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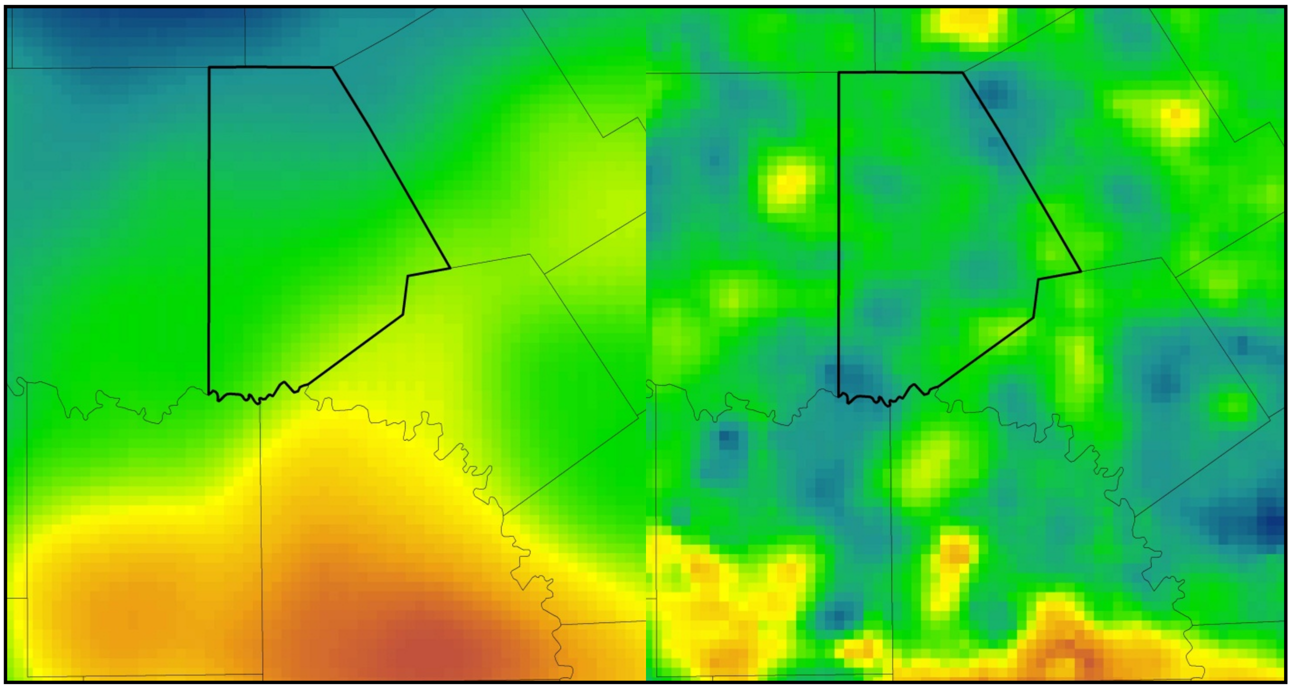
Brown County Brackish-Water Project: Ellenburger and Hickory Aquifers as a Public Water Supply



Prepared for
Brown County Water Improvement District No. 1
Brownwood, Texas

by
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Executive Summary

The purpose of this study was to determine favorable locations for test brackish water wells tapping the Hickory and Ellenburger aquifers in Brown County, Central Texas. We determined that the best location is close to the southwest tip of the county (Figure ES1), where (1) total dissolved solids (TDS) concentration is relatively low (~3,000 mg/L), (2) the aquifers are relatively thick (~350 ft for the Hickory and ~1100 ft for the Ellenburger-San Saba), and (3) the recharge zone is reasonably close (20-30 miles to the South). Another location close to the City of Brownwood will test the Ellenburger-San Saba, which is ~1200 ft thick there. Despite potentially good yield (>500 gpm), the TDS concentration is much higher at the second location, 10,000 to 15,000 mg/L in the Ellenburger and likely even higher in the Hickory, which is thinner there and more removed from recharge areas. The test wells would reach a depth of 3,000 to 3,500 ft. Both Hickory and Ellenburger exhibit relatively high levels of radium and other radionuclides: regionally, 30% of the wells have measurements above the radium maximum contaminant limit(15 pCi/L).

