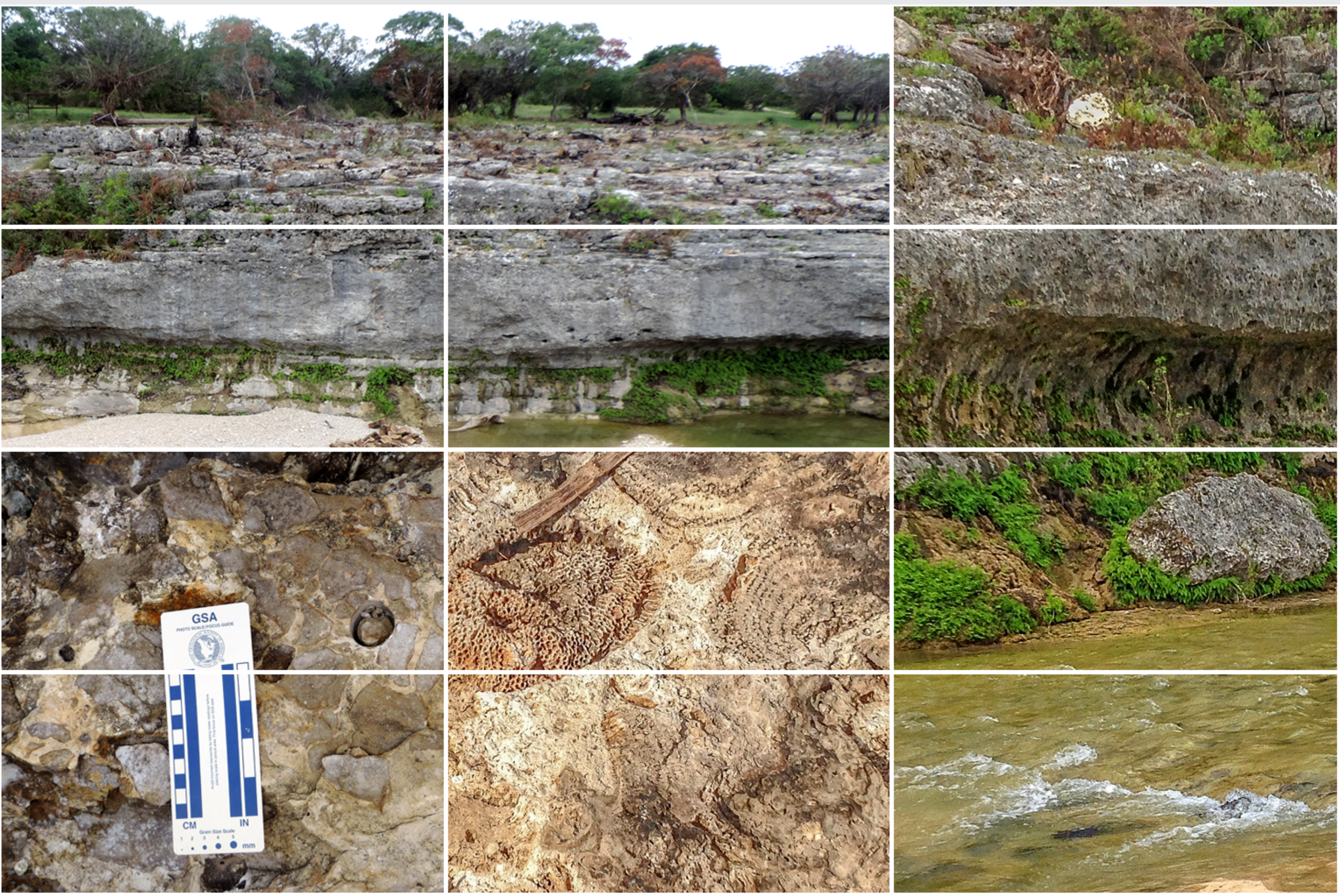
Geologic Framework, Hydrostratigraphy, and Ichnology of the Blanco, Payton, and Rough Hollow 7.5-Minute Quadrangles, Blanco, Comal, Hays, and Kendall Counties, Texas



Scientific Investigations Map 3363
Version 1.1, September 2016
Pamphlet

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

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Conversion Factors and Datum

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (cm)
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)

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

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83)

Acknowledgments

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Geologic Framework, Hydrostratigraphy, and Ichnology of the Blanco, Payton, and Rough Hollow 7.5-Minute Quadrangles, Blanco, Comal, Hays, and Kendall Counties, Texas

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Abstract

This report presents the geologic framework, hydrostratigraphy, and ichnology of the Trinity and Edwards Groups in the Blanco, Payton, and Rough Hollow 7.5-minute quadrangles in Blanco, Comal, Hays, and Kendall Counties, Texas. Rocks exposed in the study area are of the Lower Cretaceous Trinity Group and lower part of the Fort Terrett Formation of the Lower Cretaceous Edwards Group. The mapped units in the study area are the Hammett Shale, Cow Creek Limestone, Hensell Sand, and Glen Rose Limestone of the Trinity Group and the lower portion of the Fort Terrett Formation of the Edwards Group. The Glen Rose Limestone is composed of the Lower and Upper Members. These Trinity Group rocks contain the upper and middle Trinity aquifers. The only remaining outcrops of the Edwards Group are the basal nodular member of the Fort Terrett Formation, which caps several hills in the northern portion of the study area. These rocks were deposited in an open marine to supratidal flats environment. The faulting and fracturing in the study area are part of the Balcones fault zone, an extensional system of faults that generally trends southwest to northeast in south-central Texas.

The hydrostratigraphic units of the Edwards and Trinity aquifers were mapped and described using a classification system based on fabric-selective or not-fabric-selective porosity types. The only hydrostratigraphic unit of the Edwards aquifer present in the study area is hydrostratigraphic unit VIII. The mapped hydrostratigraphic units of the upper Trinity aquifer are (from top to bottom) the Camp Bullis, upper evaporite, fossiliferous, and lower evaporite which are interval equivalent to the Upper Member of the Glen Rose Limestone. The middle Trinity aquifer encompasses (from top to bottom) the Lower Member of the Glen Rose Limestone, the Hensell Sand Member, and the Cow Creek Limestone Member of the Pearsall Formation. The Lower Member of the Glen Rose Limestone is subdivided into six informal hydrostratigraphic units (from top to bottom) the Bulverde, Little Blanco, Twin Sisters, Doeppenschmidt, Rust, and Honey Creek hydrostratigraphic units.

This study used the ichnofabric index scale to interpret the amount of bioturbation in the field. Most of the geologic units in the study area are assigned to the *Cruziana* and *Thalassinoides* ichnofacies consistent with interpretations of a tidal-dominated open marine environment (sublittoral zone). Ichnofossil assemblages are dominated by *Thalassinoides* networks, but also contain *Cruziana, Ophiomorpha*, *Paleophycus*, *Planolites*, and Serpulid traces.

Introduction

The Trinity aquifer is classified as a major aquifer by the State of Texas (George and others, 2011). However, transmissivities and water yields can be comparatively lower than the Edwards aquifer to the south (Maclay, 1995; Mace and others, 2000). The lower water yield in the Trinity aquifer being attributable to its anisotropy caused by the presence of shales (Ryder, 1996) and argillaceous limestones. Population growth and drought conditions have combined to renew interest in the Trinity aquifer as a source of potable water due to growing concerns about groundwater availability (Mace and others, 2000).

The carbonate rocks composing the Edwards and Trinity aquifers have been exposed to meteoric water, surface water and groundwater, resulting in landforms containing springs and karst features such as caves, sinkholes, and other solution-enlarged areas. Meteoric water has altered the original sedimentary rocks composing the aquifers episodically from deposition through present. Porosity developed in carbonate rocks can have appreciable effects on the hydrogeologic characteristics of the formations and can create focused points or areas of recharge (Mylroie and Carew, 1990; Hanson and Small, 1995). The same porosity that can focus recharge can also result in an aquifer that is susceptible to contamination because storm-water runoff is quickly transferred to the subsurface (Ryan and Meiman, 1996).

Hydrostratigraphy is the classification of geologic structures in regard to their water-bearing characteristics (Maxey, 1964; Seaber, 1988). This work represents a continuation of efforts to understand the stratigraphy and hydrostratigraphy of these aquifers, based on a series of new geologic maps and studies along the outcrop of these aquifers. The new mapping subdivided geologic units that have not been subdivided in previous maps. Detailed hydrostratigraphic mapping of the study area is needed to help water managers determine the effects of future development of groundwater resources and aid in planning any response to various water issues (such as prolonged drought conditions) or assessment of mitigation measures (such as recharge structures or areas for aquifer storage and recovery projects).

Purpose and Scope

The purpose of this report is to present the geologic framework, hydrostratigraphy, and ichnological characteristics of a three-quadrangle portion of Blanco, Comal, Hays and Kendall Counties in order to help water managers, water purveyors, and local residents better understand and manage water resources. The mapped subdivisions will aid in identifying units that have potential to accept recharge, provide discharge and (or) act as confining units. The scope of the report is focused on geologic mapping, sedimentologic observations, and structural data of the outcrops and hydrostratigraphic units of the Edwards and Trinity aquifers within the Blanco, Payton, and Rough Hollow 7.5-minute quadrangles.

Description of the Study Area

This study area comprises the Blanco, Payton, and Rough Hollow 7.5-minute U.S. Geological Survey (USGS) quadrangles located in Blanco, Comal, Hays, and Kendall Counties, Texas (fig. 1). The study area, approximately 194 square miles (mi^2), consists of outcrops of the Lower Cretaceous Trinity (Hill, 1888) and the Lower Cretaceous Edwards Groups (Rose, 1972). Because of erosion the only remaining outcrops of the Edwards Group are the basal nodular member of the Fort Terrett Formation, which caps several hills in the northern portion of the study area.

