Geologic Map of the Edwards Aquifer and Related Rocks in Northeastern Kinney and Southernmost Edwards Counties, South-Central Texas

Pamphlet to accompany

Scientific Investigations Map 3105

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

COVER:

Fractured and jointed Salmon Peak Limestone exposed in 10-m-deep cut, Tularosa Road, about 22 km (14 mi) northeast of Brackettville in Salmon Peak quadrangle. Hills on distant horizon capped by Salmon Peak Limestone. Photograph by D.W. Moore, May 2005.

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KEN SALAZAR, Secretary

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Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2010

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Conversion Factors

Multiply	By	To obtain
	Length	
centimeter	0.3937	inch (in)
meter	3.281	foot (ft)
kilometer	0.621	mile (mi)

Vertical coordinate information is referenced to the National Geodectic Vertical Datum of 1929

North American Datum of 1983 (NAD 83)

Altitude, as used in this report, refers to distance above the vertical datum.

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Introduction

The Edwards aquifer is the most prolific carbonate aquifer in south-central Texas. It supplies water to agriculture, industry, military, natural ecosystems, and potable water to more than two million people in the region. Comanchean and Gulfian Series Cretaceous strata, consisting of the 200-m-thick Edwards aquifer and the confining rock units above and below it, dip gently and thicken southward (seaward) in northeastern Kinney and southernmost Edwards Counties (fig. 1). These shallow marine shelf carbonate strata total about 400 m in thickness and were divided into lithostratigraphic formations that were mapped at 1:24,000 scale in nine quadrangles and parts of three more (fig. 2). Previously published small-scale geologic maps that include Kinney County are those of Bennett and Sayre (1962), Lozo and Smith (1964), and the Geologic Atlas of Texas, 1977.

Normal faults, mostly downdropped to the southeast, trend northeastward across the area. They lie within a western extension of the Balcones fault zone. Other structural features include a few broad, open folds and several solution collapse features. Basaltic igneous rock bosses and dikes intrude the limestone and mudstone strata, recording Late Cretaceous volcanism, perhaps in shallow seas (Fowler, 1956; Greenwood, 1956). The northern part of the map area is the hilly Edwards Plateau cut by streams into resistant, Upper Cretaceous limestone. The plateau is bounded on the south by the Balcones Escarpment. The west Gulf Coastal Plain lies south of the escarpment.

The purpose of this report is to provide a detailed geologic map that can assist in the management of groundwater resources in Kinney County. Knowing the nature of the rock strata in the recharge and confined zones of the Edwards aquifer is necessary for understanding water volumes and flow in the aquifer.

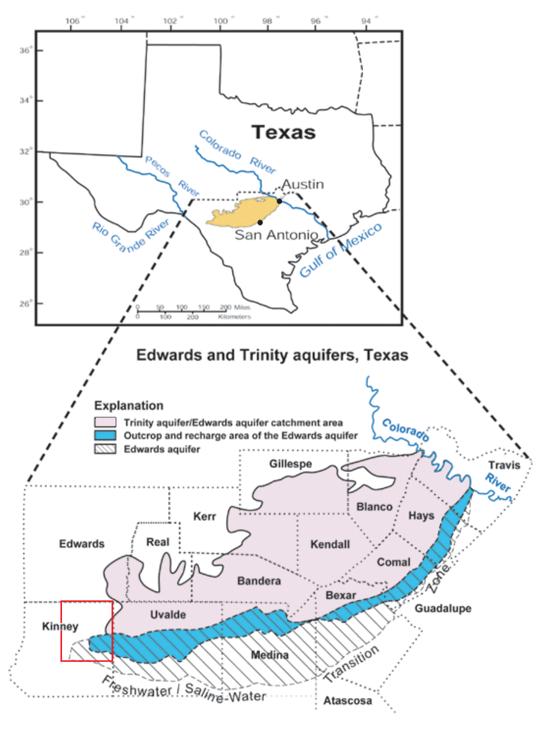

Figure 1. Area of Edwards aquifer; extent of geologic map shown by red box.

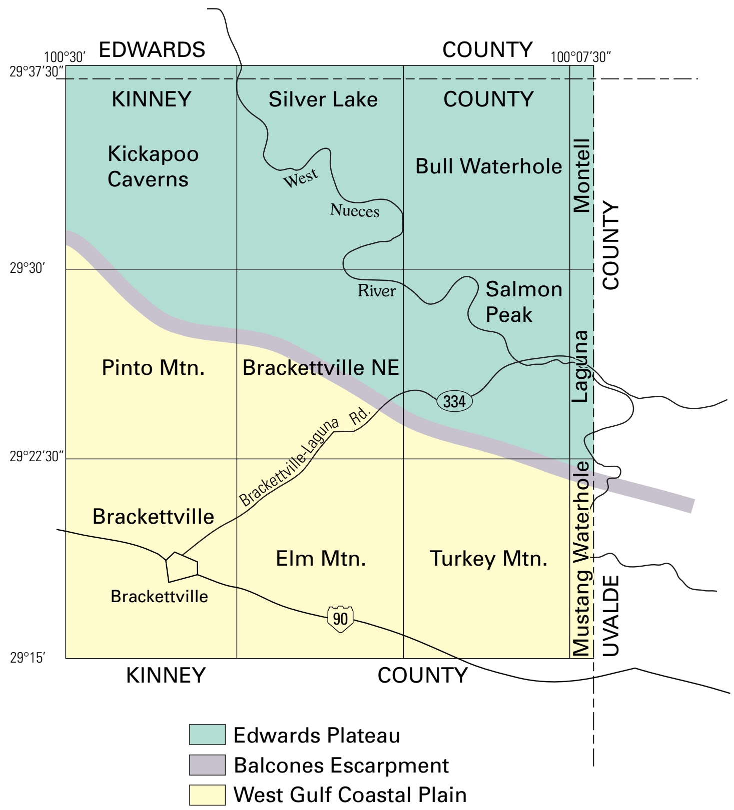

Figure 2. Nine 7.5-minute quadrangles and the western parts of three other quadrangles included in the geologic map area. Geologic mapping was done at 1:24,000 scale.

Paleogeography

A sketch of Cretaceous paleogeography of south-central Texas helps explain the origin of the mapped rock-stratigraphic units and their distinguishing characteristics. Regional studies have produced a consensus paleogeography (fig. 3) of a shallow marine, carbonate sediment environment that includes intertidal flats, bays, reefs, and open shallow seas (Young, 1959; Dunham, 1962; Fisher and Rodda, 1969; Stricklin and others, 1971; Enos, 1974; Rose, 1972; Coates, 1973; Bebout, 1974; Perkins, 1974; Bay, 1977; Smith, 1981; Miller, 1984; Humphreys, 1984; Scott, 1990). Investigations of modern carbonate depositional facies (for example, Ginsburg, 1957; Scholle and others, 1983) and Cretaceous microfacies using rock slabs and thin-sections (Miller, 1983) have refined the paleogeographic model, as has oil-exploration research, including geophysical logging, seismic profiling, petrography, and paleontology. Understanding the paleogeography of the original depositional environments helps explain variation in lithofacies, permeability, and transmissivity of the mapped rock units; these factors affect flow of groundwater in the Edwards aquifer. Diagenesis, also important (Hovorka and others, 1994), is not considered here.

