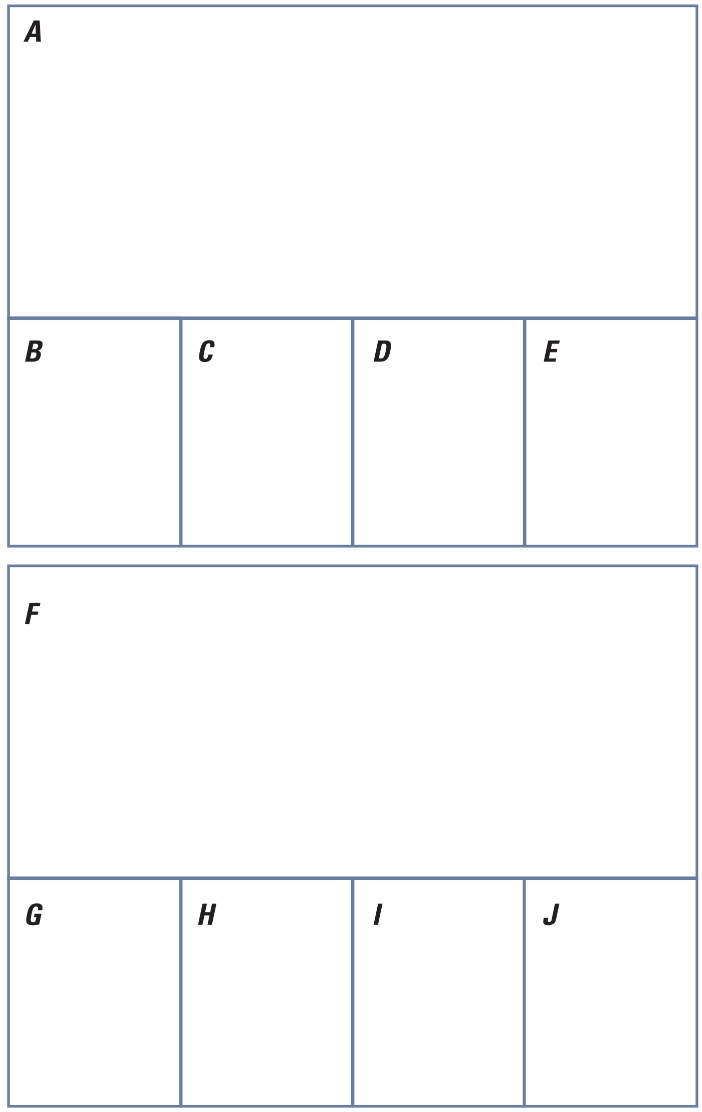
Prepared in cooperation with the Edwards Aquifer Authority

# Geologic Framework and Hydrostratigraphy of the Edwards and Trinity Aquifers Within Parts of Bandera and Kendall Counties, Texas

*Pamphlet to accompany*

Scientific Investigations Map 3518

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




**Front cover.** Photographs showing

*A*, View to the south from The Nature Conservancy's Love Creek Preserve, Bandera County, Texas (lat 29°46'35" N., long 99°24'36" W.; photograph by Allan K. Clark, U.S. Geological Survey, November 19, 2021).

*B*, Channel porosity in the Herff Falls hydrostratigraphic unit at the Cibolo Nature Center, Kendall County, Texas (lat 29°46'18" N., long 98°40'54" W.; photograph by Allan K. Clark, U.S. Geological Survey, November 4, 2020).

*C*, Dinosaur footprints in Williams Creek, Bandera County, Texas (lat 29°38' N., long 99°15' W.; photograph by Allan K. Clark, U.S. Geological Survey, May 3, 2022).

*D*, Rock cairn on the west side of Kyle Ranch Road, Bandera County, Texas (lat 29°43'05" N., long 99°12'02" W.; photograph by Allan K. Clark, U.S. Geological Survey, May 10, 2022).

*E*, Cactuses and cedar post pile near Mill Creek, northwestern Bandera County, Texas (lat 29°47'37" N., long 99°30'12" W.; photograph by Allan K. Clark, U.S. Geological Survey, June 7, 2022).

**Back cover.** Photographs showing

*F*, View to the southeast from The Nature Conservancy's Love Creek Preserve, Bandera County, Texas (lat 29°46'36" N., long 99°24'38" W.; photograph by Allan K. Clark, U.S. Geological Survey, November 19, 2021).