The Trinity Group outcrops are composed of the Hammett Shale (Lozo and Stricklin, 1956), Cow Creek Limestone (Barnes, 1981), Hensell Sand (Barnes, 1981), and the Lower and Upper Members of the Glen Rose Limestone (Lozo and Stricklin, 1956; Scott and others, 2007). These rocks comprise the upper and middle Trinity aquifer (Ashworth, 1983). The lower Trinity aquifer is contained in the Hosston and Sligo Formations (Ashworth, 1983), which are not exposed in the study area.

Methods of Study

The methods used in this study were similar to those described in the Anhalt, Fischer, and Spring Branch 7.5-minute quadrangle mapping study (Clark and Morris, 2015). The following description of data collection methods is adapted from Clark and Morris (2015).

Hydrostratigraphic maps were developed by new field mapping with previously published maps to supplement and verify the current mapping effort in those areas where access could not be gained. Geologic maps, geophysical logs, and previous reports were compiled and reviewed to aid in quality control in the final map product. Stratigraphic nomenclature of the Cretaceous rocks exposed in and around the study area are from Whitney (1952); Lozo and Stricklin (1956); Striklin and others, 1971; Rose, 1972; Striklin and Smith, 1973; Amsbury, 1974, Inden, 1974, Perkins, 1974, Barnes, 1981, Clark and others, 2009, Weirman and others, 2010, Blome and Clark, 2014, Clark and others, 2014 and the U.S. Geological Survey National Geologic Map Database, GEOLEX (http://ngmdb.usgs.gov/Geolex).

Geophysical logs near the study area in Blanco and Hays Counties (fig. 1) were correlated with gamma ray geophysical logs where the hydrostratigraphic units were first identified in northern Bexar County (fig. 1). The geophysical logs were used to pick contacts for geologic formations and members.

Additionally, aerial photography was used to investigate areas prior to the field reconnaissance and mapping areas that were not accessible. Aerial photography was used in identifying linear trends associated with faulting or vegetative trends associated with changes in lithology or water-bearing ability. Also, features such as patch reefs could be identified in aerial photos.

Field mapping of the hydrostratigraphic units (HSUs) was accomplished on an Apple iPad2 containing geospatially registered 7.5-minute USGS topographic maps and utilizing the iPad2's integrated global positioning system (GPS). The field data were transferred to Esri ArcMap (Esri 2014) then used to produce the study area's hydrostratigraphic map. Faults identified in the field were based on observed and inferred stratigraphic offsets. Bedding attitudes of fractures and faults were obtained using a handheld compass and (or) the iPad2's compass application GeoId (Apple, Inc., 2013). The GeoId data was compared with the handheld compass to cross-verify the data. Strikes of fractures and faults were entered into Grapher (Golden Software, Inc., 2003) graphing software to produce a rose diagram showing direction and abundance of the various features.

Geologic framework and hydrostratigraphic descriptions include field observations from this study, as well as descriptions from previous studies. Lithologic descriptions (table 1) are based on Dunham's (1962) carbonate rock classification system, which concentrates on the rock identification of carbonate fabrics. Hydrostratigraphy was defined based on variations in the amount and type of porosity of each lithostratigraphic unit, which can vary depending on the unit's original depositional facies, structural history, and diagenesis. Porosity type is identified as either fabric-selective or not-fabric-selective under the sedimentary carbonate classification system of Choquette and Pray (1970). Field identifications were based on observations made of the outcrops for this study and several previous studies (Stein and Ozuna, 1995; Clark, 2003, 2004, Clark and others, 2009, 2014; Clark and Morris, 2015).

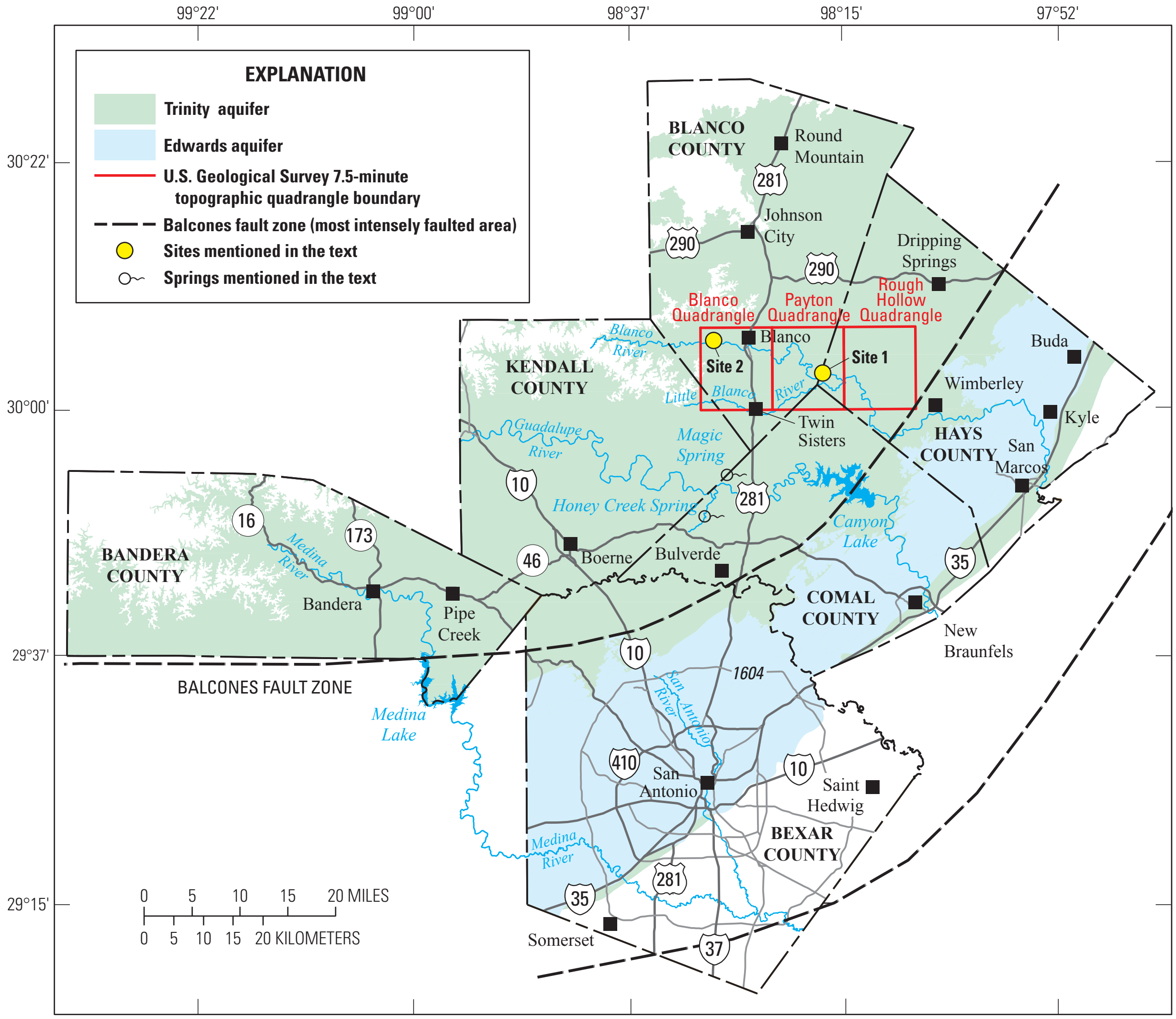


Figure 1. Location of study area.

In addition to geologic and hydrostratigraphic identification, one stratigraphic section was measured along the Blanco River in the Rough Hollow quadrangle (figs. 1 and 2). This area has previously been misidentified and because of recent flooding, much of the vegetative cover was removed from the valley. This new exposure made it possible to verify the presence of the Hensell Sand. The exposed Hammett Shale, Cow Creek Limestone, and the lower part of the Lower Glen Rose Limestone were also described in detail. The measured section was made by using a hand level and Jacobs's staff reading in decimal feet and the geologic descriptions were transferred to a geologic column (fig. 2). This study used the ichnofabric index (*ii*) scale defined by Droser and Bottjer (1986) to interpret the amount of bioturbation in the field. The *ii* scale quantifies the amount of bioturbation of a rock on a scale of 1–6. An *ii* of 1 means no bioturbation and an *ii* of 6 means more than 60 percent of the rock has been altered by bioturbation. The assigned hydrostratigraphic unit informal names are based on previously defined names (Blome and Clark, 2014; Clark and others, 2014; Clark and Morris, 2015). Formal geologic names and ages were verified using the USGS Geologic Names Lexicon (U.S. Geological Survey, 2015) in addition to applying the naming conventions of the Glen Rose Limestone and the subsurface Pearsall Formation based on references provided in this text. The descriptions below include general information about the geologic formation or member, lithology, thickness, primary fossils present, porosity, and type locality. Averages and ranges of unit thickness shown below are derived field measurements from within the study area.

Geologic Framework

The Trinity Group rocks were deposited during the Early Cretaceous (table 1) on a large, shallow-marine carbonate platform as three transgressional clastic-carbonate “couplets” during three transgressional events (Lozo and Stricklin, 1956; Stricklin and others, 1971). These three transgressional “couplets” deposited sediments that formed (1) the Hosston and Sligo Formations (Imlay, 1940); (2) the Hammett Shale (Lozo and Stricklin, 1956) and the Cow Creek Limestone (Hill, 1901); and (3) the Hensell Sand (Hill, 1901) of the Pearsall Formation and the Glen Rose Limestone (Hill, 1891; table 1). These units contain shale, mudstone to grainstone, boundstone, sandstone, and argillaceous limestone. The overlying Edwards Group (Hill, 1891) was deposited in an open marine to supratidal flats environment (Rose, 1972; Maclay and Small, 1986). The basal nodular member of the Fort Terrett Formation (Maclay and Small, 1986) was deposited in a subtidal environment at the beginning of a marine transgressional cycle (Rose, 1972).

Trinity Group

The Trinity Group overlies Pennsylvanian shale in the subsurface of the study area (Imlay, 1940). The group contains shale, mudstone to grainstone, boundstone, sandstone, and argillaceous limestone. The basal Hosston (Imlay, 1940) and Sligo Formations (Imlay, 1940) of the Trinity Group are not present in surface exposures. The thickness of the exposed Trinity Group is 635 to 802 ft in the study area. The following geologic framework descriptions are adapted from Clark and Morris (2015).