The focus of the study was on the Hickory and Ellenburger-San Saba aquifers because they represent the most extensive water sources in the county, even if they are not fresh. Other water-bearing formations include the Mid-Cambrian / Welge aquifer, the Marble Falls aquifer, several mostly brackish upper Paleozoic aquifers of limited extent, the Trinity aquifer, and alluvial aquifers along rivers. The alluvial aquifers are limited in extent and capacity. The Trinity aquifer exists only in the eastern third of the county and consists of three individual sands that can provide limited amounts of fresh water. The upper Paleozoic aquifers occur across the whole county where not covered by Trinity sediments, but in a fragmented way, with no communication between them. In addition, they quickly become brackish with depth, even if the shallow part of the aquifer is tapped for fresh water to meet local domestic and irrigation needs. The Marble Falls and Welge aquifers could supplement wells drilled to tap the Ellenburger or the Hickory.

Study conclusions rely on an extensive literature search (but on relatively little hard data) on the geology and hydrogeology of the Brown County subsurface. Rocks seem to be organized simply, with layers dipping radially away from the so-called Llano Uplift, where granite and other rocks of the Precambrian-age basement are exposed. However, the geology becomes more complicated when details needed to site a well field are considered. The geology of the Hickory and Ellenburger is not well known in Brown County but it is farther south in McCulloch and San Saba Counties, where the layers crop out. Younger strata from which oil and gas are extracted in Brown County are also better known. Nevertheless, some general observations can be made. The Hickory is the first layer to be deposited on the basement, which in Cambrian times displayed some relief with valleys and ridges. Hickory sediments followed the topography and were deposited with uneven thickness. A goal of this study was to discover those areas with larger Hickory thickness. Sediments were deposited in a marine environment, with the land mass just north of what is now Brown County causing the formation thickness to go to zero quickly. Because the Hickory was never buried deep, it has conserved, for the most part, good permeability and flow quality.

Unlike the Hickory, the Ellenburger was deposited in Ordovician times, mostly as limestone mud on an extensive platform that reached beyond Texas. It was then indurated and transformed into

dolomite. The formative event was then for the carbonate layer to emerge and be exposed to erosion for millions of years, creating an extensive network of caves (now collapsed) and fractures. This karstic process created the permeability needed for groundwater flow. However, the high-permeability features tend to follow faults, many of them not visible at the surface, making prediction as to whether a well will reach a favorable zone difficult.

The study was intended to delineate the most promising areas for future detailed investigations. The report documents our reasoning leading to the siting choices and provides supporting information. In addition to field data collection, further geological work could include examination of 2D-seismic lines for identifying faults and basement highs, a more thorough analysis of well logs, and construction of a numerical flow model.

Hickory:
Depth to the top of Hickory varies from ~2750 to >4000 ft from south to north of the county, respectively.
Thickness is 150 to 350 ft overall, decreasing toward the north; uneven base.
Salinity is unknown but can be extrapolated from shallower sections, and variations are assumed similar to those of Ellenburger (reasonable assumptions). It would range from 3000 to maybe 50,000 mg/L across the county.
Radioactivity is a potential problem—treatment probably needed.
Conductivity is likely good throughout.
Capacity is unknown; many fault compartments; recharge might be close to zero.
Well yield good at the outcrop, probably still good downdip.

Ellenburger:
Depth to top of Ellenburger varies from ~1000 to 3500 ft from south to north of the county.
Thickness of Ellenburger is ~900 ft in Brown County.
Salinity of Ellenburger varies from ~3000 mg/L at southern tip of the county to ~50,000 mg/L on Eastland county line.
Radioactivity: less than in Hickory
Conductivity: Ellenburger is a karstic aquifer with mix of high conductivity and tight areas.
Capacity is unknown; many fault compartments; recharge might be close to zero.
Well yield: need to find a fractured, karstic area.

