Geologic Framework and Hydrostratigraphy of the Edwards and Trinity Aquifers Within Northern Bexar and Comal Counties, Texas

Pamphlet to accompany
Scientific Investigations Map 3366

Cover, from left to right.

Photographs showing footwall of normal fault in the outcrop of the Edwards Group in northern Bexar County, Texas; *Skolithos* burrows in hydrostratigraphic unit VII of the Edwards aquifer, dolomitic member of the Kainer Formation (Kkd); rhizocretions in the cavernous hydrostratigraphic unit of the upper zone of the Trinity aquifer, upper member of the Glen Rose Limestone; and very high-resolution aerial view of the outlined area shown in figure 8, rudist patch reefs (circular areas) in the lower member of the Glen Rose Limestone, Doeppenschmidt hydrostratigraphic unit of the middle zone of the Trinity aquifer.

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

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
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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)

International System of Units to U.S. customary units

Multiply	By	To obtain
Length		
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)

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 Bexar and Comal Counties, Texas

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Abstract

During 2014–16, the U.S. Geological Survey, in cooperation with the Edwards Aquifer Authority, documented the geologic framework and hydrostratigraphy of the Edwards and Trinity aquifers within northern Bexar and Comal Counties, Texas. The Edwards and Trinity aquifers are major sources of water for agriculture, industry, and urban and rural communities in south-central Texas. Both the Edwards and Trinity are classified as major aquifers by the State of Texas.

The purpose of this report is to present the geologic framework and hydrostratigraphy of the Edwards and Trinity aquifers within northern Bexar and Comal Counties, Tex. The report includes a detailed 1:24,000-scale hydrostratigraphic map, names, and descriptions of the geology and hydrostratigraphic units (HSUs) in the study area.

The scope of the report is focused on geologic framework and hydrostratigraphy of the outcrops and hydrostratigraphy of the Edwards and Trinity aquifers within northern Bexar and Comal Counties, Tex. In addition, parts of the adjacent upper confining unit to the Edwards aquifer are included.

The study area, approximately 866 square miles, is within the outcrops of the Edwards and Trinity aquifers and overlying confining units (Washita, Eagle Ford, Austin, and Taylor Groups) in northern Bexar and Comal Counties, Tex. The rocks within the study area are sedimentary and range in age from Early to Late Cretaceous. The Miocene-age Balcones fault zone is the primary structural feature within the study area. The fault zone is an extensional system of faults that generally trends southwest to northeast in south-central Texas. The faults have normal throw, are en echelon, and are mostly downthrown to the southeast.

The Early Cretaceous Edwards Group rocks were deposited in an open marine to supratidal flats environment during two marine transgressions. The Edwards Group is composed of the Kainer and Person Formations. Following tectonic uplift, subaerial exposure, and erosion near the end of Early Cretaceous time, the area of present-day south-central Texas was again submerged during the Late Cretaceous by a marine transgression resulting in deposition of the Georgetown Formation of the Washita Group.

The Early Cretaceous Edwards Group, which overlies the Trinity Group, is composed of mudstone to boundstone, dolomitic limestone, argillaceous limestone, evaporite, shale, and chert. The Kainer Formation is subdivided into (bottom to top) the basal nodular, dolomitic, Kirschberg Evaporite, and grainstone members. The Person Formation is subdivided into (bottom to top) the regional dense, leached and collapsed (undivided), and cyclic and marine (undivided) members.

Hydrostratigraphically the rocks exposed in the study area represent a section of the upper confining unit to the Edwards aquifer, the Edwards aquifer, the upper zone of the Trinity aquifer, and the middle zone of the Trinity aquifer. The Pecan Gap Formation (Taylor Group), Austin Group, Eagle Ford Group, Buda Limestone, and Del Rio Clay are generally considered to be the upper confining unit to the Edwards aquifer.

The Edwards aquifer was subdivided into HSUs I to VIII. The Georgetown Formation of the Washita Group contains HSU I. The Person Formation of the Edwards Group contains HSUs II (cyclic and marine members [Kpcm], undivided), III (leached and collapsed members [Kplc,] undivided), and IV (regional dense member [Kprd]), and the Kainer Formation of the Edwards Group contains HSUs V (grainstone member [Kkg]), VI (Kirschberg Evaporite Member [Kkke]), VII (dolomitic member [Kkd]), and VIII (basal nodular member [Kkbn]).

The Trinity aquifer is separated into upper, middle, and lower aquifer units (hereinafter referred to as "zones"). The upper zone of the Trinity aquifer is in the upper member of the Glen Rose Limestone. The middle zone of the Trinity aquifer is formed in the lower member of the Glen Rose Limestone, Hensell Sand, and Cow Creek Limestone. The regionally extensive Hammett Shale forms a confining unit between the middle and lower zones of the Trinity aquifer. The lower zone of the Trinity aquifer consists of the Sligo and Hosston Formations, which do not crop out in the study area.

The upper zone of the Trinity aquifer is subdivided into five informal HSUs (top to bottom): cavernous, Camp Bullis, upper evaporite, fossiliferous, and lower evaporite. The middle zone of the Trinity aquifer is composed of the (top to bottom) Bulverde, Little Blanco, Twin Sisters, Doeppenschmidt, Rust,

Honey Creek, Hensell, and Cow Creek HSUs. The underlying Hammett HSU is a regional confining unit between the middle and lower zones of the Trinity aquifer. The lower zone of the Trinity aquifer is not exposed in the study area.

Groundwater recharge and flow paths in the study area are influenced not only by the hydrostratigraphic characteristics of the individual HSUs but also by faults and fractures and geologic structure. Faulting associated with the Balcones fault zone (1) might affect groundwater flow paths by forming a barrier to flow that results in water moving parallel to the fault plane, (2) might affect groundwater flow paths by increasing flow across the fault because of fracturing and juxtaposing porous and permeable units, or (3) might have no effect on the groundwater flow paths.

The hydrologic connection between the Edwards and Trinity aquifers and the various HSUs is complex. The complexity of the aquifer system is a combination of the original depositional history, bioturbation, primary and secondary porosity, diagenesis, and fracturing of the area from faulting. All of these factors have resulted in development of modified porosity, permeability, and transmissivity within and between the aquifers. 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.

Introduction

The Edwards and Trinity aquifers (fig. 1) are major sources of water for agriculture, industry, and urban and rural communities in south-central Texas. Both the Edwards and Trinity are classified as major aquifers by the State of Texas (George and others, 2011). The population in northern Bexar and Comal Counties is rapidly growing, increasing demands on water resources (U.S. Census Bureau, 2016). To help water-resource managers, drinking-water suppliers, and policymakers effectively manage the water resources, refined maps and descriptions of the geologic structures and hydrostratigraphic units (HSUs) of the aquifers in northern Bexar and Comal Counties, Tex., are needed. For example, compared to the information available in previous reports, detailed maps and descriptions of the hydrostratigraphic characteristics in northern Bexar and Comal Counties are needed by water-resource managers to identify areas in which urbanization of the recharge zone of the Edwards and Trinity aquifers might affect groundwater resources. Groundwater flow and storage in the Edwards and Trinity aquifers are largely controlled by the structures and hydrostratigraphy of the aquifers; therefore, refined information about these features will aid in anticipating and mitigating issues related

to changing land use and increasing groundwater demands. Hence, during 2014–16, the U.S. Geological Survey (USGS), in cooperation with the Edwards Aquifer Authority, documented the geologic framework and hydrostratigraphy of the Edwards and Trinity aquifers within northern Bexar and Comal Counties, Tex.

Purpose and Scope

The purpose of this report is to present the geologic framework and hydrostratigraphy of the Edwards and Trinity aquifers within northern Bexar and Comal Counties, Tex. The report includes a detailed 1:24,000-scale hydrostratigraphic map, names, and descriptions of the geology and HSUs in the study area. The mapped HSUs will aid in identifying units that have potential groundwater recharge or discharge and (or) that potentially act as a confining layer.

The scope of the report is focused on the geologic framework and hydrostratigraphy of the outcrops of the Edwards and Trinity aquifers within northern Bexar and Comal Counties, Tex. In addition, parts of the adjacent upper confining unit to the Edwards aquifer are included.

Previous Studies and Background Information

Previous studies such as those by the USGS and the University of Texas, Bureau of Economic Geology have mapped the geology, hydrostratigraphy, and structure in the study area at various scales. Examples of previous mapping include Brown and others (1974), Baumgardner and Collins (1991), Collins and others (1991), Raney and Collins (1991), Collins (1992a, b, c; 1993a, b, c, d, e; 1994a, b, c, d; 1995a, b, c, d), Small and Hanson (1994), Stein and Ozuna (1995), Collins (2000), and Clark and others (2009).

