connor (pl. 1)—expose the (Lower Cretaceous) Salmon Peak Formation at the surface in central parts of the study area and juxtapose it at or below the level of Upper Cretaceous rocks in the southeastern part. The Balcones escarpment—a topographic relict of the Balcones faulting—roughly parallels the Cooks and Woodard Cave faults and physiographically separates the Gulf Coastal Plain from the Edwards Plateau (Fenneman, 1931).

Geomorphic expressions of faulting are indicated along upthrown fault blocks where the branching of subsequent valleys is observed on topographic maps as roughly perpendicular to the consequent valleys—reflecting a “T-square” morphology. The formation of the consequent valleys resulted from a drop in base level on the downthrown blocks, which initiated headward erosion directly across the escarpment toward the upthrown block. The unique morphology of the terrain today possibly resulted from faulting that weakened the slopes of the consequent valleys in such a way that secondary routes of headward erosion were initiated

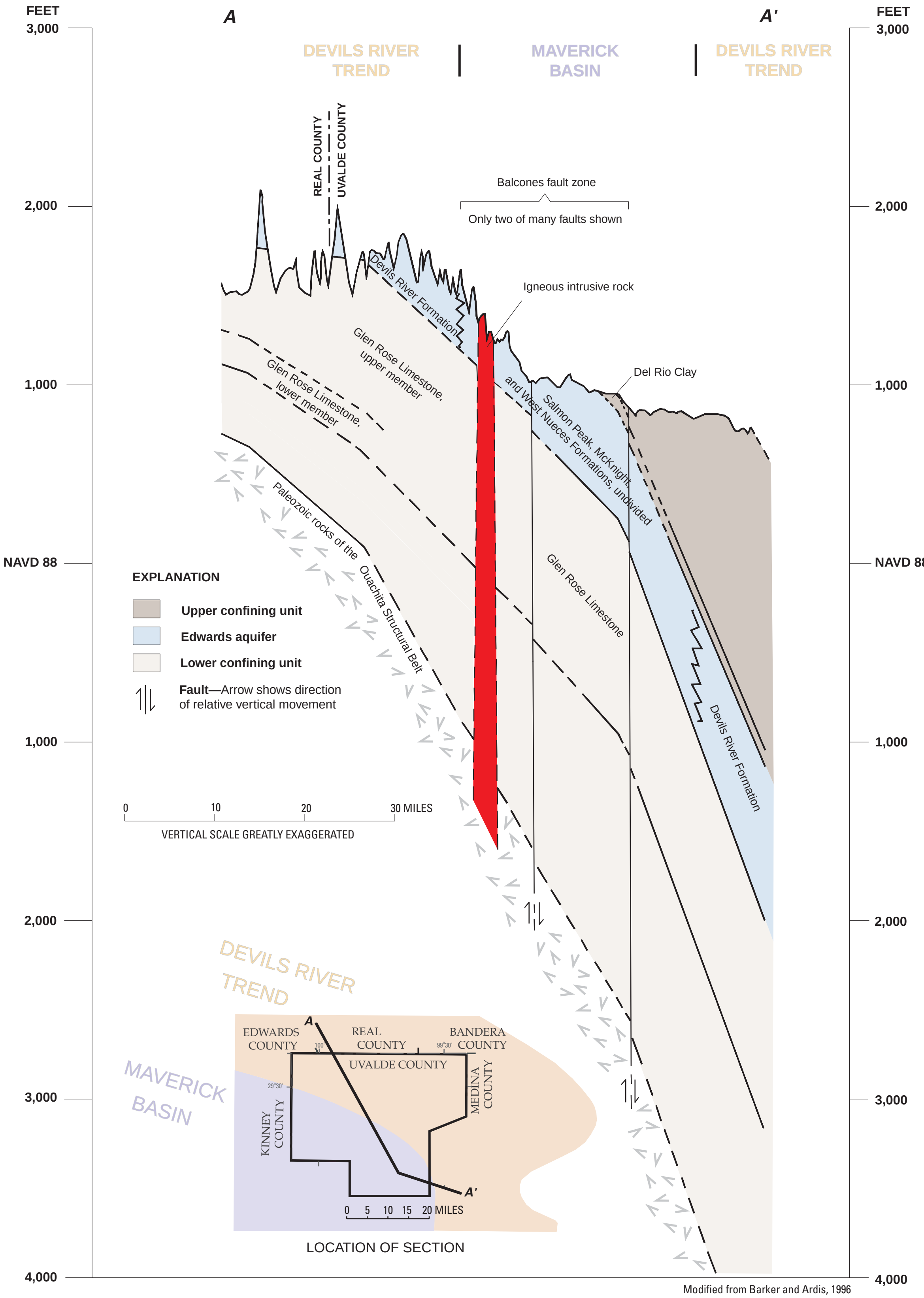

Figure 2. Hydrogeologic section showing relation among units of the Edwards aquifer and its upper and lower confining units in Uvalde County.

perpendicular to the main course of upstream erosion (Thornbury, 1962).