Hammett, Cow Creek, and Hensell Formations

Stratigraphically, the lowermost mapped unit within the study area is the Hammett Shale (table 1, figs. 2 and 3). It is approximately 50 ft thick based on data from nearby mapped areas (Clark and Morris, 2015). The contact between the Hammett Shale and the overlying Cow Creek Limestone is conformable (Wierman and others, 2010). Although usually not visible in outcrops because of alluvium, soils, and surface waters, the Hammett Shale is interpreted as being at the surface of the topographically lower sections of the study area. The interpretation of the Hammett Shale being at the surface is based on thickness of the overlying units and from field observations of topographic, vegetative, and hydrologic changes in the landscape. The Hammett Shale is a burrowed mixture of clay, terrigenous silt, carbonate mud, dolomite, and carbonate particles (Amsbury, 1974) (fig. 3). The lower 15 ft of the Hammett contains siltstone and dolomite. The upper 35 ft is primarily claystone with sandstone lenses overlain by fossiliferous dolomitic limestone (Lozo and Stricklin, 1956; Wierman and others, 2010).

The Cow Creek Limestone is approximately 40 to 72 ft thick based on the measured section and field observations in the study area, and thickens to the south (table 1, figs. 2 and 4). The upper contact of the Cow Creek with the Hensell Sand is unconformable (Wierman and others, 2010).

Generally, the lower 14 ft of the Cow Creek Limestone is composed of dolomitic oyster mudstone to wackestone grading to a dolomitic oyster wackestone to packstone (Wierman and others, 2010). Overlying the lower 14 ft of the Cow Creek Limestone is brown to white, very fine-grained to fine-grained carbonate sand (grainstone) with localized cross-bedding (Wierman and others, 2010). At site 1 (fig. 1) and downstream from site 1 on the Blanco River, a biostrome (fig. 5) topped by a rippled strandplain (fig. 6) can be found within upper part of the Cow Creek Limestone. The biostrome contain various corals (figs. 7) such as *Aplosmilia, Astrocoenia whitneyi, Tiarasmilia* sp.*, Cyathophora haysensis, Blothrocyathus* sp., *Hydnophora blancoensis, Isastrea whitneyi, Complexastrea glenrosensis, Orbicella travisensis, Thecosmilia* (?) sp. *Cyathomorpha damoni, Siderofungia irregularis, Meandraraea plummeri, Polyphyllastrea simondsi, Microsolena texana, Comalia fasciculata,* and *Epiphaxum labyrintricum* (Wells, 1932). These corals are built on a substrate of rudist bioherms which also interfinger with the reefal material. Various gastropods such as *Nerinea* can also be found interspersed in the biostromal material.

The Hensell Sand (table 1, fig. 2) is absent to 40 ft thick in the study area and conformably underlies the Lower Member of the Glen Rose Limestone. The contact between the Cow Creek Limestone and Hensell Sand commonly contains a conglomerate or breccia of red sandstone and carbonate (fig. 8). The Hensell Sand grades eastward and southward from a claystone, siltstone, and terrigenous sand into a dolomitic limestone facies attributed to the Lower Member of the Glen Rose Limestone. In far western Hays County, the Hensell Sand varies in thickness from absent to 12 ft and contains a conglomerate of cobble-sized red sandstone at its base and quartz geodes. The varying thickness has been interpreted by the authors as a deltaic lobe. The member commonly contains oyster shells and quartz geodes. The Hensell Sand commonly forms slopes, often with thicker soils and lush grasses.

Table 1. Summary of the geologic framework, hydrostratigraphy, ichnology, of the Blanco, Payton, and Rough Hollow 7.5-minute quadrangles, Blanco, Comal, Hays, and Kendall Counties, Texas. (Click here to open full-size, high-resolution image.)

[Period, Epoch, Group, Formation, Members, and lithology modified from Whitney (1952), Lozo and Stricklin (1956), Stricklin and others (1971), Rose (1972), Stricklin and Smith (1973), Amsbury (1974), Inden (1974), Perkins (1974), Clark and others (2010), Blome and Clark (2014), Clark and others (2014), and the U.S. Geological Survey National Geologic Map Database, GEOLEX (http://ngmdb.usgs.gov); aquifers from Maclay and Small (1976), Ashworth (1983); thickness from outcrop, Clark and others (2009), Weirman and others (2010), and Clark and others (2014); hydrogeologic function modified from Clark and others (2009), Weirman and others (2010), Clark and others (2014), Clark and Morris (2015); Porosity types modified from Choquette and Pray (1970). Fabric selective, I = Interparticle porosity, SH = Shelter porosity, MO = Moldic porosity, BU = Burrowed porosity, BP = Bedding plane porosity. Not-fabric selective, FR = Fracture porosity, CH = Channel porosity, BR = Breccia, VUG = vug porosity, CV = Cave porosity; *previously published identification for the hydrostratigraphic unit; **not aerially exposed in the study area.]

Geologic framework							Hydrostratigraphy					
Period	Epoch	Group	Formation	Members	Approximate thickness (feet)[1]	Lithology	Aquifer	Hydrostratigraphic unit (*)	Thickness (feet; measured at outcrop)	Hydro-geologic function	Porosity type	Field identification
		Edwards	Kainer	basal nodular	40–60	Shaly, nodular limestone; burrowed mudstone and miliolid grainstone: In western Comal County contains oyster reefs of *Ceratostreon [Exogyra] texana* and caprinid biostromes which is the transition to the Walnut Clay	Edwards	VIII	40–60	Confining, locally water bearing	BP, FR, CV	Massive, nodular and mottled limestone, BRBs[2] and orange wisps in freshly broken rock, *Ceratostreon [Exogyra] texana*
Cretaceous	Early Cretaceous	Trinity	Glen Rose Limestone	Upper	348–380 (typically 360)	Argillaceous wackestone, packstone to miliolid grainstone, argillaceous limestone; burrowed	Upper Trinity	Camp Bullis (B)	220–230	Confining	BU, BP, FR, occasional CV	Alternating beds of limestone and argillaceous limestone; fossils rare; stair-step topography
						Dissolved evaporites, highly altered crystalline limestone and chalky mudstone, breccia; commonly contains boxwork voids where the evaporites have been dissolved		Upper evaporite (C)	0–10	Aquifer	I, MO, BR	Weathers to an orangish red pebbly texture, often has less cedar growth and hardier, more abundant grasses, boxwork structure, springs and seeps
						Alternating wackestone, packstone, clay, and mudstone; thin, silty "platy" mudstone at base, *Orbitolina minuta* (Douglas, 1960), *Porocystis golobularis, Tapes decepta, Protocardia texana*, *Hemiaster* sp., *Neithea* sp., *Turritella*, gastropods and mollusks		Fossiliferous (D)	120	Confining	MO, FR, CV near top	Alternating beds of limestone and marls with *Orbitolina minuta* (Douglas, 1960) common
						Dissolved evaporites, highly altered crystalline limestone and chalky mudstone, breccia; up to three *Corbula* sp. beds; lower Corbula bed up to 1 foot thick with ripples common, commonly contains boxwork voids where evaporites have been dissolved		Lower evaporite (E)	8–10	Aquifer	I, MO, BR	Weathers to an orange; is red pebbly texture, often has less cedar growth and hardier grasses, boxwork structure, *Corbula* sp., springs and seeps
				Lowerr	195–330 (typically 200–225)	Wackestone to grainstone, agrillaceous wackestone, shale, evaporites; *Salenia texana, Macraster* sp., *Orbitolina texana* (Roemer, 1852), *Nerinia* sp., pecten, gastropods, pelecypods	Middle Trinity	Bulverde (A)	30–40 (typically 30)	Confining	BP, FR, MO and BR where evaporites have been removed	*Salenia texana* bed immediately below Corbula bed, abundant fossils including Protocardia, pectin, *Orbitolina texana* (Roemer, 1852), Porocystis, gastropods, echinoids, grades into marls, bioturbated limestone beds, and evaporite beds
						Mudstone to wackestone, argillaceous wackestone, boundstone; *Orbitolina texana* (Roemer, 1852), caprinid, toucasia, monopleurid, pectens, pelecypods, gastropods		Little Blanco (B)	30–40 (typically 30)	Aquifer	MO in patch reefs, BP, FR	Limestone beds thicker and more resistive to erosion than overlying and underlying units, *Orbitolina texana* (Roemer, 1852), rudist patch reefs
						Argillaceous wackestone and shale; *Orbitolina texana* (Roemer, 1852), pelecypods, gastropods		Twin Sisters (C)	10–40 (typically 30)	Confining shale beds	I	Thick marl beds, thin shale beds, *Orbitolina texana* (Roemer, 1852), often contains ponds and seeps, often little vegetation; steeper slopes often have "badlands" type weathering, thinner in areas of patch reefs in the underlying Doeppenschmidt Hydrostratigraphic unit
						Mudstone to grainstone, argillaceous wackestone to packstone, boundstone, miliolid grainstone; pectens, oysters, pelecypods, *Nerinia* sp., *Orbitolina texana* (Roemer, 1852), *Tylostoma* sp., caprinid, toucasia, monopleurid		Doeppenschmidt (D)	40–80 (typically 40)	Aquifer	I, MO, BU, BP, FR, CV	*Orbitolina texana* (Roemer, 1852), limestone beds thicker and more resistive than overlying and underlying, patch reefs formed on rudist, reefal talus
						Alternating beds of argillaceous wackestone to packstone and mudstone to grainstone, miliolid grainstone; pectens, oysters, pelecypods, *Nerinia* sp., *Orbitolina texana* (Roemer, 1852), *Tylostoma* sp., monopleurid		Rust (E)	40–70 (typically 40)	Confining	I, FR, CV	Tends to form stair-step topography with soils, *Orbitolina texana* (Roemer, 1852)
						Wackestone to grainstone, boundstone, burrows, *Orbitolina texana* (Roemer, 1852), *Trigonia* sp., toucasia, caprinid, shell fragments, pectens, miliolids, *Turritella*, and various corals		Honey Creek (F)	45–60 (typically 55)	Aquifer	I, MO, BU, BP, FR, CH, CV	Thick beds of wackestone to grainstone; corals, caprinid, *Trigonia* sp., cliff forming; outcrop often contains large limestone float with large channel and moldic porosity; caves and springs
			Pearsall	Hensell Sand	0–40	Claystone, siltstone, terrigenous sand; red sandstone conglomerate/breccia at base of unit; oysters, quartz geodes		Hensell	0–40	Aquifer	I, MO, SH, CV	Quartz geodes, large oyster shells, reddish sandy soil with good grass growth, red sandstone conglomerate/breccia at base
				Cow Creek Limestone	26–58	Very fine-grained to fine grained carbonate sand (grainstone) with localized cross-bedding; Areas of coral and rudist biostromes (boundstone) overlain by rippled, cross-bedded grainstone		Cow Creek	40–72	Aquifer	I, MO, BU, VUG, BP, FR, CH, CV	Carbonate sands, cross-bedding near top, biostrome composed of corals and rudist, talus slopes
					14	Dolomitic mudstone to packstone; oysters						
				Hammett Shale	50	Upper: Claystone, with siltstone lenses, overlain by fossiliferous dolomitic limestone; Lower: siltstone and dolomite	Confining unit	Hammett	50	Confining	**	Holds surface water; springs at contact with Cow Creek

