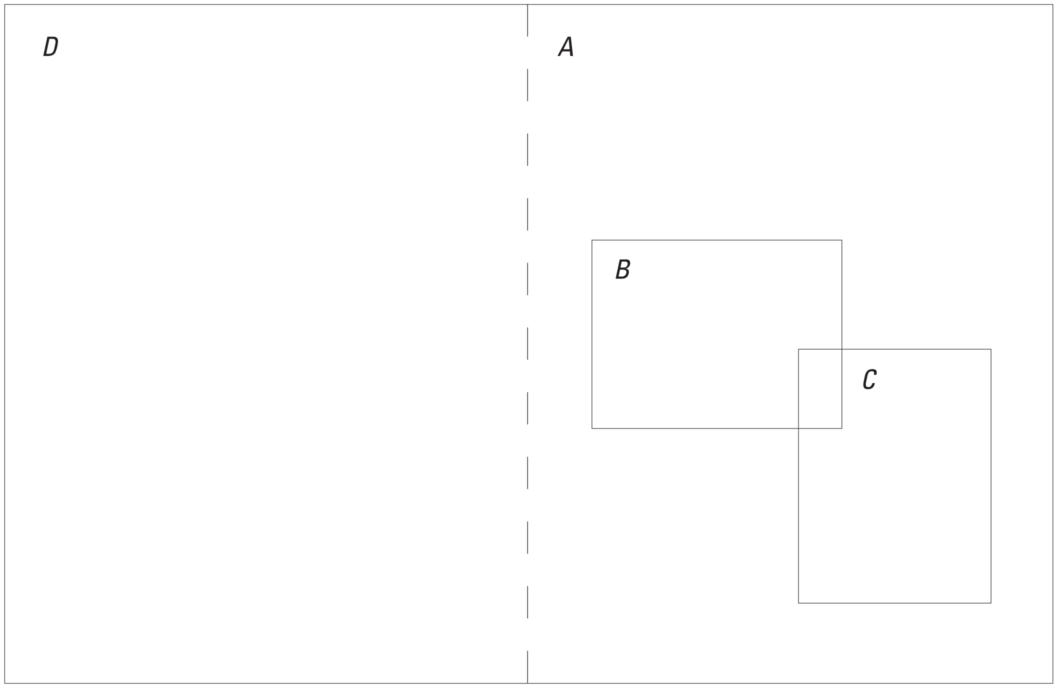
Prepared in cooperation with the Edwards Aquifer Authority

Geologic Framework and Hydrostratigraphy of the Edwards and Trinity Aquifers Within Northern Medina County, Texas

By Allan K. Clark, Robert E. Morris, and Diana E. Pedraza

Pamphlet to accompany
Scientific Investigations Map 3461

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



Cover. *A*, Northern part of Diversion Lake looking south from Old Medina Dam Road, northern Medina County, Texas (photograph by Allan K. Clark, U.S. Geological Survey, October 21, 2019). *B*, Diversion Lake Dam, northern Medina County, Texas (photograph by Allan K. Clark, U.S. Geological Survey, June 17, 2019). *C*, West Verde Creek south of the Hill Country State Natural Area, northern Medina County, Texas (photograph by Allan K. Clark, U.S. Geological Survey, March 5, 2019). *D,* Bluebonnets and the Devils River Limestone, northern Medina County, Texas (photograph by Allan K. Clark, U.S. Geological Survey, June 17, 2019).

Geologic Framework and Hydrostratigraphy of the Edwards and Trinity Aquifers Within Northern Medina County, Texas

By Allan K. Clark, Robert E. Morris, and Diana E. Pedraza

Prepared in cooperation with the Edwards Aquifer Authority

Pamphlet to accompany
Scientific Investigations Map 3461

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

U.S. Department of the Interior
DAVID BERNHARDT, Secretary

U.S. Geological Survey
James F. Reilly II, Director

U.S. Geological Survey, Reston, Virginia: 2020

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit https://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit https://store.usgs.gov/.

Suggested citation:
Clark, A.K., Morris, R.E., and Pedraza, D.E., 2020, Geologic framework and hydrostratigraphy of the Edwards and Trinity aquifers within northern Medina County, Texas: U.S. Geological Survey Scientific Investigations Map 3461, 13 p. pamphlet, 1 pl., scale 1:24,000, https://doi.org/10.3133/sim3461.

Data associated with this publication:
Pedraza, D.E., Clark, A.K., and Morris, R.R., 2020, Geospatial dataset of the geologic framework and hydrostratigraphy of the Edwards and Trinity aquifers within northern Medina County, Texas, at 1:24,000 scale: U.S. Geological Survey data release, https://doi.org/10.5066/P9HHMBX8.

ISSN 2329-1311 (print)
ISSN 2329-132X (online)

ISBN 978-1-4113-4377-1

Acknowledgments

The authors thank Susan Courage with the City of San Antonio Parks and Recreation Department and Thomas Marsalia and Jon Cradit with the Edwards Aquifer Authority for their assistance in obtaining permission to enter properties in Medina County. The authors are grateful for the assistance of the numerous landowners and managers of private and public lands who provided access to their properties for this study.

Contents

Sheet

Figures

[On sheet]

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
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).

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

Geologic Framework and Hydrostratigraphy of the Edwards and Trinity Aquifers Within Northern Medina County, Texas

By Allan K. Clark, Robert E. Morris, and Diana E. Pedraza

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 2018–20 the U.S. Geological Survey, in cooperation with the Edwards Aquifer Authority, mapped and described the geologic framework and hydrostratigraphy of the rocks composing the Edwards and Trinity aquifers in northern Medina County from field observations of the surficial expressions of the rocks. The thicknesses of the mapped lithostratigraphic members and hydrostratigraphic units were also estimated from field observations.

The Cretaceous-age rocks (listed in ascending order) in the study area are part of the Trinity Group (lower and upper members of the Glen Rose Limestone), Edwards Group (Kainer Formation [and its stratigraphic equivalent, the Fort Terrett Formation] and Person Formation), Devils River Limestone, Washita Group (Georgetown Formation, Del Rio Clay, and Buda Limestone), Eagle Ford Group, Austin Group, Taylor Group, and Late Cretaceous igneous intrusive rocks. The groups and formations are composed primarily of relatively thick layers of clays, shales, and limestone. The igneous rocks are coarse-grained ultramafic in composition.

The principal structural feature in northern Medina County is the Balcones fault zone, which is the result of late Oligocene and early Miocene extensional faulting and fracturing resulting from 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 predominately downthrown to the southeast.

Hydrostratigraphically, the rocks exposed in the study area (listed in descending order from land surface as they appear in a stratigraphic column) are igneous, the upper confining unit to the Edwards aquifer, the Edwards aquifer, the upper zone of the Trinity aquifer, and the upper part of the middle zone of the Trinity aquifer. The karstic carbonate Edwards and Trinity aquifers developed as a result of their original depositional history, primary and secondary porosity, diagenesis, fracturing, and faulting. These factors have resulted in development of modified porosity, permeability, and transmissivity within and between the aquifers.

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 in northern Medina County (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 2018–20 the U.S. Geological Survey (USGS), in cooperation with the Edwards Aquifer Authority, mapped and described the geologic framework and hydrostratigraphy of the rocks composing the Edwards and Trinity aquifers in northern Medina County from field observations of the surficial expressions of the rocks. The thicknesses of the mapped lithostratigraphic members and hydrostratigraphic units (HSUs) were also estimated from field observations. Descriptions of the geologic framework and HSUs in this report were modified from those in Stein and Ozuna (1995), Clark (2003), Clark and others (2009), Blome and Clark (2014), and Clark and others (2016a, b).

Description of Study Area

The study area (fig. 1) is the northern 442 square miles of Medina County. The rocks exposed within the study area are outcrops of the Trinity, Edwards, Washita, Eagle Ford, Austin, and Taylor Groups (Barker and Ardis, 1996) (fig. 2). The rocks are primarily sedimentary carbonates that formed during the Cretaceous age (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 trends, generally, southwest to northeast in south-central Texas (Maclay and Small, 1986). The faults are vertical to near vertical, en echelon, and are mostly 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 northern Medina County, Tex. (fig. 1). A geologic map of the surficial extent of the rocks that compose the Edwards and Trinity aquifers (fig. 3) was prepared that can be used to help assess possible areas of groundwater recharge, discharge, and groundwater flow paths.