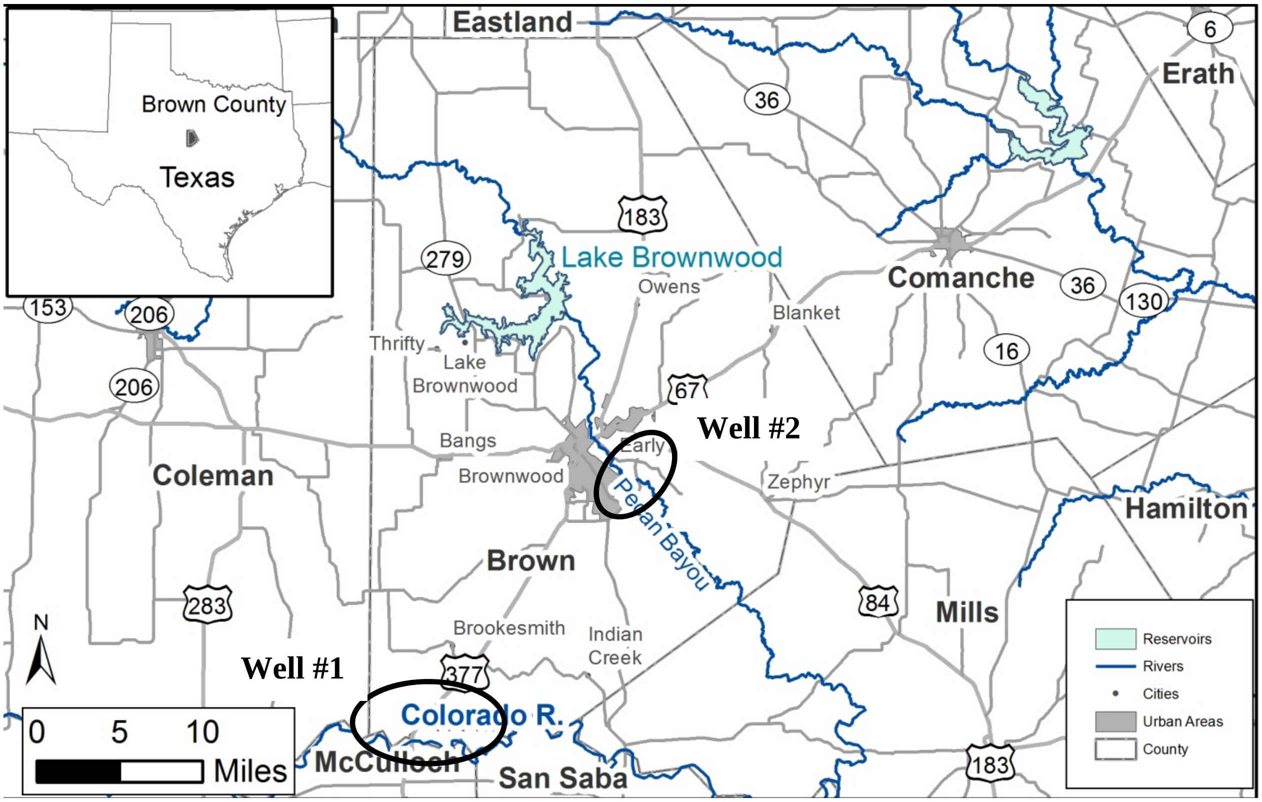

Figure ES1. Proposed drilling locations.

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Acknowledgments

The authors would like to thank Mr. Dennis Spinks, BCWID General Manager, BCWID board members, and the local public for their useful input and for sharing their knowledge of the county water use history. We are also grateful to IHS (http://www.ihs.com/) for free access to their Enerdeq database. The report also benefited from a thorough editing by Lana Dieterich.