For this report, previously published hydrostratigraphic maps of the study area were updated by using onsite field mapping done with accurate, modern mapping tools such as highly accurate Global Positioning System (GPS) hand-held devices The karstic geologic setting of northern Bexar and Comal Counties underscores the need for updated hydrostratigraphic information. For example, the dissolution of the carbonate rocks composing the Edwards and Trinity aquifers (including those found in northern Bexar and Comal Counties) results in distinctive landforms rich in both springs and karst features (caves, sinkholes, and other visible areas of solution-enlarged porosity). Porosity developed in carbonate rocks can have an appreciable effect on the hydrostratigraphic characteristics of the formations and can create focused points or areas of recharge and discharge (seeps and springs) (Hanson and Small, 1995; U.S. Geological Survey, 2011). The same porosity that can focus recharge can also result in an aquifer that is highly susceptible to contamination because stormwater runoff is quickly transferred to the subsurface (Ryan and Meiman, 1996).

Description of Study Area

The study area, approximately 866 square miles, is within the outcrops of the Edwards and Trinity aquifers and overlying confining units (Washita, Eagle Ford, Austin, and Taylor Groups) in northern Bexar and Comal Counties, Tex. (fig. 1). The boundary of the study area coincides with the county lines, except for the southern boundary. The southern boundary of the study area extends east and northeast from the western boundary of Bexar County to a few miles north of where Interstate 35 (I–35) crosses the northeastern boundary of the county. From there, the southern boundary of the study area arcs toward the northeast, a few miles northwest of and parallel to I–35, and terminates at the Comal-Hays County line (fig. 1).

The rocks within the study area are sedimentary and range in age from Early to Late Cretaceous. Early Cretaceous rocks form the Trinity and Edwards Groups, and Late Cretaceous rocks form the Washita, Eagle Ford, Austin, and Taylor Groups (Barker and Ardis, 1996). The Miocene-age Balcones fault zone is the primary structural feature within the study area. The fault zone is an extensional system of faults that generally trends southwest to northeast in south-central Texas. The faults have normal throw, are en echelon, and are mostly downthrown to the southeast (Hill, 1900; Maclay and Small, 1986).

Methods of Investigation

The methods used in this study were similar to those used in Hanson and Small (1995), Stein and Ozuna (1995), Clark (2003, 2004), Clark and others (2009), and Clark and others (2014, 2016). Geological data and previous reports were reviewed to assist in field mapping. During 2014–16, geological and hydrostratigraphic mapping was performed in northern Bexar and Comal Counties, Tex., on public and private land. Field mapping techniques consistent with previous studies were used (Clark, 2003; Clark and Morris, 2015) and were aided by the use of GPS units and tablet-based digital maps and geologic mapping applications. Observations were recorded on site by using a tablet computer loaded with geospatially registered 7.5-minute USGS topographic maps. Locations of visible and interpreted contacts, faults and fractures, marker units, and other areas of interest were recorded by using the integrated third generation (3G) network assisted GPS receiver on the tablet computer. In areas without cellular service, positions were determined by using a handheld compass and triangulation techniques. Faults identified in the field were based on observed and inferred stratigraphic offsets. Strike and dip of faults and fractures were also noted. Bedding attitudes of fractures and faults were obtained by using a hand-held compass or the tablet computer compass application. The data obtained by using the tablet-computer compass application were independently cross-verified daily with data obtained by using the hand-held compass. The field data were transferred by using ArcGIS

ArcMap version 10.3.1 (Esri, 2016), quality checked by comparison with original draft maps, and then used to examine the geologic framework and develop the hydrostratigraphic map of the study area.

Geologic names, HSU names, lithologic descriptions, and porosity type were based on previous publications. The descriptions of the geologic framework and hydrostratigraphy in this report were adapted for the study area from Clark and others (2016). Formal geologic names are consistent with those in the U.S. Geologic Names Lexicon (U.S. Geological Survey, 2016). Informal geologic and HSU names are consistent with those used in previous publications (Maclay and Small, 1976; Clark and others, 2009; Clark and others, 2014, 2016) (fig. 2). Thicknesses of the mapped lithostratigraphic members and HSUs were from field observations. Thickness variations are from variations in local depositional and erosional conditions.

Lithologic descriptions of carbonates were done according to the classification system of Dunham (1962). Descriptions of clastic rocks (sedimentary rocks composed of pieces of preexisting rocks) (Bates and Jackson, 1987) were done under the classification scale of Wentworth (1922).

HSUs were identified on the basis of variations in the amount and type of porosity visually evident in the outcrop. Porosity varies in each lithostratigraphic member, depending on the unit's original depositional environment, lithology, structural history, and diagenesis. Porosity type was described as either fabric selective or not fabric selective on the basis of the sedimentary carbonate classification system of Choquette and Pray (1970).

Sedimentological features, paleontology, and ichnofossils (tracks, trails, burrows, and other traces left by ancient life but not actual organism parts) (Hantzschel, 1962) were examined and described on site. Burrows formed by ancient marine animals represent a common ichnofossil observed in the study area during field mapping. Ichnofossils were described by using morphology, surface textures, and burrow fill (for example, Pemberton and Frey, 1982; Hasiotis and Mitchell, 1993). Ichnofabric indexes were recorded in the field and used to interpret the percentage of bioturbation as defined by Droser and Bottjer (1986). The term "bioturbation" originates from ichnology and refers to "churning and stirring of sediment by organisms" (Bates and Jackson, 1987, p. 71). The ichnofabric index is a semiqualitative field interpretation of the amount of bioturbation within strata. The ichnofabric index rates the amount of bioturbation on a scale from 1 to 6, where 1 represents a lack of any biological disturbance of the sediments that compose the formation, and 6 represents sediments that were thoroughly homogenized as a result of biologic activity (Droser and Bottjer, 1986). The ichnofabric index was used in describing the measured geologic section at site 1 (figs. 1 and 3).

An outcrop of an intact geologic section representing the middle zone of the Trinity aquifer was examined in addition to examining a near-complete geologic core representing the middle zone of the Trinity aquifer (MW9–CC) that was

obtained from Camp Stanley, San Antonio, Tex. (fig. 1) (Blome and Clark, 2014). The geologic section was measured on site with a hand level and a Jacob's staff. The near-complete core (MW9–CC) of the middle zone of the Trinity aquifer and the outcrop of the intact geologic section were described lithologically, sedimentologically, paleontologically, and ichnologically (fig. 3).

Geologic Framework

The Trinity Group (Imlay, 1940) rocks were deposited during the Early Cretaceous on a large, shallow marine carbonate platform (Comanche shelf) as clastic-carbonate "couplets" during three marine transgressional events (Lozo and Stricklin, 1956; Stricklin and others, 1971) that caused the sea level to rise and shoreline to move inland. These three distinct "couplets" deposited sediments that formed (1) the Hosston and Sligo Formations (Imlay, 1940); (2) the Hammett Shale Member (Lozo and Stricklin, 1956) and the Cow Creek Limestone Member (Hill, 1901) of the Pearsall Formation (Imlay, 1940); and (3) the Hensell Sand Member (Hill, 1901) of the Pearsall Formation, as well as the lower and upper members of the Glen Rose Limestone (Hill, 1891).

The Early Cretaceous Edwards Group (Rose, 1972) rocks were deposited in an open marine to supratidal flats environment (Rose, 1972; Maclay and Small, 1986) during two marine transgressions. The rocks that compose the Edwards Group were deposited on the landward margin of the Comanche shelf, which was sheltered from storm waves and deep ocean currents by the Stuart City reef trend in the ancestral Gulf of Mexico (Clark and others, 2006).

Following tectonic uplift, subaerial exposure, and erosion near the end of Early Cretaceous time, the area of present-day south-central Texas was again submerged during the Late Cretaceous by a marine transgression resulting in deposition of the Georgetown Formation of the Washita Group (Richardson, 1904). Much of the Georgetown Formation was subsequently removed during a marine regressive cycle. The Stuart City reef was breached, resulting in deposition of the Del Rio Clay of the Washita Group. This transgressive episode continued through the deposition of the Buda Limestone of the Washita Group, Eagle Ford Group (Adkins, 1932), Austin Group (Murray, 1961), and Taylor Group (Hill, 1892) (fig. 2).

Trinity Group

The Trinity Group contains shale, mudstone to grainstone, boundstone, sandstone, and argillaceous limestone and is composed of the Hosston, Sligo (not shown on fig. 2), and Pearsall Formations and the Glen Rose Limestone (fig. 2). The basal Hosston and Sligo Formations of the Trinity Group are not present in surface exposures in the study area and will not be discussed further in this report.

Pearsall Formation

The Pearsall Formation of the Trinity Group consists of the Hammett Shale, Cow Creek Limestone, and Hensell Sand Members and typically ranged from 90 to 183 feet (ft) thick in the study area. Stratigraphically, the lowest mapped unit within the study area is the Hammett Shale Member of the Pearsall Formation. The Hammett Shale Member is approximately 50 ft thick (Clark and Morris, 2015) and is a burrowed mixture of claystone, siltstone, dolomite, and carbonate particles (Amsbury, 1974). The lower 15 ft of the Hammett Shale Member contains siltstone and dolomite. The upper 35 ft is primarily claystone with siltstone lenses overlain by fossiliferous dolomitic limestone (Lozo and Stricklin, 1956; Wierman and others, 2010). The contact between the Hammett Shale Member and the overlying Cow Creek Limestone Member of the Pearsall Formation is conformable (Wierman and others, 2010).