Descriptions of the geologic framework and hydrostratigraphy of the Edwards and Trinity aquifers within northern Medina County are provided, as well as a detailed map of the hydrostratigraphy. In addition to the rocks that compose the Edwards and Trinity aquifers, parts of the adjacent upper confining unit to the Edwards aquifer are described. Compared to the level of detail available in existing geologic maps, the geologic map in this report was prepared at a scale of 1:24,000 to aid water managers as they work to anticipate and mitigate issues related to changing land use and increasing groundwater demands.

Methods of Investigation

Geological data and information from previous reports (Small and Clark, 2000; Clark, 2003, 2004; Clark and others, 2009; Blome and Clark, 2014; Clark and others, 2016a, b) were reviewed to assist in field mapping. During 2018–20, geologic framework and hydrostratigraphic mapping was completed on public and private land in northern Medina County. Field-mapping techniques were consistent with those used in other studies (Clark, 2003; Clark and Morris, 2015; Clark and others, 2016a, b, 2018) 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 USGS 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 fourth generation long-term evolution (LTE) network assisted GPS receiver on the tablet computer. In areas without cellular service, positions were determined by using a hand-held compass and triangulation techniques. The data obtained by using the tablet computer compass application were independently cross verified on a regular basis with data obtained by using a handheld compass. The field data were imported into a geographic information system (GIS) by using ArcMap version 10.6.1 (Esri, 2018). 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 develop the hydrostratigraphic map of the study area.

Various published sources were referred to for geologic names, lithologic descriptions, HSU names, and porosity information. Formal geologic names are consistent with those in the National Geologic Map Database (U.S. Geological Survey, 2018). Lithologic descriptions follow the classification system of Dunham (1962) and Wright (1992). The HSU names and porosity type are consistent with those used in previous publications (Maclay and Small, 1976; Clark and others, 2009, 2016a, b; Blome and Clark, 2014) (fig. 2). Porosity descriptions are based on the sedimentary carbonate classification system of Choquette and Pray (1970). Porosity varies in each lithostratigraphic unit and is dependent on the unit's original depositional environment, lithology, structural history, and diagenesis.

The descriptions of the geologic framework and hydrostratigraphy in this report were adapted for the study area from Maclay and Small (1976) and Clark and others (2016a, b). Descriptions of clastic rocks were done under the classification scale of Wentworth (1922).

The thicknesses of the mapped members (formal and informal) and HSUs were estimated from field observations. Thickness variations are caused by variations in local depositional and erosional conditions. Digital data of the geographical extent of the surficial HSUs and faulting within the study area and associated metadata are available for download in a companion data release (Pedraza and others, 2020).

Geologic Framework

The Cretaceous-age rocks (listed in ascending order) in the study area are part of the Trinity Group (Hill, 1888; Ross, 1943; Clark and others, 2009; Blome and Clark, 2014), Edwards Group (Hill and Vaughan, 1898; Rose, 1972; Maclay and Small, 1976), Devils River Limestone (Udden, 1907), Washita Group (Adkins, 1932), Eagle Ford Group (Hill, 1887; Wilmarth, 1938), Austin Group (Shumard, 1860; Adkins, 1932), Taylor Group (Hill, 1892; Stenzel, 1938), and igneous intrusive rocks (Liddle, 1918). Lithologic units are described throughout this report in ascending order.

The groups and formations are composed primarily of relatively thick layers of clays, shales, and limestone. The limestone units are composed of mudstone through grainstone, framestone and boundstone, dolomite, and argillaceous and evaporitic rocks (Clark and others, 2016a, b) (fig. 2). Sporadic igneous intrusions (Liddle, 1918) are present throughout the study area. The igneous rocks are coarse-grained ultramafic in composition (Miggins and others, 2004).

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 clastic-carbonate "couplets" during marine transgressional events; during each transgressional event, sea levels of interior seaways rose relative to land surface and then retreated (Lozo and Stricklin, 1956; Stricklin and others, 1971). The "couplets" contain sediments that formed several formations that are part of the Trinity Group, including the Glen Rose Limestone, the oldest (and only) formation of the Trinity Group described in this report (underlying the Glen Rose Limestone are additional formations that do not outcrop in the study area and are not discussed). The Glen Rose Limestone is commonly divided into a lower member and an upper member. The thickness of the lower member of the Glen Rose Limestone is between 200 and 225 feet (ft) (Blome and Clark, 2014; Clark and others, 2016b), thinning from the east to the west; however, only the upper three rock units of the lower member of the Glen Rose Limestone, which total 150 ft, are present at the land surface (fig. 2). The upper member of the Glen Rose Limestone is between 328 and 420 ft thick. Descriptions of the formal and informal members are described, and their associated lithologies are shown in figure 2.

Edwards Group and Devils River Limestone

Field-mapping observations during this study were based on better access to private land compared to the access available in previous mapping efforts. During this study, field observations indicated that the Kainer Formation and the lower part of the Person Formation extend farther into the western part of Medina County than previously observed (Small and Clark, 2000). In a previous study outcrops of the members that form the Kainer Formation were found in northern Uvalde County at Garner State Park, which is west of the northern extent of the Kainer Formation described in Small and Clark (2000).

Rocks of the late Early Cretaceous Edwards Group were deposited on the Comanche Shelf and San Marcos Arch (fig. 1) in the northwestern and eastern parts of the study area, and the late Early Cretaceous Devils River Limestone of the Devils River Trend (fig. 1) was deposited in the western part of the study area. In the study area, the Edwards Group (fig. 2) is composed of the Kainer (or Fort Terrett) and Person Formations (Rose, 1972) (fig. 2). The Fort Terrett Formation is laterally equivalent to the Kainer Formation (Rose, 1972). The Fort Terrett Formation is present in the northwestern part of the study area, and the Kainer and Person Formations are present in the eastern part. The Devils River Limestone is stratigraphically equivalent to the Edwards Group (fig. 2).

The Kainer Formation (and its stratigraphic equivalent, the Fort Terrett Formation) and Person Formation of the San Marcos Arch are primarily composed of mudstone to grainstone, shales, and chert (Rose, 1972) (fig. 2). These sediments were deposited in coastal environments ranging from open shelves to supratidal flats (Rose, 1972; Maclay and Small, 1986) during two separate marine transgressions. The 220–320 ft thick Kainer and Fort Terrett Formations are composed of the informal (bottom to top) basal nodular (Kkbn), dolomitic (Kkd), Kirschberg evaporite (Kkke), and grainstone members (Rose, 1972; Maclay and Small, 1976). The overlying Person Formation was deposited during a subsequent marine transgression (Rose, 1972) (fig. 2). The 170–204 ft thick Person Formation is composed of the informal regional dense (Kprd), leached and collapsed (undivided, Kplc), and cyclic and marine (undivided, Kpcm) members (Rose, 1972; Maclay and Small, 1976). Descriptions of each of the geologic units and their associated lithology are shown (fig. 2) and discussed in further detail in Clark and others (2016a, b) and Clark and others (2018).

In the northern part of the study area, the Fort Terrett Formation (fig. 2) of the Comanche Shelf is composed of mudstone to grainstone, crystalline limestone, dolomite, shaly limestone, and chert in the form of beds and large nodules. It is found as caps on hills and can be as much as 200 ft thick based on field observations. The Fort Terrett Formation was deposited in a low wave energy, shallow marine environment (Rose, 1972). Only the informal basal nodular and dolomitic members (mapped with Kkbn and Kkd, respectively) (fig. 2) and the formal Kirschberg Evaporite Member (mapped with Kkke) (fig. 2) of the Fort Terrett Formation are exposed in the study area.

The Devils River Limestone (fig. 2) of the Devils River Trend (fig. 1) is composed of mudstone to grainstone, boundstone to framestone, dolomitic limestone, shaly limestone, and chert in the form of beds and large nodules. The lower part of the Devils River Limestone was deposited in shallow water, intertidal to supratidal environments around the subsiding Maverick Basin west of the study area (Lozo and Smith, 1964; Rose, 1972) (fig. 1). As subsidence in the Maverick Basin continued, the upper part of the Devils River Limestone was deposited as a carbonate bank composed of rudist bioherms (patch reefs) and biostromes (Rose, 1972; Clark and Small, 1997) (fig. 4).