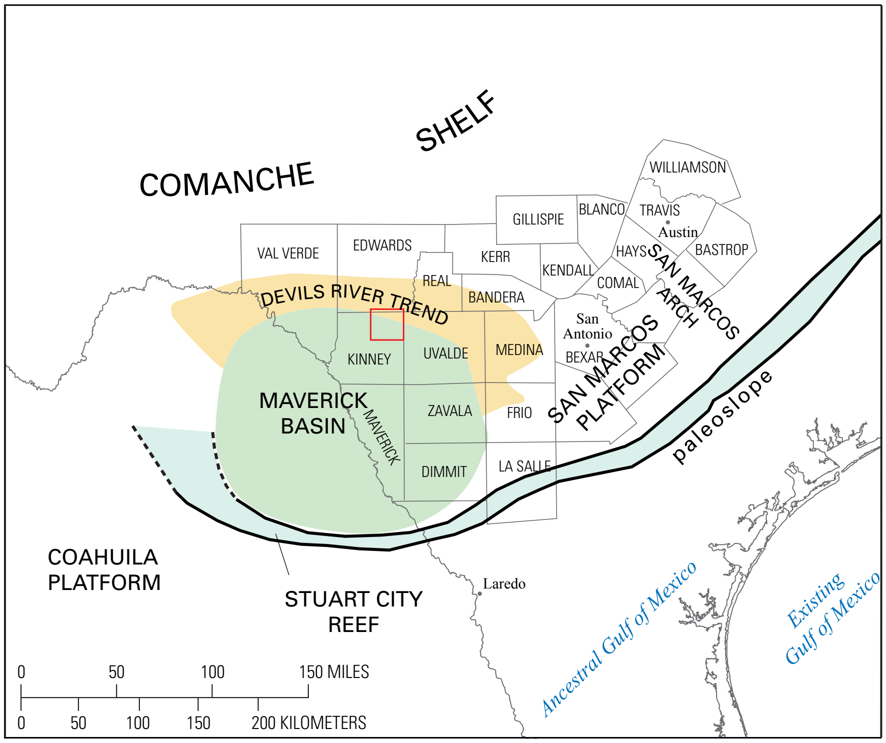

Figure 3. Paleogeography (regional depositional setting) of Comanchean and Gulfian rocks. Present-day counties and selected cities are shown. Red box locates the geologic map. Modified from Rose (1972).

In Late Triassic to Middle Jurassic time, the supercontinent Pangaea began fragmenting, rifting the lithosphere and opening the subtropical Tethys seaway and proto-Gulf of Mexico (Winker and Buffler, 1988). Rifting continued in Late Jurassic and Early Cretaceous time. The Gulf oceanic lithosphere cooled and subsided (Dunbar and Sawyer, 1987), and a rise in mid-Cretaceous global sea level forced seas northward onto the continental margin and formed a shallow sea on the Comanche shelf (fig. 3). Kinney County was located on that shelf and in the Maverick Basin (figs. 3, 4), whose intrashelf location is inferred from relatively thick Cretaceous strata in Maverick County, Texas (Winter, 1961). North of the basin stood a platform margin, the Devils River trend, containing abundant rudistid reefs and shoals (fig. 3). West of the basin was the Coahuila (Mexico) platform and east of it was the San Marcos platform (fig. 4). The south margin of the basin was delimited by the Stuart City reef in late Albian and early Cenomanian time (Scott, 1990); that reef separated the Comanche shelf from the proto-Gulf of Mexico (Winter, 1961; Rose, 1972). A reconstruction of the continental paleogeography about 101 Ma is shown (fig. 4). Shallow, subtropical seas sporadically covered both platforms and the intrashelf Maverick Basin during mid-Cretaceous and Late Cretaceous time (Young, 1986). The oldest mapped unit is the Glen Rose Formation (Kgr) of early Albian age, about 112 to 108 Ma. Most of the rock units mapped in Kinney County are of middle Albian through Santonian ages, about 108 to 84 Ma (table 1).

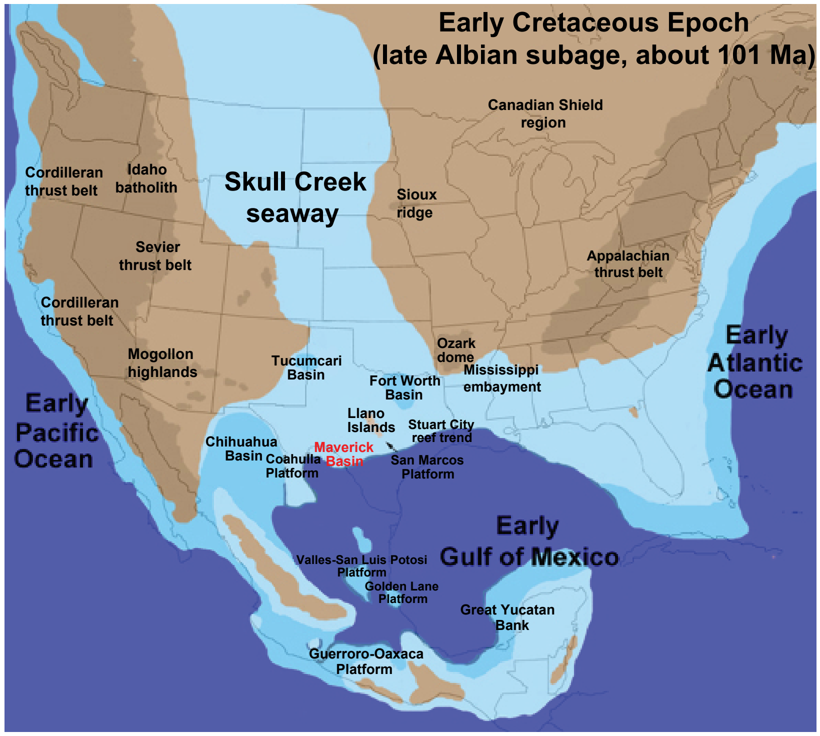

Figure 4. Paleogeography of Early Cretaceous Epoch (late Albian subage about 101 Ma). Intrashelf Maverick Basin shown in red letters. Ma, million years ago. Accessed on February 15, 2006, at: http://www.cretaceousfossils.com.

Carbonate deposition, interrupted by erosional intervals, prevailed during Early and Late Cretaceous during which the Trinity, Fredericksburg and Washita Groups, and Eagle Ford and Austin Formations were deposited (Scott and others, 1999). Carbonate-forming mollusks, especially rudistid bivalves, bryozoa, foraminifera, stromatoporoids, echinoderms, corals, other invertebrates, and possibly planktonic algae flourished in warm epicontinental seas (Friedrich and others, 2008) under a warm, equable climate (Barron, 1983; Fassell and Bralower, 1999). Carbonate mud, biogenic skeletal debris, and evaporites that accumulated on the sea floor and reef flanks were the original sediment of the Comanchean and Gulfian rocks. Production of micrite in Pleistocene coralline algal crusts by *in vivo* calcified coccoid cyanobacteria has been documented and, by analogy, is suggested as an origin of microcrystalline cements in fossil reefal limestone (Kaźmierczak and Iryu, 1999). Water depth on the Comanche shelf varied owing to sea level fluctuation, buildup of carbonate mounds or reefs, and differences in crustal stability of the San Marcos arch and the Maverick Basin (Loucks, 1977).