The thickness of the Cow Creek Limestone Member of the Pearsall Formation ranges from 40 to 72 ft in the study area. Generally, the lower 14 ft of the Cow Creek Limestone Member is composed of dolomitic mudstone, wackestone, and packstone (coarsening upwards) with oysters throughout (Wierman and others, 2010). The upper part of the Cow Creek Limestone Member is brown to white, very fine-grained (approximately 0.0024–0.0049 inch [in.]) to fine-grained (approximately 0.0049–0.0098 in.) carbonate sand (grainstone) with localized crossbedding (Wierman and others, 2010). Patch reefs formed from coral and rudists (boundstone) occur in the exposures of the Cow Creek Limestone Member along the Blanco River in Hays County, Tex. (Clark and others, 2016). The exposure of the Cow Creek Limestone Member also contains talus slopes associated with the adjacent patch reefs (Clark and others, 2016). The boundstone is overlain by rippled, crossbedded grainstone (Scott and others, 2007) interpreted as a strandplain (Owens and Kerans, 2010). According to Achauer (1985) and Loucks and Bebout (1984), rudists have been found in numerous borehole cores in this member. The contact with the overlying Hensell Sand Member is unconformable (Wierman and others, 2010).

The Hensell Sand Member of the Pearsall Formation ranges from 0 to 61 ft thick in the study area. The contact between the Cow Creek Limestone and Hensell Sand Members often contains a conglomerate or breccia of red sandstone. The Hensell Sand Member in Comal County grades southward from a claystone, siltstone, and terrigenous sand into a dolomitic limestone facies attributed to be the lower member of the Glen Rose Limestone. The Hensell Sand Member commonly contains oyster shells and quartz geodes. The contact between the Hensell Sand Member and the overlying Glen Rose Limestone is conformable (Sellards and others, 1932). In Hays County, just north of the current study area at The Narrows on the Blanco River (fig. 1), the Hensell Sand Member varies in thickness from 0 to 12 ft and was probably deposited as deltaic lobes (Clark and others, 2016). East of The Narrows, the Hensell Sand Member is not

present, and the Glen Rose Limestone overlies the Cow Creek Limestone directly. Field observations of the Hensell Sand Member noted that it often forms slopes and thick soils and supports lush grasses.

Glen Rose Limestone

The lower member of the Glen Rose Limestone of the Trinity Group commonly contains *Orbitolina texana* (Roemer, 1852), *Caprina* sp., *Toucasia* sp., *Trigonia* sp., *Turritella* sp., miliolids, and various corals including *Astreopora* (?) *leightoni* (Wells, 1932) and *Orbicella whitneyi* (Wells, 1932). In addition it contains trace fossil burrows, oysters, pectens, and shell fragments.

The lower part of the lower member of the Glen Rose Limestone contains 45–60 ft of resistive beds of wackestone to grainstone and boundstone (fig. 2) with burrows, *Orbitolina texana* (Roemer, 1852), *Caprina* sp., *Toucasia* sp., *Trigonia* sp., *Turritella* sp., miliolids, pectens, and various corals and shell fragments.

Above the 45–60 ft section of resistive beds of wackestone to grainstone and boundstone is approximately 40–70 ft of alternating beds of argillaceous wackestone to packstone and mudstone to grainstone and of miliolid grainstone (fig. 2). This 40–70 ft section is generally covered by soil and vegetation where it outcrops (Clark and others, 2016). Although the section is generally not visible in outcrops, ledges were identified that contained miliolid grainstone, grainstone, nodular bioturbated wackestone, and *Monopleura* sp. The 40–70 ft section also contains *Orbitolina texana* (Roemer, 1852), *Nerinea* sp., *Tylostoma* sp., and oysters, pectens, and pelecypods (Clark and others, 2016).

Overlying the section of approximately 40–70 ft of alternating beds of argillaceous wackestone to packstone and mudstone to grainstone and of miliolid grainstone is a section approximately 40–80 ft thick that consists of relatively resistive mudstones to grainstone and of boundstone. Within this 40–80 ft section are resistive limestone sections separated by argillaceous wackestone to packstone. The boundstone in this section is formed by rudist patch reefs and reefal talus. The patch reefs extend at least from the area near The Narrows in far western Hays County southwestward across eastern Blanco and western Comal Counties to Camp Bullis in northern Bexar County and then west to the Pipe Creek area of Bandera County, Tex. (fig. 1). In some locations, the patch reefs extend up through the overlying stratigraphic unit(s). Fossil assemblages are similar to those in the underlying 40–70 ft section, but also include *Caprina* sp. and *Toucasia* sp.

Above the 40–80 ft section is a 10–66 ft section of thick argillaceous wackestone, interspersed shale, thin shale beds, and occasional thin wackestone beds. This section commonly exhibits badlands-type weathering (intricately dissected topography with short steep slopes with narrow interfluves developed on surfaces with little or no vegetative cover (Bates and Jackson, 1987) and often contains abundant *Orbitolina*

texana (Roemer, 1852) with occasional gastropods and pelecypods.

Above the 10–66 ft section is a 30–40 ft section of resistive mudstones to wackestone with beds of argillaceous wackestone. Some areas contain boundstone formed from rudist patch reefs and reefal talus that may extend up from underlying sections. The patch reefs are formed from *Caprina* sp., *Monopleura* sp., and *Toucasia* sp. This section of the lower member of the Glen Rose Limestone often contains *Orbitolina texana* (Roemer, 1852), gastropods, pectens, and pelecypods (Clark and others, 2016).

The uppermost section of the lower member of the Glen Rose Limestone is a 30–40 ft section of wackestone to grainstone, argillaceous wackestone, shales, and evaporites. This section contains occasional fossils of *Monopleura* sp. and *Toucasia* sp. (Clark and others, 2016). The wackestone to grainstone grades upward into a bioturbated, nodular, fossiliferous wackestone named the Salenia bed by Whitney (1952). Common fossils in the Salenia bed are *Orbitolina texana* (Roemer, 1852), *Porocystis golobularis*, *Salenia texana*, *Macraster* sp., *Nerinea* sp., gastropods, pectens, and pelecypods.

The upper member of the Glen Rose Limestone of the Trinity Group thins towards northern Comal County because of variations in the depositional environment and erosion. The upper member of the Glen Rose Limestone primarily consists of repeated coarsening upward sequences of argillaceous wackestone to grainstone (Clark and others, 2016) and argillaceous limestone facies similar to the lower member of the Glen Rose Limestone but contains abundant evaporites and no rudist-dominated strata. Conditions during the deposition of the upper member of the Glen Rose Limestone never fully returned to the marine conditions of the lower member of the Glen Rose Limestone after the deposition of the Corbula bed (Fisher and Rodda, 1969).

The Corbula bed marks the boundary between the lower and upper members of the Glen Rose Limestone (Whitney, 1952). According to Lozo and Stricklin (1956), the Corbula beds are at the top of the lower member of the Glen Rose Limestone. The Corbula marker bed is the lowest, most identifiable, and laterally continuous of three Corbula beds, and the other two beds generally lay 2.5 and 5 ft above the Corbula marker bed. For the purpose of this report, the Corbula marker bed is considered part of the upper member of the Glen Rose Limestone. Generally, the Corbula marker bed is as thick as 12 in. and is characterized by ripple marks. Based on field observations, the average wavelength of the ripples is 1.1 ft with an amplitude of 1 in. The overlying Corbula beds are usually less than 0.5 in. thick. The stratotype location of the Corbula marker bed is near Blanco, Tex., on the Blanco River (Scott and others, 2007) (fig. 1). Sauropod tracks, additional ripple marks, and burrows were evident approximately 10 ft or less below the Corbula marker bed (Scott and others, 2007).

Immediately above the Corbula marker bed is a highly altered 8–10 ft thick section that originally contained

evaporites that have been removed by dissolution; within this section are the previously mentioned overlying Corbula beds. It contains crystalline limestone produced from alteration of the original rock matrix. The evaporite section also contains chalky mudstone, breccia, and boxwork voids where the evaporites have been dissolved. Where it outcrops, the vegetation in this section often consists of less woody vegetation (primarily *Juniperus ashei* [mountain cedar]) and more grass compared to the vegetation growing over the outcrops of surrounding rocks (Clark and others, 2016).

In the study area, a 120–150 ft thick section composed of alternating wackestone, packstone to miliolid grainstone, argillaceous limestone, and mudstone overlies the lower evaporite section. At the base of the 120–150 ft thick section is a thinly laminated silty mudstone with a "platy" appearance (Clark and others, 2009). *Orbitolina minuta* (Douglas, 1960), *Porocystis golobularis*, *Protocardia texana*, *Tapes decepta*, *Hemiaster* sp., *Neithea* sp., and *Turritella* sp. are abundant. Near the top of this unit is a massive caprinid biostrome that, where present, is between 0 and 40 ft thick. The massive caprinid biostrome is primarily found in Bexar County and probably formed as a result of local variations in the depositional environment. In addition to the identified fossils, numerous unidentifiable gastropods are evident.

In the southern part of the study area, a second evaporite section is often present. The second evaporite section is not continuous over the entire study area but reaches a maximum thickness of 10 ft in its southern part. This upper evaporite section is formed from dissolved evaporites and consists of a highly altered crystalline limestone and chalky mudstone, often containing breccia and boxwork voids. The upper evaporite section thins northward and eastward across the study area and is absent in northern Comal County.