The lower part of the Devils River Limestone is laterally equivalent to the Kainer Formation. Therefore, the traditional arbitrary boundary depicted in previous publications as the transition from the Edwards Group to the Devils River Trend is considered obsolete. For this report, the Devils River Limestone was informally divided into lower and upper parts. The lower part of the Devils River Limestone contains the same informal geologic units that form the Kainer Formation to the east—that is, in ascending order, the basal nodular (Kdrvlbn), dolomitic (Kdrvld), Kirschberg evaporite (Kdrvlke), and grainstone (Kdrvlg) members (Maclay and Small, 1976). The lower part of the Devils River Limestone is between 220 and 320 ft thick in the study area. Like the Person Formation to the east, the upper part of the Devils River Limestone contains the regional dense member at its base; the remainder of the upper part of the Devils River Limestone in the study area consists of mudstone to grainstone, framestone, boundstone, and chert in the form of beds and large nodules. The upper part of the Devils River Limestone is between 150 and 250 ft thick. The upper part of the Devils River Limestone thickens to the west off the San Marcos Platform facies and into the Devils River Trend. The regional dense member, within the upper part of the Devils River Limestone, contains an oolitic limestone in the upper part. Ooliths are small spheres that form as calcium carbonate is deposited on the surface of sand grains that are rolled (by wave action) around on a shallow sea floor. Overviews of the geologic units and their associated lithology for the Edwards Group and Devils River Limestone are provided (fig. 2). More detailed descriptions of the Edwards Group are available in Clark and others (2016b).

Washita, Eagle Ford, Austin, and Taylor Groups

Following the deposition of the Edwards Group (or Devils River Limestone) there were tectonic uplift, subaerial exposure, and erosion in the area that is now south-central Texas. This area was then once again submerged during the late Early Cretaceous by another marine transgression that resulted in the deposition of shale, mudstone, and wackestone that formed the Georgetown Formation (Vaughan, 1900a) of the Washita Group (fig. 2). Much of the Georgetown Formation was subsequently removed during a period of marine regression (Rose, 1972).

The Del Rio Clay of the Washita Group (figs. 2 and 5), which contains clay and packstone, was deposited in an open-shelf environment over the Georgetown Formation. The Del Rio Clay was deposited during a marine transgression during the early Late Cretaceous when the Stuart City Reef Trend (fig. 1) was breached (Fisher and Rodda, 1969; Rose, 1972, p. 17). Continued deposition of sediments in shallow subtidal to intertidal zones resulted in the mudstone and wackestone that formed the Buda Limestone (Grunig and others, 1977) of the Washita Group (fig. 2).

The Late Cretaceous Eagle Ford Group (fig. 2) was deposited as sandy shale and argillaceous limestone in a lagoonal to open-shelf marine environment (Grunig and others, 1977; Trevino, 1988). As the marine transgression continued in the Late Cretaceous, an open, shallow shelf developed, and sediments were deposited far from shore, resulting in the mudstones and wackestones that form the Austin Group (fig. 2) (Grunig and others, 1977).

The uppermost stratigraphic unit exposed in the study area is the Late Cretaceous Pecan Gap Chalk of the Taylor Group (fig. 2). The Pecan Gap Chalk is composed of argillaceous limestone and calcareous clay and was deposited in an open marine environment (Ellisor and Teagle, 1934).

Overviews of the geologic units and their associated lithology for the Washita, Eagle Ford, Austin, and Taylor Groups are provided (fig. 2). More detailed descriptions of the Washita, Eagle Ford, Austin, and Taylor Groups are available in Clark and others (2016b).

Igneous Intrusive Rocks

Two surficial exposed igneous bodies (fig. 2) were identified in Medina County based on information obtained from field mapping and previous reports (Liddle, 1918; Holt, 1956). Liddle (1918, p. 109) identified an igneous dike that is “on Cow Creek one mile from its junction with the middle Verde Creek * * * dike which has a northeast-southwest surface strike. This impervious igneous mass ascending along a fault plane * * *.”

The second igneous body (fig. 6) is along County Road 241, approximately 4 miles from the intersection of County Road 241 and Highway 173. Holt (1956, p. 52) described this second igneous body as “a small plug of olivine basalt * * * This plug is about 300 feet in diameter at the surface and is surrounded by the Edwards limestone. The limestone near the contact has been altered to a varicolored marble containing veins of serpentine.”

Smith and others (2008) indicated that there were a few igneous bodies within the study area, although most are probably buried. The igneous rocks are Late Cretaceous and are hypabyssal, composed of coarse-grained ultramafic material (Miggins and others, 2004). For a more detailed description of the composition, age dates, and locations of the igneous bodies, refer to Miggins and others (2004) and Smith and others (2008).

Structure

The principal structural feature in northern Medina County is the Balcones fault zone (fig. 1), which is the result of late Oligocene and early Miocene extensional faulting (Weeks, 1945a, b; Galloway and others, 2000, 2011; Rose, 2016, 2017) and fracturing resulting from the eastern Edwards Plateau uplift (Rose, 2017). In the Balcones fault zone, most of the faults in the study area are high-angle to vertical, en echelon, normal faults that are predominately downthrown to the southeast (George, 1952) (fig. 7).

The Balcones fault zone is considered dormant (Ewing, 2005a), and its location may be a result of a reactivation of older, deeper faulting 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). The faulting has resulted in juxtaposition of stratigraphically older rocks against younger rocks of varying lithologies. A noteworthy fault within the study area is the Haby Crossing fault (fig. 3), which from field observations has a displacement of 650 ft or more.

The amount of displacement results in the complete offset of the Edwards Group juxtaposing the Trinity Group against the Austin Chalk near the Medina Diversion Lake Dam (fig. 3).

The authors have observed that because of the faulting and subsequent development of large relay ramps (Hovorka and others, 1996) in the study area the rocks become progressively younger from northwest to southeast and from northeast to southwest. Relay ramps are common in an extensional fault system (Ferrill and Morris, 2008). Ramp structures can be relatively small features that extend less than a few yards to large features that extend tens of miles. Relay ramps form in extensional fault systems to accommodate stress relief and an increase in deformation of the rock fabric (Clark and Journey, 2006). Ramp structures link the footwall of a fault segment with the hanging wall of an overlapping fault segment (Collins, 1995; Clark and Journey, 2006; Hunt and others, 2015). As extension occurs, the increased strain on the rock fabric causes faulting that results in the formation of relay ramps with rotation and internal fracturing occurring along the ramps (Trudgill, 2002; Ferrill and Morris, 2008). Continued extension results in the formation of cross faults within the relay ramp structure (Trudgill, 2002). Some examples of reports documenting relay ramp structures within the Balcones fault zone include Collins (1995), Clark and Journey (2006), Clark and others (2013), and Hunt and others (2015).

Hydrostratigraphy

Hydrostratigraphically, the rocks exposed in the study area (listed in descending order from land surface as they appear in a stratigraphic column) are igneous, the upper confining unit to the Edwards aquifer, the Edwards aquifer, the upper zone of the Trinity aquifer, and the upper part of the middle zone of the Trinity aquifer. Descriptions of the HSUs, thicknesses, hydrologic function, porosity type, and field identification are provided (fig. 2) and are described further in Clark and others (2016b, 2018).

Igneous Intrusive Rocks

Igneous rocks may form barriers to groundwater flow because porosity within the nearby limestone units is filled by secondary minerals such as serpentine (Liddle, 1918; Holt, 1956; Miggins and others, 2004), by contact metamorphism of the limestone units (Liddle, 1918; Holt, 1956), and by the igneous material itself (Miggins and others, 2004). Liddle (1918, p. 110–111) noted, “a spring rises to the surface from the fault at the north side of the dike and flows into Cow Creek. The dike, in intruding the Glenrose formation [Glen Rose Limestone], has cut through a water-bearing horizon, and since the igneous rock is practically impervious, it has afforded an impediment to the water which, under hydrostatic pressure, rises to the surface. A shaft has been sunk [on the south side of the dike] some 90 ft in the Glenrose limestone at the contact between the limestone and the dike.” From Liddle’s description, the igneous material is impervious, resulting in a spring on the north side of the dike proving the impervious nature of the igneous material because the 90-ft shaft dug south of the dike contained no water. According to Maclay (1995), the igneous rocks in Uvalde County may influence major Edwards aquifer groundwater flow paths. From field observations in the study area and descriptions in previous reports (Liddle, 1918; Holt, 1956; Maclay, 1995; Miggins and others, 2004), it is doubtful that igneous intrusions play an appreciable role in modifying groundwater flow paths in northern Medina County.