[1]Thickness range based on minimum and maximum thickness of individual members (from field measurements and geophysical logs). The actual thickness range near the median of the possible thickness.

[2]Black rotund bodies (BRBs) probably from oxidation of Foraminifera (Small and Maclay, 1982).

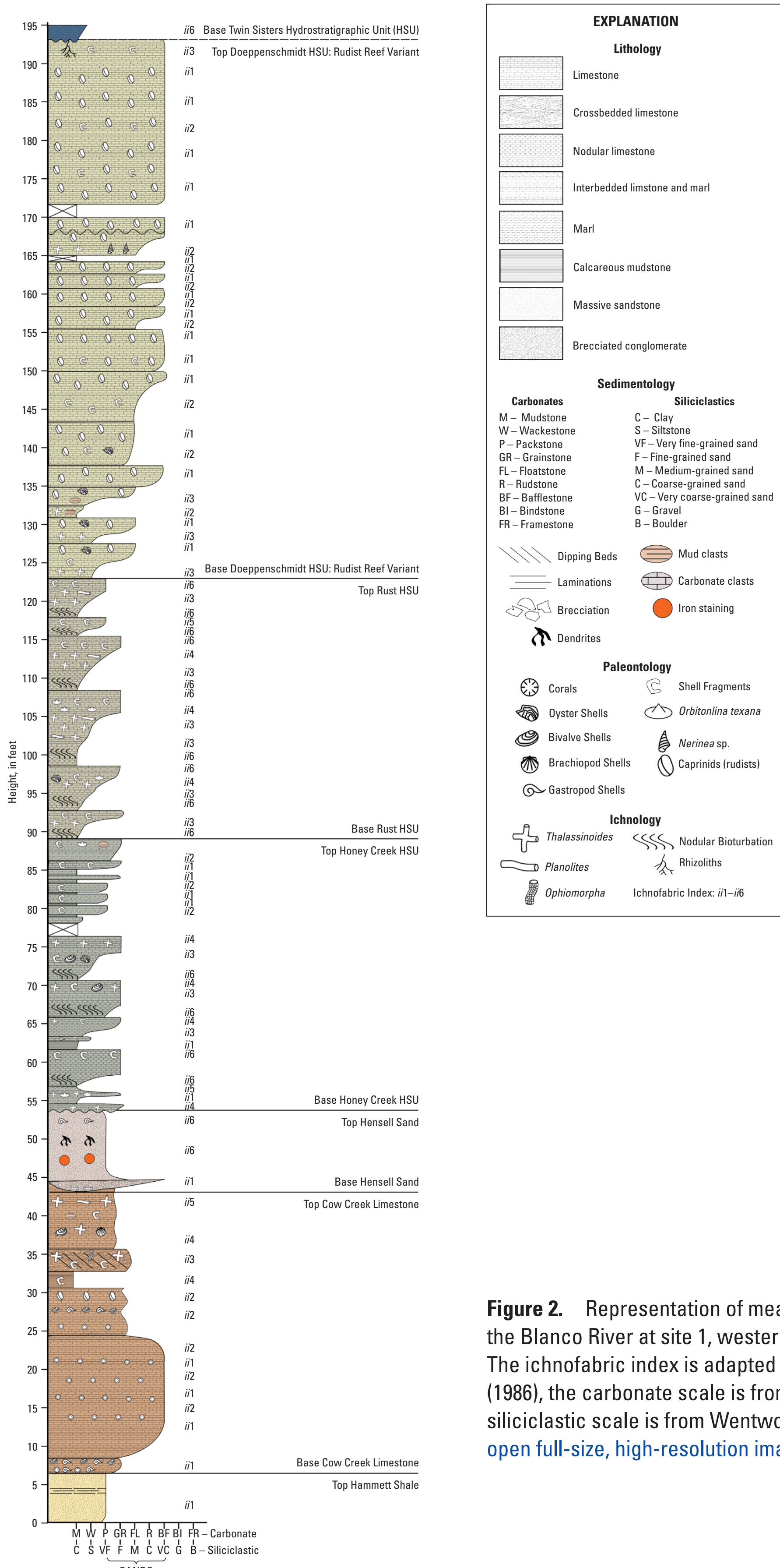


Figure 2. Representation of measured section along the Blanco River at site 1, western Hays County, Texas. The ichnofabric index is adapted from Droser and Bottjer (1986), the carbonate scale is from Dunham (1962), and the siliciclastic scale is from Wentworth (1922). (Click here to open full-size, high-resolution image.)

Figure 3. Photograph showing contact between the Hammett Shale (bottom) and Cow Creek Limestone (top) along the Blanco River at site 1, western Hays County, Texas. Photograph taken on July 13, 2015, by Allan Clark.

Figure 4. Photograph showing an outcropping of the Cow Creek Limestone along the Blanco River at site 1, western Hays County, Texas. Photograph taken on July 13, 2015, by Allan Clark.

Figure 5. Photograph showing an outcropping of a biostrome in the Cow Creek Limestone along the Blanco River at site 1, western Hays County, Texas. Photograph taken on July 13, 2015, by Robert Morris.

Glen Rose Limestone

The Glen Rose Limestone consists of alternating beds of yellowish-tan, medium-bedded limestone and argillaceous limestone with minor evaporite layers. It is composed of Lower and Upper Members (Scott and others, 2007) separated by a regionally extensive marker bed, containing the small fossil identified as *Corbula* sp. (Whitney, 1952) (table 1).

Lower Member

The Lower Member of the Glen Rose Limestone (table 1) might be as thin as 195 feet or as thick as 350 ft based on minimum and maximum thickness of the individual units; however, it has been observed to generally be 200 to 225 ft thick. In the western part of the study area (Blanco quadrangle) the Hensell Sand underlies the Glen Rose Limestone with a gradational contact. East of site 1 (Payton quadrangle), the Hensell Sand is not present; the Glen Rose Limestone overlies the Cow Creek Limestone directly.

The lower part of the Lower Member of the Glen Rose Limestone contains 45 to 60 ft (typically 55 ft) of very thick and resistive beds of wackestone to grainstone and boundstone (table 1, fig. 2). This lower part commonly contains trace fossil burrows (ichnofossil traces), shell fragments, pectens, miliolid, *Orbitolina texana* (fig. 6), *Trigonia* sp., *Turritella* sp., toucasia, caprinid and various corals including *Orbicella whitneyi* (Wells, 1932) and *Astreopora (?) leightoni* (Wells, 1932), and oysters.

Above these resistive beds are approximately 40 to 70 ft (typically 40) of alternating beds of argillaceous wackestone to packstone and mudstone to grainstone, miliolid grainstone, and (table 1, fig. 2). This 40 to 70 ft unit is generally obscured by soil and vegetation on slopes and has well-developed flatter, stair-step topography. Although the section is heavily covered, ledges were identified which contained miliolid grainstone, grainstone, nodular bioturbated wackestone, and monopleurids. Throughout the unit, pectens, oysters, other bivalves, *Nerinea* sp., *Orbitolina texana*, *Tylostoma* sp., and monopleurid can be found.

Next above is a 40 to 80 ft (typically 40 ft) section of thicker and more resistive mudstones to grainstone, and boundstone (table 1, fig. 2). The resistive limestone sections are separated by argillaceous wackestone to packstone. The boundstones are formed by rudist patch reefs with reefal talus slopes. The patch reefs extend from the area of site 1 in far western Hays County, southwestward across eastern Blanco and western Comal Counties to Camp Bullis in northern Bexar County and then west to the Pipe Creek area of Bandera County. In some locations, the patch reefs extend up through the overlying stratigraphic units. Fossil assemblages are similar to the underlying unit but include caprinids, toucasia, and monopleurid.

Moving upward is a 10 to 40 ft (typically 30 ft) section of thick argillaceous wackestone, interspersed shale, thin shale beds and occasional thin wackestone beds (table 1). This section commonly exhibits badlands-type weathering and often contains abundant *Orbitolina texana* with occasional bivalves and gastropods.

Continuing upward is a 30 to 40 ft (typically 30 ft) section of resistive mudstones to wackestone with beds of argillaceous wackestone (table 1). Some areas contain boundstone formed from rudist patch reefs and reefal talus which may extend up from underlying sections. The patch reefs are formed from caprinid, toucasia, and monopleurid species. This section of the Lower Member of the Glen Rose Limestone often contains *Orbitolina texana* (Roemer, 1852), pecten, bivalves, and gastropods.