Cretaceous paleogeography was essential to forming the distinctive, mappable, rock-stratigraphic units depicted on the geologic map. For example, the middle member of the McKnight Formation (Kmm) is almost entirely covered by a band of dense vegetation that flourishes on dark-gray, organic-rich, thin beds of mudstone and shale. This distinctive rock unit resulted from its deposition in relatively deep, low-energy, perhaps anoxic lagoonal waters on the intrashelf Maverick Basin (Lindgren and others, 2004). The lower member of the McKnight (Kml) contains evaporite minerals (subsurface) and, on outcrop, collapse breccia caused by dissolution of those minerals; the evaporites perhaps formed on tidal mudflats (Miller, 1984) or on a subtidal shelf (Lehmann and others, 1998). In contrast, the Devils River Limestone (Kdvr) in northern part of map area (fig. 3), contains shell-fragment mudstone, wackestone, and rudist-fragment wackestone, indicating high-energy water on reefs and shoals. Resistant, massive beds of dense carbonate rock of the unit form characteristic smooth hills in the northern part of the map area. Petrography of several formations (Miller, 1983) revealed differences in the prevailing sizes of carbonate grains, which reflect variation in water energy and biota of mid-Cretaceous depositional environments in bays, open marine, intertidal areas, closed alkaline lagoons, shoals, reefs, and tidal flats (Winter, 1961; Lozo and Smith, 1964; Rose, 1972). These depositional environments shifted about as sea level fluctuated through time. In a marine environment, in principle, the prevalent wave, current, thermal energy, salinity, and oxygen availability determine grain size, sorting, composition, and bedding type of the sediment. Another key factor in this regard is the biota, like foraminifera,

Table 1. Summary of lithologic and hydrologic properties of the stratigraphic units in northeastern Kinney and southernmost Edwards Counties, south-central Texas.

Age[1] (numbers = Ma)				Series		Formation or member	Thickness m (ft)	Lithology	Field identification	Porosity and permeability[2]	Cavern development
CRETACEOUS	LATE	Santonian-Coniacian		GULF		Austin (Kau)	113 (370)	Relatively soft, argillaceous, chalky, medium-bedded limestone; interbeds of marl (earthy mixture of clay and calcium carbonate). Contains coccoliths, foraminifera *Inoceramus* and *Gryphaea* shells; poorly exposed	Chalky lime mudstone; poorly exposed over most of map area; exposed in old quarry of Fort Clark Springs; forms level land covered by thick caliche	Low to moderate porosity and permeability	Probable caverns on high-angle fault or fracture(s) near Las Moras Spring
		—89— Turonian		GULF		Eagle Ford (Kef)	39 (130)	Flaggy, argillaceous limestone, calcareous mudstone and siltstone, some silicic sandstone, and silty marl. Weathers to pastel-colors of pink, light brown, reddish brown; contains sparse *Inoceramus* shells	Weathers on low-relief land surface as pastels of brown, pink, yellow flagstone pieces cemented by caliche	Primary porosity lost; low permeability	None observed
		—92— Cenomanian	late	COMANCHE		Buda (Kbu)	30–48 (100–160)	Dense, thick-bedded, argillaceous, microcrystalline, limestone (micrite) and locally dolostone. Contains fine fragments of mollusk shell	Distinctive white and beige north-facing ledge of thick beds of dense limestone; conspicuous, 2-m thick bed of white limestone at top	Low porosity; low permeability	Scattered sinkholes
			middle, early	COMANCHE		Del Rio (Kdr)	25–27 (85–90)	Calcareous shale and mudstone, contains abundant *Ilymatogyra arietina* and pecten-like shells and foraminifera. Regionally persistent unit. Only mapped unit that is predominately clayey	Brown, earthy slope below a light-colored limestone bench or ledge; abundant small "ram's horn" oysters	Negligible; primary upper confining unit to Edwards aquifer	None
	—99.6— EARLY	Albian	late	COMANCHE	Devils River (Kdvr); Edwards aquifer	Salmon Peak (Ksp)	90–95 (295–310)	Thick-bedded lime mudstone (micrite); recrystallized and dolomitized locally; porcelaneous, conchoidal fracture; some shell fragment wackestone; abundant large chert nodules in upper part	Steep, light-colored (white) conical hills; resistant, slightly dissected uplands; bedding appears massive on outcrop	Both fabric and non-fabric selective, low to high porosity and low to high permeability	Dissolution along fractures and faults (?)
			late	COMANCHE	Devils River (Kdvr); Edwards aquifer; McKnight (Km)	upper member (Kmu)	24–30 (80–100)	Laminated to medium beds and flaggy bedding; brecciated in places, few thick chert laminae; locally contorted bedding (solution collapse)	Weathers as limestone cliffs (buttresses) in river bluffs	Fabric selective and non-fabric selective porosity	Negligible to minor
			middle	COMANCHE	Devils River (Kdvr); Edwards aquifer; McKnight (Km)	middle member (Kmm)	6–12 (20–40)	Dark, laminated mudstone and petroliferous shale and clayey lime mudstone	Laminated to thin bedded, thick vegetation growth; vegetated band 9 m thick on hills	< 3 percent porosity	None
			middle	COMANCHE	Devils River (Kdvr); Edwards aquifer; McKnight (Km)	lower member (Kml)	24–30 (80–100)	Thin-bedded *Gryphaea* fragment and pellet grainstone, micrite, and laminae of chert that pinch out; few thin brecciated beds; some open folds of local extent; solution zones	Thin-bedded lime mudstone (micrite); petroliferous odor	Vuggy and breccia-type porosity; little permiability	Negligible to minor; solution cavities in lower part
			middle	COMANCHE	Devils River (Kdvr); Edwards aquifer	West Nueces (Kwn)	43 (140)	Medium to thick-bedded mudstone and recrystallized limestone, burrowed, shell-fragment wackestone, oysters, miliolids, gastropods	Crops out on lower slopes of narrow canyons in hill country bluffs along West Nueces River; distinctly nodular	5-10 percent moldic porosity; little permiability	Minor along fractures and locally above basal contact
			middle	COMANCHE	Devils River (Kdvr); Edwards aquifer	Basal nodular	21 (70)	Nodular, burrowed lime mudstone, shell fragments, "heart clams," *Exogyra texana*, miliolids, *Lunatia*			
			early	COMANCHE		Glen Rose (Kgr)	Not determined in map area	Thin alternating beds of limestone, dolostone, and marl	Alternating thin ledges and earthy intervals; poorly exposed	Negligible	Unknown

[1]For discussion of placement of the boundaries between Comanchean-Gulfian provincial chronostratigraphic units and Albian-Cenomanian ages based on biostratigraphic zonation, see Mancini (1979).
[2]From Clark (2003).

calcareous algae, mollusks, and echinoids. These ecological elements and subsequent diagenesis produced the lithofacies seen in the mapped rock-stratigraphic units. In this study, although lithofacies were not mapped, they contributed to the distinctiveness of mapped rock-stratigraphic units.

Following lithification of the sediments, Neogene epeiorogenic uplift energized streams and rivers, causing erosion of the strata, normal faulting, sculpting of the plateau, escarpment, and shaping of the coastal plain present in the map area today.

Structure

Extending across the map are en echelon, northeast-trending, mainly down-to-southeast, high-angle normal faults. They are a western extension of the Balcones fault zone that developed during Neogene uplift of the Edwards Plateau (Ewing, 1991). When mapped using aerial photographs (National Aerial Photography Program (NAPP), infrared, approximately 1:40,000 scale, dated Sept. 2, 1996), faults appeared numerous in the Del Rio Formation (Kdr), Buda Limestone (Kbu), and Eagle Ford Formation (Kef) and less common in the Salmon Peak Limestone (Ksp). I believe that this apparent difference may not be that fewer faults exist in the Salmon Peak. It may be that the bedding of the other formations is more sharply defined, making the faults more easily detected on aerial photographs. The massive and uniform beds of limestone in the Salmon Peak exhibit few clear faults on the aerial photographs. If this speculation is valid, faults may be just as numerous in the Salmon Peak Limestone as in the aforementioned three formations that overlie it.

