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An online, peer-reviewed journal
published in cooperation with the
Texas Water Resources Institute

Texas Water Journal

Volume 10 Number 1 | 2019

Texas Water Journal

Volume 10, Number 1
2019
ISSN 2160-5319

texaswaterjournal.org

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Texas Water Resources Institute
Texas Water Journal
Volume 10, Number 1, January 22, 2019
Pages 1-21

A Refined Hydrogeologic Framework Model for Gaines, Terry, and Yoakum Counties, Texas

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Abstract: Declining groundwater levels in Gaines, Yoakum, and Terry counties in the Southern High Plains have raised concerns about the amount of available groundwater and the potential for water-quality changes resulting from dewatering and increased vertical groundwater movement between adjacent water-bearing hydrogeologic units. More than 11,500 well records containing pertinent data were compiled, including data delineating the vertical extents of wells penetrating one or more of the units. Additional geophysical data were collected to improve the spatial coverage of available data across the study area and to reduce uncertainty regarding hydrogeologic unit extents. Across the study area, the average altitude of the base of the Ogallala Aquifer was approximately 1.7 feet lower compared to previous assessments of the altitude of the base of the aquifer, resulting in an increase in the saturated thickness by the same amount. Some of the largest increases in the altitude of the base of the Ogallala Aquifer were observed in central and east-central Gaines County where the units that compose the Edwards-Trinity Aquifer thin at approximately 136 feet and the largest decreases in altitudes are in Yoakum County at around 185 feet. Both the thickest and thinnest part of the Ogallala Aquifer is in Gaines County at just over 300 feet in west Gaines County and around 20 feet in northeast Gaines County.

Keywords: Ogallala, Edwards-Trinity, Fredericksburg, hydrogeologic, Gaines, Terry, Yoakum

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Citation: Thomas JV, Teeple AP, Payne JD, Ikard SJ. 2019. A refined hydrogeologic framework model for Gaines, Terry, and Yoakum counties, Texas. Texas Water Journal. 10(1):1-21. Available from: https://doi.org/10.21423/twj.v10i1.7082.

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Terms used in paper

Acronyms	Descriptive name
°F	degrees Fahrenheit
ASTER	Advanced Space Borne Thermal Emission and Reflection Radiometer
ASTM	American Society of Testing and Materials
BRACS	Brackish Resources Aquifer Characterization System
DEM	digital elevation model
EM	Electromagnetic
ft	feet
Hz	hertz
LAS	Log American Standard
LEUWCD	Llano Estacado Underground Water Conservation District
m	meter
M	Measured apparent resistivity at the given time step
mi^2	square miles
mg/L	milligrams per liter
NAVD88	North American Vertical Datum of 1988
pdf	portable document format
PVC	polyvinyl chloride
RMSE	root mean square error
Rx	Receiver
SLUWCD	Sandy Land Underground Water Conservation District
SP	spontaneous potential
SPR	single-point resistance
SPUWCD	South Plains Underground Water Conservation District
TDEM	time-domain electromagnetic
TDS	dissolved solids
Tx	Transmitter
USGS	U.S. Geological Survey

INTRODUCTION

In 2014, the U.S. Geological Survey (USGS), in cooperation with Llano Estacado Underground Water Conservation District (LEUWCD), Sandy Land Underground Water Conservation District (SLUWCD), and South Plains Underground Water Conservation District (SPUWCD), (hereinafter referred to collectively as "the districts") began a multiphase study in and near Gaines, Terry, and Yoakum counties, Texas to develop a regional conceptual model of the hydrogeologic framework and geochemistry primarily for the Ogallala and Edwards-Trinity aquifers and to a lesser degree for the Dockum Group, the hydrogeologic unit that contains the Dockum Aquifer. The results of the first phase of the study were documented in Thomas et al. (2016) and included an assessment of the differences between early development (1930–1960) and recent (2005–2015) groundwater-level altitudes and selected water-quality constituents (dissolved-solids concentrations [TDS] and nitrate concentrations) for the Ogallala, Edwards-Trinity, and Dockum aquifers. This report documents the results of the second phase of the study designed to gain a refined understanding of the hydrogeologic framework in the study area. The term "hydrogeologic framework" as used in this report refers to the lateral and vertical extents of hydrogeologic units, bed orientation, unit thickness, and outcrop and subcrop locations in the study area. An accurate characterization of the hydrogeologic framework is important because small differences in the hydrogeologic framework can cause aquifer conditions (storage and flow gradients) to vary considerably within a relatively small area (Fleming and Rupp 2018).

As described in Thomas et al. (2016), the study area consists of the different areas managed by the districts in and near Gaines, Yoakum, and Terry counties, respectively, along the Texas-New Mexico State line (Figure 1). The districts share common groundwater resources—most notably, the Ogallala Aquifer. The Ogallala Aquifer is part of the High Plains aquifer system, a vast regional aquifer system that underlies about 174,000 square miles (mi^2) from South Dakota to Texas (Gutentag et al. 1984). The Ogallala Aquifer, contained within the Ogallala Group, is the shallowest aquifer in the study area and is the primary source of water for agriculture and municipal supply in the areas managed by the districts (Rettman and Leggat 1966). Groundwater withdrawals from deeper aquifers (primarily from the Edwards-Trinity Aquifer [TWDB 2018b], augmented to a lesser amount by withdrawals from the Dockum Aquifer), are additional water sources in the study area (Figure 1). Declining groundwater levels in the study area have raised concerns about the amount of available groundwater and the potential for water-quality changes resulting from dewatering and increased vertical groundwater movement between adjacent water-bearing units.

The amount and quality of water available in the study area from the Ogallala Aquifer varies locally depending on the saturated thickness of the Ogallala Group. The base of the Ogallala Group is a complex irregular erosional surface that was shaped by hydrogeologic processes such as the development of paleochannels and alluvial deposits during the Tertiary period. Prior to the deposition of the Ogallala Group, erosional processes thinned the Cretaceous-age units underlying the Ogallala Group in many areas. Thicker alluvial deposits of Ogallala Group rocks were generally deposited where erosion of the Cretaceous-age rocks was most extensive, resulting in a greater saturated thickness of the Ogallala Aquifer where erosion of the Cretaceous-age units was most extensive (Bradley and Kalaswad 2003).

Because the Ogallala Aquifer and underlying aquifers are hydraulically connected in some locations, water quality in adjacent aquifers may be affected by the mixing associated with water-level declines. In their report on the history of water-level changes in the Ogallala Aquifer from predevelopment to 1980, Dugan et al. (1994) reported water-level declines in the Ogallala Aquifer of as much as 150 feet (ft). During the past 50 to 60 years the rate of decline has slowed and water levels in the Ogallala Aquifer have risen in a few areas (McGuire 2017). Water-level declines can be accompanied by the increased upward movement of relatively saline groundwater; changes in water quality in the Ogallala Aquifer and in the underlying Edwards-Trinity Aquifer can result from the upward movement of deeper, relatively more saline groundwater (Bradley and Kalaswad 2003).