*G*, Desiccation cracks in the sediment of a dried-up section of Medina Lake, Bandera County, Texas (lat 29°37'42" N., long 98°58'05" W.; photograph by Allan K. Clark, U.S. Geological Survey, July 18, 2022).

*H*, Blossoming *Kalmia latifolia* (mountain laurel) on a ridge west of Jackson Creek Road, Bandera County, Texas (lat 29°45'47" N., long 99°24'38" W.; photograph by Allan K. Clark, U.S. Geological Survey, April 7, 2022).

*I*, View to the south from Ranch Road 337 towards the West Prong Medina River Basin, Bandera County, Texas (lat 29°47'20" N., long 99°20'30" W.; photograph by Allan K. Clark, U.S. Geological Survey, December 2, 2021).

*J*, Dried-up section of Medina Lake, Bandera County, Texas (lat 29°37'44" N., long 98°58'50" W.; photograph by Allan K. Clark, U.S. Geological Survey, July 18, 2022).

# Geologic Framework and Hydrostratigraphy of the Edwards and Trinity Aquifers Within Parts of Bandera and Kendall Counties, Texas

By Allan K. Clark, Robert R. Morris, and Alexis P. Lamberts

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**U.S. Department of the Interior**
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# Contents



## Sheet



## Figures

## Conversion Factors

U.S. customary units to International System of Units

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| inch (in.) | 2.54 | centimeter (cm) |
| inch (in.) | 25.4 | millimeter (mm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| | Area | |
| square mile ($mi^2$) | 259.0 | hectare (ha) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |

## Datum

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).

# Geologic Framework and Hydrostratigraphy of the Edwards and Trinity Aquifers Within Parts of Bandera and Kendall Counties, Texas

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## Abstract

The karstic Edwards and Trinity aquifers are classified as major sources of water in south-central Texas by the Texas Water Development Board. During 2019–23 the U.S. Geological Survey, in cooperation with the Edwards Aquifer Authority, mapped and described the geology and hydrostratigraphy of the rocks composing the Edwards and Trinity aquifers within parts of Bandera and Kendall Counties from field observations of the surficial expressions of the rocks. The thicknesses of the mapped lithostratigraphic and hydrostratigraphic units were also estimated from field observations in the study area.

The Cretaceous rocks in the study area are part of the Trinity Group and Edwards Group. The groups, formations, and members are composed primarily of layers of marls, shales, and limestones. The limestones are composed of mudstone through grainstone, framestone and boundstone, dolomite, and argillaceous and evaporitic rocks.

The principal structural feature in the study area is the Balcones fault zone. The Balcones fault zone is the result of late Oligocene and early Miocene extensional faulting and fracturing that was a result of the eastern Edwards Plateau uplift. In the Balcones fault zone, most of the faults in the study area are high-angle to vertical, en echelon, normal faults that are predominantly downthrown to the southeast.

Hydrostratigraphically, the rocks exposed in the study area are those that contain the Edwards aquifer, the upper zone of the Trinity aquifer, and the middle zone of the Trinity aquifer. Descriptions of the hydrostratigraphic units, thicknesses, hydrologic function, porosity types, and field identification and observations are provided, including those for the informal Bandera and Love Creek hydrostratigraphic units of the Edwards aquifer, which were identified through the mapping for this study.


## Introduction

The karstic Edwards and Trinity aquifers (fig. 1) are classified as major sources of water in south-central Texas by the Texas Water Development Board (George and others, 2011). The geologic framework and hydrostratigraphy of the Edwards and Trinity aquifers largely control groundwater flow paths and storage within Bandera and Kendall Counties (Kuniansky and Ardis, 2004). Detailed maps and descriptions of the geologic framework and hydrostratigraphy are needed by water managers to effectively manage available groundwater resources in south-central Texas. During 2019–23 the U.S. Geological Survey, in cooperation with the Edwards Aquifer Authority, mapped and described the geology and hydrostratigraphy of the rocks composing the Edwards and Trinity aquifers within parts of Bandera and Kendall Counties. The map was created from field observations of the surficial expressions of the rocks in the study area. The thicknesses of the mapped lithostratigraphic and hydrostratigraphic units were also estimated from field observations. Descriptions of the geologic framework and hydrostratigraphic units in this report were modified from those in Maclay and Small (1976), Stein and Ozuna (1995), Clark (2003, 2004), Clark and others (2009), Blome and Clark (2014), and Clark and others (2016a, b, 2020), except for the Bandera and Love Creek hydrostratigraphic units, which are informally introduced in this report.