The Uvalde salient (p1. 1) elevates strata of the Edwards aquifer and of other Cretaceous rocks to land surface, where they form prominent hills. Where these hills are composed of Salmon Peak Limestone, Buda Limestone, or basaltic rocks—near Uvalde and Knippa—they are typically surrounded by lower-elevation Upper Cretaceous rocks. From about 900 ft below land surface on the west, rocks of the Edwards aquifer rise to the surface within a distance of about 8 mi and then drop back to about 800 ft below the surface within about 6 mi on the east (Welder and Reeves, 1962, pl. 3). The associated strata dip roughly 1 to 2 degrees toward the west and toward the east, away from the salient. In most cases, the structural dips must be obtained from well logs because of limited surface exposures. Welder and Reeves (1962, p. 31) inferred that the Uvalde salient is related to several clustered crustal uplifts.

A series of faults older than those usually associated with the Balcones fault zone cross the Uvalde salient and attenuate toward the southwest and northeast. Covered in places by Tertiary and Quaternary gravels, these faults locally are complex and typically exhibit little relief or surface expression. These older faults, which were modified by Balcones faulting during the Miocene (Maclay and Land, 1988), are believed to result from uplift associated with the emplacement of magma during the Late Cretaceous (Ewing and Barker, 1986).

Stratigraphic Setting

The stratigraphy of the Edwards aquifer in Uvalde County, which has evolved as a result of past studies by the petroleum industry, academic institutions, and government agencies, is summarized on plate 1 and in tables 1 and 2.

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 lateral transition between the Devils River Formation and the West Nueces, McKnight, and Salmon Peak Formations is gradational, with much interfingering and progradation across their assumed boundaries (fig. 2).

Lower Cretaceous Rocks

Glen Rose Limestone

As elsewhere in south-central Texas, the Glen Rose Limestone forms the lower confining unit of the Edwards aquifer (fig. 2). The Glen Rose Limestone unconformably underlies the Devils River Formation in the Devils River trend and conformably underlies the West Nueces Formation in the Maverick basin (Miller, 1984, p. 8). The Glen Rose Limestone, together with rocks normally associated with the Devils River trend and Maverick basin, forms the only outcrop of Lower Cretaceous rocks in the study area.

Ranging from about 900 to about 1,530 ft thick in Uvalde County (Welder and Reeves, 1962, p. 12), the Glen Rose Limestone is composed mostly of alternating layers of medium-bedded limestone and argillaceous limestone. The limestone generally is tan in surface exposures, which in places are characterized by fossilized ripple marks and sparse casts of *Tylostoma* sp., *Turritella* sp., and *Protocardia texana* (Conrad). Dinosaur footprints are preserved in the bed of the Sabinal River near Utopia. Where the contact is gradational between the Glen Rose Limestone and the overlying basal nodular unit (as in the Maverick basin), the exact boundary between the two can be difficult to identify.

Devils River Formation

Lozo and Smith (1964) redefined the Devils River Formation—from the vaguely defined “Devils River limestone” of Udden (1907)—to correspond specifically to the semicircular bank of reefal strata known as the Devils River trend (pl. 1, fig. 2). Lozo and Smith (1964, p. 297) described their type section (in Real County, 4 mi west of Leakey) as consisting primarily of “*miliolid,* pellet, rudist, shell-fragment, lime grainstones and wackestones locally dolomitized, brecciated, and chert bearing.” Rudist mounds and layers are most common in the upper parts. On the basis of available literature, most workers since Lozo and Smith (1964) have recognized that the Devils River trend lacks sufficient marker beds to permit detailed or widespread subdivision. This lack of distinguishing characteristics has effectively precluded further differentiation other than an (informal) recognition of lower and upper parts.

The lack of distinguishing characteristics within the Devils River sequence is owing to the transitional depositional environment between the relatively shallow Comanche shelf (toward the west, north, and east) and the relatively deep Maverick basin on the south (pl. 1). Differences between the shelf and basin environments increased rapidly, as rates of subsidence accelerated south of the tectonic hinge line. Consequently, the stratigraphic differences between the Devils River Formation and all laterally adjacent strata increase upward from the base.