In the field, only two minor faults were seen in bluffs of the West Nueces River. They offset beds of the West Nueces Formation by only 1–2 m. Generally elsewhere in the map area, estimated dip slips of 1–7 m on faults are less than many displacements farther east in the Balcones fault zone near San Antonio. Trending northeastward in the central part of Kinney County are two broad folds having an estimated closure of < 10 m. In addition, a monoclinal structure dips at 4–5 degrees southwestward 6–8 km northwest of Salmon Peak (north of Ranch Road 334 and West Nueces River).

Thick beds of limestone units that compose the Edwards aquifer, the Salmon Peak, McKnight, and West Nueces Formations, are brittle and jointed. Although I did not systematically analyze the abundant joints evident in the rocks, I believe the joints probably formed in Neogene time under tensional stress caused by subsidence of the oceanic crust to the south relative to a more stable continental crust to the north. Jointed Salmon Peak Limestone is well exposed in a 10-m-deep road cut on Tularosa Road, about 6 km north of the Texas Ranch Road 344 (Brackettville-Laguna Road) junction (fig. 5). In this exposure, several solution cavities as large as 1 m across are developed along high-angle joints and at joint-plane bedding-plane junctions and at junctions of variously oriented joint sets. On aerial photographs, the Salmon Peak Limestone displays extensive thin, dark lineaments that may manifest such sets of fractures or joints. If so, and if the mapped area is representative of the larger Edwards aquifer recharge zone farther east, rock units of the aquifer may be more densely fractured than generally recognized. This suggests the possibility that fracture flow of groundwater may be significant in the aquifer.

Figure 5. Fractured and jointed Salmon Peak Limestone exposed in 10-m deep cut, Tularosa Road, about 22 km (14 mi) northeast of Brackettville in Salmon Peak quadrangle. Hills on distant horizon capped by Salmon Peak Limestone. Photograph by D.W. Moore, May 2005.

Methods

Mapping of rock-stratigraphic units was accomplished chiefly by use of aerial photography, after establishing the boundaries between the units in key field reference sections. In this largely privately owned region, accessible areas and reference sections included: (1) Shahan Ranch in the Pinto Mountain quadrangle; (2) “The River Road” that leads to cliff exposures along the West Nueces River (see index map on main map). This road connects the Tularosa Road (Ranch Road 3199) and Brackettville-Laguna Road (Ranch Road 334) and accesses Lozo and Smith’s (1964) type sections for the West Nueces Formation and reference section of the McKnight Formation (figs. 6, 7). (Location of the sections on map shown by WN I, WN II, and M 1 symbols on bluffs of West Nueces River); (3) Bar-N Ranch south of the West Nueces River in southeastern Salmon Peak quadrangle; (4) Las Moras Mountain; (5) Kickapoo Cavern State Park; (6) Fort Clark Springs; and (7) exposures along public roads.

Most mapping was done using National Aerial Photography Project (NAPP) color-infrared aerial photographs, at 1:40,000 scale, after they were stereographically oriented on a Kern PG–2 analog photogrammetric stereo plotter by a technician. Geologic contacts, faults, escarpments, and collapse features were interpreted and transferred by pantograph to 1:24,000-scale topographic maps, which then were scanned and digitized. Some bedding attitudes were estimated from oriented stereographic models; these are depicted on the geologic map as a dashed bedding symbol that differs from those attitudes that were measured directly with inclinometer, which are depicted using a solid bedding symbol.

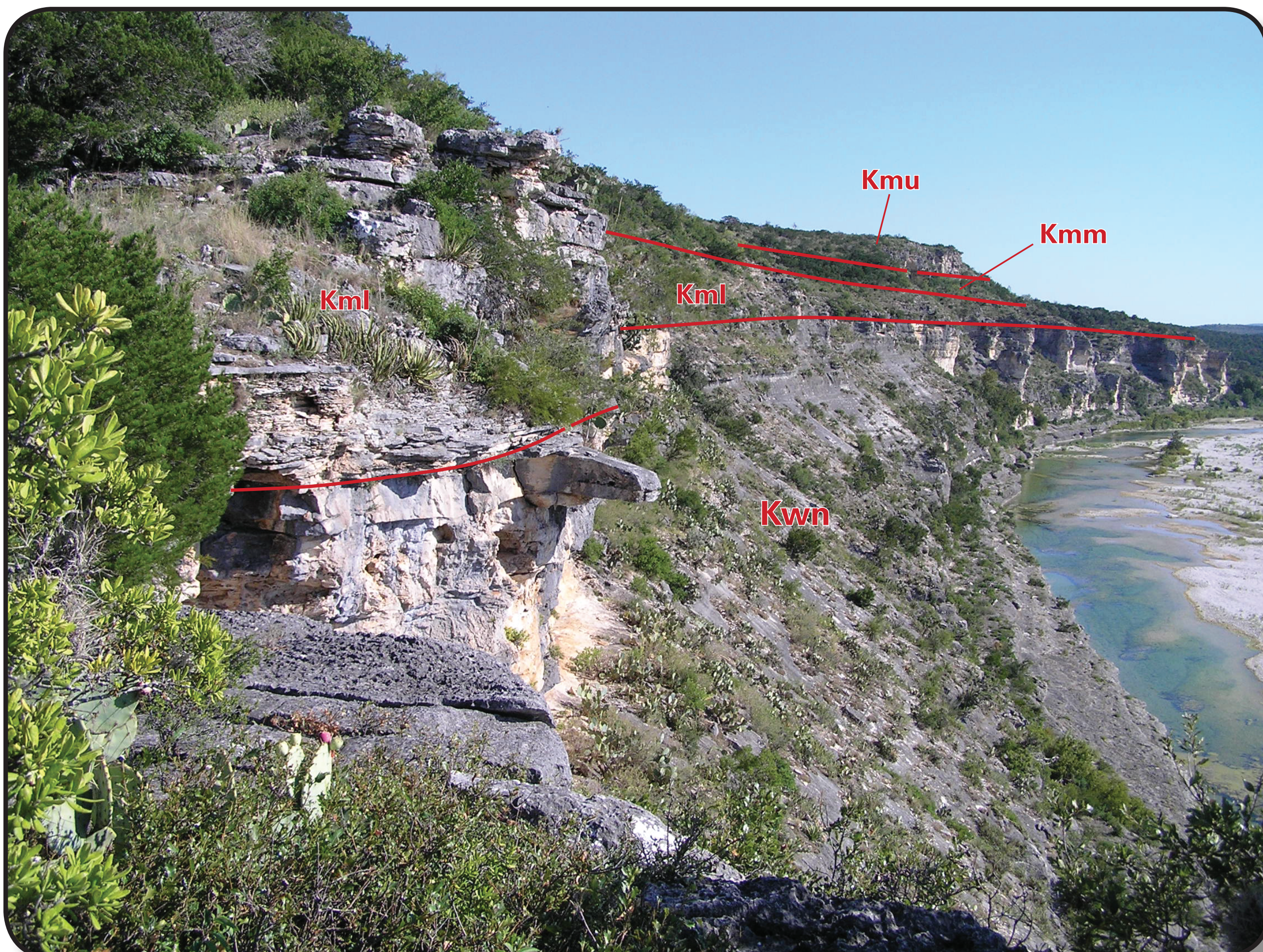

Figure 6. Type section and type locality of the West Nueces Formation (Kwn) at bluffs of the West Nueces River, northern Salmon Peak quadrangle (see type locality symbols in east-central part of map). Ledges in foreground are thin-bedded grainstone and micrite of the lower member of the McKnight Formation (Kml). Buttress-like cliffs in background are thick-bedded wackestone and lime mudstone (micrite) of the upper part of the informal “basal nodular unit” of the West Nueces Formation (Kwn). Kmm, middle member of McKnight Formation, showing characteristic vegetation band; Kmu, upper member of McKnight. Photograph by D.W. Moore, May 2005.