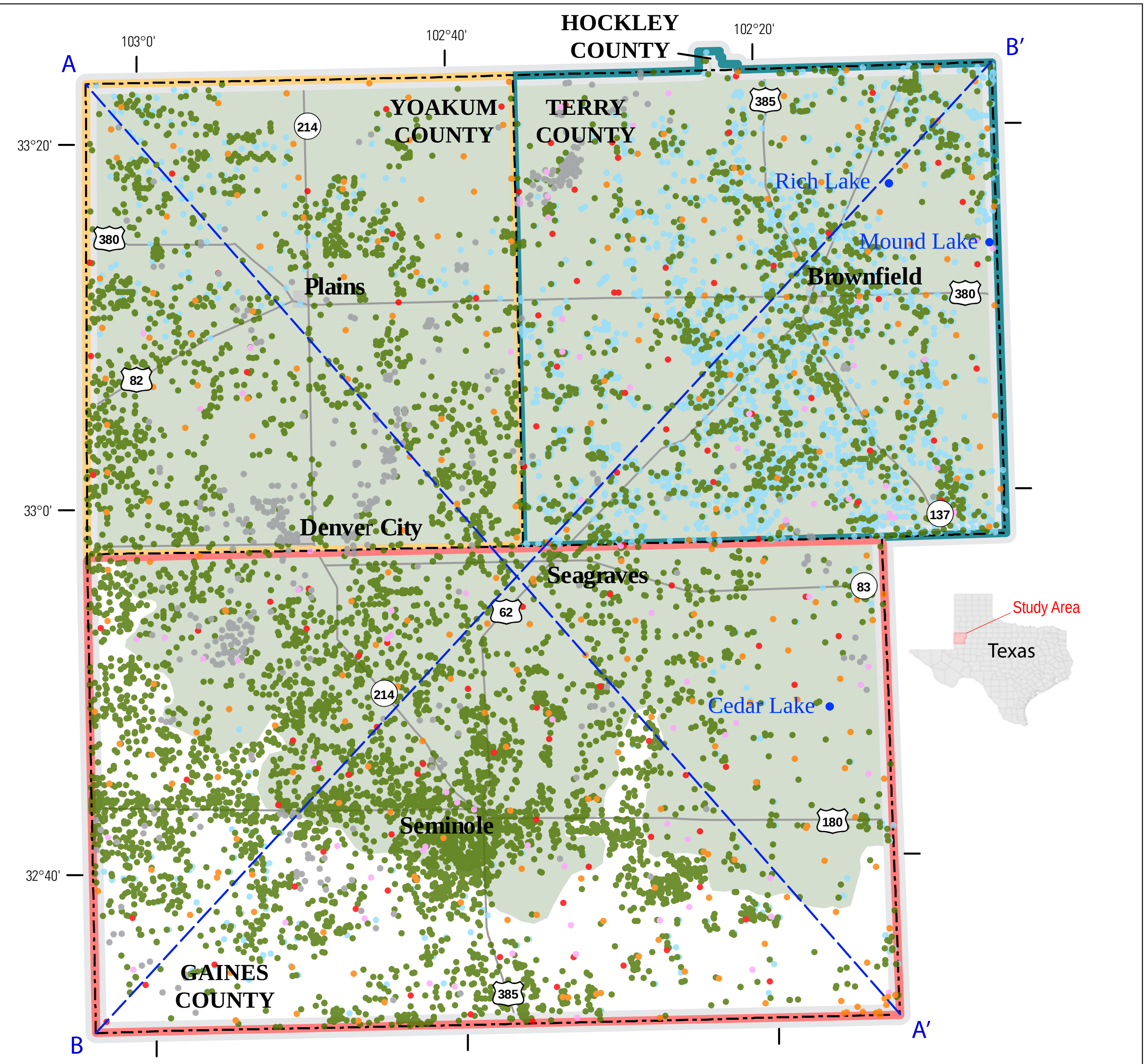
Purpose and scope

To help improve the understanding of the amount of available groundwater and the potential for water-quality changes resulting from dewatering and increased vertical groundwater movement between adjacent water-bearing hydrogeologic units, the USGS completed a study in cooperation with the districts to gain a refined understanding of the hydrogeologic framework in the study area. Existing data were primarily used in the analyses; additional geophysical data were collected to improve the spatial coverage across the study area and to reduce uncertainty regarding hydrogeologic unit extents. Of particular interest was the evaluation of data to improve the understanding of how the saturated thickness of the Ogallala Aquifer and total thickness of the hydrogeologic units that compose the Edwards-Trinity Aquifer vary laterally and vertically throughout the study area. The Dockum Group was evaluated as a single unit and the physical properties (storage, porosity, transmissivity), and neither the extent nor storage properties of Dockum Aquifer, a relatively minor source of water in the study area, were determined. All data that were compiled or collected for this assessment are available in Teeple et al. (2018).

Description of the study area

The study area (Figure 1) is bounded by the extents of the districts' management areas in Gaines, Terry, and Yoakum counties and a small part of Hockley County, Texas. The total study area covers about 3,225 mi^2, including 1,525 mi^2 in LEUWCD, 798 mi^2 in SLUWCD, and 902 mi^2 in SPUWCD (LEUWCD 2018b; SLUWCD 2018b; SPUWCD 2018a). The study area is in the Great Plains physiographic region and consists of an elevated and relatively undissected plain (Ryder 1996). As of July 1, 2017, the population of the study area was about 42,000 (USCB 2017). The combination of minimal topographic relief, availability of groundwater for irrigation, and excellent soils makes this an important agricultural region in Texas (Ryder 1996).

The climate of the study area is semiarid (Larkin and Bomar 1983). Precipitation averages 18.8 inches each year, mostly in the form of rain; the area receives about 5 inches of snow each year (NOAA 2015). The potential evapotranspiration is more than three times the annual precipitation (Larkin and Bomar 1983). The average temperature for the study area is about 60.5 degrees Fahrenheit (°F), with the warmest average monthly temperature in July (79.1 °F) and the coolest average monthly temperature in January (40.0 °F) (NOAA 2015).



Base modified from U.S. Geological Survey 1:250,000-scale to 1:2,000,000-scale digital data, Llano Estacado Underground Water Conservation District digital data, Sandy Land Underground Water Conservation District digital data, South Plains Underground Water Conservation District digital data.
Albers Equal-Area Conic Projection, Texas State Mapping System
North American Datum of 1983

EXPLANATION

- Edwards-Trinity aquifer
- Study area
- A — — A′ Section Location
- County Line
- Cedar Lake • Lake Location

Underground water conservation district boundary

- Llano Estacado Underground Water Conservation District (Teeple, 2018)
- Sandy Land Underground Water Conservation District (Teeple, 2018)
- South Plains Underground Water Conservation District (Teeple, 2018)

Hydrogeologic Structure Data and Source

- Brackish Resources Aquifer Characterization System (Teeple and others, 2018)
- INTERA Study (Teeple and others, 2018)
- Railroad Commission of Texas (Teeple and others, 2018)
- Texas Water Development Board (Teeple and others, 2018)
- U.S. Geological Survey (Teeple and others, 2018)
- Underground Water Conservation District (Teeple and others, 2018)

Figure 1. Map showing hydrogeologic data locations sources, and section locations in the study area, for Gaines, Terry, and Yoakum counties, Texas.

Table 1. Descriptions of the hydrogeologic units, their lithologic descriptions, and corresponding aquifers for Gaines, Terry, and Yoakum counties, Texas (modified from Bradley and Kalaswad 2003; Knowles et al. 1984; Thomas et al. 2016).

Era	Period	Series or group within the spatial extents of the Edwards-Trinity Aquifer	Series or group outside the spatial exents of the Edwards-Trininty Aquifer	Lithologic descriptions	Aquifers
Cenozoic	Tertiary	Ogallala Group	Ogallala Group	gravel, sand, silt, and clay	Ogallala Aquifer
Mesozoic	Cretaceous	Fredericksburg Group	Absent	clay, shale, and limestone	Edwards-Trinity Aquifer
		Trinity Group		sand and gravel	
	Truassis	Dockum Group	Dockum Group	sandstone, siltstone, mudstone, and shale	Dockum Aquifer

Hydrogeologic setting

The Ogallala Aquifer is composed primarily of poorly sorted gravel, sand, silt, and clay deposited during late Miocene and early Pliocene when the Ogallala Group formed. Multiple studies describe the general Ogallala Group structure with paleochannels eroded into the underlying hydrogeologic units that control groundwater flow and are filled with coarse gravel in the channel and often filled with sand and finer sediments in the interchannel areas (Cronin 1969; Seni 1980; Gustavson 1996). The highly variable distribution of coarse sediments influences the spatial distribution of porosity and permeability of the Ogallala Aquifer, which in turn influences water-storage capacity and water-availability characteristics (Seni 1980; TWDB 2018c).

TDS concentrations in the Ogallala typically are less than 1,000 milligrams per liter (mg/L) (the upper limit for what is generally considered freshwater [Winslow and Kister 1956]) but can vary from less than 600 to more than 6,000 mg/L within localized areas of the study area (LEUWCD 2018b; SLUWCD 2018a). In many areas, groundwater moves vertically between the Ogallala Group and the underlying Fredericksburg, Trinity, and Dockum groups (Table 1). Where the Fredericksburg and Trinity groups are absent, the Ogallala Group directly overlies the Dockum Group (Ashworth and Hopkins 1995) (Table 1).

The Cretaceous-age Edwards-Trinity Aquifer is a minor aquifer underlying the Ogallala Aquifer, except in the southern part of the study area where the Edwards-Trinity Aquifer is absent (George et al. 2011). Primary water-bearing units in the Edwards-Trinity Aquifer include sand and gravel layers of the Trinity Group and limestone layers of the overlying Fredericksburg Group (Bell and Morrison 1979). Groundwater flow in the Edwards-Trinity Aquifer is controlled by facies changes, structure orientation, local cementation, and paleochannels, that can produce local deviations in flow patterns (Fallin 1989). Groundwater from the Edwards-Trinity Aquifer is typically slightly saline (TDS concentrations range from 1,000 to 3,000 mg/L) (Winslow and Kister 1956; Fallin 1989) and contains more TDS than groundwater from the overlying Ogallala Aquifer (George et al. 2011) (Table 1).

The Dockum Aquifer is an additional minor aquifer in the study area (George et al. 2011) composed of the Triassic-age Dockum Group that underlies the Ogallala and Edwards-Trinity aquifers (Table 1) throughout much of the southern part of the High Plains physiographic region. The Dockum Group consists of sandstone, siltstone, mudstone, and shale originally deposited in fluvial and lacustrine environments (McGowen et al. 1979). Groundwater in the Dockum Aquifer is characterized by decreasing water quality with increasing depth, variable geochemistry, high concentrations of TDS and other constituents that exceed secondary drinking water standards (EPA 2016), and high concentrations of sodium that may negatively affect irrigated crops (Bradley and Kalaswad 2003).