Overlying the second evaporite section is 120–230 ft of alternating beds of burrowed wackestone, with some packstone to miliolid grainstone, and argillaceous limestone. The argillaceous limestone is not well cemented and contains varying grain sizes.

The upper part of the upper member of the Glen Rose Limestone is as much as 120 ft thick in northern Bexar County and is completely absent in the northern part of Comal County, likely because of differences in depositional environments and because of the presence of an unconformity between the Edwards and Trinity Groups. This upper part contains evaporites, wackestone, packstone, miliolid grainstone, and argillaceous limestone; it is also heavily bioturbated. Occasionally dinosaur tracks have been found near the contact of the Glen Rose Limestone and the overlying Kainer Formation of the Edwards Group (fig. 4).

Edwards Group

The Edwards Group, which overlies the Trinity Group, is composed of mudstone to boundstone, dolomitic limestone, argillaceous limestone, evaporite, shale, and chert. In the study area, the Edwards Group is composed of the Kainer and Person Formations. The Kainer Formation is subdivided into the following members (bottom to top): the basal nodular, dolomitic, Kirschberg Evaporite, and grainstone (Rose, 1972; Maclay and Small, 1976). The Person Formation is subdivided into the following members (bottom to top): the regional dense, leached and collapsed (undivided), and cyclic and marine (undivided) (Maclay and Small, 1976). All of the members of the Kainer and Person Formations are informal.

Kainer Formation

The basal nodular member at the base of the Kainer Formation is typically 40–50 ft thick in the study area. The basal nodular member is a moderately hard, shaly, nodular, burrowed mudstone to miliolid grainstone that also contains dolomite (Maclay and Small, 1976; Stein and Ozuna, 1995). According to Maclay and Small (1976, p. 25) "the basal nodular member also contains many stylolites, layers of wispy shales, and un-oxidized rock." The basal nodular member is a product of bioturbation with subsequent compaction (Sieh, 1975) and can be identified in the field by gray mudstone containing "black rotund bodies (BRBs)—0.1 to 0.5 millimeter in diameter spherical, dark colored textural features of unknown origin" (Maclay and Small, 1986, p. 1). BRBs are most likely fecal pellets of unknown origin. The basal nodular member also contains *Ceratostreon texana* (formerly *Exogyra texana*, a type of saltwater oyster) (Stein and Ozuna, 1995; Clark, 2003; Scott and others, 2007), *Caprina* sp. (eastern part of the study area), miliolids, and gastropods. The contact with the overlying dolomitic member is conformable and gradational (Rose, 1972).

The dolomitic member is typically 90–120 ft thick in the study area. The lower 20 ft of the dolomitic member does not contain chert and has alternating burrowed beds and limestone beds (Rose, 1972). Chert is found as beds and as nodules throughout the Edwards Group above this lower 20 ft of the dolomitic member. According to Maclay and Small (1976, p. 24), the dolomitic member is "a hard, dense to granular, dolomitic limestone that contains scattered cavernous layers." They further differentiate the dolomitic member, stating that the lower three-fourths of the dolomitic member is composed of sucrosic dolomites and grainstones, with hard dense limestones interspersed, and that the upper one-fourth of the dolomitic member is composed mostly of hard, dense mudstone, wackestone, packstone, grainstone, and recrystallized dolomites (Maclay and Small, 1976) with bioturbated beds. The contact between the dolomitic member and the overlying Kirschberg Evaporite Member is conformable.

The Kirschberg Evaporite Member is typically 40–50 ft thick in the study area and is a highly altered crystalline limestone and chalky mudstone with occasional grainstone

associated with tidal channels, all of which contain chert (Maclay and Small, 1976) both as beds and as nodules. Boxwork molds, which are associated with the removal of evaporites, are common, and "the matrix of the boxwork has recrystallized to a coarse grain spar" (Maclay and Small, 1976, p. 24). The Kirschberg Evaporite Member also contains intervals of collapse breccia and travertine deposits (Maclay and Small, 1976). The contact with the overlying grainstone member is unconformable.

The grainstone member is typically 40–50 ft thick in the study area and is a hard, dense limestone that consists mostly of a tightly cemented miliolid or skeletal fragment grainstone (Maclay and Small, 1976). The member also contains interspersed chalky mudstone and wackestone (Maclay and Small, 1976) and chert both as beds and as nodules. Crossbedding and ripple marks are common primarily at the contact with the overlying regional dense bed. The contact between the grainstone and regional dense bed is conformable.

Person Formation

The regional dense member of the Person Formation is a dense, shaly limestone that is typically 20–24 ft thick in the study area. Maclay and Small (1976) described the regional dense member of the Person Formation as an oyster shell mudstone and iron wackestone containing wispy shale partings. It also contains wispy iron-oxide stains with chert nodules being rarer than in the rest of the chert-bearing Edwards Group.

The leached and collapsed members (undivided) are typically 70–90 ft thick in the study area and consist of a hard, dense, recrystallized limestone (Maclay and Small, 1976; Stein and Ozuna, 1995). The member is generally a mudstone, wackestone, packstone, and grainstone containing chert and occasional collapse breccias. These units are heavily bioturbated with iron-stained beds (Stein and Ozuna, 1995) separated by more massive limestone beds. The leached and collapsed members are often stromatolitic and contain chert both as beds and as large nodules. Fossils and fragments of *Toucasia* sp. are often found just above the contact with the underlying regional dense member. Although rare, the coral *Montastrea roemeriana* and oysters can be found.

The cyclic and marine members (undivided) are typically 80–90 ft thick in the study area. The undivided cyclic and marine members were mapped and considered as one unit. Maclay and Small (1976) stated that the cyclic and marine members are locally bioturbated and are mostly composed of pelletal limestone that ranges from chalk to mudstone and miliolid grainstone. A packstone containing large caprinids also is present near the contact with the overlying Georgetown Formation. Chert is common both in the form of beds and large nodules. Some of the caprinids identified in the field

were several feet long and as much as 5 in. in diameter. The cyclic and marine members are composed of thin to massive beds; some crossbedding is evident.

Washita Group

The Georgetown Formation of the Washita Group is typically 20–30 ft thick in the study area and is a reddish-brown, gray to light tan, shaly mudstone and wackestone. It commonly contains black dendrites, iron nodules, and iron staining and often resembles the Buda Limestone. According to Maclay and Small (1976), the Georgetown Formation overlies the Person Formation of the Edwards Group unconformably. The Georgetown Formation contains dispersed pyrite and organic material in beds of dense, shaly limestone that suggest a condition of undisturbed deposition in a reducing environment (Maclay and Small, 1976). The Georgetown Formation is often fossiliferous with *Plesioturrilites brazoensis* and *Waconella wacoensis* common. *Waconella wacoensis* is the index fossil for the Georgetown Formation. The Del Rio Clay overlies the Georgetown Formation unconformably.

The Del Rio Clay of the Washita Group is typically 40–50 ft thick in the study area. It is a fossiliferous, blue-green to yellow-brown clay with thin beds of packstone. The Del Rio Clay of the Washita Group contains iron nodules and the index fossil *Ilymatogyra arietina*. The contact between the Del Rio Clay and the overlying Buda Limestone is unconformable (Martin, 1967) and easily recognized, with the Buda Limestone blocks often slumping down hillsides over the Del Rio Clay outcrops (Clark and others, 2013).

The Buda Limestone of the Washita Group is approximately 40–50 ft thick and is buff to light gray, dense, nodular mudstone and wackestone containing calcite-filled veins and bluish dendrites. It is a porcelaneous limestone that weathers from a smooth gray to a grayish white; its nodular surface has a conchoidal fracture (Adkins, 1932). The Buda Limestone commonly contains iron nodules, iron staining, and shell fragments. The contact with the overlying Eagle Ford Group is unconformable (Martin, 1967).

Eagle Ford Group

The Eagle Ford Group (undivided) is approximately 20–40 ft thick in the study area and consists of brown, flaggy, sandy shale and argillaceous limestone (Trevino, 1988). In the study area, this group contains iron nodules, the fossil *Inoceramus* sp., shark teeth, and fossil fragments. Some of these freshly fractured flagstones emit a petroliferous odor. The upper contact with the overlying Austin Group is gradational. According to Freeman (1961), there is a transitional zone of as much as 5 ft in thickness where the Eagle Ford Group beds resemble the Austin Group.

Austin Group

The Austin Group (undivided) is 130–160 ft thick and consists of massive, chalky, locally marly mudstone (Koger, 1981; Small, 1986; Hanson and Small, 1995; Maclay, 1995) containing intervals of nodular (bioturbated) wackestone. The Austin Group commonly contains iron nodules. The fossils *Gryphaea aucella* and *Inoceramus* sp. (Banta and Clark, 2012) are common. The Austin Group also contains varying amounts of volcanoclastics and terrigenous clastics (Martinez, 1982). The fractures often contain void-filling calcite, sometimes in the form of dogtooth spar. The contact with the overlying Taylor Group is unconformable (Martinez, 1982).