### Description of Study Area

The study area (fig. 1) is within parts of Bandera and Kendall Counties, Tex., and covers approximately 788 square miles. The rocks exposed within the study area are outcrops of the Trinity and Edwards Groups (Rose, 1972; Barker and Ardis, 1996) (fig. 1). The rocks are composed of sedimentary carbonates that were deposited during the Cretaceous (Barker and Ardis, 1996). Faulting in the study area occurred during the late Oligocene to early Miocene (Weeks, 1945b) and resulted in an extensional fault system known as the Balcones fault zone (Hill, 1900). The Balcones fault zone generally trends southwest to northeast in south-central Texas (Maclay and Small, 1986). In the Balcones fault zone, most of the faults in the study area are high-angle to vertical, en echelon, normal faults that are predominantly downthrown to the southeast (Hill, 1900; Maclay and Small, 1986). Karst features in the study area include sinkholes, caves, and other solution-enlarged conduit features that facilitate rapid infiltration of surface waters to the subsurface (Veni, 1988; Lindgren and others, 2011).

## Purpose and Scope

The purpose of this report is to describe the geologic framework and hydrostratigraphy of the Edwards and Trinity aquifers within parts of Bandera and Kendall Counties, Tex. (fig. 1). A geologic map of the surficial geology and hydrostratigraphy of the rocks that contain the Edwards and Trinity aquifers (fig. 3) was created (on the basis of field observations) that can be used to help assess possible areas of groundwater recharge and discharge in addition to groundwater flow paths.

The scope of the report is the geologic framework and hydrostratigraphy of the outcrops of the rocks that contain the Edwards and Trinity aquifers within parts of Bandera and Kendall Counties (fig. 1). Descriptions of the geology and hydrostratigraphy are provided (fig. 2), as well as the geologic map detailing the hydrostratigraphy (fig. 3). Compared to the level of detail in existing geologic maps for the study area, the 1:24,000 scale of the geologic map in this report provides information at a finer scale to aid water managers as they work to anticipate and mitigate issues related to changing land use and increasing groundwater demands.

# Methods of Investigation

Geologic data and information from previous reports (Barnes, 1974; Small and Lambert, 1998; Small and Clark, 2000; Clark, 2003, 2004; Clark and others, 2009; Blome and Clark, 2014; Clark and others, 2016a, b, 2020) were reviewed to assist with the field mapping. During 2019–23, geologic framework and hydrostratigraphic mapping was completed on private and public land within parts of Bandera and Kendall Counties. Field-mapping techniques were consistent with those used in other studies (Clark, 2003; Clark and Morris, 2015; Clark and others, 2016a, b, 2018, 2020) and were guided by using Global Positioning System (GPS) units, digital maps, and geologic mapping applications installed on a tablet computer. Field-mapping observations were recorded onsite by using a tablet computer loaded with geospatially registered 7.5-minute U.S. Geological Survey topographic maps. Locations of visible and interpreted geologic contacts, faults and fractures, marker units, and other areas of interest were recorded by using an integrated fifth generation long-term evolution network-assisted GPS receiver on the tablet computer. The data obtained by using the tablet computer compass application were independently cross verified on a regular basis with data obtained by using a hand-held compass. The field data were imported into a geographic information system by using ArcMap version 10.8.1 (Esri, 2022). Some data were transferred manually from the tablet computer directly into ArcMap. All transferred data were quality checked by comparison with original draft data and then used to examine the geologic framework and characterize the hydrostratigraphy of the study area.

Various published sources were consulted for geologic names, lithologic descriptions, hydrostratigraphic unit names, and porosity information. Formal geologic names are consistent with those in the U.S. Geologic Names Lexicon (Geolex; U.S. Geological Survey, 2022). Informal geologic member names are consistent with previous publications (Rose, 1972; Maclay and Small, 1976; Clark and others, 2009; Blome and Clark, 2014; Clark and others, 2016a, b, 2020). Lithologic descriptions follow the classification system of Dunham (1962) and Wright (1992). Hydrostratigraphic unit names are informal and consistent with those used in previous publications (Maclay and Small, 1976; Clark and others, 2009; Blome and Clark, 2014; Clark and others, 2016a, b, 2020) (fig. 2). New hydrostratigraphic unit names, introduced in this publication, are informal with naming conventions based on geographic feature names (Laney and Davidson, 1986). Porosity descriptions are based on the sedimentary carbonate classification system of Choquette and Pray (1970). Porosity varies in each lithostratigraphic member and is dependent on the original depositional environment, lithology, structural history, and diagenesis of the unit (fig. 2).