Estimating saturated thickness

To help evaluate their water resources, each water conservation district uses base-of-aquifer and groundwater-level potentiometric maps to estimate the saturated thickness for the Ogallala and Edwards-Trinity aquifers within their respective jurisdictions. Saturated thickness, the difference between the altitude of the water table and the altitude of the base of the aquifer at a given location, is commonly used in conjunction with other aquifer conditions (lithology, porosity, and water quality) to estimate the volume of water in storage in the aquifer (McGuire et al. 2012). The districts collect groundwater-level altitude data and publish saturated thickness maps for the Ogallala Aquifer on a yearly basis. The Fredericksburg and Trinity groups that compose the Edwards-Trinity Aquifer are considered fully saturated (LEUWCD 2018a; SLUWCD 2018a; SPUWCD 2018b).

DEVELOPMENT OF A REFINED HYDROGEOLOGIC FRAMEWORK

The base of the Ogallala Group, as defined by the districts, provided both a starting point for the data compilation efforts and a dataset for use in developing a refined hydrogeologic framework. Data used for the High Plains Groundwater Availability Model (Deeds et al. 2015) and updated INTERA conceptual model (TWDB 2018a) were also included (Figure 2) in the initial data compilation and for comparison with the refined hydrogeologic framework.

Data compilation and collection

Hydrogeologic data and interpretative information pertaining to the hydrogeologic units in the study area were compiled from previous studies done by various local, state, and federal agencies. Compiled data and information were supplemented with surface and borehole geophysical data collected by the USGS. The resulting dataset was analyzed to identify the tops and bases of the selected hydrogeologic units along with their lateral extents and relation to overlying and underlying units in the study area (Table 1). The data were used to evaluate the hydrogeologic unit features, such as extent, bed orientation, thickness, and outcrop and subcrop locations.

More than 11,500 readily available digital data records for the study area consisting of geophysical, geologic, lithologic, and drilling and well-completion log data (recorded well reports of the hydrogeologic units penetrated by a borehole) were compiled to assess spatial variations of the Ogallala, Fredericksburg, Trinity, and Dockum groups in and adjacent to Gaines, Terry, and Yoakum counties (Figure 1). Digital data from over 900 wells within a 5-mi buffer area around the study area were also included in the compilation to extend the grids past the study area and minimize possible gridding errors near the extent of the data.

Because accuracy of reported altitude information varies between different methods used at a given well or time-domain electromagnetic (TDEM) location, and older well data typically have relatively poor vertical accuracy, land-surface altitudes were determined from a digital elevation model (DEM) to provide consistency and improve accuracy. DEM data were obtained from the Advanced Space Borne Thermal Emission and Reflection Radiometer (ASTER) Global DEM Version 2 (NASA 2015) to estimate land-surface altitudes across the study area.

Where possible, data available only in hard copy were digitized and combined with existing digital data before being entered into the database (Teeple et al. 2018). Geophysical logs typically are reliable sources for subsurface information; however, those determined to have inaccurate spatial data or missing information were not used in this assessment. To be used in this assessment, the geophysical log needed to provide correct, discernible location information, complete and correct header information, detailed well completion information, and valid, useable calibration data. Existing geophysical logs collected with appropriate methods and that contained sufficient spatial data were used to help identify the tops and bases of each hydrogeologic unit. Hydrogeologic and lithologic descriptions from Meyer et al. (2012) and Herald (1957) were used to help characterize the lithologic and geophysical properties of each hydrogeologic unit.

Depths to tops and bases of the hydrogeologic units were converted to altitudes by subtracting the depths from the ASTER Global DEM Version 2 (NASA 2015); depth data were referenced by altitude and spatial location for correlation among neighboring wells to create a regional network of data points.

Evaluating spatial coverage of compiled data

Compiled data were plotted, and maps for each hydrogeologic surface grid were used to evaluate the spatial data coverage and identify areas with higher uncertainty where the spatial distribution of data was relatively sparse. Generally, as the distance between data points becomes greater, correlation between points lessens, and uncertainty in areas between points increases (Isaaks and Srivastava 1989). Instead of only evaluating the distance between data points, variance maps were prepared by using a kriging process to evaluate the uncertainty in the

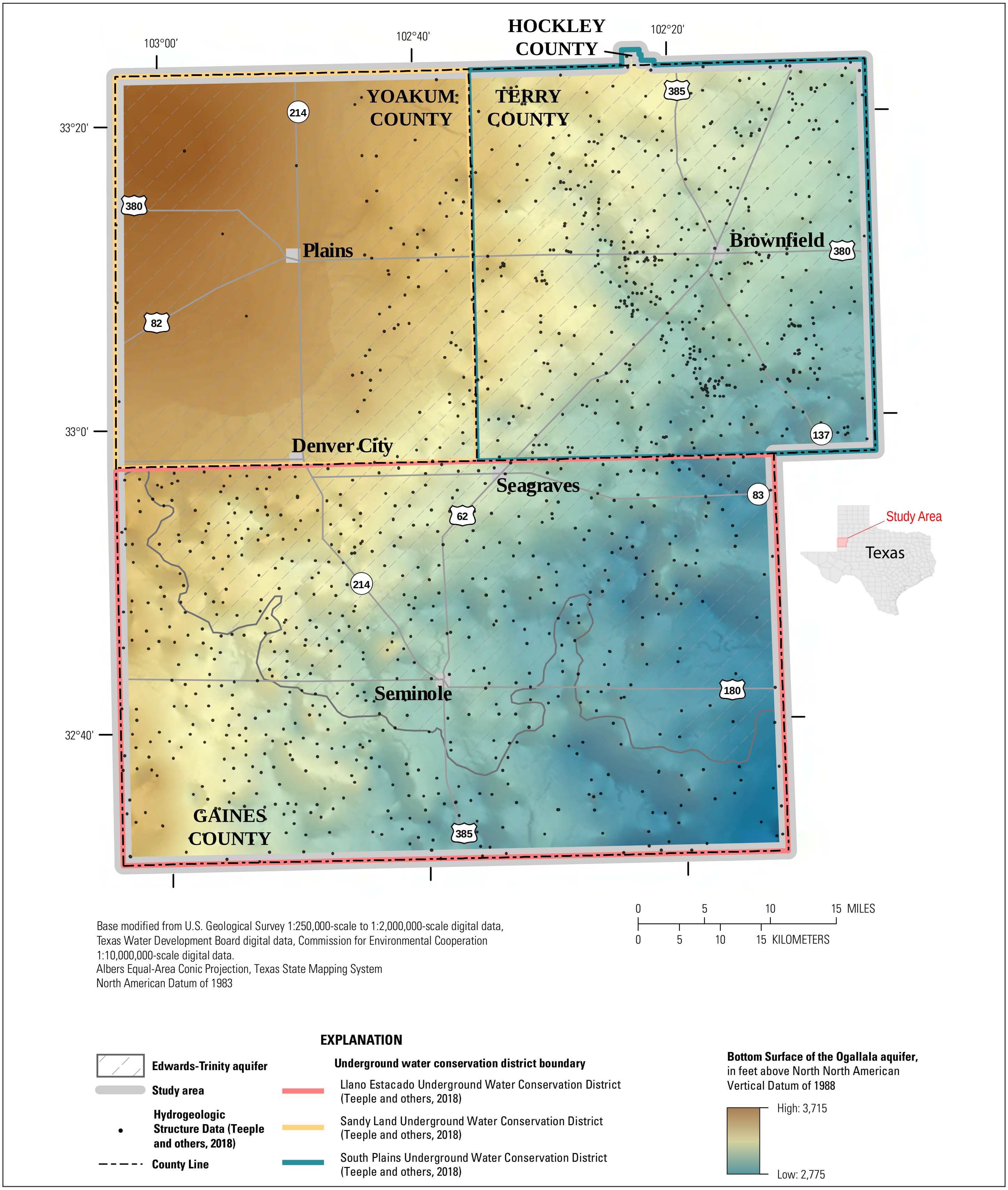


Figure 2. Existing mapped base of the Ogallala Aquifer and hydrogeologic data locations prior to this study.

gridded-surfaces for the entire study area (Isaaks and Srivastava 1989). These variance maps were used to identify areas with higher uncertainty and in the planning of additional data collection.

Collection of additional geophysical data

To improve the spatial coverage across the study area and to reduce uncertainty, the compiled dataset was supplemented by the collection of additional geophysical data (Figure 3). Borehole geophysical logs, including caliper, natural gamma, induction conductivity, normal resistivity, temperature, fluid resistivity, and surface time-domain electromagnetic soundings were collected to improve spatial coverage and reduce data gaps and gridding uncertainty.

Borehole geophysics

Conventional borehole geophysical logs were collected at 38 sites across the study area (Figure 3) where additional hydrogeologic information was needed (USGS 2018; Teeple et al. 2018). Additional information about the borehole geophysical methods used in this study are available in Teeple et al. (2018). All borehole geophysical data were collected by using a Century Geophysical, LLC system VI logging system or a Mount Sopris Instruments Matrix logging system. For this study, the Mount Sopris Instruments system was used to collect neutron logs; all other logs were collected using the Century Geophysical Corporation system. Explanations regarding the limitations of the logging systems, calibration procedures, and algorithms of the geophysical probes are available from the manufacturers (CGC 2018; MSI 2018). The additional geophysical logs were collected during 2012–2015 following American Society of Testing and Materials (ASTM) borehole geophysical standard procedures (ASTM 2004, 2007, and 2010). These geophysical logs were collected digitally in the proprietary format of the data acquisition equipment used to collect the logs. The geophysical logs data were converted to and stored as Log American Standard (LAS) Code for Information Interchange Standard for tabular data (CWLS 2018). All digital geophysical logs are available online on the Geolog Locator geophysical log archive (USGS 2018).