Taylor Group

In the study area the Taylor Group (undivided) is composed of the Pecan Gap Formation. According to Arnow (1963), the Taylor Group is approximately 230–540 ft thick in Bexar County, thickening southward. The formation is mostly marl and calcareous clay and is blue in the subsurface but weathers greenish yellow. Fossils are common, the most notable fossil being the large *Exogyra ponderosa* (Arnow, 1963).

Structure

The principal structural feature in Bexar and Comal Counties is the Balcones fault zone, which is the result of Miocene-age faulting (Weeks, 1945) and fracturing. As is typical elsewhere in the Balcones fault zone, most of the faults in the study area are high-angle to vertical, en echelon, normal faults that are downthrown to the southeast (fig. 5) (George, 1952). As with any normal fault extensional system, this also includes horst and graben structures (Pantea and others, 2014).

The structurally complex Balcones fault zone contains relay ramps (Hovorka and others, 1996), which are a common feature formed during the growth of normal and extensional fault systems (Hus and others, 2005). Several reports provide detailed descriptions of relay ramps and relay ramp development in the Balcones fault zone; these include but are not limited to Hovorka and others (1996), Collins and Hovorka (1997), Ferrill and others (2003), Faith (2004), and Clark and Journey (2006). Relay ramps form in extensional fault systems to allow for deformation changes along the fault block (Clark and Journey, 2006). Ramp structures connect the footwall of a fault segment to the stratigraphically higher segment (hanging wall) of the overlapping fault. As stress (extension) occurs and strain along the ramp increases, rotation and internal fracturing occur along the relay ramp (Trudgill, 2002). Subsequently, continuing extension produces cross faults within the relay ramp structure.

The primary orientation of mapped fractures and faults in the study area is southwest to northeast between 45 and 50 degrees. The conjugate fractures trend perpendicular to the Balcones fault zone at approximately 145–150 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 represent a section of the upper confining unit to the Edwards aquifer, the Edwards aquifer, the upper zone of the Trinity aquifer, and the middle zone of the Trinity aquifer. In the study area the Edwards aquifer is composed of the Georgetown Formation and of the rocks forming the Edwards Group. The Trinity aquifer is composed of the rocks forming the Trinity Group. The Edwards and Trinity aquifers are karstic with high secondary permeability and porosity along bedding and fractures (Maclay and Small, 1983; Johnson and others, 2002; Ferrill and others, 2003; Gary and others, 2011). The following descriptions of the hydrostratigraphy and porosity of individual HSUs are modified and expanded from Choquette and Pray (1970), Maclay and Small (1976), Stein and Ozuna (1995), Clark and others (2009), Blome and Clark (2014), and Clark and Morris (2015). An electronic ArcGIS version of the 1:24,000-scale hydrostratigraphic map of the study area is included with this report (app. 1).

Upper Confining Unit to the Edwards Aquifer

The Pecan Gap Formation (Kpg), Austin Group (Ka), Eagle Ford Group (Kef), Buda Limestone (Kb), and Del Rio Clay (Kdr) collectively are generally considered to be the upper confining unit to the Edwards aquifer (Maclay and Small, 1976; Hanson and Small, 1995). Because the formations and groups are generally categorized as a confining unit to the Edwards aquifer and not as separate water-bearing aquifers, the lithologic terms (group, formation, limestone, and clay) will hereinafter be used to describe both the geologic framework and hydrologic characteristics of the HSU being described. The upper confining unit to the Edwards aquifer does not supply appreciable amounts of water to wells in the study area with the exception of the Austin Group (Petitt and George, 1956); for this reason, of the units that compose the upper confining unit to the Edwards aquifer, only the Austin Group will be described.

The Austin Group supplies water to several springs in the study area, as well as to some domestic and irrigation wells (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 (Veni, 1988; Banta and Clark, 2012).

Edwards Aquifer

The Edwards aquifer was subdivided into HSUs I to VIII by Maclay and Small (1976). The Georgetown Formation of the Washita Group contains HSU I (Kg). The Person Formation of the Edwards Group contains HSUs II (cyclic and marine members [Kpcm, undivided]), III (leached and collapsed members [Kplc, undivided]), and IV (regional dense member [Kprd]), and the Kainer Formation of the Edwards Group contains HSUs V (grainstone member [Kkg]), VI (Kirschberg Evaporite Member [Kkke]), VII (dolomitic member [Kkd]), and VIII (basal nodular member [Kkbn]).

Barker and Ardis (1996, p. B42) wrote, "the Edwards aquifer primarily is recharged by (1) seepage from streams draining the Hill Country, where the streams flow onto permeable outcrop areas of the Edwards Group and Devils River Formation (Puente, 1978) (2) infiltration of precipitation on the outcrop areas; (3) subsurface inflow across the up-dip margin of the Balcones fault zone where the Trinity aquifer is laterally adjacent to down-faulted Edwards strata (Veni, 1994); and (4) diffuse upward leakage from the underlying Trinity aquifer."

Hydrostratigraphic Unit I (Kg)

HSU I is considered part of the Edwards aquifer, but hydrologically it functions as a confining unit (George, 1952; Maclay and Small, 1976; Hanson and Small, 1995). Porosity is generally fabric selective formed by isolated molds surrounded by a rock matrix. According to Maclay and Small (1976), HSU I contains porosity of less than 5 percent. Maclay and Small (1976) further stated that the capillary forces of the small voids do not allow the rocks to drain by gravity. Arnow (1959) considered HSU I to be part of the Edwards aquifer because this unit is the primary target used by water well drillers when setting well casings. George (1952), Land and Dorsey (1988), Blome and others (2005), and Clark and others (2006) have considered this unit as part of the upper confining unit to the Edwards aquifer. Stein and Ozuna (1995) stated that the Georgetown Formation is not known to produce water.

Hydrostratigraphic Unit II (Kpcm)

HSU II contains less than 15 percent porosity in the form of fabric-selective molds and burrows and not-fabric-selective fractures (Maclay and Small, 1976). Hanson and Small (1995) observed that HSU II also contains not-fabric-selective vug porosity. Field observations show burrow porosity associated with bioturbation in the form of cylindrical interconnected burrows (*Thalassinoides*) (Ehrenberg, 1944). In addition, the unit has not-fabric-selective porosity associated with bedding planes and caves. Hanson and Small (1995) also noted that the unit is water bearing, although field observations during the study documented in this report indicate that HSU II has only slightly less porosity than HSU III.

Hydrostratigraphic Unit III (Kplc)

HSU III has a reported porosity of 20 percent, which makes it the most porous and permeable part of the Person Formation (Maclay and Small, 1976). It contains fabric-selective burrow porosity and not-fabric-selective vug, breccia, fracture, bedding plane, and cave porosity. The fabric-selective burrow porosity is associated with bioturbated zones (*Thalassinoides*). Maclay and Small (1976) associated the breccia and cave porosity with the collapsed zones resulting from dissolution of evaporites. In addition, Hanson and Small (1995) stated that many of the springs, such as Comal Springs (fig. 1), issue from faults that are believed to be near the base of the HSU III. The unit is water bearing and has the highest reported porosity in the upper part of the Edwards aquifer.

Hydrostratigraphic Unit IV (Kprd)

HSU IV has less than 5 percent porosity and yields no water (Maclay and Small, 1976). This HSU is likely the least porous or permeable unit of the Edwards aquifer and locally might be a confining unit (Hanson and Small, 1995). According to Stein and Ozuna (1995), it probably is an effective vertical confining unit between HSU III and HSU V; however, not-fabric-selective fracture and cave porosity are present in the unit, which might greatly reduce the confining effects of this HSU in some areas. All of the caves known in this HSU are vertical shafts, often with major horizontal cavern development either above or below the unit (Veni, 2005).

Hydrostratigraphic Unit V (Kkg)

HSU V has a reported porosity of less than 10 percent (Maclay and Small, 1976) with minor fabric-selective interparticle and intergranular porosity (Hanson and Small, 1995). The unit also contains not-fabric-selective fracture, bedding plane, and cave porosity (Maclay and Small, 1976). Maclay and Small (1976) reported that the middle of the unit contains a fabric-selective burrow porosity that has resulted in the development of not-fabric-selective cave porosity.

Hydrostratigraphic Unit VI (Kkke)

HSU VI is the most porous and permeable unit in the lower part of the Edwards aquifer, with porosity of more than 20 percent that occurs in several forms (Maclay and Small, 1976). The unit has abundant fabric-selective intergranular and moldic porosity and not-fabric-selective vug, fracture, breccia, and cave porosity. The moldic porosity is often in the form of boxwork voids caused by the removal of evaporites and the deposition of secondary neospar and travertine (Hanson and Small, 1995). Fracture porosity is associated with faulting, and breccia porosity is associated with the removal of evaporites (Maclay and Small, 1976).

Hydrostratigraphic Unit VII (Kkd)

HSU VII has between 5 and 20 percent porosity (both fabric-selective and not-fabric-selective). The fabric-selective porosity consists of interparticle, intergranular, intercrystalline, moldic, and burrow porosity. The not-fabric-selective porosity consists of vug, fracture, bedding plane, and cave porosity (Maclay and Small, 1976). Moldic and burrow porosity are common within the bioturbated beds. Burrowed beds primarily consist of *Thalassinoides*. In one location, *Skolithos* burrows (fig. 6) can be seen in the outcrop. These burrows are not interconnected. HSU VII is water bearing and according to Veni (2005) forms some of the deepest vertical pits in Texas.