Figure 7. Rock units of the Edwards aquifer. Telephoto view northward toward West Nueces River and type locality (Lozo and Smith, 1964) of West Nueces Formation (Kwn). Kml, Kmm, Kmu are lower, middle, and upper members of McKnight Formation respectively. Ksp, Salmon Peak Limestone. Photograph by D.W. Moore, September 2005.

The naming convention of Lozo and Smith (1964) was used for rock units making up the Edwards aquifer. Names of units above and below the Edwards aquifer follow conventional nomenclature in south-central Texas (table 1). The Devils River Limestone (Kdvr) was mapped in the Devils River trend (fig. 1), which extends along the north edge of the map area. The Kdvr unit was mapped where I could not differentiate the West Nueces (Kwn), McKnight (Km), and Salmon Peak Formations (Ksp). The mapped rock units of the Comanchean Series contain the Edwards aquifer, which is included within the West Nueces, McKnight, and Salmon Peak Formations. These units and other rock-stratigraphic units above and below them, make up the geologic map.

In describing and naming carbonate rocks, two schemes are used. The first, standard definitions of rock types (Bates and Jackson, 1980) were applied during field examination. The second scheme, that of Dunham (1962), assigns carbonate rock names based on depositional texture (carbonate microfacies). Miller (1984) determined these microscopically and I used his names for some rock units in the Description of Map Units section on the map sheet.

Terminology

[Descriptions of colors from Munsell Color, 1975]

Caliche—Light-colored, commonly white (10YR 8/2), grayish-orange-pink (10R 8/2), very pale orange (10YR 8/2), locally soft, porous, and punky, also hard, massive and laminated calcium carbonate formed either in the soil-forming zone (pedogenic carbonate) or below the soil zone by precipitation from groundwater. In the map area, **caliche** is an extensive deposit 0.3–2 m thick, which engulfs angular pieces of bedrock on outcrops, forms thick laminations on bedrock, and cements alluvial gravel and colluvium in meters-thick aprons adjacent to streams and arroyos. On the coastal plain, it is ubiquitous and cements residuum and alluvium.

Carbonate rock names—Two schemes were used. First scheme: standard field definitions (Bates and Jackson, 1980), for example, lime mudstone, or simply mudstone, made mostly of carbonate silt or clay particles. Second scheme: Dunham's (1962) rock classification based on sedimentary depositional textures seen through microscopic examination of thin sections (by Miller, 1984). For example, a preponderance of microscopic calcareous silt and clay particles in mudstone (field term) yields the term microcrystalline limestone, (micrite). I named some rocks based on Miller's (1984) microscope work that uses the Dunham scheme.

Colors—Colors of unconsolidated deposits were compared to standard color chips (Munsell Color, 1975). Colors of rock were compared to a rock-color chart, Geological Society of America (1970).

Euxinic—Depositional environment of restricted circulation and stagnant or anaerobic conditions.

Facies—Areally restricted part of a stratigraphic unit that exhibits lithologic and paleontological characters different from those in another part of the same unit (Bates and Jackson, 1980).

Marl—Soft rock, chiefly commingled clay and calcium carbonate formed under marine conditions. For the purposes of this report, marl includes poorly consolidated calcareous claystone and impure, argillaceous limestone.

Pantograph—Mechanical system of fulcrums and a pencil connected to the moveable arm of an analog photogrammetric stereoscope that moves in concert with a stereoscope. The pencil traces paths of those movements onto a paper base map. The pantograph transfers contacts between rock-stratigraphic units from their location on an aerial photograph to their precise location on a topographic base map.

Gradational boundary—Boundary on the geologic map depicted by a change in color of map units and gradational contact symbol (see Explanation on map). This type of boundary indicates where details on the ground are lost that allowed detailed mapping of units and, across the boundary, only a general, undifferentiated unit is identifiable. For example, upper (Kmu), middle (Kmm), and lower (Kml) McKnight units were mappable as far as a gradational boundary, and across it only the McKnight (Km) Formation, undifferentiated, was recognized and mapped. Also a gradational boundary was mapped where the West Nueces (Kwn), McKnight, and Salmon Peak (Ksp) units were no longer differentiated, and a correlative unit, the Devils River Limestone (Kdvr), was mapped instead.

Description of Map Units

[Color of units from Munsell Color, 1975]

Qal **Alluvium (Holocene and late Pleistocene)**—White (10YR 8/2) and very pale brown (10YR 8/3) silt, sand, granules, pebbles, and cobbles. The unit weathers gray (10YR 6/1), is mostly unconsolidated, and is composed of subrounded clasts, predominantly limestone and minor chert. Present in channels, floodplains, on low terraces, and mapped as sheetwash alluvium in large sinkholes and closed topographic depressions. In hilly terrain (northern part of area) the unit is caliche-cemented, laminar in places, sandy, angular limestone and minor chert gravel; 1–3 m thick adjacent to channels, grading to colluvium upward on hillslopes. Forms point bars of rounded cobbles and pebbles adjacent to channels of West Nueces River (northeast part of map area). On nearly flat land, as in the upper valley of Pinto Creek (2 km southwest of Alamo Village, on Ranch Road 674 in west-central part of map), unit is grayish-brown (10YR 4.5/2) and brown (10YR 5/3) calcareous, silty clay, clay, and fine sand cut by channels 2–3 m deep; channels expose abundant limestone pebbles in lower part. On broad flats, unit is highly calcareous and clayey and contains rounded gravel; unit absorbs and releases runoff. Base covered; estimated thickness 0.3–5 m

Qc **Colluvium (Holocene and late Pleistocene)**—Thin colluvium covers much of the map area except the steepest hillslopes in the northern area. Only exceptionally thick colluvium was mapped, generally on 4–5 percent slopes on flanks of small valleys. Silty clay with abundant gray limestone pebbles, cobbles, and angular fragments on surface. Cementing the colluvium on nearly flat land (southern half of the area) is caliche, 0.5–1 m thick, which is mostly soft and punky, and capped locally by wavy laminar hard surface; caliche forms rinds 2–4 mm thick on limestone and chert clasts. As developed on Devils River (Kdvr) and Salmon Peak (Ksp) Limestones in the hilly northern part of map area, bedrock crops out upslope of concave-upward footslopes, which are covered by colluvium made of pebbly clay and silty soil that supports grass and abundant shrubs. Thickness of unit 2–5 m

Qls **Landslide deposit (Holocene and late Pleistocene)**—Jumbled soil material, talus, and blocks of limestone, siltstone, and basic igneous rock on the flanks of Turkey Mountain. Thickness estimated 2–10 m

Qaf **Fan alluvium (Holocene and late Pleistocene)**—Similar to alluvium (Qal) compositionally and texturally except deposits form fans at the mouths of small watersheds in the central part of map. Thickness estimated 2–6 m

Qt **Terrace alluvium (late Pleistocene)**—Alluvium in terraces 5–10 m higher than modern channel of West Nueces River. Brown (10YR 5/3) clast-supported, rounded limestone pebble and cobble gravel, and sand, silt, and clay matrix. Apparently mostly planar bedded; calcite-cemented, resistant ledges locally. Common erosional scarps (depicted on map) in unit record scouring of alluvium during floods of West Nueces River. Base covered. Estimated thickness 3–8 m