Surface geophysics

Surface geophysical resistivity methods, specifically TDEM soundings (Zohdy et al. 1974), were used to detect changes in the electrical properties of the subsurface across the study area (Figure 3). The electrical properties of soil and rock are determined by water content, porosity, clay content and mineralogy, and conductivity (reciprocal of electrical resistivity) of the pore water (Lucius et al. 2007). Additional information about the surface geophysical resistivity methods used in this study are available in Teeple et al. (2018). Comprehensive descriptions of the theory and application of surface geophysical resistivity methods, as well as tables of the electrical properties of earth materials, are presented in Keller and Frischknecht (1966) and Lucius et al. (2007). All surface geophysical data were collected in accordance with methods defined by the ASTM (1999).

Interpretation of hydrogeologic unit interfaces and hydrogeologic contacts

Hydrogeologic unit interfaces and hydrogeologic contacts between units were interpreted from the compiled and newly collected geophysical data that were combined to create the comprehensive database for the study area (Teeple et al. 2018). Hydrogeologic unit contact grids were created by using Oasis montaj (Geosoft 2015) and kriging techniques. Kriging is a geostatistical method that determines the most probable value at each grid node (200 meter [m] by 200 m [about 656 ft by 656 ft] for this study) based on a statistical analysis of the entire dataset (Isaaks and Srivastava 1989). Variance maps developed during the kriging process were used to evaluate the uncertainty in hydrogeologic unit surface grids in the planning of additional data-collection tasks. Generally, as the distance between data points became greater, correlation between points lessened, and uncertainty in areas between points increased (Isaaks and Srivastava 1989). Additional information on kriging is available in Isaaks and Srivastava (1989).

Preliminary hydrogeologic unit surface grids were periodically created as hydrogeologic contacts were interpreted and entered into a preliminary database, and used to help evaluate hydrogeologic features, extents, and data coverage. Gridded hydrogeologic unit surface grids were interactively compared to interpreted contact altitudes to evaluate outliers, grid accuracy, and clustered data. All outlier locations were evaluated through a correlation process to determine data-point uncertainty. The correlation process involved the comparison of hydrogeologic unit contacts at a given site to the hydrogeologic unit contacts at nearby sites and preliminary grids. Outliers were removed if review of the original data source indicated that data were questionable. Throughout the process, all hydrogeologic unit contacts were reviewed and revised as needed to provide the best possible final representation of each hydrogeologic unit (Teeple et al. 2018).

HYDROGEOLOGIC FRAMEWORK REFINEMENTS

Hydrogeologic unit contact interpretations were used to assess the vertical and lateral extents of hydrogeologic units, bed orientation, unit thickness, and outcrop and subcrop locations. In general, the Ogallala, Fredericksburg, Trinity, and

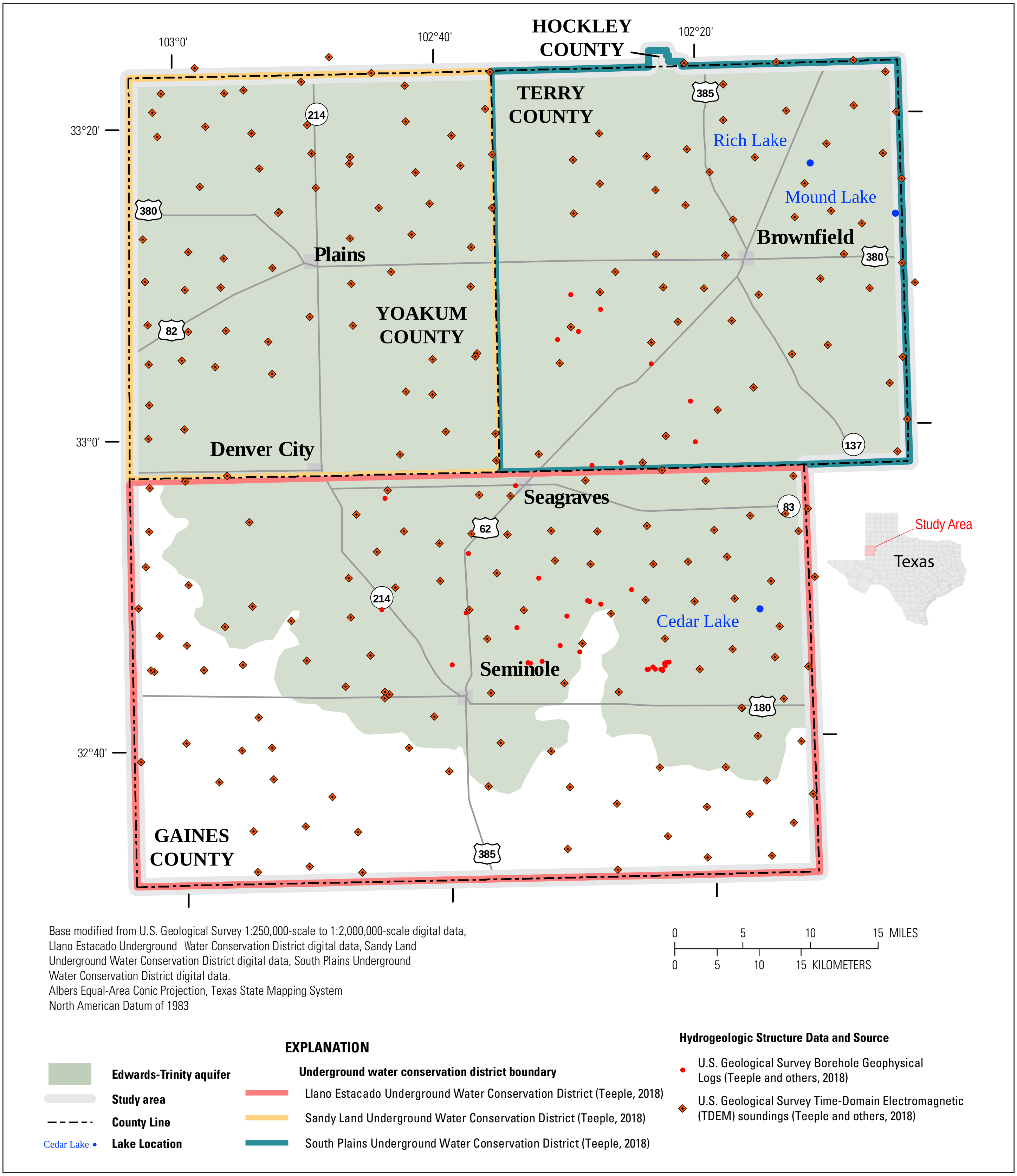


Figure 3. Map showing location of additional surface and borehole geophysical data across the study area, for Gaines, Terry, and Yoakum counties, Texas.

Table 2. Basic statistics for the primary hydrogeologic groups for each conservation district in the study area.

		LEUWCD	SLUWCD	SPUWCD	Study Area
Depth to base of Ogallala Group	min (ft)	21	65	30	21
	max (ft)	303	288	264	303
	mean (ft)	170	168	156	165
Thickness of Ogallala Group	min (ft)	21	65	30	21
	max (ft)	303	288	264	303
	mean (ft)	170	168	156	165
Change in base of Ogallala Group	min (ft)	-136	-84	-99	-136
	max (ft)	117	185	82	185
	mean (ft)	-14	27	4.3	1.7
Area of Ogallala Group	(mi^2)	1,525	798	902	3,225
Depth to Base of Fredericksburg Group	min (ft)	33	154	91	33
	max (ft)	335	406	431	431
	mean (ft)	192	272	266	244
Thickness of Fredericksburg Group	min (ft)	0	0	0	0
	max (ft)	102	228	237	237
	mean (ft)	35	106	111	86
Area of Fredericksburg Group	(mi^2)	840	795	890	2,526
Depth to Base of Trinity Group	min (ft)	35	193	152	35
	max (ft)	363	458	460	460
	mean (ft)	221	321	349	298
Thickness of Trinity Group	min (ft)	0	0	0	0
	max (ft)	147	164	157	164
	mean (ft)	30	49	83	55
Area of Trinity Group	(mi^2)	850	796	890	2,536

LEUWCD; Llano Estacado Underground Water Conservation District, SLUWCD; Sandy Land Underground Water Conservation District, SPUWCD; South Plains Underground Water Conservation District, min; minimum, max; maximum, ft; feet, mi^2 square miles

Dockum groups exhibit a slight regional dip to the southeast. Although the Ogallala and Dockum groups are present across the entire study area, the Fredericksburg and Trinity groups thin to the south and are absent in the southern part of the study area.