Over a relatively small part of the Devils River trend in northern Uvalde County, Miller (1984, p. 15) divided the lower part of the Devils River Formation into (informal) basal nodular, burrowed, dolomitic, and Kirschberg evaporite units. Hereinafter, only the basal nodular unit is differentiated (informally) from the rest of the Devils River Formation, which is left undivided.

The basal nodular unit is a nodular, burrowed mudstone or wackestone that typically contains pyrite-replaced marker fossils known as black rotund bodies (BRBs). Because the BRBs weather rapidly, they are not everywhere apparent; where present, they resemble small rust spots (Ted Small, U.S. Geological Survey [retired], oral commun., 2002). The thickness of the basal nodular unit ranges from about 20 ft near Little Blanco Creek (Trio quadrangle) to about 50 to 70 ft throughout most the area. According to Shinn and others (1977), the nodular nature of this unit results from the compaction of heavily bioturbated wackestones (and mudstones). Fossils, ranging from sparse to locally abundant and visible without magnification, include *miliolids*, gastropods, and *Exogyra texana*.

The Devils River Formation is about 600 ft thick in Uvalde County (Miller, 1984); the lower 20 to 70 ft consists of the basal nodular unit, which is overlain by burrowed mudstones that alternate with more massive mudstone. The mudstone becomes thicker bedded and less burrowed upward, away from the basal nodular unit. Chert, which in the study area is found about 20 ft above the basal nodular unit, can be traced laterally as either chert nodules or chert beds into most of the Edwards Group (Rose, 1972), including both the Fort Terrett Formation (to the north) and the Kainer Formation (to the east). A gray, vuggy spar (crystalline mineral of nonspecific origin) with scattered medium-bedded wackestone to grainstone, lies above the relatively thick-bedded mudstone.

The upper 250 ft of the Devils River Formation consists of light-gray wackestone, packstone, *miliolid* grainstone, and rudist boundstone. Rudists, shell fragments, chert nodules, and thin chert beds are scattered throughout and are abundant locally. Caprinid fossils, along with other varieties of rudists, are present locally and commonly form boundstone or have been replaced by chert.

West Nueces Formation

The West Nueces Formation (Lozo and Smith, 1964) is the lowermost formation composing the Edwards aquifer in the Maverick basin. The informally designated basal nodular unit—characterized by distinctively “lumpy” wackestone and mudstone—comprises the bottom 20 to 60 ft of the West Nueces Formation (Miller, 1984). The basal nodular unit is overlain by mostly gray, thick-bedded, burrowed, shell-fragment wackestone, packstone, and grainstone. The undivided, upper part of the formation contains scattered to locally abundant caprinids, *miliolids*, gastropods, and *Texigryphaea*. Although the West Nueces Formation is as much as 260 ft thick near Chalk Bluff (pl. 1), its thickness decreases to as little as 120 ft where it grades northward into the Devils River Formation. Owing to this facies transition, the boundary between the West Nueces Formation and equivalent parts of the Devils River Formation is placed along the northernmost extent of the fissile, carbonaceous lime mudstone of the middle McKnight unit (Miller, 1984, p. 9).

McKnight Formation

The McKnight Formation, which overlies the West Nueces Formation, can be subdivided into three informal units (pl. 1; table 2). The lower unit is about 60 to 80 ft thick in the western part of the study area near Laguna. It thickens to the southwest, thins to the north and east, and is completely absent at the town of Montell (pl. 1), north of Chalk Bluff. The lower unit is composed of thinly bedded *miliolid*, gryphaeid fragmented mudstone to grainstone with thin solution zones and chert beds. It also contains laminated pellet mudstone to packstone (Miller, 1983). Collapse breccia near the top of the lower unit probably is the result of evaporite dissolution. The middle McKnight unit is about 40 ft thick near Laguna. This unit also thins to the north and east and is absent at Montell. It is a dark, laminated, fissile mudstone with scattered oyster fragments. Typically, on aerial photographs the middle unit is coincident with a dark band of vegetation.

At Chalk Bluff, where the upper McKnight unit is about 160 ft thick, it is a brownish, thin-bedded, laminated mudstone to grainstone with thick beds of shell-fragment and pellet wackestones to packstones. There is additionally a brecciated zone that likely has resulted from evaporite dissolution. West of Laguna, the upper McKnight unit is about 100 ft thick.