Ql **Leona Formation (Pleistocene)**—Grayish-brown (10YR 8/2) and light-brownish-gray (10 YR 6/2) calcareous, clayey, silty, and sandy unconsolidated alluvium containing limestone granules and pebbles, and caliche fragments, which are abundant in the lower part of unit. Soft masses of calcium carbonate are present in the uppermost 1–2 m. The unit underlies wide terraces that slope southward at <1 percent gradient; terraces are a few meters higher than Pinto Creek and Elm Creek (western part of map area). The unit also underlies narrow terraces adjacent to, and 2–4 m higher than, the Holocene floodplains of Las Moras Creek and Lindsey Creek (south edge of map area). The unit probably is coeval with some terrace alluvium (Qt) mapped along the West Nueces River. The Leona records pre-Holocene fluvial aggradation as streams widened their valleys in the upper coastal plain south of the Balcones Escarpment (Sayre, 1936). Unit is widely exposed 50 km east of Kinney County along the Nueces and Leona Rivers in Uvalde County. In the early 20th century, wells dug in the Leona yielded sufficient water for domestic use or livestock, but reportedly were dry during severe droughts (Bennett and Sayre, 1962; Vaughan, 1900). The Leona thus may be an accessible, shallow aquifer in wet years. Base of unit covered; in the mapped area, estimated maximum thickness 5 m. Unit pinches out away from streams

Ki **Igneous instrusive rocks (Late Cretaceous, Campanian)**—Very dark gray (5Y 3/1) alkaline mafic rock of basaltic affinity present as bosses, dikes, sills, and some possible laccoliths. Rock weathers dark yellowish brown (10 YR 4/4). Forms erosional, isolated hills (Pinto, Las Moras, Turkey, and Elm Mountains) that rise above the upper coastal plain. Dikes appear as dark, narrow lineaments on aerial photographs; on the ground they weather recessively and are hidden by dark soil and dense vegetation. Centimeter-sized pieces of basalt were dug from soil over a dike at one locality. In these samples, olivine(?) is altered to pseudomorphs of amber-colored iddingsite, an oriented micaceous mineral, and brown, hydrous iron oxide (limonite and goethite?). Spencer (1969) classified similar rocks in the Uvalde region as melilite-olivine nephelinite, olivine nephelinite, analcite phonolite, olivine basalt, and nepheline basanite, in order of decreasing abundance. Greenwood (1956) described volcanic mudflows and the mineralogy of an alkali peridotite intrusion into the Del Rio Formation 18 km S62°E from Turkey Mountain (a few kilometers east of the map area in Uvalde County). Miggins and others (2004) obtained $^{40}Ar/^{39}Ar$ ages of 82–80 Ma and 74–72 Ma on similar rocks in Uvalde County. Dike thickness 1–3 m; sill thicknesses estimated as 5–10 m, possibly >10 m in places

Kau **Austin Chalk (Upper Cretaceous, Santonian-Coniacian)**—Relatively soft, argillaceous, chalky, medium- to thick-bedded micritic limestone, and mudstone intercalated by very thin beds of marl. Poorly exposed on coastal plain under a 1- to 1.5-m thick caliche hardpan. Best exposed at Fort Clark Springs (at Brackettville) in an 8-m-high wall of the old quarry, now an outdoor amphitheater, 180 m south of the Las Moras Springs. Inoceramid and nonspecific pelecypod shell fragments were observed in the quarry; *Inoceramus* sp. and *Gryphaea* sp. were observed in the map area. Workers report that the Austin Chalk in central Texas contains coccoliths, planktonic foraminifera, oyster benthic fauna (for example, *Exogyra*), *Inoceramus* sp. (Czerniakowski and others, 1984) and the oyster *Gryphaea aucella* (Bennett and Sayre, 1962; Blome and others, 2005); Bardack (1968) reported the holostean long-snouted fish *Belonostomus* sp. Exposures of Austin Chalk near Bracketville contain sparse, dark-brown, framboids 0.3–1 cm in diameter which are subspherical, densely clustered, intergrown cubes, pyritohedrons, and octahedrons of limonite? or goethite? pseudomorphs after pyrite. Sparse framboids on the light-colored weathered surface of the Austin helps distinguish it from exposures of the underlying Eagle Ford (Kef) Formation, which apparently lacks many framboids. It is unclear what the pyrite indicates about the Austin Chalk depositional environment. The origin of the framboidal pyrite is debatable; pyrite framboids may form in oxygen-depleted, pelagic or benthic water columns during sedimentation or may be diagenetic (Wilkin and Barnes, 1997). Modern, microscopic pyrite is common in recent sediments, microbial mats, and soils (Schelble and others, 2003). The Austin-Eagle Ford contact is obscure on the plain in the southern part of the map area, although Freeman (1961) reported it obvious in Val Verde County, west of Kinney County. The contact was interpreted as unconformable in Kinney County (Bennett and Sayre, 1962), and as conformable in southwestern Kinney County (Smith, 1981) and in Val Verde County (Freeman, 1961; Lock and Peschier, 2006). According to Hovorka and Nance (1994) the unit was deposited as nannoplanktonic oozes in water < 200 m deep, north and west of the San Marcos platform during a world-wide Coniacian-Santonian sea-level highstand. Unit thickens toward center of Maverick Basin (fig. 3). Measured thickness of unit near southeastern corner of map area from well log RP–70–55–2AA at Highway 90 and West Fork Turkey Creek, 1.4 km south of south edge of geologic map, is 113 m (see fig. 8 on map)

Kef **Eagle Ford Formation (Upper Cretaceous, Turonian)**—Flaggy, argillaceous limestone, calcareous mudstone and siltstone, in very thin beds and thick (<1 cm) laminae; some calcareous, very fine-grained, silicic sandstone, and silty marl. Unit appears as shallow exposures of flaggy rock pastel-colored, “pink,” “tan,” and “pale red” on the coastal plain surface; unit is partly obscured by caliche hardpan. Color-chart colors are: pink (5YR 7/4), light-brown (7.5YR 6/4), light-brownish-gray (10YR 6/2), and reddish-brown (5YR 5/3), reddish-yellow (7.5YR 6/8), and yellow (10YR 8/4). Depositional textures include very finely crystalline limestone, lime mudstone, and peloid wackestone of about 0.06 mm-diameter microspheres, in lime mud matrix. The microspheres may be of cyanobacterial origin (Duque-Botero and Maurrasse, 2005). Unit contains *Inoceramus* sp. as large as 6 cm diameter, echinoids, shark teeth, and fish teeth. A few, small exposures in roadcuts show planar shale laminations 0.5–5 cm thick and beds as thick as 30 cm. Hummocky bedding, not exposed in Kinney County and well exposed in Val Verde County (60 km west of Brackettville), was interpreted as contourites formed in moderately deep water on the upper continental slope during an exceptionally high sea stand (Lock and Peschier, 2006) and interpreted by Trevino and Smith (2002) as tidal flat or shallow shelf deposits; unit contains slump folded beds and turbidites in