Upper Confining Unit of the Edwards Aquifer

The rocks that form the upper confining unit to the Edwards aquifer are (from top to bottom) the Taylor, Austin, Eagle Ford, and Washita Groups (Maclay and Small, 1976; Small and Clark, 2000; Clark and others, 2016b) (fig. 2). These groups are generally categorized as a confining unit to the Edwards aquifer and are not separated into HSUs. Except for the Austin Group (Petitt and George, 1956) and parts of the Georgetown Formation of the Washita Group (Stein and Ozuna, 1995), the rocks that form the upper confining unit to the Edwards aquifer do not supply appreciable amounts of water to wells in the study area. Therefore, the hydrologic characteristics of only the Austin Group and the Georgetown Formation of the Washita Group are described in this report.

The Austin Group is hydrologically connected to the underlying Edwards aquifer (Groschen, 1996; Banta and Clark, 2012) and in some places the Trinity aquifer (Clark and others, 2016b) depending on the amount of displacement along faults. The Austin Group supplies water to several springs in Uvalde, Medina, and Bexar Counties, as well as to some domestic and irrigation wells (Holt, 1959; Garza, 1962; Arnow, 1963; Banta and Clark, 2012). The most prolific wells and springs within the Austin Group likely tap water that moves up faults and fractures under artesian conditions from the underlying Edwards aquifer (Livingston and others, 1936; Veni, 1988; Banta and Clark, 2012).

The Georgetown Formation of the Washita Group has been extensively described in the literature both as part of the Edwards aquifer and as part of the upper confining unit to the Edwards aquifer (George, 1952; Maclay and Small, 1976; Stein and Ozuna, 1995; Clark and others, 2016b). This traditional manner of describing the Georgetown Formation of the Washita Group as both a confining unit and part of the Edwards aquifer is continued in this report. During field-mapping work, field observations indicated that earthen, unlined stock tanks are commonly built directly on the outcrop of the Georgetown Formation of the Washita Group, which is consistent with the premise that the unit is generally confining.

Edwards and Trinity Aquifers

In the study area, the Edwards aquifer resides within the rocks composing the Edwards Group and the Devils River Limestone, and the Trinity aquifer resides within the rocks of the Trinity Group. The karstic carbonate Edwards and Trinity aquifers developed as a result of their original depositional history, primary and secondary porosity, diagenesis, fracturing, and faulting. These factors have resulted in development of modified porosity, permeability, and transmissivity within and between the aquifers. Most of the permeability within the Edwards and Trinity aquifers is associated with enhanced secondary porosity that is 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 on the basis 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. Hydrologic connection between the Trinity and Edwards aquifers also occurs by lateral groundwater movement across faults. Hydrologic connection where faulting has occurred has resulted in water-bearing units of the aquifers and HSUs within 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 HSUs, thicknesses, hydrologic function, porosity type, and field identification is provided (fig. 2).

Edwards Aquifer

In the study area, the following formations compose the Edwards aquifer: the Georgetown Formation of the Washita Group, the Person and Kainer (or Fort Terrett) Formations of the Edwards Group, and the equivalent Devils River Limestone. The parts of the Edwards aquifer formed in the Georgetown Formation of the Washita Group and in the Person and Kainer Formations of the Edwards Group were subdivided informally into HSUs I–VIII by Maclay and Small (1976) (fig. 2). For this report, the part of the Edwards aquifer formed in the Fort Terrett Formation of the Edwards Group was subdivided based on Maclay and Small (1976) and Rose (1972). The uppermost subdivision of the Edwards aquifer is the Georgetown Formation of the Washita Group, which Maclay and Small (1976) designated as HSU I. Maclay and Small (1976) noted that HSU I of the Edwards aquifer was typically the unit where drillers would set casing before drilling through to the water-bearing units in the underlying Edwards aquifer. The Person Formation was designated as follows: HSU II for the informal cyclic and marine members (undivided), HSU III for the informal leached and collapsed members (undivided), and HSU IV for the informal regional dense member. Maclay and Small (1976) further defined the Kainer Formation into the following: HSU V for the informal grainstone member, HSU VI for the informal Kirschberg evaporite member (formal member of the Fort Terrett Formation of the Edwards Group), HSU VII for the informal dolomitic member, and HSU VIII for the informal basal nodular member.

The part of the Edwards aquifer within the Devils River Trend has been mapped as undivided in previous reports. According to Clark and Small (1997), the Devils River Trend, which is in the Devils River Limestone, is one of the most porous and permeable units in the Edwards aquifer.

Working within the informal hydrostratigraphic framework established by Maclay and Small (1976), the authors of this report identified the upper part of the Devils River Limestone as HSU IIA and HSU IV (fig. 2). HSU IIA is laterally equivalent to HSUs II and III (figs. 2 and 8) of the Edwards aquifer of the Edwards Group. HSU IV is laterally equivalent to HSU IV (fig. 2) of the Edwards aquifer of the Edwards Group. The lower part of the Devils River Limestone has similar hydrologic characteristics to the lower part of the Edwards aquifer of the Edwards Group and has been designated HSUs V, VI, VII, and VIII (fig. 2) based on laterally equivalent stratigraphy.

Trinity Aquifer

Ashworth (1983) subdivided the Trinity aquifer into upper, middle, and lower zones. In the study area only the upper zone and the upper part of the middle zone of the Trinity aquifer are exposed at the land surface (fig. 2). The middle and lower parts of the middle zone of the Trinity aquifer are not exposed at land surface and therefore are not mapped or represented in figure 2. The upper zone of the Trinity aquifer yields water from the upper member of the Glen Rose Limestone. The part of the middle zone of the Trinity aquifer present in the study area yields water from the lower member of the Glen Rose Limestone.

From field observations, the authors suggest that beds of argillaceous limestone in the upper and middle zones of the Trinity aquifer slow the movement of groundwater, probably because of the varying grain sizes that form the beds. The argillaceous beds likely function as zones of groundwater retention, with water stored in the argillaceous beds being slowly released into fractures in adjacent limestone beds, bedding planes, and caves. The groundwater would then slowly make its way to larger conduits that either discharge in springs or wells or migrate into the juxtaposed and adjacent Edwards aquifer. In addition, the argillaceous beds may retain substantial quantities of water in the vadose zone.

The upper zone of the Trinity aquifer was provisionally subdivided into five HSUs by Clark (2003) and was later informally named by Clark and others (2009). The five informal HSUs composing the upper zone of the Trinity aquifer are (top to bottom) as follows: cavernous (figs. 9, 10, and 11), Camp Bullis, upper evaporite, fossiliferous, and lower evaporite. Descriptions of these HSUs are provided (fig. 2).

The middle zone of the Trinity aquifer was informally subdivided into eight HSUs by Blome and Clark (2014) and Clark and others (2014). In the study area, the three upper HSUs are exposed at the land surface; these are (top to bottom) Bulverde, Little Blanco, and Twin Sisters. Based on field-mapping observations, the hydrostratigraphic characteristics of the exposed HSUs in northern Medina County have similar characteristics to those in Bexar and Comal Counties (Clark and others, 2016b).

Structure

Groundwater recharge and flow paths in the study area are affected not only by the hydrostratigraphic characteristics of the individual HSUs but also by faults, fractures, and geologic structure. Citing in part the work of 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 HSUs 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 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 2018–20, the U.S. Geological Survey, in cooperation with the Edwards Aquifer Authority, mapped and described the geologic framework and hydrostratigraphy of the rocks composing the Edwards and Trinity aquifers in northern Medina County from field observations of the surficial expressions of the rocks. The thicknesses of the mapped lithostratigraphic members and hydrostratigraphic units (HSUs) were also estimated from field observations. A map of the surficial extent of the rocks that compose the Edwards and Trinity aquifers was prepared that can be used to help assess possible areas of groundwater recharge, discharge, and groundwater flow paths.