The descriptions of the geologic framework and much of the hydrostratigraphy in this report were adapted and modified for the study area from Maclay and Small (1976) and Clark and others (2016a, b, 2020). Field identification of newly identified hydrostratigraphic units was based on observations made during field mapping.

The thicknesses of the mapped members (formal and informal) and hydrostratigraphic units were estimated from field observations. Thickness variations are caused by variations in local depositional and erosional conditions. Digital data of the geographic extent of the surficial hydrostratigraphic units and faulting within the study area and associated metadata are available for download in a companion data release (Lamberts and others, 2024).

# Geologic Framework

The Cretaceous rocks (listed in ascending order here and throughout the remainder of the report) in the study area are part of the Trinity Group (Hill, 1888; Ross, 1943; Clark and others, 2009; Blome and Clark, 2014) and Edwards Group (Hill and Vaughan, 1898; Rose, 1972; Maclay and Small, 1976). The groups, formations, and members are composed primarily of layers of marl, shale, and limestone (fig. 2). The limestones are composed of mudstone through grainstone, framestone, and boundstone. In addition, the limestones are often dolomitic, argillaceous, and evaporitic rocks (Clark and others, 2016a, b; 2020). The description of the geologic framework provided herein is modified from previous reports (Clark, 2003; Clark, 2004; Clark and others, 2009; Clark and others, 2014, 2016a, b, 2018, 2020, 2023; Clark and Morris, 2015).

## Trinity Group

The Early Cretaceous to late Early Cretaceous Trinity Group was deposited as sediments on a large, shallow marine carbonate platform (the Comanche shelf, fig. 1) as sequences of alternating clastic and carbonate deposition that occurred during marine transgressional events. During each transgressional event, sea levels of interior seaways rose relative to land surface and then retreated. Each of the transgressional events resulted in deposition of sediments that formed several formations that are part of the Trinity Group (Lozo and Stricklin, 1956; Stricklin and others, 1971).

The Pearsall Formation of the Trinity Group is the oldest geologic unit present at land surface in the study area (fig. 2). The Pearsall Formation (Ashworth and others, 2001) is composed of the Hammett Shale (which does not crop out in the study area), Cow Creek Limestone, and Hensell Sand Members. The thickness of each geologic unit in the study area varies appreciably. In the study area the outcroppings of the exposed Pearsall Formation are between 40 and 133 feet (ft) thick. Overlying the Pearsall Formation is the Glen Rose Limestone, which is commonly divided into a lower member and an upper member. The lower member of the Glen Rose Limestone is between 115 and 356 ft thick. The upper member of the Glen Rose Limestone is between 318 and 430 ft thick. Variations in thicknesses of the formations result from the thinning and thickening of individual members across the study area. Descriptions of the formal and informal members and their associated lithologies are shown in figure 2.

## Edwards Group

Rocks of the late Early Cretaceous Edwards Group were deposited on the Comanche shelf and San Marcos platform (Barker and Ardis, 1996) (fig. 1). In the study area, the Edwards Group is composed of the Fort Terrett and Segovia Formations (Rose, 1972) (fig. 2). The Fort Terrett Formation is laterally equivalent to the Kainer Formation (Rose, 1972), and the Segovia Formation is laterally equivalent to the Person Formation (Clark and others, 2006).

According to Rose (1972), the Fort Terrett Formation was deposited in shallow water and supratidal environments and is primarily composed of mudstone to grainstone, shales, and chert (fig. 2). In ascending order, the Fort Terrett Formation is composed of the basal nodular, burrowed, dolomitic, Kirschberg Evaporite, and grainstone members (Rose, 1972; Maclay and Small, 1976). Based on field mapping observations, the average thickness of the Fort Terrett Formation is 220 ft. The observed average thickness and the calculated minimum and maximum thicknesses of 170 and 320 ft of the Fort Terrett Formation, as indicated on figure 2, result from the thinning and thickening of individual members across the study area. Mapping of the individual members across the study area shows that the grainstone and dolomitic members thin towards the northwest but that the burrowed member thickens towards the northwest.