The contact between the upper McKnight unit and the middle unit is gradational, just as the upper unit is conformable with the overlying Salmon Peak Formation. A "conglomeratic zone," consisting of bored rip-up clasts, lies just below the Salmon Peak Formation. Lozo and Smith (1964) believed this horizon of rip-up clasts represented a disconformable base to the Salmon Peak Formation. However, Miller (1983) states that this horizon represents not an unconformity, but rather an interval of mass flow debris that can be mapped as part of the upper McKnight unit (Dr. Charles Smith, University of Texas at Arlington [retired], oral commun., 1989).

Salmon Peak Formation

The Salmon Peak Formation (Humphreys, 1984) is predominately a dense, thick-bedded, deep-water mudstone that grades upward into a crossbedded, rudist-shell grainstone. The Salmon Peak Formation, about 385 ft thick, has been divided informally into lower and upper units (Lozo and Smith, 1964). The lower unit consists mostly of thick-bedded to massive lime mudstone with abundant grainstone and chert in the upper 165 ft. The upper unit of the Salmon Peak Formation is about 75 ft thick and consists mostly of lime grainstones and wackestones with bioclastic grainstones near the top.

Upper Cretaceous Rocks

The upper confining unit of the Edwards aquifer in Uvalde County comprises the Del Rio Clay, Buda Limestone, Eagle Ford Group, Austin Group, Anacacho Limestone, and Escondido Formation (tables 1, 2). Because the Del Rio Clay is hydrologically the most relevant, owing to its direct contact with the underlying rocks of the Edwards aquifer (fig. 2), only the Del Rio Clay is discussed in this report. Rose (1972) and Clark and Small (1997) provide information about the overlying units.

Del Rio Clay

The Del Rio Clay directly overlies the Lower Cretaceous formations over much of southern Uvalde County. Thickening from east to west, the Del Rio Clay varies between 50 and 110 ft thick where it occurs in the study area. It is mostly a dark blue-green to yellow-brown clay with thin beds of impervious limestone. Iron nodules and the fossil oyster *Ilymatogyra arietina* are locally abundant. Secondary gypsum commonly occurs as fracture fillings in clay outcrops near igneous bodies. Excellent exposures of the Del Rio Clay are found north of Uvalde and 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 "west prong" beds (Greenwood, 1956; Lozo and Smith, 1964), which occur locally in the Maverick basin between the Del Rio Clay and the Salmon Peak Formation, are considered to be essentially the same age and facies as the Georgetown Formation on the San Marcos platform (Rose, 1972, p. 26). On the outcrop and in the shallow subsurface—where the "west prong" beds grade upward into the Del Rio Clay (and are considered basal Del Rio)—the unit is disconformable with the underlying Salmon Peak Formation (Humphreys, 1984, fig. 4). Deep within the subsurface of the Maverick basin—where any such depositional hiatus is less apparent—the "west prong" beds are considered equivalent to the uppermost Salmon Peak Formation (Humphreys, 1984, fig. 8).

"West prong" bedding is thin to absent over most of the Edwards aquifer area, with a maximum known thickness of about 20 ft. Where present, the "west prong" beds consist of a reddish-brown, gray to light-tan, argillaceous limestone that typically contains the brachiopod *Waconella wacoensis*. The author has mapped excellent exposures of this lithology along the West Nueces River about 4.5 river miles upstream of its confluence with the Nueces River (pl. 1). Where erosion has removed the "west prong" beds, the Del Rio Clay (if it exists) lies directly atop the Salmon Peak Formation.

Igneous Rocks, Undivided

Extrusive and intrusive igneous rocks extend southward from the Edwards aquifer outcrop into an area generally coincident with the southern one-half of the Uvalde salient (pl. 1). Extrusive igneous rocks can be seen readily at Black Waterhole (Lonsdale, 1927, p. 29) and Traprock. These extrusive rocks probably are remnants of both submarine and subaerial volcanoes (Ewing and Barker, 1986) and possibly of unroofed laccoliths (Deussen, 1924, p. 119). Ewing and Barker (1986) used the term "Frio River line" for volcanoes aligned approximately with the axis of the Uvalde salient. The intrusive rocks—believed to form the core of many Lower Cretaceous exposures, such as at

Frio Hill and Salt Mountain—apparently result from Late Cretaceous and Early Tertiary igneous activity (Getzendaner, 1931). Basaltic plugs, sills (Lonsdale, 1927, p. 39), and dikes—consisting of melilite-olivine nephelinite, nepheline basanite, olivine basalt, olivine nephelinite, and phonolite (Ewing and Barker, 1986)—penetrate both Lower Cretaceous and Upper Cretaceous rocks in the study area. Taylor Hills (pl. 1) is composed of an intrusive complex that has been eroded to its igneous core.