The Cretaceous-age rocks (listed in ascending order) in the study area are part of the Trinity Group, Edwards Group, Devils River Limestone, Washita Group, Eagle Ford Group, Austin Group, Taylor Group, and igneous intrusive rocks. The groups and formations are composed primarily of relatively thick layers of clays, shales, and limestone. The limestone units are composed of mudstone through grainstone, framestone and boundstone, dolomite, and argillaceous and evaporitic rocks. The igneous rocks are coarse-grained ultramafic in composition.

The principal structural feature in northern Medina County is the Balcones fault zone, which is the result of late Oligocene and early Miocene extensional faulting and fracturing resulting from 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 predominately downthrown to the southeast.

Hydrostratigraphically, the rocks exposed in the study area (listed in descending order from land surface as they appear in a stratigraphic column) are igneous, the upper confining unit to the Edwards aquifer, the Edwards aquifer, the upper zone of the Trinity aquifer, and the upper part of the middle zone of the Trinity aquifer. Descriptions of the HSUs, thicknesses, hydrologic function, porosity type, and field identification are provided.

Igneous rocks may form barriers to groundwater flow because porosity within the nearby limestone units is filled by secondary minerals such as serpentine, by contact metamorphism of the limestone units, and by the igneous material itself. From field observations in the study area and data from previous reports, it is doubtful that igneous intrusions play an appreciable role in modifying groundwater flow paths in northern Medina County.

The rocks that form the upper confining unit to the Edwards aquifer are (from top to bottom) the Taylor, Austin, Eagle Ford, and Washita Groups. Except for the Austin Group and parts of the Georgetown Formation of the Washita Group, the rocks that form the upper confining unit to the Edwards aquifer do not supply appreciable amounts of water to wells in the study area.

The Austin Group is hydrologically connected to the underlying Edwards aquifer and in some places the Trinity aquifer, depending on the amount of displacement along faults. The Georgetown Formation of the Washita Group has been extensively described in the literature both as part of the Edwards aquifer and as part of the upper confining unit to the Edwards aquifer. This traditional manner of describing the Georgetown Formation of the Washita Group as both a confining unit and part of the Edwards aquifer is continued in this report. During field-mapping work, field observations indicated that earthen, unlined stock tanks are commonly built directly on the outcrop of the Georgetown Formation of the Washita Group, which is consistent with the premise that the unit is generally confining.

In the study area, the Edwards aquifer resides within the rocks composing the Edwards Group and the Devils River Limestone, and the Trinity aquifer resides within the rocks of the Trinity Group. The karstic carbonate Edwards and Trinity aquifers developed as a result of their original depositional history, primary and secondary porosity, diagenesis, fracturing, and faulting. These factors have resulted in development of modified porosity, permeability, and transmissivity within and between the aquifers. The parts of the Edwards aquifer formed in the Georgetown Formation of the Washita Group and in the Person and Kainer Formations of the Edwards Group were subdivided informally into HSUs I–VIII. The authors of this report identified the upper part of the Devils River Limestone as HSU IIA and HSU IV. HSU IIA is laterally equivalent to HSUs II and III of the Edwards aquifer of the Edwards Group. HSU IV is laterally equivalent to HSU IV of the Edwards aquifer of the Edwards Group. The lower part of the Devils River Limestone has similar hydrologic characteristics to the lower part of the Edwards aquifer of the Edwards Group and has been designated HSUs V, VI, VII, and VIII based on laterally equivalent stratigraphy.

Previous researchers subdivided the Trinity aquifer into upper, middle, and lower zones. In the study area only the upper zone and the upper part of the middle zone of the Trinity aquifer are exposed at the land surface. From field observations, the authors suggest that beds of argillaceous limestone in the upper and middle zones of the Trinity aquifer slow the movement of groundwater, probably because of the varying grain sizes that form the beds. The argillaceous beds likely function as zones of groundwater retention, with water stored in the argillaceous beds being slowly released into fractures in adjacent limestone beds, bedding planes, and caves. The groundwater would then slowly make its way to larger conduits that either discharge in springs or wells or migrate into the juxtaposed and adjacent Edwards aquifer. In addition, the argillaceous beds may retain substantial quantities of water in the vadose zone.

The five informal HSUs composing the upper zone of the Trinity aquifer are as follows (top to bottom): cavernous, Camp Bullis, upper evaporite, fossiliferous, and lower evaporite. The three upper HSUs of the middle zone of the Trinity aquifer are exposed at the land surface; these are (top to bottom) Bulverde, Little Blanco, and Twin Sisters.

Groundwater recharge and flow paths in the study area are affected not only by the hydrostratigraphic characteristics of the individual HSUs but also by faults, fractures, and geologic structure. Faulting and the resulting structures common in fault zones may increase the potential of controlling or altering local groundwater flow by juxtaposing permeable and less permeable lithologies against one another.

References Cited

Adkins, W.C., 1932, The Mesozoic system in Texas, *in* Sellards, E.H., Adkins, W.C., and Plummer, F.B., eds., The geology of Texas: Austin, Tex., University of Texas, Publication 3252, p. 329–518.

Arnow, T., 1963, Ground-water geology of Bexar County, Texas: U.S. Geological Survey Water-Supply Paper 1588, 36 p., 12 pls., accessed July 25, 2018, at https://doi.org/10.3133/wsp1588.

Ashworth, J.B., 1983, Ground-water availability of the Lower Cretaceous formations in the Hill Country of south-central Texas: Texas Department of Water Resources Report 273, 172 p., accessed July 25, 2018, at https://www.edwardsaquifer.org/wp-content/uploads/2019/02/1983_Ashworth_GroundWaterAvailability.pdf.

Banta, J.R., and Clark, A.K., 2012, Groundwater levels and water-quality observations pertaining to the Austin Group, Bexar County, Texas, 2009–11: U.S. Geological Survey Scientific Investigations Report 2012–5278, 18 p., 2 apps., accessed July 25, 2018, at https://doi.org/10.3133/sir20125278.

Barker, R.A., and Ardis, A.F., 1996, Hydrogeological framework of the Edwards-Trinity aquifer system, west-central Texas: U.S. Geological Survey Professional Paper 1421–B, 61 p., accessed July 25, 2018, at https://doi.org/10.3133/pp1421B.

Blome, C.D., and Clark, A.K., 2014, Key subsurface data help to refine Trinity aquifer hydrostratigraphic units, south-central Texas: U.S. Geological Survey Data Series 768, 1 sheet, accessed October 4, 2019, at https://doi.org/10.3133/ds768.

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

Clark, A.K., 2003, Geologic framework and hydrogeologic features of the Glen Rose Limestone, Camp Bullis Training Site, Bexar County, Texas: U.S. Geological Survey Water-Resources Investigations Report 03–4081, 9 p., 1 pl., scale 1:24,000, accessed July 20, 2018, at https://doi.org/10.3133/wri034081.

Clark, A.K., 2004, Geologic framework and hydrogeologic characteristics of the Glen Rose Limestone, Camp Stanley Storage Activity, Bexar County, Texas: U.S. Geological Survey Scientific Investigations Map 2831, 1 p., 1 pl., scale 1:24,000, accessed July 20, 2018, at https://doi.org/10.3133/sim2831.pdf.

Clark, A.K., Blome, C.D., and Morris, R.R., 2014, Geology and hydrostratigraphy of Guadalupe River State Park and Honey Creek State Natural Area, Kendall and Comal Counties, Texas: U.S. Geological Survey Scientific Investigations Map 3303, 8 p. pamphlet, 1 sheet, scale 1:24,000, accessed January 15, 2020, at https://doi.org/10.3133/sim3303.

Clark, A.K., Faith, J.R., Blome, C.D., and Pedraza, D.E., 2006, Geologic map of the Edwards aquifer in northern Medina and northeastern Uvalde Counties, south-central Texas: U.S. Geological Survey Open-File Report 2006–1372, 23 p., 1 pl., scale 1:75,000, accessed July 20, 2018, at https://doi.org/10.3133/ofr20061372.