Ogallala Aquifer

Compiled data were used in conjunction with geophysical data collected by the USGS to depict the base (bottom surface) of the Ogallala Aquifer (Figure 4). To help evaluate how the newly developed depiction of the base of the Ogallala Aquifer was refined from the existing depiction of the base of the Ogallala Aquifer (Figure 2), the surfaces were compared by subtracting the refined altitude surface obtained during this assessment from the previously mapped altitude surface (Figure 5). Most of the locations where the base of the Ogallala was shallower than previously depicted were in the southern part of the study area. Specifically, in areas where the Ogallala Aquifer overlies the southern extent of the Edwards-Trinity Aquifer, there were large areas where the Ogallala Aquifer was more than 100 ft shallower than previously mapped (Table 2; Figure 5). Along an erosional feature about 10 mi east of Seminole, Texas, where the Edwards-Trinity Aquifer is absent, the base of the Ogallala Aquifer was as much as 100 ft deeper than previously mapped. Across the northeast part of the study area there was relatively minimal change in the depiction of the base of the Ogallala Aquifer. The largest areas where the refined base of the Ogallala Aquifer was more than 50 ft deeper than the previous base were in western Yoakum County (Figure 5).

The altitudes of the top of the Ogallala Group range from about 2,950 ft to about 3,900 ft above North American Vertical Datum of 1988. The highest altitudes in the northwest corner of the study area, northwest of Plains, Texas, and the lowest altitudes in the southeast corner of the study area, southeast of Seminole.

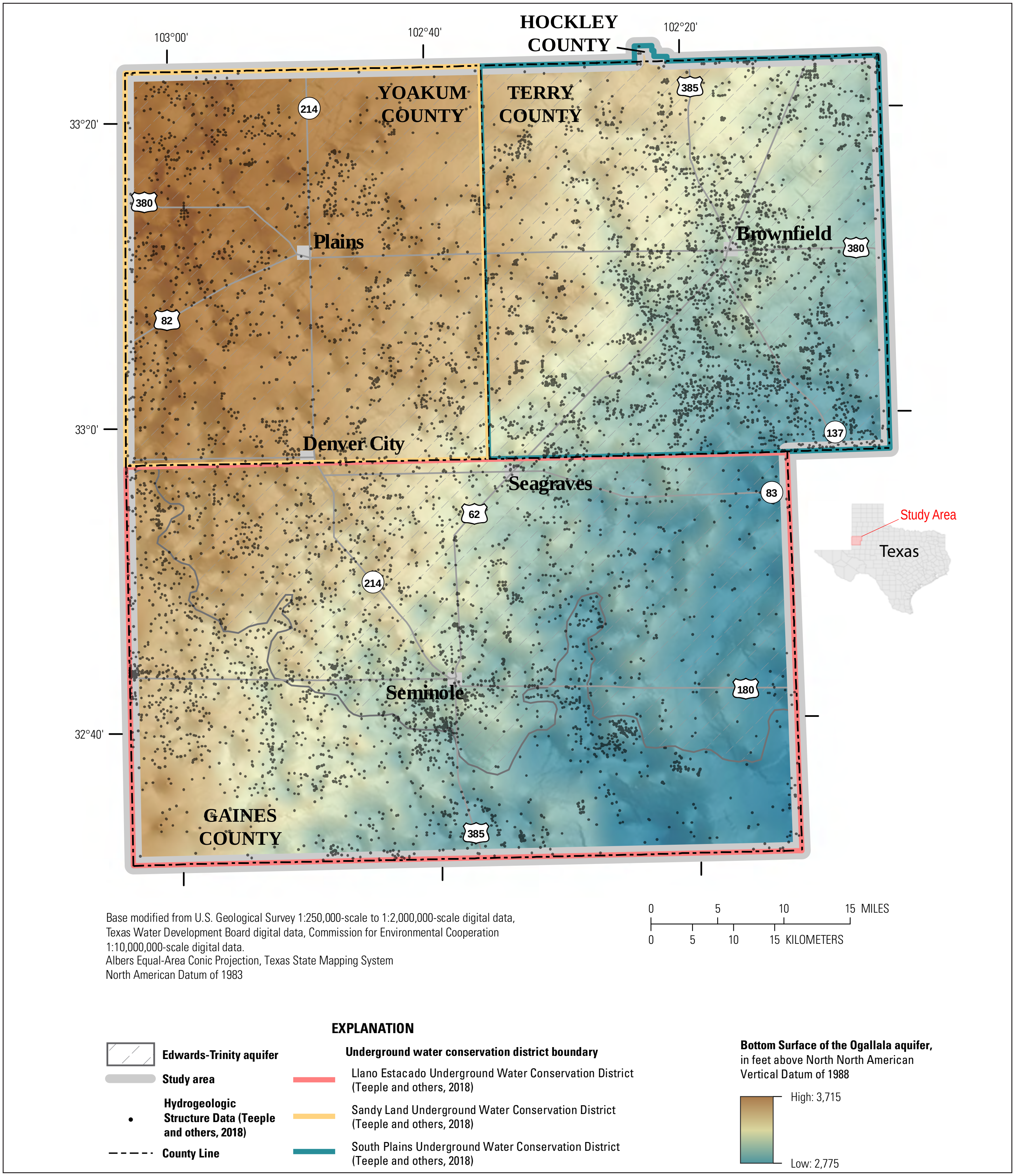


Figure 4. Revised (2018) base (bottom surface) of the Ogallala Aquifer and hydrogeologic data locations.

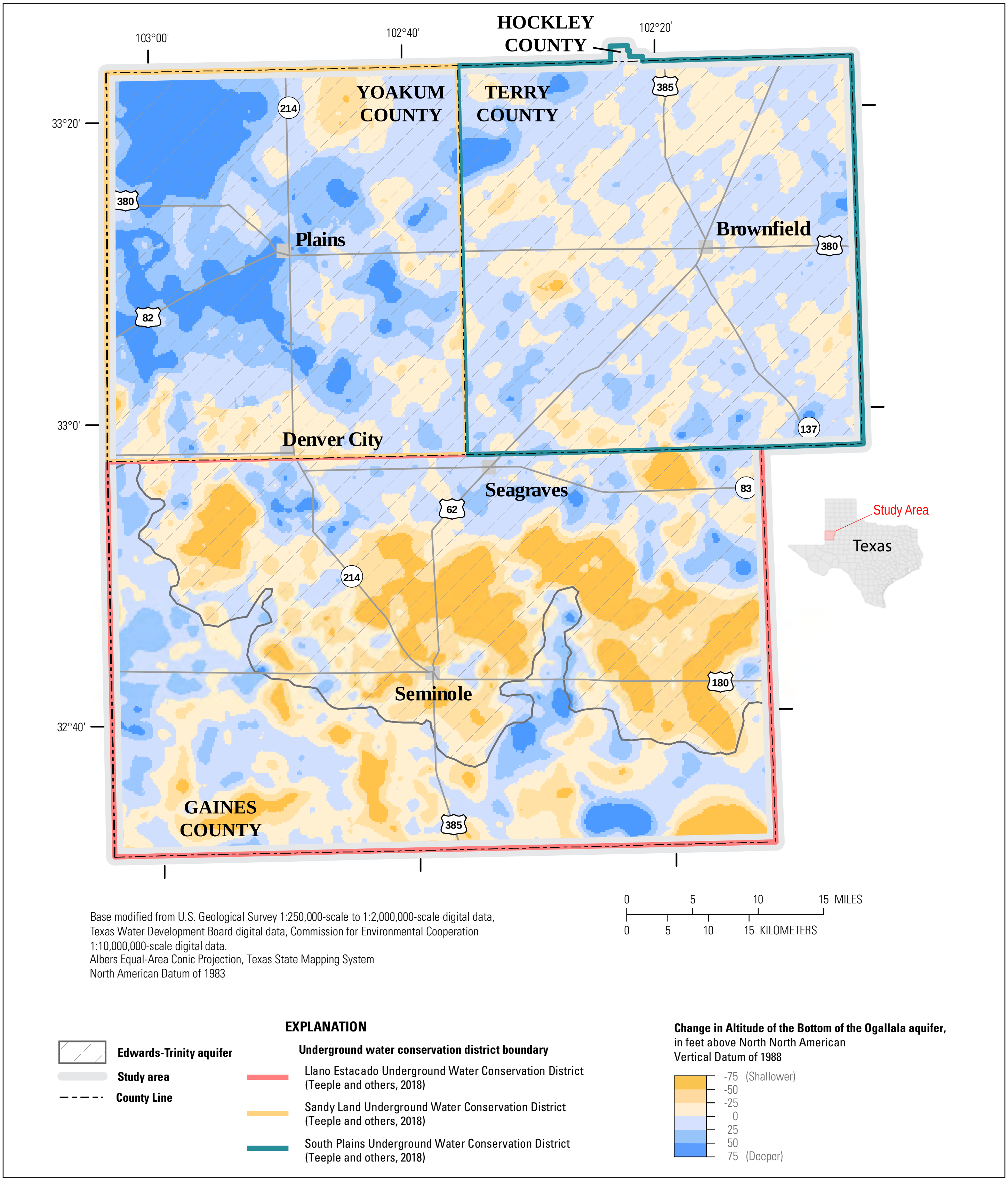


Figure 5. Change in altitude of the mapped base (bottom surface) of the Ogallala Aquifer between the existing depiction of the mapped base of the Ogallala Aquifer and the newly (2018) developed depiction of the base of the Ogallala Aquifer.