Finally, the highest section of the Lower Glen Rose Limestone is a 30 to 40 ft (typically 30 ft) section of wackestone to grainstone with occasional monopleurid and toucasia. It also contains argillaceous wackestone, shales, and evaporite beds (table 1). The wackestone to grainstone grades upward into an 8 to 10 ft thick bioturbated, nodular, fossiliferous wackestone named the Salenia bed by Whitney (1952). Common fossils in the Salenia bed are *Salenia texana*, *Macraster* sp., *Orbitolina texana* (Roemer, 1852), *Nerinea* sp., pecten, gastropods, and bivalves (Douglas, 1960; Finsley, 1989).

Figure 6. Photograph showing an outcropping of strandplain at the top of the Cow Creek Limestone at site 1 along the Blanco River, western Hays County, Texas. Note dipping ripple marked beds of talus. Photograph taken on July 13, 2015, by Robert Morris.

Figure 7. Photograph showing a close-up of corals that form the biostrome at site 1 in the Cow Creek Limestone along the Blanco River, western Hays County, Texas. Photograph taken on July 13, 2015, by Allan Clark.

Figure 8. Photograph showing a close-up of the conglomerate/breccia bed at the base of the Hensell Sand at site 1 along the Blanco River, western Hays County, Texas. Note circular hole where rock plug was removed. Photograph taken on July 13, 2015, by Allan Clark.

Figue 9. Corbula bed containing ripples along Ledgerock Road, southeastern Rough Hollow quadrangle, western Hays County. Note hammer for scale. Photograph taken of August 18, 2015, by Robert Morris.

Upper Member

The Upper Member of the Glen Rose Limestone of the Trinity Group is 348 to 380 ft thick (typically 360 ft) in the study area. The Corbula bed marks the boundary between the Lower and Upper Members of the Glen Rose Limestone (table 1). According to Lozo and Stricklin (1956), the Corbula bed is at the top of the Lower Member of the Glen Rose Limestone. This report considers the Corbula marker bed to be at the base of the Upper Member of the Glen Rose Limestone because up to three Corbula beds have been found in the study area. The marker bed is the lowest of three Corbula beds, and the remaining two beds generally lie 2.5 and 5 ft above the marker Corbula bed. The lower Corbula bed is used for mapping purposes because it is the thickest and most regionally extensive although Scott and others (2007) consider the upper Corbula bed to be the boundary between the Upper and Lower Glen Rose Limestone. Generally, the Corbula marker bed contains ripples (fig. 9) and is up to 12 inches thick. The overlying upper two Corbula beds are usually less than ½ inch thick. The stratotype location of the Corbula marker bed (site 2) (Scott and others, 2007) is near the town of Blanco on the Blanco River (fig. 1). At the stratotype location (fig. 1), sauropod tracks, ripple marks, and burrows can be found below the Corbula marker bed within approximately 10 feet. The 10-ft thick unit of dissolved evaporites which overlies the Corbula marker bed is highly altered crystalline limestone produced from alteration of the original rock matrix. The evaporite bed also contains chalky mudstone, breccia, and boxwork voids where the evaporites have been dissolved. This unit often has less cedar and hardier grass growth on the outcrop than the surrounding rocks.

A 120-ft thick unit (table 1) overlies the lower evaporite unit in the study area. This unit is composed of alternating wackestone, packstone, clay, and mudstone. Overlying the lower evaporite unit is a thinly laminated silty mudstone that can be easily recognized by its “platy” character in outcrop (Clark and others, 2009). Commonly abundant fossils are *Orbitolina minuta (*Douglass, 1960), *Porocystis golobularis*, *Tapes decepta*, *Protocardia texana*, *Turritella* sp., *Hemiaster* sp., *Neithea* sp., gastropods and mollusks (Adkins, 1928; Finsley, 1989). According to Douglas (1960), *Orbitolina minuta* are restricted to the Upper Member of the Glen Rose Limestone.

In the southern part of the study area, a second evaporite unit (table 1) overlies the 120-ft thick unit. It is not continuous over the entire study area but reaches a maximum thickness of 10 feet in the southern part of the study area. The upper evaporite is similar to the lower evaporite layer. It is formed from dissolved evaporites and is a highly altered crystalline limestone and chalky mudstone breccia that commonly contains boxwork voids where the evaporites have been dissolved. The upper evaporite unit thins northward and eastward across the study area and is absent in much of the study area. This unit often has less cedar growth and hardier grass growth than adjacent rocks.

Overlying the upper evaporite unit is 220 to 230 ft of alternating beds of burrowed wackestone with some packstone to miliolid grainstone and argillaceous limestone. The argillaceous limestone is not well cemented and contains varying grain sizes (table 1). The upper 90-plus ft of the Upper Glen Rose Limestone seen in northern Bexar County is absent from the study area because of differences in depositional environments and a disconformity between the Edwards and Trinity Groups.

Edwards Group

The Edwards Group, which overlies the Trinity Group, is composed of mudstone to boundstone, dolomitic limestone, argillaceous limestone, evaporite, shale, and chert. In the study area, many of these rocks have been removed by erosion. The Fort Terrett Formation makes up the lower part of the Edwards Group (table 1). The unit at the base of the Fort Terrett Formation, often referred to as the basal nodular member (Rose, 1972), is a shaly, nodular limestone; burrowed mudstone to miliolid grainstone. The basal nodular unit is approximately 40 to 60 ft thick in the study area; it can be identified in the field by nodular gray mudstone containing black rotund bodies (locally called “BRBs”) and the occurrence of miliolids, gastropods, and the fossil oyster *Ceratostreon texana* (formerly *Exogyra texana*; Stein and Ozuna, 1995; Clark, 2003).

Structural Features

The structural feature descriptions used in this study are similar to those described in the Anhalt, Fischer, and Spring Branch 7.5-minute quadrangle mapping study (Clark and Morris, 2015). Faulting and fracturing in the study area are part of the Miocene Balcones fault zone, although mainly present south of the study area, some minor Balcones faults extend into the study area but with much less fault displacement. The Balcones fault zone is an extensional system of faults that generally trend southwest to northeast in south-central Texas. The faults have normal throw, are en echelon, and are mostly downthrown to the southeast. Variation in strikes and dips of the faults in the outcrop is a result of stress-strain relations of the different lithologies of the rocks (Trudgill, 2002; Ferrill and others, 2003; Clark and others, 2014).

The primary orientation of mapped faults in the study area is southwest to northeast and is between 45 and 67°, which is similar to the trend of the Balcones fault zone in the area (fig. 10). The conjugate fractures trend perpendicular to the Balcones fault zone at approximately 145–167°. Dips on the fractures vary between 45 and 90°, and vary based on the changes in rock lithologies.

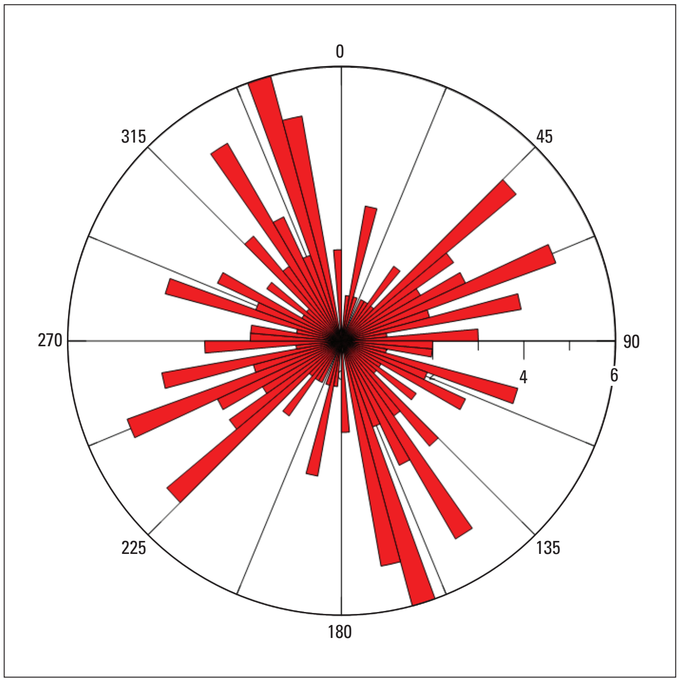


Figure 10. Rose diagram depicting trend of fractures.

Hydrostratigraphy

The rocks exposed in the study area compose a section of the Edwards aquifer, upper Trinity aquifer, and middle Trinity aquifer. In the study area, the Edwards aquifer is composed of the basal nodular member of the Fort Terrett Formation. The upper Trinity aquifer is contained in the Upper Member of the Glen Rose Limestone. The middle Trinity aquifer is composed of the Lower Member of the Glen Rose Limestone and the Hensell Sand Member and Cow Creek Limestone Member of the Pearsall Formation. The Hammett Shale Member of the Pearsall Formation forms a barrier between the middle Trinity aquifer and the lower Trinity aquifer. In the study area, the Edwards aquifer is up to 60 ft thick on the tops of several hills, the upper Trinity aquifer is 348 to 380 ft thick (typically 360 ft), and the middle Trinity aquifer is from 195 to 330 ft thick (typically 200 to 225 ft). The lithostratigraphy of the study area was field mapped and combined with the porosity characteristics using the classification system developed by Choquette and Pray (1970) to determine the hydrostratigraphic units. The descriptions below include general information about the geologic formation or member, lithology, thickness, primary fossils present, porosity, and type locality. Averages and ranges of unit thickness shown below are derived from within the study area.

Hydrostratigraphic units were first defined by Maxey (1964, p. 164) as "bodies of rock with considerable lateral extent that compose a geologic framework for a reasonably distinct hydrologic system." Choquette and Pray (1970) proposed a geological nomenclature and classification system for porosity of carbonates. According to Choquette and Pray, porosity that develops as a result of the deposition of the rock is classified as fabric-selective (primary porosity). Porosity that results from factors not associated with deposition is classified as not-fabric-selective (secondary porosity). To characterize the hydrostratigraphic units in this report (sheet 1), only dominant porosity types were used. The fabric-selective porosity types identified in the study area are interparticle, moldic, shelter, bedding plane, and burrowed (ichnofossils). The not-fabric-selective porosity types in the study area are fracture, breccia, channel, vug, or cave porosity.