Many wells in Uvalde County penetrate basalt and what is known locally as "serpentine," which refers to a "soft, green to yellow claylike material" probably related to an alteration of pyroclastic and basaltic rocks (Welder and Reeves, 1962, p. 30). The soft, easily eroded, heavily altered pyroclastics are abundant along the Frio River from Black Waterhole to Connor Lane (pl.1) and commonly are found in stream cuts. The best exposures of pyroclastics are found just south of the West Nueces River on the Ruby Ranch where they interfinger with the Austin Group and can be seen where downfaulted against the Salmon Peak Formation.

Recent drilling near the Frio River in the southern part of the study area penetrated about 400 ft of igneous rocks (John Waugh, San Antonio Water System, oral commun., 2002). Recent magnetic and gravity surveys have identified additional igneous bodies in the subsurface, and some previously unmapped igneous rocks probably crop out, or nearly crop out, in the study area (Ted Small, U.S. Geological Survey [retired], oral commun., 2002).

HYDROGEOLOGIC CHARACTERISTICS

The porosity in carbonate rocks can be classified as either fabric selective or non-fabric selective (Choquette and Pray, 1970). Fabric selective porosity results from depositional and diagenetic effects along specific lithostratigraphic horizons. Non-fabric selective porosity results from structural and solutional features that can occur in any lithostratigraphic horizon. Permeability is the capacity of porous rock to transmit water. The fundamental control on the permeability of carbonate strata is the history of the diagenetic (post-depositional) processes responsible for the rock's porosity.

Most carbonate sediments, like those in the study area, initially contained evaporites and other unstable (soluble) constituents. Because these constituents are susceptible to dissolution, the ultimate extent and distribution of permeability can depend on the extent and distribution of fabric selective porosity that results from the early dissolution of these constituents. Under the right conditions, such early occurrences of fabric selective porosity can enhance the entry and circulation of fresh, meteoric water—which, in turn, increases the chances that appreciable permeability will evolve. Whereas early fabric selective porosity in fine-grained sediment (such as carbonate mud) typically degenerates into unconnected, ineffective porosity with virtually no permeability, grain-supported sediment (such as grainstone) is more apt to evolve into an effective interconnection of pores and appreciable permeability.

Choquette and Pray (1970, p. 222) designated seven "basic" types of porosity as being "extremely common and volumetrically important" toward providing the bulk of pore space in carbonate rocks. Those of the fabric selective class are interparticle, intraparticle, intercrystalline, moldic, and fenestral. Fracture and vug are considered non-fabric selective. Breccia porosity is a subcategory of interparticle porosity that can be either fabric selective or non-fabric selective. In terms of providing appreciable permeability in the study area, the most important porosity types probably are moldic, fracture, breccia, and vug—or vuggy, as used hereinafter.

The permeability of carbonate rock depends on the size, shape, and distribution of the porosity as well as the degree of interconnection among the pores. Secondary effects resulting from post-depositional conditions such as cementation, faulting, and the chemical alteration of unstable carbonate minerals and fossils are important. Permeability might be greater in some directions than in others and concentrated in certain stratigraphic horizons as the result of faulting, fracturing, and dissolution (Ford and Williams, 1989, p. 150). Although the Edwards aquifer in Uvalde County—as elsewhere in the flow system (Maclay and Small, 1984)—is relatively permeable, zones of infinitely large permeability associated with cavernous porosity are rare.

Maclay and Small (1984, p. 33) define flow-barrier faults as faults with vertical displacements greater than 50 percent of the total thickness of the displaced aquifer, which is sufficient to juxtapose permeable strata against relatively impermeable strata. Because the thickness of the Edwards aquifer in the study area ranges from about 500 to 700 ft, faults with vertical displacements between 250 and 350 ft or greater are considered flow-barrier faults. The Connor, Cooks, and Trio faults (pl. 1) are known barriers to the lateral flow of ground water. These barrier faults, together with the many “ordinary” faults that strike in different directions, undoubtedly increase the complexity of the resulting flowpaths in Uvalde County (Maclay and Land, 1988, p. A20).