Clark, A.K., Golab, J.A., and Morris, R.R., 2016a, Geologic framework, hydrostratigraphy, and ichnology of the Blanco, Payton, and Rough Hollow 7.5-minute quadrangles, Blanco, Comal, Hays, and Kendall Counties, Texas: U.S. Geological Survey Scientific Investigations Map 3363, 21 p. pamphlet, 1 sheet, scale 1:24,000, accessed July 20, 2018, at https://doi.org/10.3133/sim3363.

Clark, A.K., Golab, J.A., and Morris, R.R., 2016b, Geologic framework and hydrostratigraphy of the Edwards and Trinity aquifers within northern Bexar and Comal Counties, Texas: U.S. Geological Survey Scientific Investigations Map 3366, 28 p. pamphlet, 1 sheet, scale 1:24,000, accessed July 20, 2018, at https://doi.org/10.3133/sim3366.

Clark, A.K., and Journey, C.A., 2006, Flow paths in the Edwards aquifer, northern Medina and northeastern Uvalde Counties, Texas, based on hydrologic identification and geochemical characterization and simulation: U.S. Geological Survey Scientific Investigations Report 2006–5200, 48 p., accessed July 20, 2018, at https://doi.org/10.3133/sir20065200.

Clark, A.K., and Morris, R.R., 2015, Geologic and hydrostratigraphic map of the Anhalt, Fischer, and Spring Branch 7.5-minute quadrangles, Blanco, Comal, and Kendall Counties, Texas: U.S. Geological Survey Scientific Investigations Map 3333, 13 p. pamphlet, 1 sheet, scale 1:50,000, accessed July 20, 2018, at http://doi.org/10.3133/sim3333.

Clark, A.K., Pedraza, D.E., and Morris, R.R., 2013, Geologic framework, structure, and hydrogeologic characteristics of the Knippa Gap area in eastern Uvalde and western Medina Counties, Texas: U.S. Geological Survey Scientific Investigations Report 2013–5149, 35 p., 1 pl., accessed July 20, 2018, at http://doi.org/10.3133/sir20135149.

Clark, A.K., Pedraza, D.E., and Morris, R.R., 2018, Geologic framework and hydrostratigraphy of the Edwards and Trinity aquifers within Hays County, Texas: U.S. Geological Survey Scientific Investigations Map 3418, 11 p. pamphlet, 1 sheet, scale 1:24,000. [Also available at https://doi.org/10.3133/sim3418.]

Clark, A.K., and Small, T.A., 1997, Geologic framework of the Edwards aquifer and upper confining unit, and hydrogeologic characteristics of the Edwards aquifer, south-central Uvalde County, Texas: U.S. Geological Survey Water-Resources Investigations Report 97–4094, 11 p., 1 pl., scale 1:24,000 [Also available at https://doi.org/10.3133/wri974094.]

Clark, A.R., Blome, C.D., and Faith, J.R., 2009, Map showing the geology and hydrostratigraphy of the Edwards aquifer catchment area, northern Bexar County, south-central Texas: U.S. Geological Survey Open-File Report 2009–1008, 24 p., 1 pl., scale 1:50,000, accessed July 20, 2018, at http://doi.org/10.3133/ofr20091008.

Collins, E.W., 1995, Structural framework of the Edwards aquifer, Balcones fault zone, central Texas: Gulf Coast Association of Geological Societies Transactions, v. 45, p. 135–142, accessed September 4, 2018, at http://archives.datapages.com/data/gcags/data/045/045001/0135.htm.

Douglas, R.C., 1960, The foraminiferal genus *Orbitolina* in North America: U.S. Geological Survey Professional Paper 333, 52 p., accessed July 25, 2018, at https://doi.org/10.3133/pp333.

Dunham, R.J., 1962, Classification of carbonate rocks according to depositional texture, *in* Ham, W.E., ed., Classification of carbonate rocks symposium: American Association of Petroleum Geologists Memoir 1, p. 108–121.

Ellisor, A.C., and Teagle, J., 1934, Correlation of Pecan Gap Chalk in Texas: American Association of Petroleum Geologists, v. 18, no. 11, p. 1506–1536.

Esri, 2018, ArcGIS Desktop—Release 10.6.1: Redlands, Calif., Esri, accessed December 2, 2019, at http://desktop.arcgis.com/en/arcmap.

Ewing, T.E., 2005a, Structural mapping of the Edwards aquifer in eastern and central Uvalde County, Texas, using seismic, well and outcrop data—Public report on Uvalde County mapping: Frontera Exploration Consultants, 21 p., accessed June 24, 2005, at https://www.edwardsaquifer.org/wp-content/uploads/2019/05/2005_Ewing_2005StructuralMappingKnippaReport.pdf.

Ewing, T.E., 2005b, Phanerozoic development of the Llano Uplift: South Texas Geological Society Bulletin, v. 45, no. 9, p. 15–25.

Ferrill, D.A., and Morris, A.P., 2008, Fault zone deformation controlled by carbonate mechanical stratigraphy, Balcones fault system, Texas: The American Association of Petroleum Geologists Bulletin, v. 92, no. 3, p. 359–380. https://doi.org/10.1306/10290707066.

Ferrill, D.A., Sims, D.W., Morris, A.P., Waiting, D.J., and Franklin, N.M., 2003, Structural controls on the Edwards aquifer/Trinity aquifer interface in the Camp Bullis quadrangle, Texas: Edwards Aquifer Authority and U.S. Army Corps of Engineers, prepared by Southwest Research Institute, San Antonio, Tex., variously paged.

Fisher, W.L., and Rodda, P.U., 1969, Edwards Formation (Lower Cretaceous), Texas—Dolomitization in a carbonate platform system: The American Association of Petroleum Geologists Bulletin, v. 53, no. 1, p. 55–72.

Galloway, W.E., Ganey-Curry, P.F., Li, X., and Buffler, R.T., 2000, Cenozoic depositional history of the Gulf of Mexico Basin: The American Association of Petroleum Geologists Bulletin, v. 84, p. 1743–1774.

Galloway, W.E., Whiteaker, T.L., and Ganey-Curry, P., 2011, History of Cenozoic North American drainage basin evolution, sediment yield, and accumulation in the Gulf of Mexico Basin: Geosphere, v. 7, no. 4, p. 938–973, accessed July 24, 2018. https://doi.org/10.1130/GES00647.1.

Gary, M., Veni, G., Shade, B., and Gary, R., 2011, Spatial and temporal recharge variability related to groundwater interconnection of the Edwards and Trinity aquifers, Camp Bullis, Bexar and Comal Counties, Texas, *in* Interconnection of the Trinity (Glen Rose) and Edwards aquifers along the Balcones fault zone and related topics: Karst Conservation Initiative, February 17, 2011, Meeting, Proceedings, Austin, Texas, July 2011, p. 6–10, accessed February 9, 2016, at http://www.speleogenesis.info/directory/karstbase/publication.php?id=9869.

Garza, S., 1962, Recharge, discharge, and changes in groundwater storage in the Edwards and associated limestones, San Antonio area, Texas—A progress report of studies, 1955–59: Texas Water Development Board Bulletin 6201, 42 p., accessed July 25, 2018, at http://www.twdb.texas.gov/publications/reports/bulletins/doc/B6201.pdf.

George, P.G., Mace, R.E., and Petrossian, R., 2011, Aquifers of Texas: Texas Water Development Board Report 380, 172 p., accessed July 25, 2018, at https://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R380_AquifersofTexas.pdf?d=23236.398949342703.

George, W.O., 1952, Geology and ground-water resources of Comal County, Texas, *with sections on* Surface-water runoff *by* Breeding, S.D., and Chemical character of the water *by* Hastings, W.W.: U.S. Geological Survey Water Supply Paper 1138, 126 p., 3 pls., accessed July 25, 2018, at https://doi.org/10.3133/wsp1138.

Groschen, G.E., 1996, Hydrogeologic factors that affect the flow path of water in selected zones of the Edwards aquifer, San Antonio region, Texas: U.S. Geological Survey Water-Resources Investigations Report 96–4046, 73 p., accessed July 25, 2018, at https://doi.org/10.3133/wri964046.

Grunig, D., Young, K., Jordan, M.A., and Parker, D.L., 1977, Guidebook to the geology of Travis County: Austin, Tex., University of Texas, 143 p., accessed December 4, 2017, at http://www.library.utexas.edu/geo/ggtc/ch1.html.