Hydrostratigraphic Unit VIII (Kkbn)

HSU VIII has a porosity of less than 10 percent (Maclay and Small, 1976); it contains fabric-selective interparticle, moldic, and burrow porosity and not-fabric-selective bedding plane, fracture, and cave porosity. The unit is probably best described as a semiconfining unit; the degree to which it functions as a confining unit likely depends on the amount of interconnected burrow porosity and cave porosity (Clark and others, 2016). According to Veni (2005), HSU VIII contains some of the largest cave chambers and passages in the study area. These cave features probably formed as a result of downward migrating groundwater encountering highly bioturbated beds within the unit or in the underlying cavernous unit.

Trinity Aquifer

Ashworth (1983) subdivided the Trinity aquifer into upper, middle, and lower aquifer units (hereinafter referred to as "zones"). The upper zone of the Trinity aquifer is in the upper member of the Glen Rose Limestone. The upper zone of the Trinity aquifer is divided into the cavernous (Kgrc), Camp Bullis (Kgrcb), upper evaporite (Kgrue), fossiliferous (upper [Kgruf] and lower [Kgrlf]), and lower evaporite (Kgrle). The middle zone of the Trinity aquifer is formed in the lower member of the Glen Rose Limestone, Hensell Sand, and Cow Creek Limestone. The middle zone of the Trinity aquifer is divided into the Bulverde (Kgrb), Little Blanco (Kgrlb), Twin Sisters (Kgrts), Doeppenschmidt (Kgrd), Rust (Kgrr), Honey Creek (Kgrhc), Hensell (Kheh), and Cow Creek (Kcccc) HSUs. The regionally extensive Hammett HSU (Khah) forms a confining unit between the middle and lower zones of the Trinity aquifer. The lower zone of the Trinity aquifer does not crop out in the study area.

According to Barker and Ardis (1996), the Trinity aquifer is recharged by, in order of importance (most to least), lateral subsurface inflow of groundwater from the Edwards Plateau, infiltration of precipitation on the outcrop, and seepage of surface water from shallow, tributary streams. Ashworth (1983) stated that sinkholes in streambeds in the

Glen Rose Limestone frequently intercept surface water to provide substantial amounts of recharge to the Trinity aquifer. Fractures and faults, as well as various other types of porosity, link the upper, middle, and lower zones of the Trinity aquifer and result in a "leaky-aquifer system" (Ashworth and others, 2001).

Upper Zone of the Trinity Aquifer

The upper zone of the Trinity aquifer was informally subdivided into five HSUs by Clark (2003) that were subsequently informally renamed by Clark and others (2009). These five HSUs are (top to bottom) the cavernous (Kgrc), Camp Bullis (Kgrcb), upper evaporite (Kgrue), fossiliferous (Kgruf, Kgrlf), and lower evaporite (Kgrle).

Cavernous Hydrostratigraphic Unit (Kgrc)

The cavernous HSU is approximately 0–120 ft thick; it contains fabric-selective porosity associated with molds and burrows. The not-fabric-selective porosity is in the form of bedding planes, fractures, and caves. The unit is considered water bearing. The cavernous HSU contains evaporite beds along with large amounts of bioturbation which includes beds of *Thalassinoides* (Golab and others, 2015; Clark and others, 2016) and rhizocretions (fig. 7), which are "pedodiagenetic mineral accumulations around plant roots" (Klappa, 1980, p. 615). The bioturbated beds have resulted in interconnected lateral flow and linked bedding planes, fractures, and caves. Field observations indicate that the interval is more porous than the underlying Camp Bullis HSU. The cavernous HSU, however, has a small lateral extent and is not present at the surface through most of the study area (Clark and Morris, 2015). The high permeability of the overlying Edwards aquifer has introduced meteoric water into faults and fractures creating karstic groundwater flow paths that continue into the Trinity aquifer from the Edwards aquifer (Clark, 2004; Smith and others, 2005). Johnson and others (2010) have shown through dye tracing that the cavernous HSU of the upper zone of the Trinity aquifer is hydrologically indistinguishable from the Edwards aquifer. This hydrologic connection has been further enhanced by fault juxtaposition of the cavernous HSU against parts of the Edwards aquifer.

Camp Bullis Hydrostratigraphic Unit (Kgrcb)

The Camp Bullis HSU is approximately 120–230 ft thick in the study area. Fabric-selective burrow porosity and not-fabric-selective bedding plane and fracture porosity are the primary porosity types identified in the field. Some cave development, which was likely caused by the intersection of fractures with bedding planes, has been observed. Most of the observed Camp Bullis HSU has little solution enlargement of fractures and is considered a confining unit (Clark, 2004; Clark and Morris, 2015). Field observations indicate that beds in the Camp Bullis HSU likely prevent appreciable vertical

fluid flow but instead perch groundwater on less soluble beds. This perched groundwater is likely transmitted laterally through bioturbated beds consisting of *Thalassinoides* and *Ophiomorpha* (Clark and others, 2016) resulting in conduits and caves that yield water to seeps and springs.

Upper Evaporite Hydrostratigraphic Unit (Kgrue)

The upper evaporite HSU is not continuous throughout the study area; however, where present it can be as much as 10 ft thick. It contains fabric-selective interparticle, moldic (boxwork), and burrow porosity and fabric-selective breccia porosity as a result of collapse. The extensive bioturbation of this unit aided in the development of the fabric-selective porosity (Fisher and Rodda, 1969). This HSU is considered water bearing and diverts groundwater laterally to discharge at springs and seeps (Clark, 2004; Clark and others, 2009).

Upper and Lower Fossiliferous Hydrostratigraphic Unit (Kgruf, Kgrlf)

The fossiliferous HSU (Kgrf) is 120–150 ft thick in the study area. In parts of the study area, the unit can be informally subdivided into an upper part that is 0–40 ft thick (Kgruf) and a lower part that is 80–150 ft thick (Kgrlf). The upper part of the fossiliferous HSU is distinguishable from the lower part of the fossiliferous HSU by a biostrome present in southern and western Bexar County and parts of Comal County. In Comal County, the biostrome gradually thins and disappears, making it impossible to distinguish between the upper and lower parts of the fossiliferous HSU in extreme northern Comal County. The upper fossiliferous HSU contains extensive not-fabric-selective burrow, fracture, and cave porosity and fabric-selective moldic porosity (Clark, 2003). This unit likely contains numerous caves that readily transport water a long distance, some of which discharge at springs (George Veni, written commun., 1999).

The lower part of the fossiliferous HSU contains fabric-selective moldic and burrow porosity and not-fabric-selective fracture porosity (Clark, 2003). The lower part of the fossiliferous HSU is generally considered a confining unit (Clark, 2003; Clark and others, 2009). The lower part of the fossiliferous HSU contains an extensive network of bioturbated beds consisting of *Thalassinoides* that facilitate the lateral movement of groundwater (Golab and others, 2015; Clark and others, 2016).

Lower Evaporite Hydrostratigraphic Unit (Kgrle)

The lower evaporite HSU is approximately 8–10 ft thick in the study area and contains fabric-selective interparticle, moldic (boxwork), and burrow porosity. It also contains fabric-selective breccia porosity. According to Fisher and Rodda (1969), the extensive bioturbation of the lower evaporite HSU aided in the development of the fabric-selective porosity. The lower evaporite HSU is water bearing and discharges laterally along its contact with the underlying Bulverde HSU at springs and seeps (Clark, 2003; Clark and others, 2009).

Middle Zone of the Trinity Aquifer

The middle zone of the Trinity aquifer is composed of the Bulverde, Little Blanco, Twin Sisters, Doeppenschmidt (figs. 8–9), Rust, Honey Creek, Hensell, and Cow Creek HSUs (Clark and Morris, 2015). Underlying the Cow Creek HSU is the regional confining unit, the Hammett HSU, separating the middle and lower zones of the Trinity aquifer. The lower zone of the Trinity aquifer does not outcrop in the study area. Within the Trinity aquifer, the middle zone of the Trinity aquifer is the primary region of water production for both public and domestic wells.

Bulverde Hydrostratigraphic Unit (Kgrb)

The Bulverde HSU is the uppermost unit of the middle zone of the Trinity aquifer. The Bulverde HSU is typically 30 ft thick in the study area, but its thickness can range from 30 to 40 ft. It contains fabric-selective moldic porosity associated with bioturbation and breccia porosity formed from the dissolution of evaporites (Clark and others, 2016). It also contains not-fabric-selective bedding plane and fracture porosity. The shale bed, which is several feet thick, at the top of the unit is a semiconfining unit and restricts the downward migration of water that results in water moving laterally to discharge as seeps and springs. Field observations indicate that this unit is a confining unit and is often used for constructing stock ponds.