The overlying Segovia Formation was deposited in an open marine to supratidal environment (Rose, 1972) (fig. 2). In the study area, the 220–330 ft thick Segovia Formation is composed of the Burt Ranch Member, above which lies the undivided Segovia Formation (Rose, 1972). The Burt Ranch Member is laterally equivalent to the regional dense member of the Edwards Group in Bexar County. Northwest of the study area, Rose (1972) identified several informal lithologic units that were not observed in the study area. Descriptions of each of the geologic units observed in the study area and their associated lithologies are shown in figure 2. For an in-depth discussion of the Edwards Group, the Fort Terrett and Segovia Formations, and the Burt Ranch Member, see Rose (1972).

## Structure

The principal structural feature in the study area is the Balcones fault zone (fig. 1). The Balcones fault zone is the result of late Oligocene and early Miocene extensional faulting and fracturing, resulting from the eastern Edwards Plateau uplift (Weeks, 1945a, b; Galloway and others, 2000, 2011; Rose, 2016, 2017). In the study area, most of the faults crossing the Balcones fault zone are predominantly normal faults that are high angle to vertical, en echelon, and downthrown to the southeast (George, 1952) (fig. 3). Alpha and Lahr (1990, p. 2) explained that a normal fault occurs when there is a “dipping fracture surface on which the block above the fault plane, the hanging-wall block, is downthrown with respect to the block below, called the footwall block.”

The Balcones fault zone is considered dormant (Ewing, 2005a), and its location may be a result of reactivation of older, deeper faults associated with the Ouachita structural belt (Ewing, 2005b) (fig. 1). As is typical with extensional fault zones, the Balcones fault zone includes horst and graben structures (Pantea and others, 2014). Faulting has resulted in juxtaposition of stratigraphically older rocks against younger rocks of varying lithologies. A noteworthy fault within the study area is a fault at Seco Pass (fig. 3); from field observations, the displacement of this fault is 80 ft or more.

The structurally complex Balcones fault zone contains relay ramps (Hovorka and others, 1996), which commonly form during the growth of normal and extensional fault systems (Hus and others, 2005). Relay ramps form in extensional systems to allow for deformational changes along the fault block (Clark and Journey, 2006). For a more in-depth discussion of relay ramps and relay ramp development in the

Balcones fault zone, see Hovorka and others (1996), Collins and Hovorka (1997), Ferrill and others (2003), and Clark and Journey (2006).

The faulting, some of which has appreciable displacement (fig. 4), has resulted in the placement of rocks of varying lithologic and depositional types against one another. The faulting has also resulted in appreciable fracturing (fig. 5). The primary orientation of mapped fractures and faults in the study area is southwest to northeast between 40 and 50 degrees. The secondary fractures trend perpendicular to the Balcones fault zone at approximately 120–130 degrees. 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).

# Hydrostratigraphy

Hydrostratigraphically, the rocks exposed in the study area (listed in descending order from land surface, as they appear in a stratigraphic column) are those that contain the Edwards aquifer, the upper zone of the Trinity aquifer, and the middle zone of the Trinity aquifer. Descriptions of the hydrostratigraphic units, thicknesses, hydrologic function, porosity types, and field identification and observations are provided in figure 2 and, except for the newly identified, informal Bandera and Love Creek hydrostratigraphic units of the Edwards aquifer, are further described in Clark and others (2016b, 2018).