Acronyms

AF	Acre-foot (1 AF = 325,851 gallons or 1 million gallons ~3 AF)
kAF	Thousand AF
BCC	Brownwood Chamber of Commerce
BCWID	Brown County Water Improvement District
BEG	Bureau of Economic Geology
GAM	Groundwater Availability Model
GAT	Geological Atlas of Texas
gpm	Gallons per minute
MCL	Maximum Contaminant Limit
MGD	Millions of gallons per day
TCEQ	Texas Commission on Environmental Quality
TDS	Total Dissolved Solids
TWDB	Texas Water Development Board

I. Introduction

This work represents the first step of a possibly larger project whose goal is to understand brackish and other underutilized groundwater resources in Brown County, Central Texas. The Brown County Water Improvement District No. 1(BCWID, http://www.bcwid.org/) and the City of Brownwood rely mostly on Lake Brownwood (Figure 1) as a water source; groundwater resources are tapped only for local domestic and irrigation use. To diversify its water base and successfully face potential extreme drought conditions, BCWID tasked the Bureau of Economic Geology at The University of Texas at Austin (BEG) with a preliminary exploratory study of brackish-water aquifers within the county. The District currently provides ~9 million gallons a day (MGD)—more than half of the county water use, all uses combined—and would need to develop a 2 to 3 MGD brackish-water well field to help meet future demand during drought conditions.

The focus of this document is on deeper aquifers, the Hickory and Ellenburger aquifers, known in neighboring counties to the south to provide significant amounts of water. Groundwater in lower Paleozoic strata (mainly the Hickory Sandstone of Cambrian age and the Ellenburger Group of Ordovician age) has generally not been used in Brown County because (1) it is relatively deep in the subsurface, (2) the water has higher total dissolved solids (TDS), and (3) surface water and groundwater from shallower aquifers have been sufficient to meet needs. Southern Brown County has been using groundwater that occurs in the Ordovician and Pennsylvanian (Ellenburger, Strawn, Canyon, and Cisco) formations and Quaternary alluvium, primarily for domestic and livestock use.

This document examines the option of expanding the use of the Ordovician and Pennsylvanian formations and/or the Hickory Sandstone or other Cambrian units as a brackish-water source. From a general geologic standpoint, some information can be gathered on Ordovician and Pennsylvanian formations, but few studies of the Cambrian formations have been performed in Brown County. The report summarizes known facts about groundwater occurrence, hydraulic properties, and water quality, with a focus on the deeper formations (Ellenburger and Hickory), but also includes information about regional diagenetic and tectonic history, depositional environments of the sediments, petrography, and geological structure of the Paleozoic aquifers, softer information from which a better understanding of the hydrogeology of Brown County can be extracted. The report is based on literature review, data compilation from relevant agency databases and publically available data, and expert geological insight. Although the ultimate goal of the project is to determine best locations (in terms of quality and yield) for groundwater production, this study serves also as the first phase of development of a groundwater model.

The study and report follow a conventional approach: (1) literature review and compilation of available water-related data, (2) broadening of data search to fill in gaps in water-related data, (3) development of a conceptual model, and (4) application to the problem at hand.

The Texas Water Development Board (TWDB) is the go-to agency for accessing historical reports and data on water use and quality (http://www.twdb.state.tx.us/publications/). Several reports are dedicated to or touch upon groundwater sources in Brown County and are listed in the Previous Studies Section. TWDB is also the repository of a large database containing historical to present water levels and water quality analyses (http://www.twdb.state.tx.us/groundwater/data/gwdbrpt.asp). Another database (http://www.twdb.state.tx.us/groundwater/data/drillersdb.asp) is the electronic repository of information on water wells drilled after 2001. The Texas Commission on Environmental Quality (TCEQ) website contains scanned pages of drilling reports for older wells. Information about geology and geological features was found in several BEG reports, some dating back to a century ago, and in university theses. The singular Llano Uplift has attracted many researchers, but their work tends to focus on outcrops. Nonetheless, many relevant observations, such as depositional environments and diagenesis (that is, evolution of the sediments toward becoming a rock), and their likely impact on hydraulic conductivity distribution, can be extracted from these reports. We also obtained data so as to produce accurate structure maps showing the tops of formations of interest. From a practical standpoint, we directly imported scanned images of published and publicly available reports when relevant to the study, although we also created new figures as needed.