Little Blanco Hydrostratigraphic Unit (Kgrlb)

The Little Blanco HSU is typically 30 ft thick in the study area, but its thickness can range from 30 to 40 ft. It contains fabric-selective moldic and burrow porosity. The unit also has not-fabric-selective bedding plane and fracture porosity. According to Golab and others (2015), fabric-selective *Thalassinoides* and other biogenic porosity have likely created a network of interconnected porosity that is a major component of this unit's ability to transmit water. Several caves and underground streams are present in this HSU (George Veni, written commun., 2016). The Little Blanco HSU is considered water bearing in the study area.

Twin Sisters Hydrostratigraphic Unit (Kgrts)

The Twin Sisters HSU is typically 30 ft thick in the study area, but its thickness can range from 10 to 66 ft. It contains fabric-selective interparticle porosity. In the study area, the Twin Sisters HSU functions as a semiconfining unit in the shale beds (Clark and others, 2016). Water in the unit moves laterally, resulting in discharge from seeps and springs along hillsides providing water to numerous stock ponds (Clark and Morris, 2015).

Doeppenschmidt Hydrostratigraphic Unit (Kgrd)

The Doeppenschmidt HSU can range from approximately 40 to 80 ft thick in the study area but typically is about 40 ft thick. It contains fabric-selective interparticle, moldic, and burrow porosity. In addition, the unit contains not-fabric-selective bedding plane, fracture, and cave porosity. There are seeps and springs near the contact with the underlying Rust HSU. The Doeppenschmidt grades laterally into patch reefs that contain appreciable interconnected moldic porosity formed by *Caprina* sp. In addition, it contains some bioturbated beds that might link fabric-selective and not-fabric-selective porosity resulting in its ability to transmit water rapidly (Golab and others, 2015; Clark and others, 2016). The Doeppenschmidt HSU is water bearing in the study area.

Rust Hydrostratigraphic Unit (Kgrr)

The Rust HSU is approximately 40–70 ft thick in the study area. It contains fabric-selective interparticle porosity and not-fabric-selective fracture and cave porosity. Fracture porosity is not well developed, but several of the thicker limestone beds have fractures with solution enlargement. The unit contains cave and conduit porosity primarily near faults; most caves probably formed as a result of roof collapse of caves in the underlying Honey Creek HSU. Caves in the Rust HSU are also present that initially formed in the overlying Doeppenschmidt HSU and continued dissolution downward into and in some cases through the Rust HSU. The Rust HSU appears to function as a semiconfining unit in nonfaulted areas (Clark and others, 2016), restricting subsurface flow, because springs and seeps occur near its contact with the overlying Doeppenschmidt HSU. The unit contains bioturbated beds of *Paleophycus* and *Planolites*, but they do not increase fabric-selective biogenic porosity as much as occurs in other, more transmissive HSUs (Golab and others, 2015; Clark and others, 2016).

Honey Creek Hydrostratigraphic Unit (Kgrhc)

The Honey Creek HSU is approximately 45–60 ft thick and is the lowest HSU in the lower member of the Glen Rose Limestone. The Honey Creek HSU contains fabric-selective interparticle, moldic, and burrow porosity. Fabric-selective biogenic porosity is primarily from *Paleophycus* with some *Thalassinoides* networks (Golab and others, 2015; Clark and others, 2016). While defined as a transmissive unit, most of the biogenic porosity of the Honey Creek HSU appears to be restricted to the lower half of the unit. It also contains not-fabric-selective bedding plane, fracture, channel, and cave porosity. Most fracture and karstic development also appears in the lower portions of the Honey Creek HSU (Clark and Morris, 2015), which probably reflects the importance of the biogenic porosity in forming the initial pathways for groundwater flow. The Honey Creek HSU is considered water bearing and is likely the most transmissive part of the

Glen Rose Limestone based on field observations and water level data from the Camp Stanley area. Many large springs issue from this HSU within the study area including Honey Creek Spring, which supplies base flow to the Guadalupe River (fig.1). The Honey Creek cave system is the longest known cave system in Texas; more than 20 miles of the cave system have been mapped (Smith and Veni, 1994; Texas State Historical Association, 2016).

Hensell Hydrostratigraphic Unit (Kheh)

The Hensell HSU is 0–61 ft thick and is the uppermost HSU of the Pearsall Formation. The upper part of the Hensell HSU contains fabric-selective interparticle and moldic porosity; the lower part of the Hensell HSU contains fabric-selective moldic and shelter porosity (Clark and others, 2014). Minor amounts of not-fabric-selective cave porosity are present in both the upper and lower parts of the Hensell HSU. The cave porosity is likely associated with roof collapse of caves in the underlying Cow Creek HSU (Clark and others, 2014). The Hensell HSU transitions from being a water-bearing unit northwest of the study area to a confining unit southeast of the study area. The Guadalupe River approximately follows the transition zone between the water-bearing and confining units of the Hensell HSU. The Hensell HSU also transmits the groundwater to the Honey Creek cave system.

Cow Creek Hydrostratigraphic Unit (Kcccc)

The Cow Creek HSU is approximately 40–72 ft thick in the study area. It contains fabric-selective interparticle, moldic, and burrow porosity. It also contains not-fabric-selective vug, bedding plane, fracture, channel, and cave porosity (Clark and others, 2014). In areas that contain biostromes of coral and rudist, the HSU contains well-developed interconnected moldic porosity. In addition, the strandplain parts of the Cow Creek HSU contain interconnected fabric-selective fenestral porosity. The Cow Creek HSU is water bearing and the primary source for water well production within the middle zone of the Trinity aquifer. Based on field observations the Cow Creek HSU is recharged from streams crossing outcrops of the Cow Creek HSU along the Guadalupe and Blanco Rivers; it also receives recharge through the Hensell HSU (Reeves, 1967; Ashworth, 1983). Discharge from the Cow Creek HSU also occurs along these rivers depending on the hydrologic gradient and water levels within the aquifer. South of the Guadalupe River it is more likely recharged laterally by fault juxtaposition with the Glen Rose Limestone (Veni, 1994) and by vertical recharge along fractures through the Glen Rose Limestone.

Hammett Hydrostratigraphic Unit (Khah)

The Hammett HSU is approximately 50 ft thick. It is not exposed at the surface in the study area; however, on the basis of stratigraphic thicknesses of the overlying units, it is

shown on the map where it is inferred to underlie areas along the Guadalupe River. On the basis of field observations and reported data (Ashworth, 1983; Wierman and others, 2010; Clark and others, 2014), the interval functions as a confining unit, restricting the downward migration of groundwater and resulting in the formation of springs near the base of the Cow Creek HSU.

Hydrologic Characteristics of Structure

Groundwater recharge and flow paths in the study area are influenced not only by the hydrostratigraphic characteristics of the individual HSUs but also by faults and fractures and geologic structure. As stated in Clark and others (2013), faulting associated with the Balcones fault zone (1) might affect groundwater flow paths by forming a barrier to flow that results in water moving parallel to the fault plane (Maclay, 1995), (2) might affect groundwater flow paths by increasing flow across the fault because of fracturing and juxtaposing porous and permeable units, or (3) might have no effect on the groundwater flow paths. Based on Small (1986), Maclay (1995) stated that faults could be barriers to groundwater flow paths where the aquifer is offset by 50 percent or more, causing groundwater to flow parallel to the fault. Clark and Journey (2006, p. 2) noted that "the amount of displacement along a particular fault tends to vary, and thus the effectiveness of a fault as a barrier to flow probably changes along the fault plane. Near a fault tip (that is, where a fault ends) no barrier to flow exists; as displacement down the fault plane increases, the effectiveness of the fault as a barrier to flow increases." Faulting and the resulting structures (grabens and horsts) 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. Recent dye tracing studies by Johnson and others (2010) indicate that the permeable zones in juxtaposed members might be narrow; however, if cavernous permeability is present then all available water might be transmitted at or through the fault. When juxtaposed against zones with relatively more permeability, zones with relatively less permeability might act as a barrier to groundwater flow (Stein and Ozuna, 1995).

According to Ferrill and Morris (2003), faults within the Edwards Group are more dilatant (open) than in the Glen Rose Limestone because the Edwards Group lithologies are more competent. They also stated that fault deformation increases permeability at or near faults. Fault permeability in the Glen Rose Limestone is heterogeneous and affects groundwater flow both parallel and perpendicular to faults (Ferrill and Morris, 2003). Clay smear and calcite deposition can affect cross-fault flow and may inhibit the flow if it is appreciable (Ferrill and Morris, 2003). Faulting in the Glen Rose Limestone is complex, and the clay and shale in it can appreciably affect cross-fault flow (Ferrill and Morris,

2003). Solution-enlarged fractures and conduits might also form parallel to the dip of relay ramps in the Edwards Group (Clark and Journey, 2006) because of the northeast to southwest extension.

According to Veni (1988), cave formation is strongly guided by secondary fractures that form as a result of faulting, rather than by the actual fault plane. Clark and Journey (2006) stated that the fractures generally are parallel to or perpendicular to the main fault trend of the Balcones fault zone (Clark and Journey, 2006). Faulting affects cave development through fractures that form as a result of extension perpendicular to the Balcones fault zone (Clark and Journey, 2006). As extension of the series of en echelon, mainly down-to-the-coast (northwest to southeast) faults associated with the Balcones fault zone occurred, the same amount of material had to occupy a larger area, resulting in extension perpendicular to the fault zone (Clark and Journey, 2006).