Hammond, W.W., Jr., 1984, Hydrogeology of the lower Glen Rose aquifer, south-central Texas: Austin, Tex., University of Texas, Ph.D. dissertation, 245 p.

Hazzard, R.T., 1939, Notes on the Comanche and pre-Comanche(?) Mesozoic formations of the Arkansas-Louisiana-Texas area and a suggested correlation with northern Mexico: Shreveport Geological Society, Guidebook no. 14, June 2–4, 1939, p. 155–189, accessed May 6, 2020, at https://ngmdb.usgs.gov/Prodesc/proddesc_101753.htm.

Hill, R.T., 1887, The topography and geology of the Cross Timbers and surrounding regions in northern Texas: American Journal of Science, 3d ser., v. 33, no. 196, p. 291–303.

Hill, R.T., 1888, The Trinity formation of Arkansas, Indian Territory, and Texas: Science, v. 11, no. 258, p. 21.

Hill, R.T., 1891, The Comanche Series of the Texas-Arkansas region: Geological Society of America Bulletin, v. 2, no. 1, p. 503–528.

Hill, R.T., 1892, Geologic evolution of the non-mountainous topography of the Texas region—An introduction to the study of the Great Plains: The American Geologist, v. 10, no. 2, p. 105–115.

Hill, R.T., 1900, Physical geography of the Texas region: U.S. Geological Survey Topographic Atlas of the United States, Folio 3.

Hill, R.T., 1901, Geography and geology of the Black and Grand Prairies, Texas, with detailed descriptions of the Cretaceous formations and special reference to artesian waters, *in* Walcott, C.D., ed., Twenty-first annual report of the United States Geological Survey to the Secretary of the Interior, 1899–1900—Part VII—Texas: U.S. Geological Survey Annual Report 21, p. 128–337. [Also available at https://doi.org/10.3133/ar21_7.]

Hill, R.T., and Vaughan, T.W., 1898, Geology of the Edwards Plateau and Rio Plain adjacent to Austin and San Antonio, Texas, with reference to the occurrence of underground waters, *in* Walcott, C.D., Eighteenth annual report of the United States Geological Survey to the Secretary of the Interior, 1896–1897—Part II—Papers chiefly of a theoretical nature: U.S. Geological Survey Annual Report 18, p. 193–321. [Also available at https://doi.org/10.3133/ar18.

Holt, C.L.R., Jr., 1956, Geology and ground-water resources of Medina County, Texas: Texas Board of Water Engineers Bulletin 5601, 220 p., accessed December 3, 2019, at https://www.twdb.texas.gov/publications/reports/bulletins/doc/bull.htm/B5601.asp.

Holt, C.L.R., Jr., 1959, Geology and ground-water resources of Medina County, Texas: U.S. Geological Survey Water-supply Paper 1422, 220 p., accessed December 3, 2019, at http://doi.org/10.3133/wsp1422.

Hovorka, S.D., Dutton, A.R., Ruppel, S.C., and Yeh, J.S., 1996, Edwards aquifer ground-water resources—Geologic controls on porosity development in platform carbonates, south Texas: Austin, Tex., The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 238, 75 p.

Hunt, B.B., Andrews, A.G., and Smith, B.A., 2016, Hydraulic conductivity testing in the Edwards and Trinity aquifers using multiport monitor well systems, Hays County, central Texas: Barton Springs/Edwards Aquifer Conservation District, Report of Investigations 2016–0831, 39 p., accessed July 25, 2018, at https://bseacd.org/uploads/Hunt-et-al.-2016_Slug-Testing_FINAL.pdf.

Hunt, B.B., Smith, B.A., Andrews, A., Wierman, D.A., Broun, A.S., and Gary, M.O., 2015, Relay ramp structures and their influence on groundwater flow in the Edwards and Trinity aquifers, Hays and Travis Counties, central Texas: National Cave and Karst Institute, symposium 4, 14th Sinkhole Conference, 12 p., accessed July 25, 2018, at https://www.researchgate.net/publication/281558159_Relay_Ramp_Structures_and_Their_Influence_on_Groundwater_Flow_in_the_Edwards_and_Trinity_Aquifers_Hays_and_Travis_Counties_Central_Texas.

Inden, R.F., 1974, Lithofacies and depositional model for a Trinity Cretaceous sequence, central Texas, *in* Perkins, B.F., and Amsbury, D.L., eds., Aspects of Trinity Division geology—A symposium: Baton Rouge, La., Louisiana State University, Geoscience and Man, v. 8, p. 37–52.

Johnson, S., Esquilin, R., Mahula, D., Thompson, E., Mireles, J., Gloyd, R., Sterzenback, J., Hoyt, J., and Schindel, G., 2002, Hydrogeologic data report for 2001: Edwards Aquifer Authority, 134 p.

Johnson, S., Schindel, G., and Veni, G., 2010, Tracing groundwater flow paths in the Edwards aquifer recharge zone, Panther Springs Creek Basin, northern Bexar County, Texas: Edwards Aquifer Authority Report 10–01, 112 p.

Kuniansky, E.L., and Ardis, A.F., 2004, Hydrogeology and ground-water flow in the Edwards-Trinity aquifer system, west-central Texas—Regional aquifer-system analysis—Edwards-Trinity: U.S. Geological Survey Professional Paper 1421–C, 78 p. [Also available at https://doi.org/10.3133/pp1421C.]

Liddle, R.A., 1918, The geology and mineral resources of Medina County: Austin, Tex., University of Texas, Bureau of Economic Geology and Technology, University of Texas Bulletin No. 1860, October 25, 1918, p. 106–111, accessed August 26, 2020, at https://repositories.lib.utexas.edu/handle/2152/23691.

Lindgren, R.J., Houston, N.A., Musgrove, M., Fahlquist, L.S., and Kauffman, L.J., 2011, Simulations of groundwater flow and particle-tracking analysis in the zone of contribution to a public-supply well in San Antonio, Texas: U.S. Geological Survey Scientific Investigations Report 2011–5149, 93 p., accessed April 28, 2020, at https://doi.org/10.3133/sir20115149.

Livingston, P., Sayre, A.N., and White, W.N., 1936, Water resources of the Edwards limestone in the San Antonio area, Texas: U.S. Geological Survey Water-Supply Paper 773–B, 113 p., accessed July 25, 2018, at https://doi.org/10.3133//wsp773BB.

Lozo, F.E., and Stricklin, F.L., Jr., 1956, Stratigraphic notes on the outcrop basal Cretaceous, central Texas: Gulf Coast Association of Geological Societies Transactions, v. 6, p. 67–78.

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

Maclay, R.W., 1995, Geology and hydrology of the Edwards aquifer in the San Antonio area, Texas: U.S. Geological Survey Water-Resources Investigations Report 95–4168, 69 p., 12 sheets.

Maclay, R.W., and Small, T.A., 1976, Progress report on geology of the Edwards aquifer, San Antonio area, Texas, and preliminary interpretation of borehole geophysical and laboratory data on carbonate rocks: U.S. Geological Survey Open-File Report 76–627, 65 p. [Also available at https://doi.org/10.3133/ofr76627.].

Maclay, R.W., and Small, T.A., 1983, Hydrostratigraphic subdivisions and fault barriers of the Edwards aquifer, south-central Texas: Journal of Hydrology (Amsterdam), v. 61, nos. 1–3, p. 127–146. https://doi.org/10.1016/0022-1694(83)90239-1.

Maclay, R.W., and Small, T.A., 1986, Carbonate geology and hydrology of the Edwards aquifer in the San Antonio area, Texas: Texas Water Development Board, Report 296, 90 p., accessed July 25, 2018, at http://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R296/R296.pdf.

Miggins, D.P., Blome, C.D., and Smith, D.V., 2004, Preliminary 40Ar/39Ar geochronology of igneous intrusions from Uvalde County, Texas—Defining a more precise eruption history for the southern Balcones volcanic province: U.S. Geological Survey Open-File Report 2004–1031, 27 p., accessed December 5, 2019, at https://doi.org/10.3133/of20041031.