II. Background

Brown County is located in Central Texas (Figure 1) north of a prominent geographic and geologic feature called the Llano Uplift. It has a population of ~38,000 inhabitants (http://quickfacts.census.gov/qfd/states/48/48049.html, 2010 census), more than half (~20,000) of whom reside in Brownwood, the county seat in the middle of the county. The county covers ~950 mi^2.

II-1. Physical Geography

A discussion of the physical geography is important because it helps in understanding infiltration and recharge (Are precipitation events spread out during the year or concentrated in a few summer or winter months? What is the interannual variability?) and evapotranspiration (What is the natural landscape? What is the native vegetation? What is the current land use?). The climate there is classified as subtropical subhumid (Larkin and Bomar 1983). Long-term average annual precipitation is ~27 to 28 inches (Figure 2a), with large summer precipitation events (Figure 2b). The average monthly low temperature in January is 31°F, and the average monthly high temperature in July is 96°F. Relative to the Llano Uplift, changes in land-surface elevation in Brown County are small (Figure 3). The east part of Brown County is in a cross-timbers ecoregion, and the west part is in the central Great Plains (Griffith et al., 2004; Figure 4). The cross-timbers ecoregion, which contains irregular plains with some low hills and tablelands, is made up of a mix of prairie, savanna, and woodland and makes the connection between the more heavily forested, east part of the state and the almost treeless Great Plains. The central Great Plains were once grassland prairie but are now a major winter-wheat growing area. The cross-timber area is not as suitable for growing crops and consists mostly of rangeland and pastureland. Brown County lies almost entirely within the Colorado River basin, except for a small fraction in the northeast that lies within the Brazos River basin. Local waterways include Pecan Bayou and its tributaries. Lake Brownwood is situated on Pecan Bayou. The Colorado River forms the south boundary of the county (Figure 1).

II-2. Regional Groundwater Sources

TWDB defines major aquifers as those that are important water sources for large communities or those that contain large water reserves (Ashworth and Hopkins, 1995; Smith, 2004; George et al., 2011). Minor aquifers are those that are locally important but that cannot be classified as major aquifers. Note than many aquifers are described neither as major nor minor by the TWDB. Outcrop of the Trinity aquifer, a major aquifer, is present in the eastern third of Brown County. Three minor aquifers of early Paleozoic age are defined in the footprint of the Llano Uplift: the Hickory, Ellenburger-San Saba, and Marble Falls aquifers. The first two form a ring around the Precambrian basement and brush the southern county line of Brown County, where their downdip limits are defined by an estimated 3,000 mg/L TDS line. The 1,000 mg/L, generally defined as the limit between fresh and brackish water, is farther south outside of Brown County. The Marble Falls aquifer is defined as a minor aquifer only in its outcrop area north of the Llano Uplift proper, but it lies also farther downdip toward Brown County. In addition to the Hickory, Ellenburger-San Saba, Marble Falls, and Trinity aquifers, smallish upper Paleozoic aquifers are also used, consisting of sand lenses tapped where they are relatively shallow. Another water-bearing formation, the Welge aquifer, lies between the Hickory and the Ellenburger aquifers but is not used as a water source.