Three-dimensional representations of the hydrogeologic framework were prepared by using Oasis montaj (Geosoft 2015) to depict the unsaturated and saturated thickness of the Ogallala Group; the total unit thicknesses of the Fredericksburg, Trinity, and Dockum groups were also depicted (Figures 6-7). Across the study area, the total unit thickness of the Ogallala Group ranges from less than about 25 ft to more than 300 ft (Table 2), with a mean thickness of about 165 ft (Teeple et al. 2018). In general, the thickest parts of the Ogallala Group are in western Gaines County near Seminole (Teeple et al. 2018) and the northwest corners of Yoakum and Terry counties (Table 2); the thinnest parts are in the eastern part of the study area. Localized areas where the Ogallala Group is relatively thin occur in some low-lying areas (for example, near Cedar Lake, Mound Lake, and Rich Lake [Table 1]). To quantify the saturated thickness of the Ogallala Aquifer, a potentiometric surface of the Ogallala Aquifer developed by Thomas et al. (2016) was used in conjunction with the altitude of the base of the Ogallala Aquifer. This potentiometric surface was developed by using Ogallala Aquifer water-level measurements collected during each dormant part of the growing season (November through April) from 2005 through 2015 when groundwater withdrawals were typically lower compared to the rest of year. A detailed description of the data and methods used to develop the potentiometric surface of the Ogallala Aquifer during the dormant season is provided by Thomas et al. (2016). Two-dimensional and three-dimensional representations of different hydrogeologic cross sections (cross sections A–A' and B–B') of the study area were prepared (Figures 8-9).

The saturated thickness of the Ogallala Aquifer can vary substantially in a relatively small area in response to changes to the base (bottom surface) of the Ogallala Group. For example, there is evidence of erosional paleochannels, such as elongated areas of increased saturated thickness, in the updated base (bottom surface) of the Ogallala Group (Figure 4) and in a three-dimensional representation of the hydrogeologic framework (Figures 6-7). To help evaluate paleochannels across the study area, generalized derivative grids were developed (Figure 7) that calculate curvature of the potential field response and is an attribute that is helpful in enhancing smaller features obscured by larger gradients (Geosoft 2018). Smaller paleochannels in the base of the Ogallala Aquifer vary in orientation whereas the larger paleochannels typically trend from the northwest to the southeast in orientation and deepen and widen downgradient (Figures 4 and 6) to the south and east. The saturated thickness of the Ogallala Aquifer ranges from less than 10 ft in the far southern extent of the study area to more than 150 ft southeast of Seminole and northwest of Brownfield, Texas. Although the saturated thickness varies locally, a regionally thinner section of the Ogallala Aquifer extends from central Terry County to the southwest and a regionally thicker section extends from northeast Yoakum County to the southeast corner of Gaines County. The volume of water stored within the saturated thickness depends on many factors including the lithology, specific yield, and porosity of the hydrogeologic unit (Gutentag et al. 1984).

Fredericksburg and Trinity groups of Edwards-Trinity Aquifer

In general, the Fredericksburg and Trinity groups thin to the south and are not present in the southern part of Gaines County (Figures 6-9). Although the Fredericksburg and Trinity groups are present throughout most of the northern parts of the study area, there are localized areas where one or both groups thin or are absent (Figure 6; Table 2). The frequency of thinning or absence of the Fredericksburg and Trinity groups increases at the southern extent of the aquifer, particularly in the Fredericksburg Group (Figure 6).

Similar to the Ogallala Group, the thickness of the Fredericksburg and Trinity groups varies locally depending on the presence of erosional features such as paleochannels (Figure 7). Although the orientations of erosional features in the Ogallala Group are typically toward the southeast or south, erosional features in the Fredericksburg and Trinity groups are generally oriented toward the east (Figure 7). The mean unit thicknesses of the Fredericksburg and Trinity groups are 86 ft and 55 ft, respectively (Table 2). Throughout the study area, the thickness of the Fredericksburg Group is more variable than the thickness of the Trinity Group (Figure 6; Table 2). The Fredericksburg Group is thickest in the north-central part of the study area (about 237 ft thick), whereas the Trinity Group is thickest in northeast Yoakum County (about 164 ft thick). Among the three counties that compose most of the study area (Gaines, Terry and Yoakum counties), the average thickness of the Trinity Group is the greatest in Terry County (about 83 ft thick). The Trinity Group increases in thickness to the east along an erosional feature starting near the Yoakum-Gaines County line, south of Plains, where it is about 50 ft thick, and increases to the east, where it is more than 150 ft thick, near Brownfield (Figure 6).

Dockum Group

The water-bearing units of the Dockum Group were not evaluated for this study, and the extent of the Dockum Aquifer was not determined. Relative to the other geologic units assessed for this study (the Ogallala, Fredericksburg, and Trinity groups), the Dockum Group was found to have a much larger mean thickness (approximately 1,795 ft). The Dockum Group is mostly composed of siltstone and shale, with only a small amount of sandstone that could serve as a productive aquifer (Bradley and Kalaswad 2003). Natural gamma and resistivity geophysical data were the primary data used to identify the signature of the various units. This signature of the base

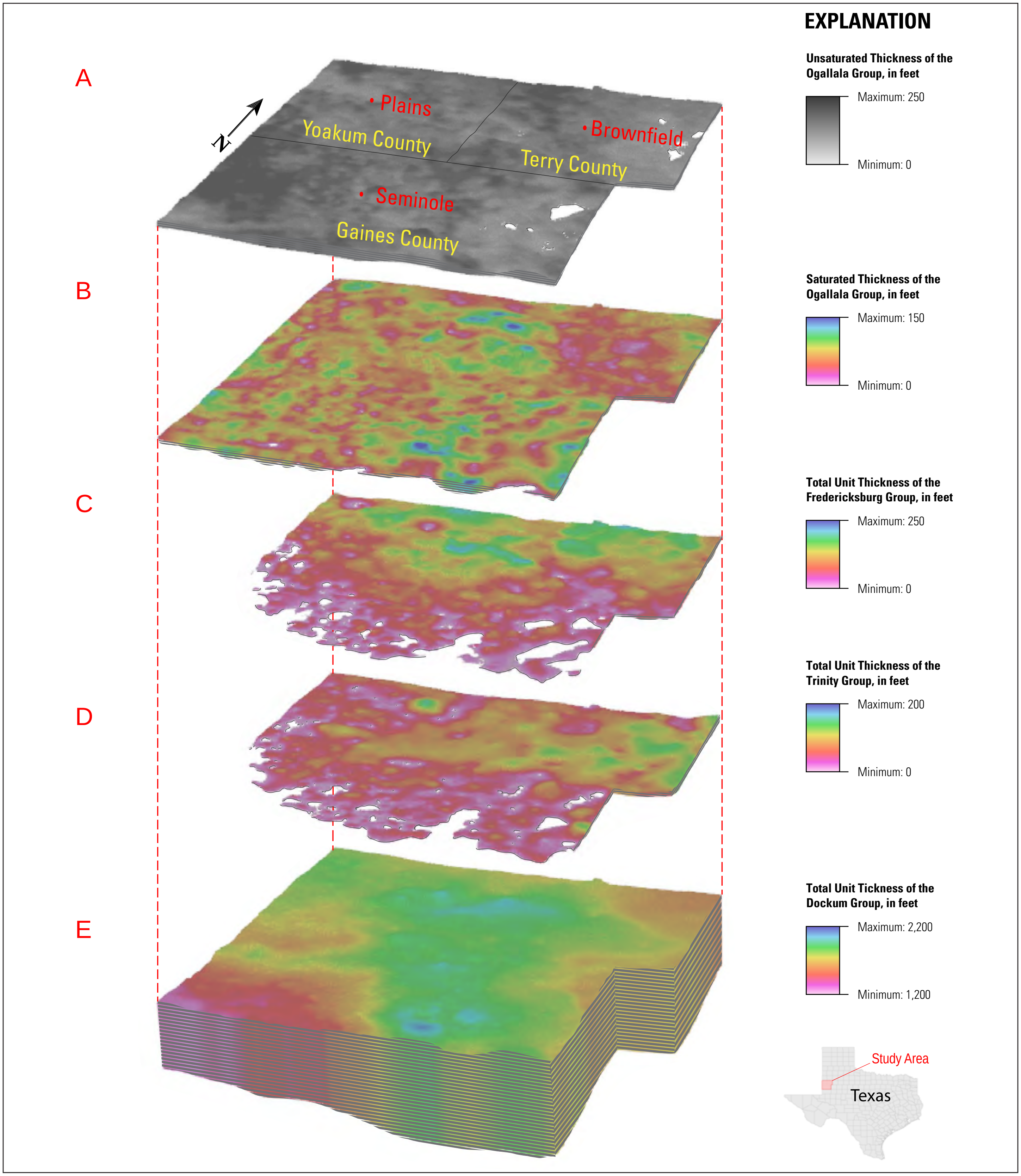


Figure 6. Three-dimensional representation of the hydrogeologic framework for Gaines, Terry, and Yoakum counties, Texas, including (A) unsaturated thickness of the Ogallala Group; (B) saturated thickness of the Ogallala Aquifer; (C) the total unit thickness of the Fredericksburg Group; (D) the total unit thickness of the Trinity Group; and (E) the total unit thickness of the Dockum Group.