In the study area, the Edwards aquifer resides within the rocks composing the Edwards Group, and the Trinity aquifer resides within the rocks composing the Trinity Group (Rose, 1972; Barker and Ardis, 1996). The karstic carbonate Edwards and Trinity aquifers formed as a result of their original depositional history, primary and secondary porosity, diagenesis, fracturing, and faulting—factors that combined to modify the porosity and permeability of each aquifer, as well as the transmissivity within and between the two aquifers. Most of the permeability within the Edwards and Trinity aquifers is associated with enhanced secondary porosity that developed along bedding planes, fractures, and caves (Maclay and Small, 1983; Veni, 1987, 1988, 1994; Johnson and others, 2002; Ferrill and others, 2003; Gary and others, 2011). The Edwards and Trinity aquifers have been considered separate aquifers because of differences in permeability (Hammond, 1984; Kuniansky and Ardis, 2004); however, other assessments have shown that the Edwards aquifer and the upper part of the upper zone of the Trinity aquifer might function as a single aquifer (Johnson and others, 2002; Clark, 2003; Clark and others, 2009; Hunt and others, 2016). Barker and Ardis (1996) also stated that recharge to the Edwards aquifer from the underlying Trinity aquifer occurs from diffuse upward leakage. A hydrologic connection between the Trinity and Edwards aquifers also occurs by lateral groundwater movement across faults where faulting has resulted in permeable units of the aquifers being in direct lateral contact with one another (Clark and Journey, 2006; Clark and others, 2006; Johnson and others, 2010). A detailed description of the hydrostratigraphic units, thicknesses, hydrologic function, porosity types, and field identification and observations is provided in figure 2.

## Edwards Aquifer

In the study area, the Fort Terrett and Segovia Formations of the Edwards Group contain the Edwards aquifer. In a previous study in the San Antonio segment of the Edwards aquifer, Maclay and Small (1976) subdivided the Edwards aquifer into eight informal hydrostratigraphic units I–VIII. In the current study area, hydrostratigraphic unit I is not present because it has been removed by erosion. Hydrostratigraphic units II–IV are not present because of lateral lithologic changes west and north of the Edwards aquifer outcrop where Maclay and Small (1976) defined their associated members. The informal Bandera hydrostratigraphic unit (fig. 2), which is undivided, is introduced in this report and is laterally equivalent to Maclay and Small's (1976) hydrostratigraphic units II and III. The informal Love Creek hydrostratigraphic unit (fig. 2) is also introduced in this report and is laterally equivalent to Maclay and Small's (1976) hydrostratigraphic unit IV. For a more in-depth discussion of hydrostratigraphic units I–VIII forming the Edwards aquifer, see Maclay and Small (1976) and Clark and others (2016b, 2018).

The part of the Edwards aquifer that is contained in the Segovia Formation is subdivided (top to bottom) into the Bandera and Love Creek hydrostratigraphic units (fig. 2). The Bandera hydrostratigraphic unit (fig. 2), which is laterally equivalent to hydrostratigraphic units II and III (Maclay and Small, 1976), has been given this designation because there is not a distinction between hydrostratigraphic units II and III within the study area (Rose, 1972). The Love Creek hydrostratigraphic unit (fig. 2), which is laterally equivalent to hydrostratigraphic unit IV (Maclay and Small, 1976), has been given a new designation because of differences in the porosity associated with a change in the lithology. The porosity and lithologic changes identified between hydrostratigraphic unit IV and the Bandera hydrostratigraphic unit are attributed to an increase in terrigenous material.

The part of the Edwards aquifer that is formed in the Fort Terrett Formation is subdivided as follows (top to bottom): hydrostratigraphic units V, VI, VII, Seco Pass (fig. 6), and VIII (fig. 2). The informal Seco Pass hydrostratigraphic unit was identified in Clark and others (2023) on the basis of an appreciable increase in burrowed porosity. Rose (1972, p. 34) first identified this part of the Edwards Group as the burrowed member and noted that it was the chief water-bearing unit.

## Trinity Aquifer

Ashworth (1983) subdivided the Trinity aquifer into upper, middle, and lower zones. In the study area, only the upper zone and the middle zone of the Trinity aquifer are exposed at the land surface (fig. 2). The upper zone of the Trinity aquifer yields water from the upper member of the Glen Rose Limestone. The middle zone of the Trinity aquifer yields water from the lower member of the Glen Rose Limestone, the Hensell Sand Member, and the Cow Creek Limestone Member.

On the basis of field observations in Bexar, Comal, Hays, and Medina Counties (Clark and others, 2020, 2023), the authors hypothesize that beds of argillaceous limestone (marls) in the upper and middle zones of the Trinity aquifer slow the movement of groundwater both in the vadose and phreatic parts of the aquifer. The authors believe that the permeability of the argillaceous beds is likely low despite their apparent high porosity (more than 20 percent; Blome and Clark, 2014) and that the beds likely function as zones of groundwater retention because of the variability of grain sizes and tortuous groundwater pathways through the beds. In addition, the argillaceous beds do not support the development of larger porosity (channels and fractures) because of their lithology. On the basis of field observations, it is likely that water stored in the argillaceous beds slowly moves into adjacent beds that are more permeable. Field observations indicate that groundwater is retained in the argillaceous beds of the outcrop for several days, weeks, or even months after a rain event. The argillaceous beds were observed by the authors to be wet and spongy to the touch, with water trickling out of fractures in limestone beds below the argillaceous beds.