II-3. Water Use History

Brown County does not belong to any Groundwater Conservation District but is a component county in Groundwater Management Area 8. Texas has 16 Groundwater Management Areas created "…to provide for the conservation, preservation, protection, recharging, and prevention of waste of the groundwater, and of groundwater reservoirs or their subdivisions, and to control subsidence caused by withdrawal of water from those groundwater reservoirs or their subdivisions" (Texas Water Code §35.001). Brown County belongs to the Region F Water Planning area. Regional water planning is a process for analyzing water demands and water availability and developing strategies to meet future near-term water needs.

The major surface reservoir in Brown County is Lake Brownwood, which is owned and operated by BCWID. The lake is located at the confluence of Pecan Bayou and Jim Ned Creek, about 8 miles north of Brownwood. Construction of the lake was completed in 1933. The lake supplies water to city of Brownwood, all the water for irrigation in the district (~5000 acres), and rural customers in Brown and Coleman Counties (http://bcwid.org/).

Fresh groundwater in Brown County occurs mainly in the Cretaceous-age Trinity Group (part of the productive Trinity aquifer) in the eastern one-third of the county (Figure 5). Current groundwater production from Paleozoic rocks and alluvium deposits in the west part of the county is small and is used mainly for domestic, stock, and agricultural purposes. The downdip boundary of the Llano Uplift aquifers (primarily the Ellenburger and Hickory) reaches southern Brown County and represents approximately the 3,000-mg/L TDS contour line. Summary of groundwater pumpage from the Ellenburger and Hickory aquifers for all users within the footprint of the aquifers shows that groundwater pumpage from the Hickory is about four times that of the Ellenburger (Figure 6). Overall groundwater use from the Hickory aquifer, in the 25 to 15 thousand acre-feet per year (AF/yr) range, seems to be decreasing since the 1980's. No significant trend as to the amount of groundwater use from the Ellenburger aquifer (6 thousand AF/yr) can be seen.

The most recent TWDB water-use survey summarizing the year 2009 water use states that Brown County used ~16.5 thousand acre-feet (equivalent to 14.7 MGD) for a population of ~39,000 people. (http://www.twdb.state.tx.us/wrpi/wus/2009est/2009wus.asp). An examination of overall groundwater pumpage in the county as reported by the state shows that groundwater use has varied in the 3+ to ~0.5 thousand AF range in the past 30 years, mostly from the Trinity aquifer, but also includes a small percentage from unnamed aquifers, presumably from Paleozoic aquifers shallower than the Hickory and Ellenburger aquifers in the west half of the county (http://www.twdb.state.tx.us/wushistorical/DesktopDefault.aspx?PageID=2). Annual variations are due to irrigation demand and municipal and livestock uses, making up ~400 AF/yr consistently for the past 20 years. In 2008, TWDB reported that 1334 AF was produced from the Trinity aquifer out of a total of 1482 AF. These figures illustrate that Brown County is >90% dependent on surface-water sources. That not much water is produced from shallow wells in the west half of the county is a clear indication that these aquifers are not suitable for municipal use.

II-4. Oil and Gas Wells

Oil and gas extraction has long been part of the Brown County economy (~50 oil wells drilled in 2011; Jackson, 1980). Analysis of a commercial oil and gas well database (IHS Enerdeq, http://www.ihs.com/) indicates that ~5,700 oil and gas wells were or have been active in Brown County between 1919 and 2012—~1,100 wells produce or produced gas, ~4,600 are oil wells, and a few are oil and gas wells. ~64% of oil wells have information about producing formations (Table 1). Among them, ~45% have producing formations in the Pennsylvanian Strawn Group (particularly Caddo Limestone and Cross Cut Sandstone), 20% in the Pennsylvanian Bend Group (particularly Marble Falls Limestone), and 11% in younger Pennsylvanian formations. ~88% of gas wells have information about producing formation. Among them, ~57% show producing formations in the Bend Group (particularly Marble Falls Limestone), 18% in the Strawn Group (particularly Caddo Limestone and Fry Sandstone), and 8% from Mississippian and Devonian rocks (particularly Chappel Formation and Duffer limestones).