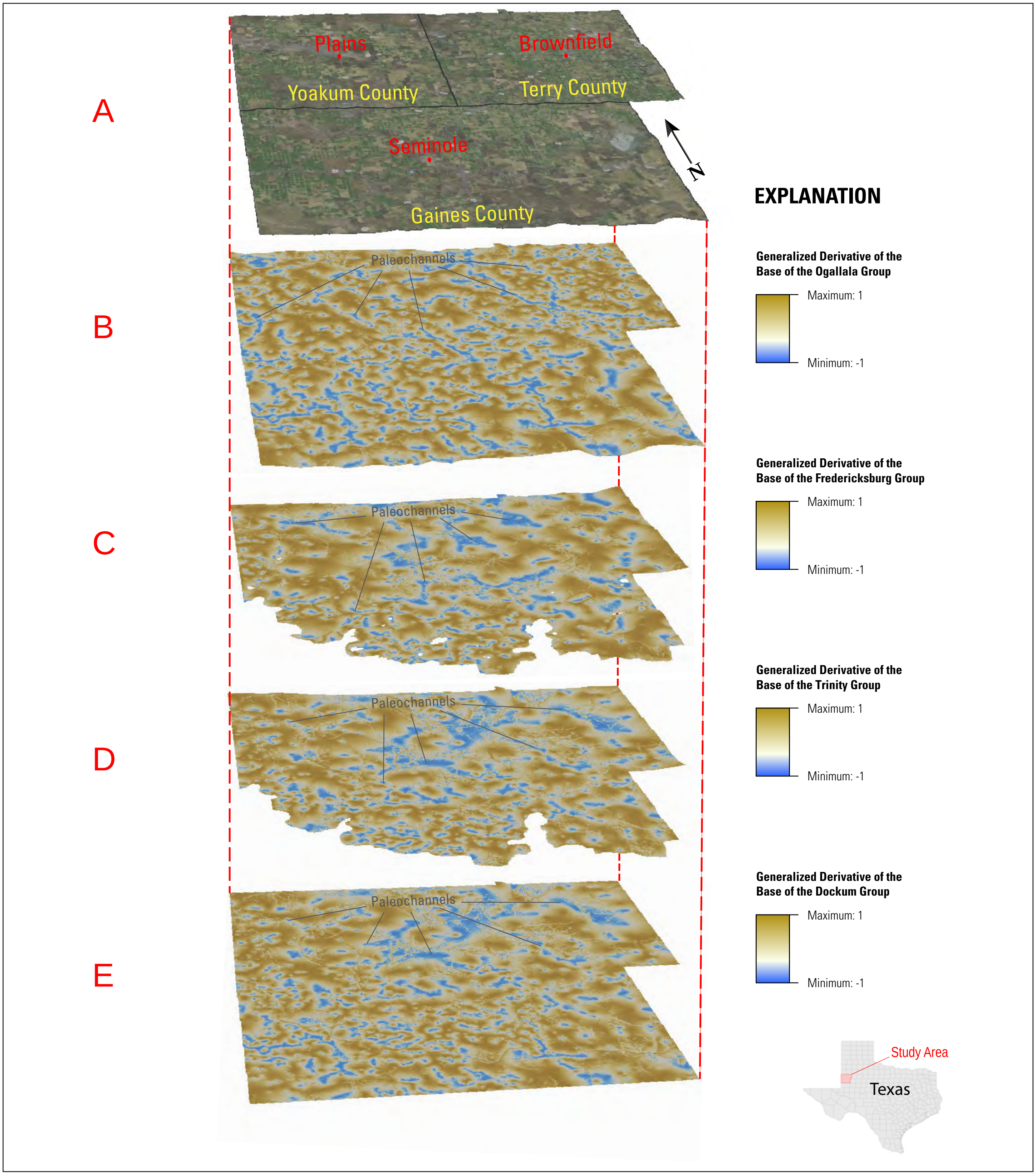


Figure 7. Three-dimensional representation showing paleochannel locations in the base surfaces of the hydrogeologic framework for Gaines, Terry, and Yoakum counties, Texas, including (A) satellite imagery of the study area; (B) generalized derivative map of the base of the Ogallala Group (C) generalized derivative map of the base of the Fredericksburg Group; (D) generalized derivative map of the base of the Trinity Group; and (E) generalized derivative map of the base of the Dockum Group.

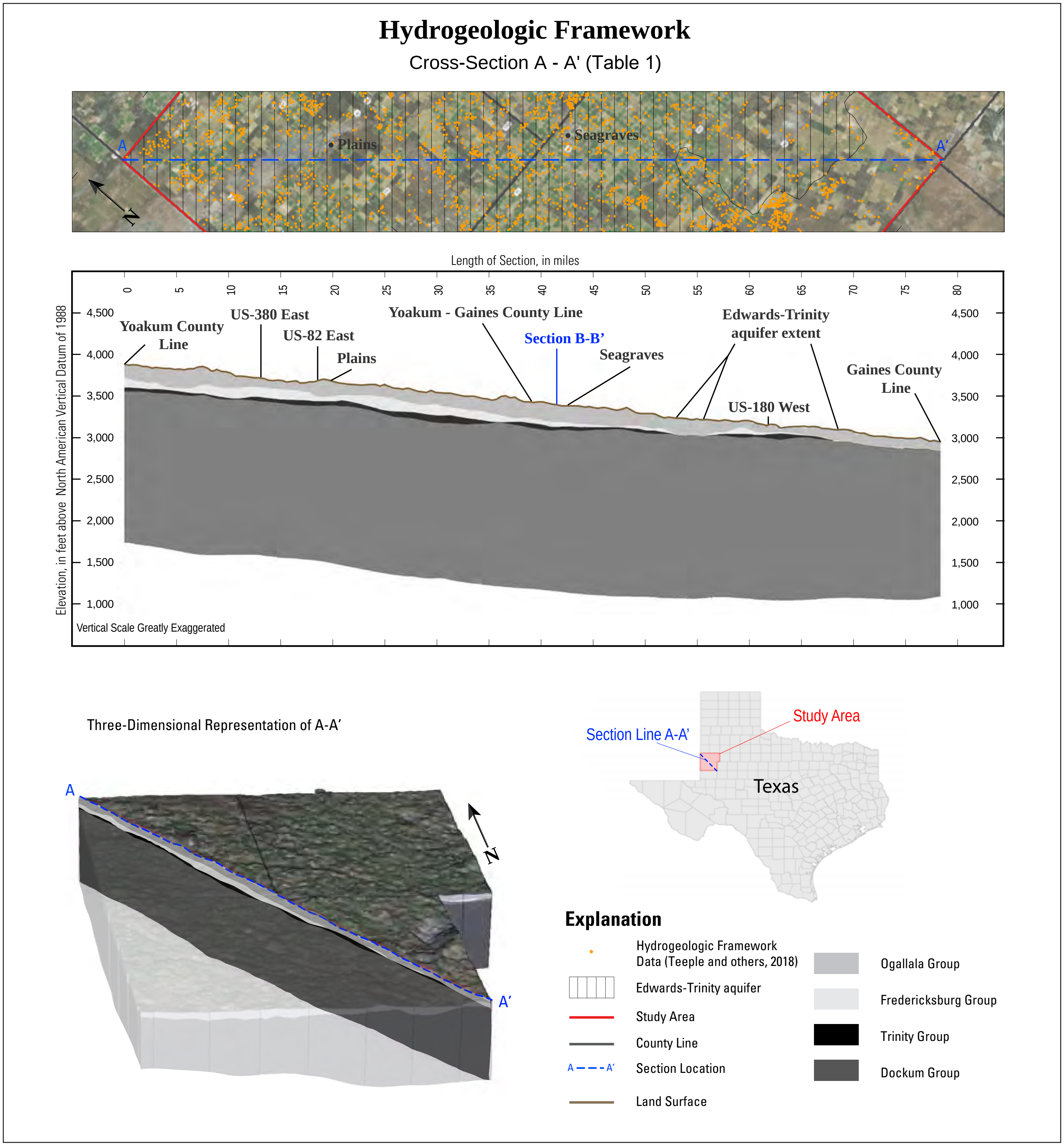


Figure 8. Two-dimensional and three-dimensional representations of the hydrogeologic framework from A to A' for Gaines, Terry, and Yoakum counties, Texas, of the Ogallala Group, Fredericksburg Group, Trinity Group, and the Dockum Group.