The upper zone of the Trinity aquifer was provisionally subdivided into five hydrostratigraphic units A–E by Clark (2003). These five hydrostratigraphic units were later informally named by Clark and others (2009) as (top to bottom) the cavernous, Camp Bullis, upper evaporite, fossiliferous (upper and lower), and lower evaporite (figs. 7 and 8). Descriptions of these hydrostratigraphic units are provided in figure 2. In-depth discussions of the previously published hydrostratigraphic units forming the upper zone of the Trinity aquifer are provided in Clark and others (2016b, 2018).

The part of the middle zone of the Trinity aquifer contained within the lower member of the Glen Rose Limestone was provisionally subdivided into six hydrostratigraphic units A–F by Blome and Clark (2014). Clark and others (2014) informally renamed these six hydrostratigraphic units, and in this report, the middle zone of the Trinity aquifer is subdivided into the following seven units (from top to bottom): Bulverde (fig. 9), Little Blanco, Twin Sisters, Doeppenschmidt, Herff Falls (where present, figs. 10, 11, and 12), Rust, and Honey Creek. Because the Herff Falls hydrostratigraphic unit is formed within a series of patch reefs that trend along a specific zone through the study area, it is not present in all locations and is equivalent in age to the Little Blanco, Twin Sisters, and Doeppenschmidt hydrostratigraphic units. The Hensell and Cow Creek hydrostratigraphic units form the lower two hydrostratigraphic units in the middle zone of the Trinity aquifer of the Pearsall Formation. For a more in-depth discussion of the hydrostratigraphic units that form the middle zone of the Trinity aquifer, see Clark and others (2016b, 2018).

### Structure

Groundwater in the study area is affected not only by the hydrostratigraphic characteristics of the individual hydrostratigraphic units but also by faults, fractures, and geologic structure. According to Clark and others (2016b, p. 13), "faulting and the resulting structures * * * common in fault zones like the Balcones fault zone may increase the potential of controlling or altering local groundwater flow (Pantea and others, 2014) by juxtaposing permeable and less permeable lithologies against one another. * * * Faulting produced highly fractured areas that have allowed for rapid infiltration of water and subsequently formed solutionally enhanced fractures, bedding planes, channels, and caves that are highly permeable and transmissive. The juxtaposition resulting from faulting has resulted in areas of interconnectedness between the Edwards and Trinity aquifers and the various hydrostratigraphic units that form the aquifers." An example of the effect of faulting on groundwater flow paths is reported by Saribudak and Hawkins (2019, p. 164); they describe the Haby Crossing Fault in Medina County near the Diversion Lake Dam (fig. 1) as a "lateral barrier to groundwater flow between the Edwards aquifer recharge zone and the confined portion of the Edwards aquifer."

## Summary

The karstic Edwards and Trinity aquifers are classified as major sources of water in south-central Texas by the Texas Water Development Board. During 2019–23 the U.S. Geological Survey, in cooperation with the Edwards Aquifer Authority, mapped and described the geology and hydrostratigraphy of the rocks composing the Edwards and Trinity aquifers within parts of Bandera and Kendall Counties. The map was created from field observations of the surficial expressions of the rocks in the study area. The thicknesses of the mapped lithostratigraphic members and hydrostratigraphic units were also estimated from field observations. A geologic map of the surficial extent of the rocks that contain the Edwards and Trinity aquifers was created (on the basis of field observations) that can be used to help assess possible areas of groundwater recharge and discharge in addition to groundwater flow paths.

The Cretaceous rocks in the study area are part of the Trinity Group and Edwards Group. The groups, formations, and members are composed primarily of layers of marls, shales, and limestones. The limestones are composed of mudstone through grainstone, framestone and boundstone, dolomite, and argillaceous and evaporitic rocks.

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In the study area, most of the faults crossing the Balcones fault zone are predominantly normal faults that are high angle to vertical, en echelon, and downthrown to the southeast.