In addition to ground-water flow in the study area depending on the permeability and structure of the carbonate rocks, it depends on the distribution of igneous rocks. Although faulted and dissolutioned carbonate strata are common characteristics of the Edwards aquifer (Maclay and Small, 1984), the presence of igneous rocks has added another dimension to the complexity of ground-water flow in Uvalde County.

Welder and Reeves (1962, p. 41) indicated that the eastward flow of ground water from the northwestern part of Uvalde County follows “devious paths” owing to the presence of igneous intrusives. Recognizing from their potentiometric map that most ground-water flow through central Uvalde County occurs along the northwestern part of the Uvalde salient, Welder and Reeves (1962) inferred that the complex faulting associated with that structure might have juxtaposed parts of the Edwards aquifer against relatively impermeable igneous rocks, thus blocking or impeding eastward flow.

Subsurface igneous bodies (especially those of the intrusive variety) can be relatively impermeable (Todd, 1959). Because rocks composing dikes and sills generally have porosities of less than 5 percent (Erdelyi and Galfi, 1988), these features typically impede the flow of ground water. The permeability of igneous rocks tends to be highly localized, resulting mostly from primary and secondary structures, such as intersecting vesicles and joints caused by cooling (Davis and DeWiest, 1966).

Igneous activity in the study area typically has resulted in barriers to ground-water flow. The initial permeability of the carbonate rocks was obliterated or greatly reduced where they were baked during the igneous activity and where primary voids were filled with magma and (or) secondary minerals (Frank Welder, U.S. Geological Survey, written commun., 1957). Evidence of low porosity and permeability are found at the Black Waterhole (pl. 1) and at similar depressions along the lower Frio River where basaltic and pyroclastic rocks are exposed. Localized cones of water-level depression resulting from ground-water withdrawals are believed to be directly related to the presence of igneous rocks (Ted Small, U.S. Geological Survey [retired], oral commun., 2002). Although faulting and fracturing can result from the emplacement and subsequent contraction of igneous bodies, such effects are difficult to determine owing to the extent of alluvial cover in the study area.

Upper Confining Unit

The Del Rio Clay, Buda Limestone, Eagle Ford Group, Austin Group, Anacacho Limestone, and Escondido Formation compose the upper confining unit (fig. 2) of the Edwards aquifer in the Devils River trend (table 1) and in the Maverick basin (table 2). These Upper Cretaceous rocks crop out mostly in the southeastern one-half of the study area (pl. 1). The Del Rio Clay, consisting mostly of calcareous shale, clay, and silt with negligible porosity and permeability, directly overlies the Edward aquifer and effectively isolates the aquifer from younger strata.

The “west prong” beds, which are found locally near the base of the Del Rio Clay, are eroded mostly from the outcrop of the Edwards aquifer in Uvalde County. Even where present in the subsurface (Humphreys, 1984), the “west prong” beds do no more than help confine the underlying aquifer, owing to their relatively high clay content.

Edwards Aquifer

The Edwards aquifer is an extremely complex system that is recharged across a faulted, fractured, and locally karstic outcrop, or recharge zone. Precipitation on the recharge zone and leakage from streams across the outcrop are the sources of most recharge to the aquifer. Streams originating north of the recharge zone generally flow southward across the outcrop, where they lose most, if not all, of their flow to solutionally enlarged fractures, bedding planes, and other crevices.

Water entering the aquifer in Uvalde County moves south and east to points of discharge (mostly through irrigation and municipal wells) in Uvalde, Medina, and Bexar Counties and then northeast—parallel or nearly parallel to the northeast-trending Balcones fault zone—into Comal and Hays Counties, where it discharges mostly through wells and springs. While recharge to the Edwards aquifer in Uvalde County alone has averaged about 45 percent (300,000 acre-ft/yr) of the total recharge to the entire Edwards aquifer since 1934, discharge from wells and springs in Uvalde County probably has averaged only about 10 percent

(70,000 acre-ft/yr) of the total discharge during that time (Slattery and Thomas, 2001).

Devils River Trend

The Devils River Formation in the Devils River trend (table 1) is one of the more porous and permeable units in the study area. The permeable zones generally are associated with solutionally enlarged bedding planes and fractures. Although most of the permeability probably results from fracture porosity, some also results from zones of breccia, cavern, vuggy, moldic, and intercrystalline porosity. Strata containing isolated molds, casts, and burrows with large secondary porosity typically exhibit little permeability because the openings rarely are connected.

Vertical fractures near the top of the Devils River Formation provide the most effective paths for recharge in the Devils River trend. Where exposed at land surface, these fractures greatly enhance the conditions necessary for water to infiltrate the land surface and percolate to the saturated zone.