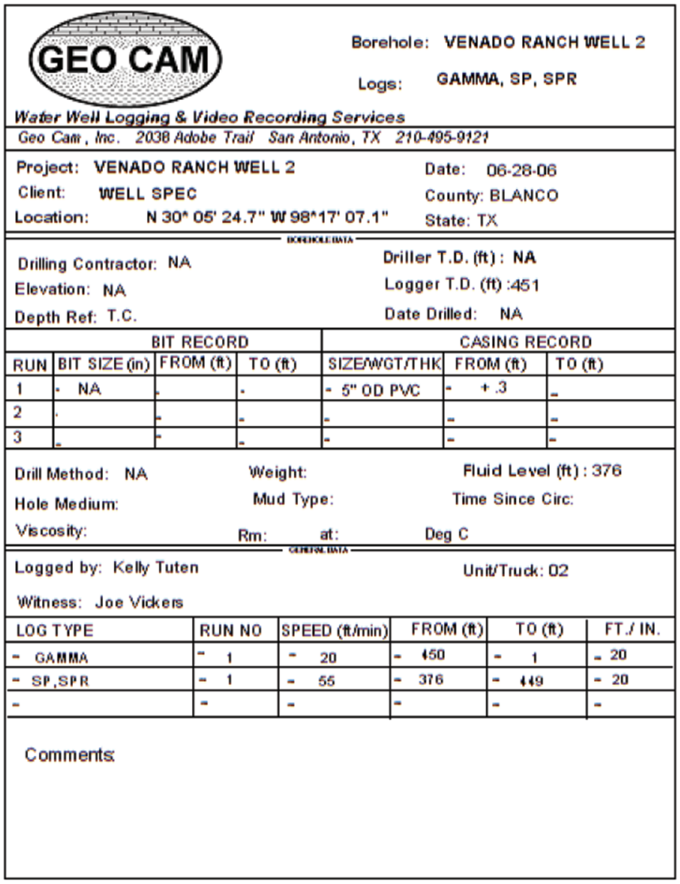
Fabric-selective and not-fabric-selective porosity have two distinct roles in groundwater storage and movement within the study area. Fabric-selective porosity of the VIII, Camp Bullis, fossiliferous, Bulverde, Twin Sisters, and Rust HSUs of the Edwards, and upper and middle Trinity aquifers appear to store groundwater. Many of these units contain argillaceous limestones (marls), shales, and evaporites which probably retain water because of the smaller scale porosity.

From field observations, the HSUs that are dominated by not-fabric-selective porosity contain limestone beds and less argillaceous beds. The limestone beds allow for more rapid fluid flow which results in the enlargement of fractures and ultimately support the development of caves. The following HSUs are the ones that primarily contain not-fabric-selective porosity resulting in larger porosity and higher permeability: the upper evaporite, lower evaporite, Little Blanco, Doeppenschmidt, Honey Creek, Hensell, and Cow Creek HSUs of the upper and middle Trinity aquifer. The Honey Creek and Cow Creek units supply base flow to the streams within the study area.

Maclay and Small (1976) originally proposed mapping the Edwards aquifer outcrops using HSUs. Maclay and Small (1976) separated the Edwards aquifer into eight HSUs (I through VIII). In the study area, only the HSU VIII remains, which caps several hills (sheet 1).

The upper Trinity aquifer is composed of the Upper Member of the Glen Rose Limestone and is approximately 348 to 380 feet thick (typically 360 ft). In the northern Bexar County area, the Upper Member of the Glen Rose Limestone was subdivided into five informal HSUs (named A through E from top to bottom) to better describe the unit's hydrologic properties (Clark, 2003, 2004). These HSUs were mapped in northern Bexar County and renamed as (top to bottom) cavernous, Camp Bullis, upper evaporite, fossiliferous, and lower evaporite, respectively (Clark and others, 2009, 2011; Blome and Clark, 2014). The cavernous HSU is absent from the current study area because of differences in depositional environments and a disconformity.

The middle Trinity aquifer encompasses, from top to bottom, the Lower Member of the Glen Rose Limestone and the Hensell Sand and the Cow Creek Limestone Members of the Pearsall Formation (Ashworth, 1983). Thickness of the middle Trinity aquifer is approximately 240 to 337 ft in the study area. In the northern Bexar County area, the Lower Member of the Glen Rose Limestone was divided into six informal



GEO CAM

Water Well Logging & Video Recording Services

Geo Cam, Inc. 2038 Adobe Trail San Antonio, TX 210-495-9121

Borehole: VENADO RANCH WELL 2

Logs: GAMMA, SP, SPR

Project: VENADO RANCH WELL 2 Date: 06-28-06

Client: WELL SPEC County: BLANCO

Location: N 30° 05' 24.7" W 98°17' 07.1" State: TX

BOREHOLE DATA

Drilling Contractor: NA Driller T.D. (ft): NA

Elevation: NA Logger T.D. (ft): 451

Depth Ref: T.C. Date Drilled: NA

BIT RECORD				CASING RECORD		
RUN	BIT SIZE (in)	FROM (ft)	TO (ft)	SIZE/WGT/THK	FROM (ft)	TO (ft)
1	NA			5" OD PVC	+ .3	
2						
3						

Drill Method: NA Weight: Fluid Level (ft): 376

Hole Medium: Mud Type: Time Since Circ:

Viscosity: Rm: at: Deg C

GENERAL DATA

Logged by: Kelly Tuten Unit/Truck: 02

Witness: Joe Vickers

LOG TYPE	RUN NO	SPEED (ft/min)	FROM (ft)	TO (ft)	FT./ IN.
GAMMA	1	20	450	1	20
SP, SPR	1	55	376	449	20

Comments:

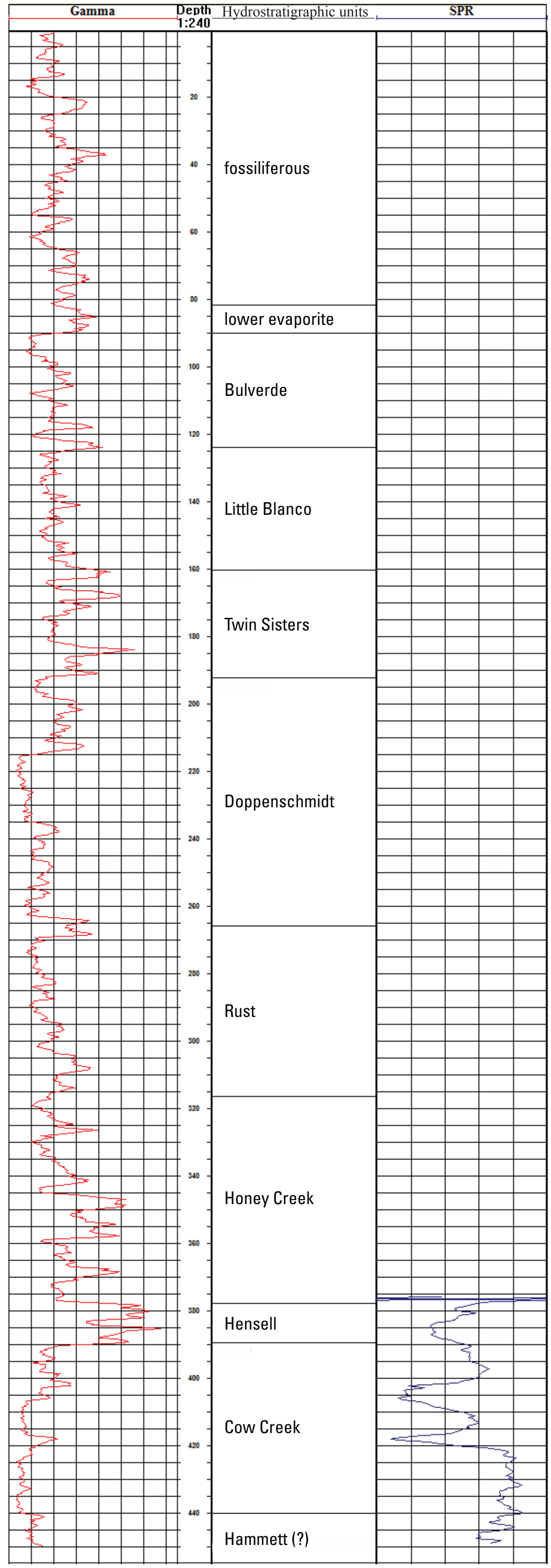


Figure 11 (above and right). Geophysical log with breakdown of hydrostratigraphic units based on variations in the gamma log.

hydrostratigraphic units (named A through F from top to bottom) (Blome and Clark, 2014; Pantea and others, 2014). These HSUs were renamed (top to bottom) as Bulverde, Little Blanco, Twin Sisters, Doeppenschmidt, Rust, and Honey Creek (Clark and others, 2014; Pantea and others, 2014; Clark and Morris, 2015).

The informal HSUs of the upper and middle Trinity aquifer have been mapped (sheet 1) using porosity types and lithologic characteristics identified in the field during mapping in conjunction with data from previous studies (Wierman and others, 2010; Blome and Clark, 2014; Clark and others, 2014; Pantea and others, 2014). Blome and Clark (2014) is the primary publication used in defining the hydrostratigraphic units. Blome and Clark (2014) described borehole cores and took plugs from those cores for both thin-section and permeability analysis. In addition, geophysical data were obtained from wells in Blanco, Comal, and Hays Counties to identify specific HSU contacts based on contacts identified in the gamma logs (fig. 11).

Hydrostratigraphy of Edwards Aquifer

Hydrostratigraphic Unit VIII

HSU VIII has a porosity of less than 10 percent (Maclay and Small, 1976); contains fabric-selective interparticle (Maclay and Small, 1976), moldic, and burrow porosity; and not-fabric-selective bedding plane, fracture, and cave porosity. The unit is probably best described as a semi-confining unit which depends on the amount of interconnected bioturbated porosity. The lithology of the unit yields itself to be a confining unit; however, caves that form in the unit can be quit extensive. According to Veni (2005), the HSU VIII contains some of the largest chambers and passages in the study area. These caves probably formed as a result of downward migrating groundwater encountering highly bioturbated beds within the unit.