Val Verde County (Lock and Peschier, 2006). Interbedded marine limestone, calcareous mudstone and siltstone, and very fine-grained sandstone suggest deposition below storm wave-base. Smith (1981) assigned an age of late Turonian to Langtry Member of Boquillas Formation. The Boquillas is mapped in west Texas and is correlative to the Eagle Ford in Kinney County. The basal contact of the unit on the Buda Limestone (Kbu) was not observed in northeastern Kinney County; it was interpreted by Lock and Peschier (2006) to be sharp and unconformable in Val Verde County, west of the map area. Thickness about 42 m in drill hole RP–70–55–2AA at Highway 90 and West Fork Turkey Creek, 1.4 km south of south edge of geologic map (see fig. 8 on map and note at bottom right of geologic map border)

Kbu **Buda Limestone (Upper Cretaceous, Turonian-Cenomanian)**—White (10YR 8/2), pale yellow (2.5Y 7/4), and light-gray (10YR 7/2), locally very pale orange (10YR 8/2) dense, argillaceous, thick-bedded, microcrystalline limestone (lime mudstone), intrasparite, and locally dolostone. Unit weathers olive gray (5YR 3/2); smooth to conchoidal fracture; contains silt-size iron oxide particles and scattered sub-millimeter size fragments of mollusk shell. Typically, the unit is a sequence of resistant, planar 0.5- to 1.5-m-thick beds that dip southward and crop out in a north-facing cuesta. A 2-m-thick white limestone bed at the base of this sequence is conspicuous and can be traced east-west across the entire map area. The outcrop caps the brown, earthy, low slope of the underlying Del Rio Formation (Kdr). Basal contact on Del Rio is sharp; possible depositional environment is middle to outer shelf, open-marine environments (Denison and others, 2003). The Cenomanian-Turonian boundary probably is present within the unit, based on foraminifera in the Buda in the Big Bend region 400 km west of the map area (Frush and Eicher, 1975). Thickness 25–40 m along strike in map area, thickening westward and southward. Thickness about 30.5 m in drill hole RP–70–55–2AA at Highway 90 and West Fork Turkey Creek, 1.4 km south of south edge of geologic map (see fig. 8 on plate and note at bottom right of geologic map border)

Kdr **Del Rio Formation (Upper Cretaceous, early Cenomanian-late Albian)**—Formerly mapped as Grayson Marl and Grayson Formation (Bennett and Sayre, 1962), from outcrops in Grayson County, Texas (Cragin, 1894). Unit crops out as light-yellowish-brown and brownish-yellow, silty, calcareous shale and mudstone in an earthy, low-angle, generally north-facing slope; base of unit is generally covered. Drill hole samples of unit are dark-bluish-gray, dense, plastic, laminated clay and claystone. Exposures contain 5–20-cm-thick beds of calcite-cemented claystone and laminations of iron-oxide and calcite-cemented, fine-grained sandstone; gypsiferous in places. Contains abundant, 2–3 cm-long “ram’s horn” marine oysters *Ilymatogyra arietina* (previously *Exogyra arietina*), *Texigryphaea graysonana,* pectens, and *Globigerina* foraminifera. Other fossils reported in the unit in central Texas and Maverick basin (not seen in map area) include: echinoids (starfish), *Ptychodus* sp. (teeth of shell-crushing shark or ray), *Cretolamna* (shark teeth), and ostracodes. The unit contains the *Graysonites* ammonoid fauna (*G. lozoi*, *G. adkinsi*), which define the Albian-Cenomanian boundary in the Gulf region (Mancini, 1979). The Albian-Cenomanian boundary is in the basal 1.5 m of Grayson Formation (Del Rio equivalent) near Waco, Texas, based on the presence of the planktonic foraminiferan *Rotalipora evoluta* (Pessagno, 1969). Researchers have interpreted depositional environments of the Del Rio Formation as 1) modest water-depth tempestites (Lock, 2008), 2) shallow near-shore, muddy siliclastic marine transgressive (Jones, 1993), and 3) open shelf, moderately deep water, low wave and current energy (Rose, 1972). The formation is extensive in southern-central and eastern Texas, on the San Marcos platform, and in southern Oklahoma and is the only unit in the Fredericksburg-Washita stratigraphic interval composed chiefly of clay. The Del Rio is part of the upper confining unit of the underlying Edwards aquifer (table 1). Outcrop thickness 25–27 m; thickness from well logs in Grass Valley is 29 m (Roberto Esquilin, written commun., 2007); thickness is 40 m in a 1055 ft-deep well (RP–70–55–2AA, drilled April 29, 1982) 3.0 km southeast of junction of U.S. Highway 90 and State Road 1572 (to Spofford) and 60 m south of U.S. Highway 90, in Odlaw quadrangle, 1.4 km south of south edge of geologic map (see fig. 8 on map for gamma log); unit is >76 m thick in southwestern Zavala County, southeast of Kinney County (fig. 3)

Ksp **Salmon Peak Limestone (Lower Cretaceous, upper Albian)**—Very pale orange (10YR 8/2; fresh break), porcelaneous microcrystalline limestone (micrite) to finely crystalline limestone (recrystallized?), conchoidal fracture; weathers gray (10 YR 5/1) and medium olive gray (5Y 5/1). Abundant chert nodules 5–25 cm across exposed discontinuously along horizons, which is typical in northeastern

Kinney County and in the "lower unit" at Chalk Bluff type section in western Uvalde County (Lozo and Smith, 1964). Lower part is thick-bedded (0.5–1.5 m) globigerinid lime mudstone. Unit includes partly burrowed, miliolid packstone. The contact with the underlying McKnight Formation was interpreted as disconformable by Lozo and Smith (1964). Unit name was proposed (Lozo and Smith, 1964) to replace the "Georgetown Limestone" and was named after Salmon Peak located 30 km northeast of Brackettville (see map). Unit represents reef margin and basin facies (for a detailed facies and cyclical stratigraphic analysis of this unit, see Zahm and others, 1995; Humphreys, 1984). Forms light-toned, whitish, conical hills, northeast part of map area. Is upper unit of Edwards aquifer. Thickness about 115 m at Chalk Bluff type section, Uvalde County, 37 km east of Brackettville. Eroded thickness in map area typically 90–95 m; more than about 215 m in subsurface of Maverick Basin, Maverick County, south of map area

Km **McKnight Formation, undivided (Lower Cretaceous, Albian)**—Laminated and thin-bedded, light-gray (10YR 7/2) lime mudstone, petroliferous shale, and cyclic, subtidal, dark organic-rich argillaceous limestone; mild fetid odor on fresh break. Locally developed breccia and collapsed bedding, probably caused by dissolution of evaporite minerals. Depositional environment of the unit was basinal, calm, sometimes euxinic, hypersaline, and evaporitic (Rose, 1972; Sheu and Burkart, 1982); at other times carbonate-forming, probably in a low energy, restricted lagoon. Studies of marine mud deposits (Schieber and others, 2007; Macquaker and others, 2007) concluded that currents and burrowing by diminutive macrofauna are active at many mud-water interfaces, suggesting some energy there. This unit and its informal members (described below) are the middle part of the Edwards aquifer. Thickness was reported as 42.7 m by Lozo and Smith (1964) at their Bitter Ranch type section (see symbol on map, Salmon Peak quadrangle). Unit is about 91 m thick in a drill hole (International Boundary and Water Commission ID–22 core test, 6 km WNW of Del Rio, Val Verde County, Tex.). Thickness in northeast part of map area 50–61 m