From field observations and previous studies, it is apparent that the hydrologic connection between the Edwards and Trinity aquifers and the various HSUs is complex. The complexity of the aquifer system is a combination of the original depositional history, bioturbation, primary and secondary porosity, diagenesis, and fracturing of the area from faulting. All of these factors have resulted in development of modified porosity, permeability, and transmissivity within and between the aquifers. The original depositional sediments have produced layers of shales, impure limestones, and limestones which in turn have varying types of porosity related to biological activity and to subsequent diagenesis. 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.

Summary

During 2014–16, the U.S. Geological Survey, in cooperation with the Edwards Aquifer Authority, documented the geologic framework and hydrostratigraphy of the Edwards and Trinity aquifers within northern Bexar and Comal Counties, Texas. The Edwards and Trinity aquifers are major sources of water for agriculture, industry, and urban and rural communities in south-central Texas. To help water managers, drinking-water suppliers, and policymakers effectively manage the water resources in the area, refined maps and descriptions of the geologic structures and hydrostratigraphic units (HSUs) of the aquifers in northern Bexar and Comal Counties, Tex., are needed. Groundwater flow and storage in the Edwards and Trinity aquifers are largely controlled by the structures and hydrostratigraphy of the aquifers; therefore,

refined information about these features will aid in anticipating and mitigating issues related to changing land use and increasing groundwater demands.

The purpose of this report is to present the geologic framework and hydrostratigraphy of the Edwards and Trinity aquifers within northern Bexar and Comal Counties, Tex. This report presents a detailed 1:24,000-scale hydrostratigraphic map, names, and descriptions of the geology and HSUs in the study area. The mapped HSUs will aid in identifying units that have potential groundwater recharge and discharge and (or) that potentially act as confining layer.

The scope of the report is focused on geologic framework and hydrostratigraphy of the outcrops of the Edwards and Trinity aquifers within northern Bexar and Comal Counties, Tex. In addition, parts of the adjacent upper confining unit to the Edwards aquifer are included.

The study area, approximately 866 square miles, is within the outcrops of the Edwards and Trinity aquifers and overlying confining units (Washita, Eagle Ford, Austin, and Taylor Groups) in northern Bexar and Comal Counties, Tex. The rocks within the study area are sedimentary and range in age from Early to Late Cretaceous. The Miocene-age Balcones fault zone is the primary structural feature within the study area. The fault zone is an extensional system of faults that generally trends southwest to northeast in south-central Texas. The faults have normal throw, are en echelon, and are mostly downthrown to the southeast.

The Trinity Group rocks were deposited during the Early Cretaceous on a large, shallow-marine carbonate platform (Comanche shelf) as clastic-carbonate "couplets" during three marine transgressional events that caused the sea level to rise and shoreline to move inland. These three distinct "couplets" deposited sediments that formed (1) the Hosston and Sligo Formations; (2) the Hammett Shale Member and the Cow Creek Limestone Member of the Pearsall Formation; and (3) the Hensell Sand Member of the Pearsall Formation, as well as the lower and upper members of the Glen Rose Limestone.

The Early Cretaceous Edwards Group rocks were deposited in an open marine to supratidal flats environment during two marine transgressions. The rocks that compose the Edwards Group were deposited on the landward margin of the Comanche shelf, which was sheltered from storm waves and deep ocean currents by the Stuart City reef trend in the ancestral Gulf of Mexico. The Edwards Group is composed of the Kainer and Person Formations, which were deposited during two marine transgressions. Following tectonic uplift, subaerial exposure, and erosion near the end of Early Cretaceous time, the area of present-day south-central Texas was again submerged during the Late Cretaceous by a marine transgression resulting in deposition of the Georgetown Formation of the Washita Group. Much of the Georgetown Formation was subsequently removed during a marine regressive cycle. The Stuart City reef was breached, resulting in deposition of the Del Rio Clay of the Washita Group. This transgressive episode continued through the deposition of the

Buda Limestone of the Washita Group, Eagle Ford Group, Austin Group, and Taylor Group.

The Trinity Group contains shale, mudstone to grainstone, boundstone, sandstone, and argillaceous limestone and is composed of the Hosston, Sligo, and Pearsall Formations and the Glen Rose Limestone. The Pearsall Formation is further subdivided into the Hammett Shale, Cow Creek Limestone, and Hensell Sand Members. The Glen Rose Limestone is subdivided into the lower and upper members.

The Edwards Group, which overlies the Trinity Group, is composed of mudstone to boundstone, dolomitic limestone, argillaceous limestone, evaporite, shale, and chert. In the study area, the Edwards Group is composed of the Kainer and Person Formations. The Kainer Formation is subdivided into (bottom to top) the basal nodular, dolomitic, Kirschberg Evaporite, and grainstone members. The Person Formation is subdivided into (bottom to top) the regional dense, leached and collapsed (undivided), and cyclic and marine (undivided) members.

The principal structural feature in Bexar and Comal Counties is the Balcones fault zone, which is the result of Miocene-age faulting and fracturing. The primary orientation of mapped fractures and faults in the study area is southwest to northeast between 45 and 50 degrees. The conjugant fractures trend perpendicular to the Balcones fault zone at approximately 145–150 degrees.

Hydrostratigraphically the rocks exposed in the study area represent a section of the upper confining unit to the Edwards aquifer, the Edwards aquifer, the upper zone of the Trinity aquifer, and the middle zone of the Trinity aquifer. In the study area the Edwards aquifer is composed of the Georgetown Formation and of the rocks forming the Edwards Group. The Trinity aquifer is composed of the rocks forming the Trinity Group. The Edwards and Trinity aquifers are karstic with high secondary permeability and porosity along bedding and fractures.

The Pecan Gap Formation (Kpg), Austin Group (Ka), Eagle Ford Group (Kef), Buda Limestone (Kb), and Del Rio Clay (Kdr) collectively are generally considered to be the upper confining unit to the Edwards aquifer. The upper confining unit to the Edwards aquifer does not supply appreciable amounts of water to wells in the study area.

The Edwards aquifer was subdivided into HSUs I to VIII. The Georgetown Formation of the Washita Group contains HSU I. The Person Formation of the Edwards Group contains HSUs II (cyclic and marine members [Kpcm, undivided]), III (leached and collapsed members [Kplc, undivided]), and IV (regional dense member [Kprd]), and the Kainer Formation of the Edwards Group contains HSUs V (grainstone member [Kkg]), VI (Kirschberg Evaporite Member [Kkke]), VII (dolomitic member [Kkd]), and VIII (basal nodular member [Kkbn]).

The Trinity aquifer is separated into upper, middle, and lower aquifer units (hereinafter referred to as "zones"). The upper zone of the Trinity aquifer is in the upper member of the Glen Rose Limestone. The middle zone of the Trinity

aquifer is formed in the lower member of the Glen Rose Limestone, Hensell Sand, and Cow Creek Limestone. The regionally extensive Hammett Shale forms a confining unit between the middle and lower zones of the Trinity aquifer. The lower zone of the Trinity aquifer consists of the Sligo and Hosston Formations, which do not crop out in the study area.

The upper zone of the Trinity aquifer is subdivided into five informal HSUs (top to bottom): cavernous (Kgrc), Camp Bullis (Kgrcb), upper evaporite (Kgrue), fossiliferous (Kgruf, Kgrlf), and lower evaporite (Kgrle). The middle zone of the Trinity aquifer is composed of the (top to bottom) Bulverde (Kgrb), Little Blanco (Kgrlb), Twin Sisters (Kgrts), Doeppenschmidt (Kgrd), Rust (Kgrr), Honey Creek (Kgrhc), Hensell (Kheh), and Cow Creek (Kcccc) HSUs. The underlying Hammett (Khah) HSU is a regional confining unit between the middle and lower zones of the Trinity aquifer. The lower zone of the Trinity aquifer is not exposed in the study area.

The effects of faulting on cave development might be from fracture development that forms from extension perpendicular to the Balcones fault zone. Extension perpendicular (northeast to southwest) to the down-to-the-coast extension (northwest to southeast) commonly associated with the Balcones fault zone forms because the same amount of material has to occupy a larger area. Solutionally enlarged fractures and conduits may form parallel to the dip of the relay ramp because of the northeast to southwest extension.

Groundwater recharge and flow paths in the study area are influenced not only by the hydrostratigraphic characteristics of the individual HSUs but also by faults and fractures and geologic structure. Faulting associated with the Balcones fault zone (1) might affect groundwater flow paths by forming a barrier to flow which results in water moving parallel to the fault plane, (2) might affect groundwater flow paths by increasing flow across the fault because of fracturing and juxtaposing porous and permeable units, or (3) might have no effect on the groundwater flow paths.

The hydrologic connection between the Edwards and Trinity aquifers and the various HSUs is complex. The complexity of the aquifer system is a combination of the original depositional history, bioturbation, primary and secondary porosity, diagenesis, and fracturing of the area from faulting. All of these factors have resulted in development of modified porosity, permeability, and transmissivity within and between the aquifers. 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.

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