Hydrostratigraphy of Upper Trinity Aquifer

Camp Bullis Hydrostratigraphic Unit

The Camp Bullis HSU is approximately 220 to 230 ft thick in the study area (table 1, sheet 1). Fabric-selective burrow porosity and not-fabric-selective bedding plane and fracture porosity are the primary porosity types identified in the field, although some cave development has been observed, likely caused by the intersection of fractures with bedding planes. Most of the observed Camp Bullis HSU has little solution enlargement along fractures and is a confining unit except where caves are present (Clark, 2004; Clark and Morris, 2015).

Upper Evaporite Hydrostratigraphic Unit

Where present, the upper evaporite HSU is approximately 10 thick in the study area (table 1, sheet 1). It contains fabric-selective interparticle, moldic (box work), and breccia porosity (table 1, sheet 1). This HSU appears to divert the downward percolation of groundwater laterally to discharge at springs and seeps (Clark, 2004; Clark and others, 2009).

Fossiliferous Hydrostratigraphic Unit

The fossiliferous HSU is approximately 120 ft thick in the study area (table 1, sheet 1). The fossiliferous HSU contains some fabric-selective moldic porosity. Not-fabric-selective porosity is generally fracture and cave porosity occurring near the top of the unit (Clark, 2004). This HSU is considered a confining unit (Clark, 2003; Clark and others, 2009).

Lower Evaporite Hydrostratigraphic Unit

The lower evaporite HSU is 8 to 10 ft thick in the study area (table 1, sheet 1). It contains the same fabric-selective porosity and water-bearing characteristics as the upper evaporite unit. The lower evaporite HSU contains fabric-selective interparticle, moldic (boxwork) porosity, and fabric-selective breccia porosity as a result of collapse (table 1, sheet 1). The unit intercepts the downward percolation of groundwater and diverts water laterally along the contact with the underlying Bulverde HSU, discharging it as springs and seeps (Clark, 2004; Clark and others, 2009).

Hydrostratigraphy of the Middle Trinity Aquifer

Bulverde Hydrostratigraphic Unit

The Bulverde HSU is the uppermost unit of the middle Trinity aquifer (table 1, sheet 1). The Bulverde HSU is typically 30 ft thick in the study area and contains fabric-selective moldic and breccia porosity where evaporites have been dissolved. It also contains not-fabric-selective bedding plane and fracture porosity. The shale bed at the top of the unit is a local barrier to downward migration of water and results in water moving laterally to discharge as seeps and springs. Field observations indicate that this unit is a confining unit and is often used for constructing stock ponds.

Little Blanco Hydrostratigraphic Unit

The Little Blanco HSU is typically 30 ft thick in the study area (table 1, sheet 1). It contains fabric-selective moldic porosity, and not-fabric-selective bedding plane and fracture porosity. Patch reefs contain fabric-selective moldic porosity. The Little Blanco HSU functions as an aquifer.

Twin Sisters Hydrostratigraphic Unit

The Twin Sisters HSU is typically 30 ft thick in the study area. It contains fabric-selective interparticle porosity (table 1, sheet 1). In the study area, the Twin Sisters HSU functions as a confining unit in the shale beds. Water in the unit moves laterally resulting in discharge from seeps and springs along hillsides providing water to numerous stock ponds (Clark and Morris, 2015).

Doeppenschmidt Hydrostratigraphic Unit

The Doeppenschmidt HSU is 0 to 80 ft thick in the study area. It contains fabric-selective interparticle, moldic, and burrowed porosity (table 1, sheet 1). In addition, the unit contains not-fabric-selective bedding plane, fracture, and cave porosity. There are seeps and springs near the contact with the underlying Rust HSU. The Doeppenschmidt HSU functions as an aquifer within the thicker beds of limestone (Clark and others, 2014) and patch reefs.

Rust Hydrostratigraphic Unit

The Rust HSU is approximately 40 to 70 ft thick in the study area. It contains fabric-selective interparticle porosity and not-fabric-selective fracture and cave porosity (table 1, sheet 1). Fracture porosity is not well developed but several of the thicker limestone beds have fractures with solution enlargement. The unit contains cave porosity which is probably a result of roof collapse from caves in the underlying Honey Creek HSU. This HSU appears to function as a barrier to subsurface flow, because springs and seeps flow from near its contact with the Doeppenschmidt HSU.

Honey Creek Hydrostratigraphic Unit

The Honey Creek HSU is approximately 45 to 60 ft thick in the study area and is the lowest HSU in the Lower Member of the Glen Rose Limestone (table 1, sheet 1). The Honey Creek HSU contains fabric-selective interparticle, moldic (fig. 11), and burrow porosity. It also contains not-fabric-selective bedding plane, fracture, channel, and cave porosity. This HSU functions as an aquifer and exhibits well-developed porosity and permeability (Clark and others, 2014). Cave porosity in this unit is extensive; many major springs issue from this unit including Honey Creek Cave Spring and Magic Springs to the south of the study area (fig. 1) The Honey Creek Cave system is the longest explored cave system in Texas, with over 20 miles mapped (Texas Speleological Survey, 2012).

Hensell Hydrostratigraphic Unit

The Hensell HSU is absent to 40 ft thick in the study area. It contains fabric-selective interparticle and moldic porosity in its upper part and fabric-selective moldic and shelter porosity in the lower part (table 1, sheet 1; Clark and others, 2014). The unit also contains not-fabric-selective cave porosity. The cave porosity is likely associated with roof collapse of caves in the underlying Cow Creek unit. The Hensell HSU functions as an aquifer in the study area.

Cow Creek Hydrostratigraphic Unit

The Cow Creek HSU is approximately 40 to 72 ft thick in the study area. It contains fabric-selective interparticle, moldic, and burrow porosity. It also contains not-fabric-selective vug, bedding plane, fracture, channel, and cave porosity (table 1, sheet 1; Clark and others, 2014). This HSU functions as an aquifer and is the primary interval targeted for water-well drilling in the area.

Hammett Hydrostratigraphic Unit

The Hammett HSU is approximately 50 ft thick. It is not exposed at the surface in the study area; however, based on stratigraphic thicknesses of the overlying units, it is shown on the map where it is inferred to underlie areas along the Blanco River (sheet 1). The interval functions as a confining unit, based on field observations and reported data (Ashworth, 1983; Weirman and others, 2010; Clark and others, 2014), restricting the downward migration of groundwater resulting in the formation of springs near the base of the Cow Creek HSU unit.

Ichnology

Ichnofossils are common throughout the marine carbonate units of south-central Texas and provide additional data on depositional and environmental history. Most carbonate beds in the region have been extensively bioturbated, resulting in a vug to nodular texture for many of the units. The ichnofabric index (*ii*) defined by Droser and Bottjer (1986) was used to describe the amount of bioturbation observed in the field on a scale of 1 to 6. Most strata in the study area are assigned to the *Cruziana* and *Thalassinoides* ichnofacies, which are consistent with an open marine tidal-dominated system (sublittoral zone). The *Thalassinoides* burrows commonly increase the porosity of the rocks in which they are present. The increase in porosity is associated with the diagenesis of the burrow fill and (or) the sediments in which the burrows were created resulting in interconnected moldic porosity. Ichnologic assemblages are dominated by *Thalassinoides* networks, but also contain *Cruziana, Ophiomorpha, Paleophycus, Planolites*, and Serpulid worm tubes.

Thalassinoides are three-dimensional boxworks of passively infilled or open cylindrical burrows that branch near 90° (Uchman, 1995) and are common in higher energy, shallow marine systems (Sheehan and Schiefelbein, 1984; Uchman, 1995) (figs. 12 and 13). Common *Thalassinoides* tracemakers include *Callianassa* sp. and other arthropods (Sheehan and Schiefelbein, 1984). *Thalassinoides* in the Glen Rose Limestone range from 0.2 to 0.98 in. in diameter and may be solution-enhanced to greater than 1.6 in, commonly multigenerational tiered and their interpreted ichnofabric index decreases up section in individual beds (*ii*5 to *ii*2) with increasing interpreted depositional energy. Burrow infill is similar to overlying beds and directly related to depositional energy and rate of siliciclastic input.

Paleophycus, *Planolites*, and *Ophiomorpha* are present as individual traces, but are often found associated with *Thalassinoides* networks. *Paleophycus* are lined, cylindrical burrows with fill similar to the matrix or the sediments immediately above the burrow(s) (Pemberton and Frey, 1982). *Paleophycus* are commonly found in units with lower ichnofabric index (*ii*2 to *ii*3) but are similar in diameter and fill to associated *Thalassinoides* networks. *Paleophycus* is made by various invertebrates including arthropods and annelids. *Planolites* are unlined burrows parallel to bedding planes created by deposit feeders (Uchman, 1998). *Planolites* (fig. 14) are distinct as they are found isolated from *Thalassinoides* networks and burrow fill is often mud dominated. Common tracemakers for *Planolites* include annelid worms. *Paleophycus* and *Planolites* may be difficult to distinguish if the burrow lining is not seen in cross section (Pemberton and Frey, 1982).

Ophiomorpha are cylindrical burrows that may branch and are lined with mud pellets (Uchman, 1995). The mud pellets are created by the tracemaker to increase the structural integrity of the burrow (Uchman, 1995). *Ophiomorpha* in the Glen Rose Limestone are horizontally oriented and found associated with *Thalassinoides* networks in beds with a higher interpreted depositional energy. Common tracemakers

Figure 12. *Thalassinoides* network filled with grainstone dominated by *Orbitolina texana* with a weather-eroded mudstone matrix, western Rough Hollow quadrangle, western Hays County (white box shown in close-up in figure 13). Photograph taken on July 13, 2015, by Robert Morris.