Pantea, M.P., Blome, C.D., and Clark, A.K., 2014, Three-dimensional model of the hydrostratigraphy and structure of the area in and around the U.S. Army-Camp Stanley Storage Activity Area, northern Bexar County, Texas: U.S. Geological Survey Scientific Investigations Report 2014–5074, 13 p. [Also available at https://doi.org/10.3133/sir20145074.].

Pedraza, D.E., Clark, A.K., and Morris, R.R., 2020, Geospatial dataset of the geologic framework and hydrostratigraphy of the Edwards and Trinity aquifers within northern Medina County, Texas, at 1:24,000 scale: U.S. Geological Survey data release, https://doi.org/10.5066/P9HHMBX8.

Perkins, B.F., 1974, Paleoecology of a rudist reef complex in the Comanche Cretaceous, Glen Rose Limestone, central Texas, *in* Perkins, B.F., ed., Aspects of Trinity Division geology—A symposium: Baton Rouge, La., Louisiana State University, Geoscience and Man, v. 8, p. 131–173.

Petitt, B.M., Jr., and George, W.O., 1956, Ground-water resources of the San Antonio area, Texas—A progress report of current studies: Texas Board of Water Engineers Bulletin 5608, v. 1, 80 p., accessed May 4, 2020, at http://www.twdb.texas.gov/publications/reports/bulletins/doc/B5608_V1.pdf.

Roemer, F., 1852, Die Kreidebildungen von Texas und ihre organischen Einschlüsse [The Cretaceous formations of Texas and their organic inclusions]: Bonn, Germany, Adolph Marcus Publishing, 100 p., 11 pls. [In German] [Also available at https://doi.org/10.5962/bhl.title.15015.]

Rose, P.R., 1972, Edwards Group, surface and subsurface, central Texas: Austin, Tex., University of Texas, Bureau of Economic Geology Report of Investigations 74, 198 p. [Also available at https://doi.org/10.23867/RI0074D.]

Rose, P.R., 2016, Late Cretaceous and Tertiary burial history, central Texas: Gulf Coast Association of Geological Societies Journal, v. 5, p. 141–179, accessed July 25, 2018, at http://www.gcags.org/Journal/2016.GCAGS.Journal/2016.GCAGS.Journal.v5.09.p141-179.Rose.pdf.

Rose, P.R., 2017, Regional stratigraphy of the Edwards Group and associated formations of Texas (lower Cretaceous, Comanchean)—In defense of the classic view: Gulf Coast Association of Geological Societies Journal, v. 6, p. 111–134, accessed July 25, 2018, at http://www.gcags.org/Journal/2017.GCAGS.Journal/2017.GCAGS.Journal.v6.08.p111-134.Rose.pdf.

Ross, C.P., 1943, Geology and ore deposits of the Shafter mining district, Presidio County, Texas: U.S. Geological Survey Bulletin 928–B, p. 45–125. [Also available at https://doi.org/10.3133/b928B.]

Saribudak, M., and Hawkins, A., 2019, Hydrogeophysical characterization of the Haby Crossing fault, San Antonio, Texas, USA: Journal of Applied Geophysics, v. 162, p. 164–173, accessed May 4, 2020. https://doi.org/10.1016/j.jappgeo.2019.01.009.

Shumard, B.F., 1860, Observations upon the Cretaceous strata of Texas: Academy of Science of St. Louis Transactions, v. 1, p. 583–590.

Small, T.A., and Clark, A.K., 2000, Geologic framework and hydrogeologic characteristics of the Edwards aquifer outcrop, Medina County, Texas: U.S. Geological Survey Water-Resources Investigations Report 2000–4195, 15 p. [Also available at https://doi.org/10.3133/wri004195.].

Smith, D.V., McDougal, R.R., Smith, B.D., and Blome, C.D., 2008, Distribution of igneous rocks in Medina and Uvalde Counties, Texas, as inferred from aeromagnetic data: U.S. Geological Survey Scientific Investigations Report 2007–5191, 12 p., 1 pl., scale 1:250,000, accessed December 10, 2019, at https://doi.org/10.3133/sir20075191.

Stein, W.G., and Ozuna, G.B., 1995, Geologic framework and hydrogeologic characteristics of the Edwards aquifer recharge zone, Bexar County, Texas: U.S. Geological Survey Water-Resources Investigations Report 95–4030, 8 p. [Also available at https://doi.org/10.3133/wri954030.].

Stenzel, H.B., 1938, The geology of Leon County, Texas: Austin, Tex., The University of Texas, Bureau of Economic Geology, no. 3818, 295 p.

Stricklin, F.L., Smith, C.I., and Lozo, F.E., 1971, Stratigraphy of Lower Cretaceous Trinity deposits of central Texas: Austin, Tex., University of Texas, Bureau of Economic Geology, Report of Investigations No. 71, 63 p.

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

Trudgill, B.D., 2002, Structural controls on drainage development in the Canyonlands grabens of southeast Utah, USA, *in* Underhill, J.R., and Trudgill, B.D., eds., The structure and stratigraphy of rift systems: American Association of Petroleum Geologists Bulletin Special Issue, v. 86, no. 6, p. 1095–1112, accessed July 25, 2018, at http://archives.datapages.com/data/bulletns/2002/06jun/1095/images/02_1095.pdf.

Udden, J.A., 1907, Report on a geological survey of the lands belonging to the New York and Texas Land Company, Ltd., in the Upper Rio Grande embayment in Texas: Rock Island, Ill., Augustana Library Publications, no. 6, p. 51–107.

U.S. Geological Survey, 2018, National Geologic Map Database, Geolex search: U.S. Geological Survey, accessed July 23, 2018, at http://ngmdb.usgs.gov/Geolex/search.

Vaughan, T.W., 1900a, Uvalde folio, Texas: Washington, D.C., U.S. Geological Survey Geologic Atlas of the United States Folio GF–64, 7 p., 3 pls.

Vaughan, T.W., 1900b, Reconnaissance in the Rio Grande coal fields of Texas: Washington, D.C., U.S. Geological Survey Bulletin 164, 95 p., 11 pls.

Veni, G., 1987, Fracture permeability—Implications on cave and sinkhole development and their environmental assessments, *in* Beck, B.F., and Wilson, W.L., eds., Karst hydrogeology—Engineering and environmental applications: Boston, A.A. Balkema, p. 101–105.

Veni, G., 1988, The caves of Bexar County (2d ed.): Austin, Tex., University of Texas, Texas Memorial Museum Speleological Monographs 2, 300 p.

Veni, G., 1994, Geomorphology, hydrology, geochemistry, and evolution of the karstic Lower Glen Rose aquifer, south-central Texas: University Park, Pa., Pennsylvania State University, Ph.D. dissertation, 712 p.

Weeks, A.W., 1945a, Oakville, Cuero, and Goliad Formations of Texas Coastal Plain between Brazos River and Rio Grande: The American Association of Petroleum Geologists Bulletin, v. 29, p. 1721–1732.

Weeks, A.W., 1945b, Balcones, Luling and Mexia fault zones in Texas: The American Association of Petroleum Geologists Bulletin, v. 29, no. 12, p. 1733–1737.

Wentworth, C.K., 1922, A scale of grade and class terms for clastic sediments: The Journal of Geology, v. 30, no. 5, p. 377–392. https://doi.org/10.1086/622910.

Wilmarth, M.G., 1938, Lexicon of geologic names of the United States (including Alaska): U.S. Geological Survey Bulletin 896, pts. 1–2, 2,396 p.

Wright, V.P., 1992, A revised classification of limestones: Sedimentary Geology, v. 76, no. 3–4, p. 177–185, accessed October 11, 2019. https://doi.org/10.1016/0037-0738(92)90082-3.

For more information about this publication, contact
Director, Oklahoma-Texas Water Science Center
U.S. Geological Survey
1505 Ferguson Lane
Austin, TX 78754–4501
gs-w-txpublicinfo@usgs.gov
or visit https://www.usgs.gov/centers/tx-water

Publishing support provided by
Lafayette Publishing Service Center

Clark and others—**Geologic Framework and Hydrostratigraphy of the Edwards and Trinity Aquifers Within Northern Medina County, Texas**—SIM 3461

ISSN 2329-1311 (print)
ISSN 2329-132X (online)
https://doi.org/10.3133/sim3461

ISBN 978-1-4113-4377-1