Kmu **Upper member**—Light gray (10YR 7/2), very pale brown (10YR 8/4), mottles of yellow (10YR 7/6) and brownish yellow (10YR 6/6), wisps of yellow (10YR 7/6), dense micrite; weathers gray (10YR 5/1). Mostly thin-bedded, some thick beds (0.4–0.6 m), porcelaneous, conchoidal fracture. Unit contains evaporite minerals in the subsurface, as inferred from geophysical logs. Chert laminae present; bedding is locally brecciated and collapsed. Thin-bedded, some thick-bedded pellet lime wackestone and packstone and thin beds of silty, lime mudstone. In places unit forms a subtle bench below the uniform hillslopes eroded in the overlying Salmon Peak Limestone (Ksp). Evaporite minerals (subsurface only) suggest tidal mudflat and hypersaline, shallow lagoonal depositional environments (Miller, 1984). Thickness 24–30 m

Kmm **Middle member**—White (10YR 8/1, 10YR 8/2) dense microcrystalline limestone (micrite or lime mudstone), weathers gray (10YR 6/1); petroliferous odor on fresh break, conchoidal fracture. Very thinly bedded (flaggy) and laminated dark-gray, carbonaceous, somewhat petroliferous, lime mudstone; organic rich; locally common chert laminae about 1 cm thick; local thin beds of shell hash. Brecciated in places, probably owing to dissolution of beds of evaporitic minerals, causing localized collapse. Some micrite beds contain thin pieces of oyster shell. Within an area less than 4 km from Salmon Peak (north-central part of map), this middle member forms a conspicuous horizontal vegetation band about 7 m thick; mapping of unit within this area is certain. Northeast of Salmon Peak the vegetation band divides into two and three thinner bands, making the upper and lower limits of the unit less certain. Unit was deposited in a lagoonal environment (Miller, 1984), which was hypersaline at times. Thickness 6–12 m

Kml **Lower member**—Very pale brown (10YR 8/3) and white (10YR 8/2) lime mudstone (micrite). Some rock in the unit is uniform and porcelaneous and breaks smoothly or conchoidally; other rock is micro-vuggy, porous, recrystallized, very finely crystalline, thin-bedded (5–30 cm thick) limestone that weathers gray (10YR 6/1) and contains common to abundant 1-cm-thick chert laminae repeating in sets that are as much as 30 cm thick; typical lime mudstone beds are 20–40 cm thick. Scarce, local oyster packstone beds (coquina beds of oysters 2–4 cm long). Thin-bedded pellet and shell-fragment grainstone. Locally brecciated beds are attributed to dissolution of evaporite minerals. Unit accumulated on an evaporite-dominated tidal mudflat and in shallow lagoons (Miller, 1983). Unit apparently intertongues with upper part of underlying West Nueces Formation (Kwn) northeastward from Salmon Peak (northeast part of map). Thickness 24–30 m

Kwn **West Nueces Formation (Lower Cretaceous, Albian)**—Light gray (10YR 7/1) nodular limestone. Lower 21 m is a thick-bedded, distinctively nodular limestone, not mapped separately, but shown in table 1; this regionally persistent part is known informally as “basal nodular unit” and “basal transgressive unit.” Depositional texture is chiefly a nodular, shell-fragment wackestone that contains common, dark-brown spherules (0.2–0.5 mm diameter) and about 3 percent calcite spar void fillings. The nodular appearance may result from recent weathering of the clayey limestone, originally lime mud, that underwent thorough burrowing by organisms. A few thick (0.5–1 m) interbeds of pinkish-gray (7.5YR N/4) grainstone are interspersed in the nodular limestone. Unit is jointed and contains common, small (<1 m) solution cavities in well-exposed, kilometer-long cliffs of the West Nueces River in the Salmon Peak quadrangle (fig. 6); in the cliffs, only one normal fault of 1-m displacement was evident. Unit contains common oyster fragments, *Ceratostreon texanum* (*Exogyra texana*), heart clams, and *Texigryphaea,* an oyster. Lozo and Smith’s type sections in bluffs of West Nueces River shown on geologic map by symbols WN I and WN II. The formation is the lowest part of the Edwards aquifer (table 1). Unit overlies Glen Rose Formation (Kgr), possibly conformably in most of Maverick Basin, although in the wider region, basal contact is generally nonconformable. The base was not observed in the map area. Thickness of unit according to Lozo and Smith (1964) is about 44 m; thickness as mapped in this report 36–43 m

Kdvr **Devils River Limestone (Lower Cretaceous, Albian)**—Unit is a carbonate ramp reefal facies of the Devils River trend, laterally equivalent to the Salmon Peak (Ksp), McKnight (Km), and West Nueces (Kwn) Formations (Maverick Basin facies). Unit is white (10YR 8/2) dense, microcrystalline limestone (lime mudstone), grainstone, and packstone that weathers light gray (10YR 7/2) and gray (10YR 5/1). Outcrops on hillslopes in northern part of map area commonly are pocked, pitted, and show fluted dissolution features and are topped by scattered chert nodules. Also includes laterally persistent, 1.5- to 2-m-thick beds of micrite; skeletal grainstone, and rudist packstone. Miliolid, pellet, rudist, shell-fragment lime grainstone and wackestone are locally recrystallized, dolomitized, and brecciated (Lozo and Smith, 1964). Lower 15–18 m is nodular, shell-fragment wackestone containing heart clams and *Ceratostreon texanum* (*Exogyra texana).* This part correlates to basal nodular unit of West Nueces Formation (Kwn) (Miller, 1984). Pastel-colored (pink, tan, pale red, and yellow), concentrically layered, oblate and semi-spherical nodules of chert are abundant in parts of unit; nodules are 1–3 cm in diameter, 2–20 cm long. Unit is exposed in northern part of map area, an area of mature, dendritic, stream patterns and smoothly rounded hills and small canyons. Unit was deposited north of the Maverick Basin in high-energy reefs, shoals, and marine carbonate banks (Devils River trend; fig. 3) and at times in shallow to deep subtidal settings (Zahn and others 1995). The Devils River Limestone was mapped where the Salmon Peak, McKnight, and West Nueces Formations were indistinguishable; the unit makes up the entire Edwards aquifer north of the Maverick Basin. Eroded thickness about 67 m

Kgr **Glen Rose Formation (Lower Cretaceous, lower Albian)**—Alternating thin to medium beds of relatively resistant limestone, dolostone, and soft claystone and marl. Unit is poorly exposed to concealed on low-angle slopes and flats in the east-central part of map area immediately north of the West Nueces River and in the valleys of Sycamore and Live Oak Creeks (northeast-central part of map). The uppermost beds probably crop out locally in the channel of the West Nueces River (Ted Small, U.S. Geological Survey, oral commun., 2005). Samples there were ambiguous as to lithostratigraphic unit. The distinct basal nodular unit of the West Nueces Formation (Kwn), which overlies the Glen Rose, is clearly exposed at the mouth of, and in the valley walls of, Chalk Creek, 2 km west of Salmon Peak, where a previous map (Lozo and Smith, 1964) erroneously depicts Glen Rose Formation. Other areas where the Glen Rose Formation should crop out (based on a 44 m thickness of the overlying West Nueces Formation) are obscured by colluvium and alluvium and the unit was mapped based on float. Unit accumulated in Trinity time (early Albian, see table 1.) in intertidal to restricted shallow marine, low wave energy and current energy on a carbonate ramp that prograded seaward, built upward, and evolved into a rudist reef complex that fringed the Comanche Shelf (Rose, 1972; Bay, 1977). The Glen Rose is the lower confining unit of the Edwards aquifer (table 1). Thickness of the unit undetermined in map area, approximately 335–473 m thick in a well[1] in western Kinney County

[1]Well G–2 Richardson Oil Co. Martin Rose no. 1, and Well T–1 Austral Oil and Exploration Co. Wardlaw-Whitehead Est. no. A–1 (from Bennett and Sayre, 1962, pl. 3).

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