The upper part of the undivided Devils River Formation consists of rocks with both fabric selective and non-fabric selective porosity, and the resulting permeability appears to be much greater than that in the rest of the study area. Although scattered chert nodules and beds probably restrict ground-water flow in places and might locally confine some areas, upper parts of the undivided Devils River Formation contain some of the most porous and permeable rocks in Uvalde County. In addition to containing the typical types of moldic, fracture, and vuggy porosity, the upper part of the undivided Devils River Formation contains solutionally enlarged bedding planes; some cavernous porosity has developed along what were initially bedding planes. Moldic porosity resulting from the dissolution of rudists is an additional source of permeability. Rudist patch reefs probably were initial sites of concentrated freshwater infiltration, rapid ground-water circulation, and aggressive carbonate dissolution that promoted the further development of vuggy, channel, and cavernous porosity.

The middle part of the undivided Devils River Formation is characterized by a gray, vuggy spar that resulted from the dissolution of evaporites, with some medium-bedded wackestone and grainstone. The interconnected vuggy porosity makes the middle part of the unit permeable, although probably less so than that of the upper part of the unit.

The lower part of the undivided Devils River Formation contains massive mudstone beds with porosity that ranges from less than 3 to about 15 percent (Small and Maclay, 1982). Where this mudstone is locally burrowed and (or) dissolved to the extent of being honeycombed, it is permeable. The mostly burrowed mudstone toward the bottom of the massive beds contains about 8 percent porosity (mainly the fracture, intercrystalline, and vuggy types) but little permeability because the porosity typically is not interconnected.

The basal nodular unit, at the bottom of the Devils River Formation, is non-fabric selective and generally has very low porosity (less than 3 percent) and little permeability (Sieh, 1975).

Maverick Basin

The permeability of the Salmon Peak Formation (table 2) decreases downward from the top. The upper Salmon Peak unit comprises some of the most porous and permeable rocks in Uvalde County. Whereas the porosity of the upper unit typically ranges from less than 1 to about 25 percent (Sieh, 1975), Hovorka and others (1993) indicate that porosity might average between about 25 and 35 percent in places. The most effective porosity appears to result from solutionally enlarged fractures and bedding planes, in addition to a small amount of cavern development. Solutionally enlarged features provide the primary avenues for recharge through the upper Salmon Peak unit, which typically is unsaturated owing to its relatively high topographic, as well as stratigraphic, position. The lowermost 250 ft of this unit has relatively low fracture and vuggy porosity (less than 3 percent) and, therefore, little permeability (Small and Maclay, 1982).

The upper McKnight unit contains both fabric selective and non-fabric selective porosity. Unaltered fractures are the main source of non-fabric selective porosity, albeit providing little permeability. The fabric selective porosity evolved from the early removal of evaporites and from the breccia resulting from the subsequent collapse of weakened, insoluble bedding. These brecciated zones in the upper McKnight afford the most effective porosity and provide the only significant permeability in the McKnight Formation. The middle McKnight unit, with less than 3-percent porosity (Hovorka and others, 1993), appears to provide no permeability other than some relatively insignificant permeability associated with tight fractures. The lower unit of the McKnight Formation contains porosity of mainly the vuggy and breccia types owing to the early dissolution and subsequent collapse of evaporitic bedding. Except for locally distributed brecciated zones of perhaps 25-percent porosity (Small and Maclay, 1982), the lower McKnight unit contains less than 5-percent porosity (Hovorka and others, 1993) and little to no permeability.

The West Nueces Formation in the Maverick basin contains mostly moldic porosity that ranges between about 5 and 10 percent (Hovorka and others, 1993)—although without sufficient void connection to provide appreciable permeability. Fractures in this formation typically are filled with secondary calcite (Small and Maclay, 1982). What limited permeability there is results mostly from scattered pockets of non-fabric selective porosity.

Lower Confining Unit

In south-central Texas, the upper part of the Trinity aquifer (upper member of the Glen Rose Limestone) generally is much less permeable than the Edwards aquifer in the Balcones fault zone. The potential of the Trinity aquifer to yield and transmit water is appreciably less than that of the Edwards aquifer (Barker and Ardis, 1996, p. B40; B47). Because the differences in water-yielding and water-transmitting characteristics between the two aquifers are so large, the Trinity aquifer, where it underlies the Edwards aquifer, commonly is considered the lower confining unit of the Edwards aquifer. Because most porosity in the upper member of the Glen Rose Limestone results from carbonate dissolution along fractures, it is considered primarily non-fabric selective.