Hydrostratigraphically, the rocks exposed in the study area are those that contain the Edwards aquifer, the upper zone of the Trinity aquifer, and the middle zone of the Trinity aquifer. Descriptions of the hydrostratigraphic units, thicknesses, hydrologic function, porosity types, and field identification and observations are provided. The descriptions include the informal Bandera and Love Creek hydrostratigraphic units of the Edwards aquifer, which were identified through the mapping for this study.

In the study area, the Edwards aquifer resides within the rocks composing the Edwards Group, and the Trinity aquifer resides within the rocks composing the Trinity Group. The karstic carbonate Edwards and Trinity aquifers formed as a result of their original depositional history, primary and secondary porosity, diagenesis, fracturing, and faulting—factors that combined to modify the porosity and permeability of each aquifer, as well as the transmissivity within and between the two aquifers. Most of the permeability within the Edwards and Trinity aquifers is associated with enhanced secondary porosity that developed along bedding planes, fractures, and caves. The Edwards and Trinity aquifers have been considered separate aquifers because of differences in permeability; however, other assessments have shown that the Edwards aquifer and the upper part of the upper zone of the Trinity aquifer might function as a single aquifer. Previous authors have also stated that recharge to the Edwards aquifer from the underlying Trinity aquifer occurs from diffuse upward leakage. A hydrologic connection between the Trinity and Edwards aquifers also occurs by lateral groundwater movement across faults where faulting has resulted in permeable units of the aquifers being in direct lateral contact with one another.

In the study area, the Fort Terrett and Segovia Formations of the Edwards Group contain the Edwards aquifer. Previous studies in the San Antonio segment of the Edwards aquifer subdivided the aquifer into eight informal hydrostratigraphic units I–VIII. In the current study area, hydrostratigraphic units I–IV are not present either because of removal by erosion or because of lateral lithologic changes west and north of the San Antonio segment of the Edwards aquifer. The informal Bandera hydrostratigraphic unit, which is undivided, is introduced in this report and is laterally equivalent to hydrostratigraphic units II and III. The informal Love Creek hydrostratigraphic unit, which is laterally equivalent to hydrostratigraphic unit IV, is also introduced in this report and has been given a new designation because of changes in the porosity associated with a change in the lithology of that unit. A previous publication introduced the Seco Pass hydrostratigraphic unit on the basis of an appreciable increase in burrowed porosity between hydrostratigraphic units VII and VIII.

Previous researchers subdivided the Trinity aquifer into upper, middle, and lower zones. In the study area, only the upper zone and the middle zone of the Trinity aquifer are exposed at the land surface. The upper zone of the Trinity aquifer yields water from the upper member of the Glen Rose Limestone. The middle zone of the Trinity aquifer yields water from the lower member of the Glen Rose Limestone, the Hensell Sand Member, and the Cow Creek Limestone Member.

On the basis of field observations in Bexar, Comal, Hays, and Medina Counties, the authors hypothesize that beds of argillaceous limestone (marls) in the upper and middle zones of the Trinity aquifer slow the movement of groundwater both in the vadose and phreatic parts of the aquifer. The argillaceous beds, although highly porous, are likely low permeability and likely function as zones of groundwater retention because of the variability of grain sizes and tortuous groundwater pathways through the beds. In addition, the argillaceous beds do not support the development of larger porosity (channels and fractures) because of their lithology. On the basis of field observations, it is likely that water stored in the argillaceous beds slowly moves into adjacent beds that are more permeable.

The five informal hydrostratigraphic units composing the upper zone of the Trinity aquifer are (top to bottom) as follows: cavernous, Camp Bullis, upper evaporite, fossiliferous (upper and lower), and lower evaporite. The middle zone of the Trinity aquifer consists of (top to bottom) the Bulverde, Little Blanco, Twin Sisters, Doeppenschmidt, Herff Falls (where present), Rust, Honey Creek, Hensell, and Cow Creek hydrostratigraphic units.

Groundwater in the study area is affected not only by the hydrostratigraphic characteristics of the individual hydrostratigraphic units but also by faults, fractures, and geologic structure. The faulting has caused the juxtaposition of the hydrostratigraphic units resulting in areas of interconnectedness between permeable units of the Edwards and Trinity aquifers and increasing the potential of controlling or altering local groundwater flow paths.

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