Figure 13. Close-up of *Thalassinoides* network filled with grainstone dominated by *Orbitolina texana* with a weather-eroded mudstone matrix, western Rough Hollow quadrangle, western Hays County, Texas. Photograph taken on July 13, 2015, by Robert Morris.

Figure 14. Plan view of a single *Planolites* northwestern Blanco quadrangle, approximately 3 miles west of the town of Blanco, Texas. Lens cap is 2.28 in. in diameter. Photograph taken August 19, 2014, by James Golab.

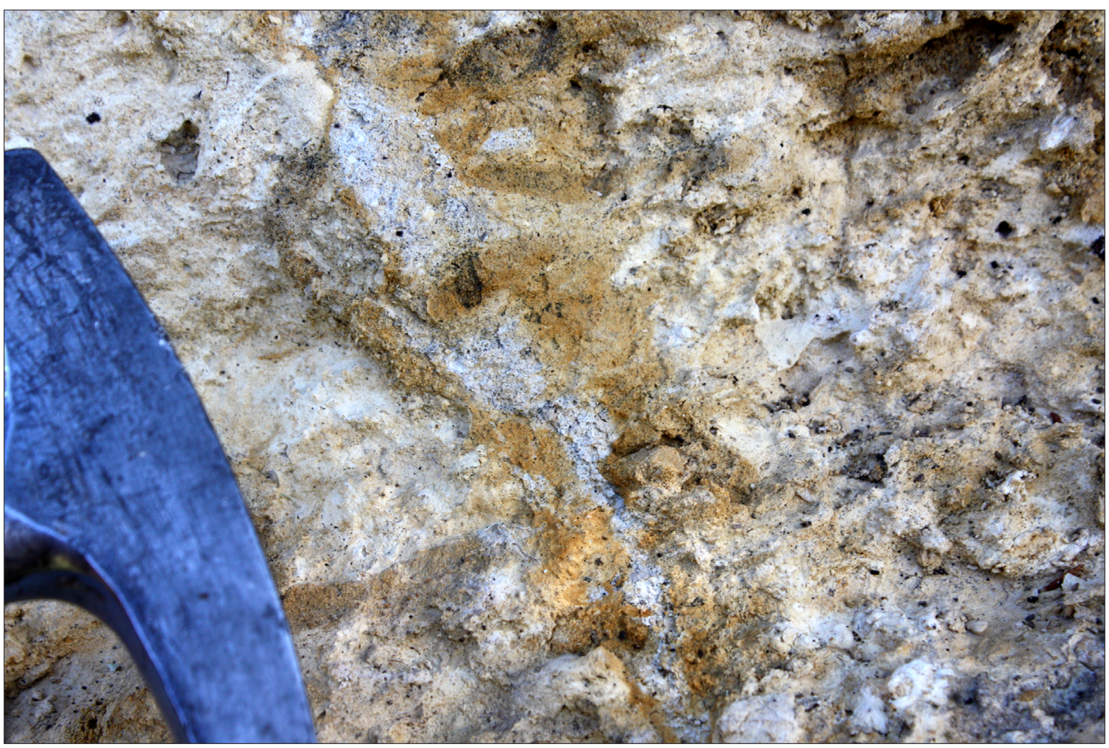


Figure 15. Rhizoliths with a yellow-tan rhizohalo observed in eastern Blanco quadrangle approximately 2 miles north of the town of Blanco, Texas, along US Hwy 281. Note head of geologic hammer for scale. Photograph taken on June 17, 2015, by James Golab.

for *Ophiomorpha* include *Callianassa* and similar arthropods (Uchman, 1995). *Ophiomorpha* within the Glen Rose Limestone have a diameter of slightly over one inch.

Cruziana are bilobate furrows with a medial ridge and transverse striations. Large *Cruziana* are observed in the Camp Bullis HSU at one location about 10 mi south of the study area (fig. 1) and are approximately 5.1 in wide and vary in length from 18.7 to 23.3 in. Serpulid worm tubes are created by annelid worms of the genus *Serpula* and consist of calcareous cylindrical coiled tubes that are anchored to a solid surface or hardground. Serpulid tubes in the Trinity aquifer are colored brown to tan, distinct from the surrounding strata, and some may be found anchored on oyster or bivalve shells.

Rhizoliths, rhizohalos, and rhizocretions associated with subaerial exposure were present due to sea-level fluctuations. These terrestrial plant traces extend downward from subaerial exposure surfaces into underlying strata and may crosscut bedding surfaces. Some rhizocretions have a nodular texture from calcium carbonate buildup along root fibers during growth (fig. 15).

Ichnologic Porosity

Ichnofossils can have an impact on porosity and subsequently groundwater flow paths by acting as fluid pathways or barriers to flow depending on the lithologic characteristics of the material that filled the burrow and the amount of bioturbation (Cunningham and others, 2012; Golab and others, 2015).

The study by Cunningham and others (2012) showed permeability associated with *Thalassinoides*-dominated ichnofabric controls horizontal fluid flow within most of the Edwards aquifer, where unfilled ichnofossils form interconnected fluid conduits. The mudstone and marl within the Trinity aquifer, however, complicates such ichnofabric analysis, as many Glen Rose Limestone *Thalassinoides* are filled with grainstone to mudstone acting either as conduits or barriers. Burrow fill is commonly similar to overlying beds and is directly related to changes in depositional energy and rate of siliciclastic input. Transmissive beds have *ii*3 to *ii*4 and burrows are commonly open or have permeable fill, whereas confining beds have either higher or lower *ii* than permeable units.

Post-depositional solution enhancement of ichnofossils is also common and has increased lateral and vertical fluid connectivity in some HSUs. Most ichnofossils in the Trinity aquifer are solution enhanced by meteoric water associated with epikarst and cavern development. Introduction of meteoric water likely began with the exhumation of strata along the normally faulted Balcones fault zone during the Miocene (Caran and others, 1982; Horvorka and others, 1994). Solution enhancement leads to increased connectivity of fractures and burrows and cavern development (Tonkin and others, 2010). Increased permeability is reflected in fluid-flow differences between HSUs. Modern meteoric water may further dissolve the matrix or the infilling, or both, and thereby enhance infiltration and recharge, or increase susceptibility to contaminant infiltration.

Summary

The Trinity aquifer is classified as a major aquifer by the State of Texas. However, transmissivities and water yields can be comparatively lower than the Edwards aquifer to the south. The lower water yield in the Trinity aquifer is attributable to its anisotropy caused by the presence of shales and argillaceous limestones. Population growth and drought conditions have combined to renew interest in groundwater availability of the Trinity aquifer as a source of potable water. This report describes the geologic framework, hydrostratigraphy, and ichnological characteristics of a three–quadrangle portion of Blanco, Comal, Hays and Kendall Counties in order to help water managers, water purveyors, and local residents better understand and manage water resources.

The study area, approximately 194 square miles (mi^2), is composed of the Blanco, Payton, and Rough Hollow 7.5-minute U.S. Geological Survey (USGS) quadrangles located in Blanco, Comal, Hays, and Kendall Counties, Texas (fig. 1). The study area consists of outcrops of the Early Cretaceous Trinity and Edwards Groups. The portion of the Balcones fault zone within the study area is an extensional system of faults that generally trend southwest to northeast, in south-central Texas. The faults have normal throw, are en echelon, and are mostly downthrown to the southeast. The measured faults and fractures in the study area have a primary orientation of between 45° and 67°. The conjugate fractures trend perpendicular to the Balcones fault zone at approximately 145° to 167°. Dips on the fractures vary between 45° and 90°, based on the variation in rock lithologies.

The only remaining outcrop of the Edwards Group is the basal nodular member of the Fort Terrett Formation, which caps several hills in the northern portion of the study area. These rocks were deposited in an open marine to supratidal flats environment and compose the Edwards aquifer HSU VIII.

The Trinity Group outcrops in the study area are the Hammett Shale, Cow Creek Limestone, Hensell Sand, and the Lower and Upper Members of the Glen Rose Limestone. These rocks compose the upper and middle Trinity aquifers. The lower Trinity aquifer is contained in the Hosston and Sligo Formations, which are not exposed in the study area.

The upper Trinity aquifer is composed of the Upper Member of the Glen Rose Limestone and is approximately 348 to 380 feet thick. In the northern Bexar County area, the Upper Member of the Glen Rose Limestone was subdivided into five informal HSUs (named A through E from top to bottom) to better describe the unit's hydrologic properties. These HSUs were mapped in northern Bexar County and renamed as (top to bottom) cavernous, Camp Bullis, upper evaporite, fossiliferous, and lower evaporite, respectively. The cavernous HSU is absent from the current study area because of differences in depositional environments and a disconformity.

The middle Trinity aquifer encompasses, from top to bottom, the Lower Member of the Glen Rose Limestone and the Hensell Sand and the Cow Creek Limestone Members of the Pearsall Formation. Thickness of the middle Trinity aquifer is approximately 195 to 330 ft in the study area. In the northern Bexar County area, the Lower Member of the Glen Rose Limestone was divided into six informal hydrostratigraphic units (named A through F from top to bottom). These HSUs were renamed (top to bottom) as Bulverde, Little Blanco, Twin Sisters, Doeppenschmidt, Rust, and Honey Creek.

The informal HSUs of the upper and middle Trinity aquifer were mapped using porosity types identified in the field, in conjunction with data from previous studies, as well as from geophysical data obtained from wells in Blanco, Comal, and Hays Counties. In addition to geologic and hydrostratigraphic identification, one stratigraphic measured section was developed along the Blanco River in the Rough Hollow quadrangle.

The role of biogenic activity in the development of porosity also appears to be substantial within carbonate units of the study area. The ichnofossils can have an impact on porosity and subsequently groundwater flow paths by acting as fluid pathways or barriers to flow depending on the lithologic material that has filled the burrow and the amount of bioturbation. Ichnofossils are common throughout the study area. Most of the geologic units in the study area are assigned to the *Cruziana* ichnofacies, which is in the sublittoral zone, and are dominated by *Thalassinoides* networks, but also contain *Cruziana, Ophiomorpha, Paleophycus, Planolites*, and Serpulid worm tubes.

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