Although the porosity of the basal nodular unit commonly results from fractures, its largest permeability results from cavernous porosity that typically occurs at or just above the contact with the underlying Glen Rose Limestone. Owing to the generally smaller permeability at the top of the Glen Rose Limestone, water that has moved downward through the basal nodular unit typically is diverted laterally, causing springs to issue from or just above the top of the Glen Rose Limestone.

SUMMARY

In addition to providing large quantities of water to agriculture, industry, and major springs outside the study area, the Edwards aquifer is the major source of water for Uvalde County and the sole source of water for the city of Uvalde. This aquifer consists primarily of fractured and solutionally enlarged carbonate (mostly dolomitic limestone) strata, which in the study area is composed of the Devils River Formation and of the West Nueces, McKnight, and Salmon Peak Formations.

The Edwards aquifer is an extremely complex system that is recharged across a faulted, fractured, and locally karstic outcrop. Precipitation on the outcrop (recharge zone) and leakage from streams across the outcrop are the main sources of recharge. While recharge to the Edwards aquifer in Uvalde County alone has averaged about 45 percent (300,000 acre-ft/yr) of the total recharge to the entire Edwards aquifer since 1934, discharge from Uvalde County probably has averaged only about 10 percent (70,000 acre-ft/yr) of the total discharge during that time.

Streams originating north of the recharge zone generally flow southward across the outcrop and lose most, if not all, of their flow to solutionally enlarged fractures, bedding planes, and other crevices resulting from the dissolution of soluble minerals and fossils. From the recharge zone in Uvalde County, water moves south and east to points of discharge (through mostly irrigation and municipal wells) in Uvalde, Medina, and Bexar Counties and then northeast, parallel or almost parallel to the northeast-trending Balcones faults into Comal and Hays Counties, where it discharges mostly through wells and springs.

Lower Cretaceous rocks in the study area formed mainly in relatively restricted shallow marine environments. Relatively rapid and nearly continuous subsidence kept the Maverick basin submerged throughout most of the Early Cretaceous. Depositional environments inside the basin were isolated by the Devils River trend, which today contains the Devils River Formation. The Maverick basin today contains the West Nueces, McKnight, and Salmon Peak Formations. All stratigraphic units that compose the Edwards aquifer were intruded during the Late Cretaceous and (or) Early Tertiary by mostly basaltic igneous rocks.

The carbonate rocks of the Maverick basin and the Devils River trend are products of assorted tectonic and depositional conditions that affected the depth and circulation of the Cretaceous seas. The West Nueces, McKnight, and Salmon Peak Formations resulted mostly from partly restricted to open marine, tidal-flat, and restricted deep-basinal environments in the Maverick basin. The Devils River Formation formed in a fringing carbonate bank—the Devils River trend—in mostly open shallow marine environments of relatively high wave and current energy. The Devils River

Formation is stratigraphically equivalent to the combined West Nueces, McKnight, and Salmon Peak Formations.

The Balcones fault zone is the principal structural feature in Uvalde County, although the displacement along the fault zone is less in Uvalde County than in Medina and Bexar Counties. Many of the most recently mapped faults are relatively minor (with less than 20 ft of displacement) and are recognizable only from aerial photographs. The Uvalde salient is a structural high in south-central Uvalde County consisting of several closely connected crustal uplifts that have differentially elevated parts of the Edwards aquifer. The intrusive basaltic rocks that form the axis of the Uvalde salient are remnants probably of both submarine and subareal volcanoes.

The porosity of the Edwards aquifer in Uvalde County results from depositional and diagenetic conditions along specific lithostratigraphic horizons (fabric selective) and from structural and solutional features that can occur in any lithostratigraphic horizon (non-fabric selective). Whereas fractures and vugs probably provide the primary non-fabric selective porosity important toward the development of permeability, moldic and breccia probably are the most important types of fabric selective porosity.

In addition to depending on the effects of fracturing and the dissolution of chemically unstable minerals and fossils, the resultant permeability depends on the size, shape, and distribution of the pores, as well as the interconnection among the pores. Upper parts of the Devils River Formation and the upper unit of the Salmon Peak Formation compose some of the most permeable rocks in Uvalde County.

Although fractured and partially dissolved (honeycombed) strata are the most common characteristics of this faulted and locally karstic carbonate aquifer, another factor affecting permeability in the study area is the occurrence of igneous rocks. As with the major faults, most of the igneous intrusives are barriers to ground-water flow.

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