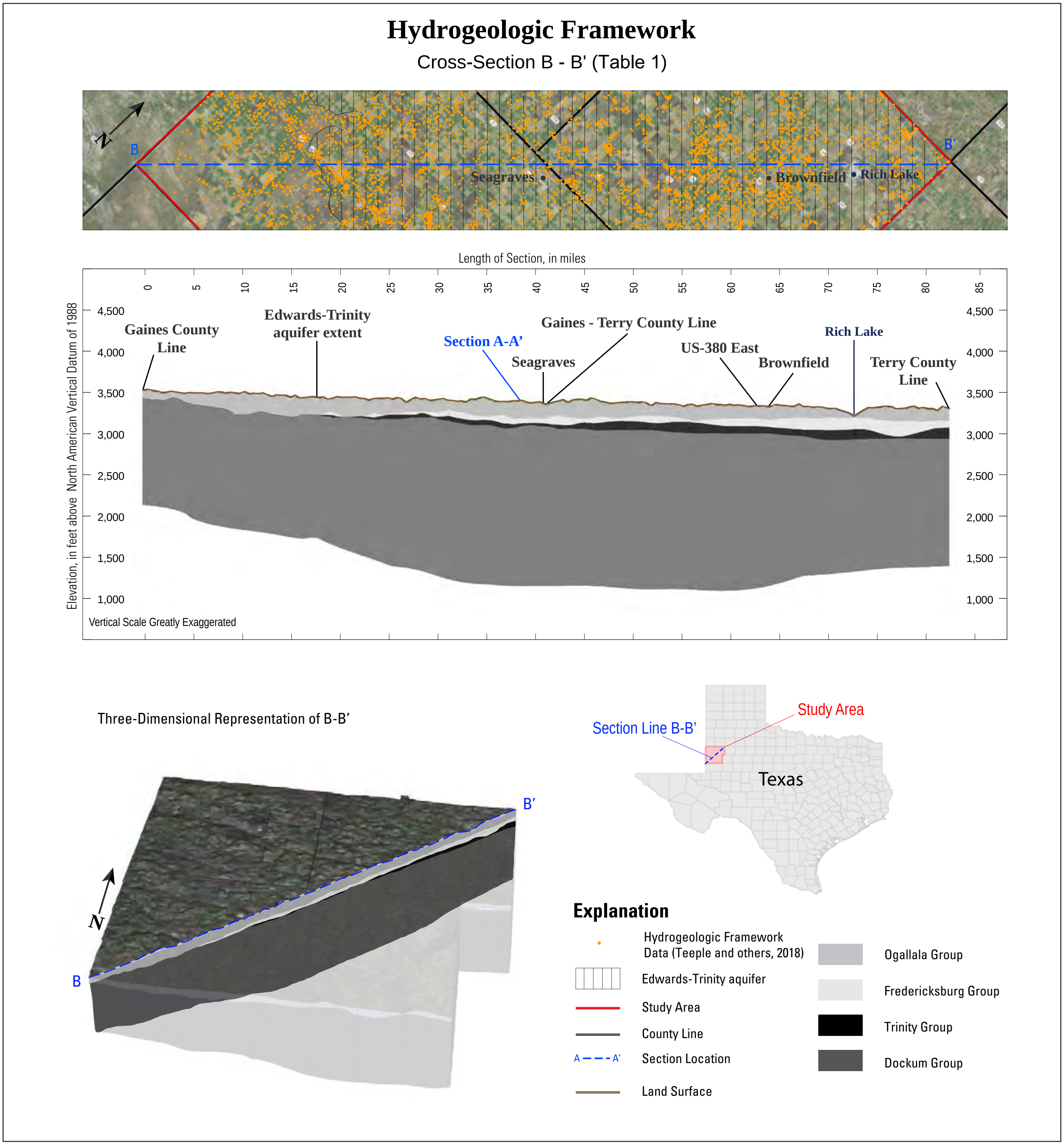


Figure 9. Two-dimensional and three-dimensional representations of the hydrogeologic framework from B to B' for Gaines, Terry, and Yoakum counties, Texas, of the Ogallala Group, Fredericksburg Group, Trinity Group, and the Dockum Group.

of the Dockum Group varied some across the study area but in general the top of the Dockum was determined as the top of the red beds (high natural gamma/low resistivity) and the base of the Dockum Group was determined as the top of the Dewey Lake Formation. Key words in compiled drillers' logs were also reviewed to identify the base of the Dockum Group. The top of the Dockum Group is deepest to the north, where the overlying Fredericksburg and Trinity groups are present and shallowest to the south where the Dockum Group directly underlies the Ogallala Group (Figures 7-9). The thickness of the Dockum Group is mostly consistent across the study area, except in the northeast and southwest where it thins (Figures 6-9). The thickness of the Dockum Group ranges from approximately 1,260 ft in the southwest corner of Gaines County to more than 2,145 ft in the south-central part of the study area, southeast of Seminole (Figures 6, 9). A relatively small amount of data were collected as part of this assessment pertaining to the Dockum Group; to better quantify the water content of the Dockum Group, additional data are needed to better define various layers of the Dockum Group and the viability of the unit as a water-supply resource for the area.

REFINEMENT AND IMPROVED RESOLUTION OF THE HYDROGEOLOGIC-UNIT INTERFACES

The refinement and improved resolution of the hydrogeologic-unit interfaces provides water resource managers a tool to better understand the groundwater system, and the surfaces can be used with potentiometric water-level surfaces to calculate Ogallala Aquifer saturated thicknesses, help estimate the volume of water in storage, and assess aquifer changes over time. Refinements to the saturated thickness of the Ogallala Aquifer can be indirectly assessed by evaluating changes to the base of the Ogallala Group, and therefore the Ogallala Aquifer. Compared to previous datasets, the altitude of the refined base of the Ogallala Aquifer is on average 14.7 ft higher in 25% of the study area; in an additional 25% of the study area, the altitude is 18.9 ft lower (Figure 5). Across the entire study area, the average altitude of the base of the Ogallala Aquifer is approximately 1.7 ft lower compared to the previous assessments of the altitude of the base of the aquifer (Table 2), resulting in a subsequent increase in the saturated thickness by the same amount. Some of the largest areas where the altitude of the base of the Ogallala Aquifer are higher are in central and east-central Gaines County where the Edwards-Trinity Aquifer thins (Figure 5). The large differences between the previously identified base altitude and the revised base altitude may have implications for availability of stored water. Local water resource managers and stakeholders can use this revised understanding of the base of the Ogallala Aquifer, along with aquifer hydraulic properties, to refine water management strategies.

CONCLUSION

Declining groundwater levels have raised concerns about the amount of available groundwater in the study area and the potential for water-quality changes resulting from dewatering and increased vertical groundwater movement between adjacent water-bearing units. Hydrogeologic data and interpretative information from previous studies done by various local, state, and federal agencies were compiled and supplemented with surface and borehole geophysical data collected by the USGS. The resulting dataset was analyzed to identify the tops and bases of the selected hydrogeologic units along with the lateral extent and relation to overlying and underlying units in the study area.

Most of the locations where the altitude of the base (bottom surface) of the Ogallala Aquifer was higher (shallower) than previously depicted were in the southern part of the study area. Specifically, in areas where the Ogallala Aquifer overlies the southern extent of the Edwards-Trinity Aquifer, there were large areas where the base of the Ogallala Aquifer was more than 100 ft higher than previously mapped. Along an erosional feature about 10 mi east of Seminole, where the Edwards-Trinity Aquifer is absent, the base of the Ogallala Aquifer was as much as 100 ft lower (deeper) than previously mapped. Across the entire study area, the average altitude of the base of the Ogallala Aquifer was approximately 1.7 ft lower compared to the previous assessments of the altitude of the base of the aquifer, resulting in a subsequent increase in the saturated thickness by the same amount. Localized areas where the Ogallala Group is relatively thin are found in some low-lying areas such as lakes (for example, Cedar Lake, Mound Lake, and Rich Lake). The saturated thickness of the Ogallala Aquifer ranges from less than 10 ft in the far southern extent of the study area, to more than 150 ft southeast of Seminole and northwest of Brownfield.

Although the Fredericksburg and Trinity groups are present throughout most of the northern parts of the study area, there are localized areas where one or both groups thin or are absent. The mean unit thicknesses of the Fredericksburg and Trinity groups are 86 ft and 55 ft, respectively. Throughout the study area, the thickness of the Fredericksburg Group is more variable than the thickness of the Trinity Group. The Fredericksburg Group is thickest in the north-central part of the study area (about 237 ft thick), whereas the Trinity Group is thickest in northeast Yoakum County (about 164 ft thick). The Trinity Group increases in thickness to the east along an erosional feature starting near the Yoakum-Gaines County line, south of

Plains, where it is about 50 ft thick, and increases to the east, where it is more than 150 ft thick, near Brownfield.

Relative to the other geologic units assessed for this study, the Dockum Group has a much larger mean unit thickness of approximately 1,795 ft, much of which is composed of siltstone and shale, with only a small amount of sandstone that could serve as a productive aquifer. The top of the Dockum Group is deepest to the north, where the overlying Edwards-Trinity Aquifer is present and shallowest to the south where it directly underlies the Ogallala Aquifer.

ACKNOWLEDGEMENTS

The authors thank the property owners for graciously providing access to their land. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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