Spatial distribution of oil wells (Figure 7) and gas wells (Figure 8) illustrates that high-density oil-well areas are in the northwest, middle west, and, to a lesser extent, southwest of Brown County. Gas wells are more spread out but follow similar spatial patterns as those of oil wells, ~60% of oil which (2800 wells) have information about formation at total depth. Among them, ~32% show formation at total depth in the Strawn Group, 24% in the Bend Group, and 10% in the Ellenburger Group. A total of ~82% of gas wells (900 wells) have information on formation at total depth. Among them, ~53% are drilled to the Bend Group, 16% to the Strawn Group, and 15% to the Ordovician Ellenburger Group. The oil and gas wells that penetrate to the Ellenburger Group and Hickory Formation are shown in Figure 9 and Figure 10, respectively. Producing formations recently targeted (year 2011) include the Caddo, Cross-Cut, and Marble Falls Formations (Strawn and Bend Groups).

Table 1. Formations that most oil and gas wells tapped into.

Category	Rank	Group	%	Note
Oil	1	Strawn	45	Mostly Caddo and Cross Cut Sandstones
	2	Bend	20	Mostly Marble Falls Limestone
	3	Pennsylvanian	11	
	4	Permian	6	
	5	Mississippian/Devonian	6	Duffer Limestone
	6	Ellenburger	3	
Gas	1	Bend	57	Mostly y Marble Falls
	2	Strawn	18	Mostly Caddo and Fry Sandstones
	3	Mississippian/Devonian	8	Mostly Chappel and Duffer Limestones
	4	Canyon	2	

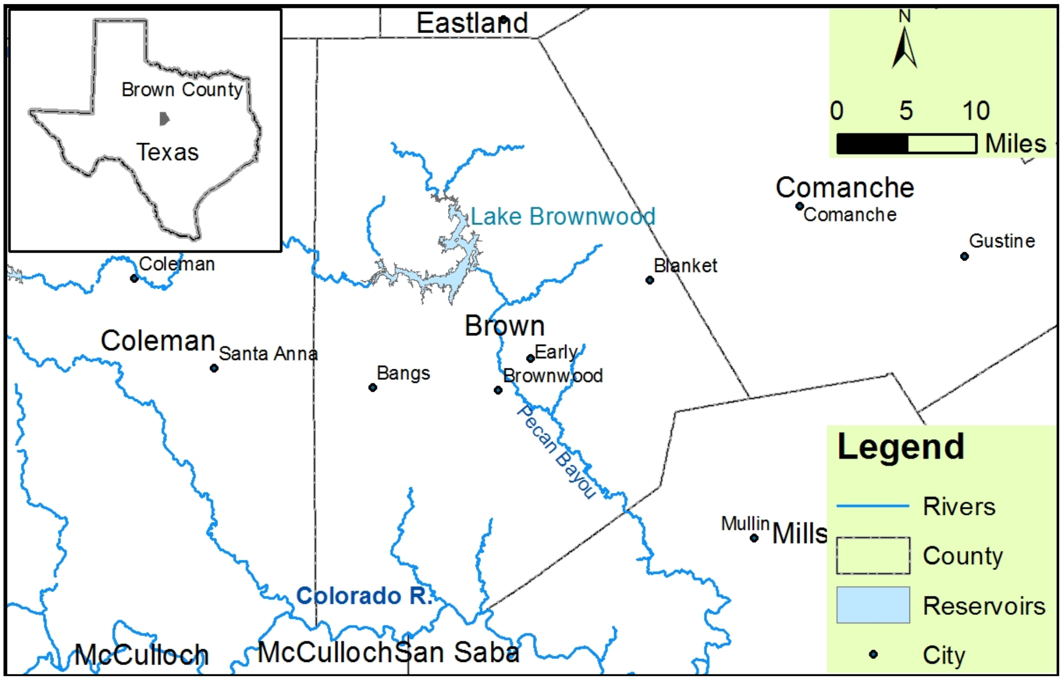
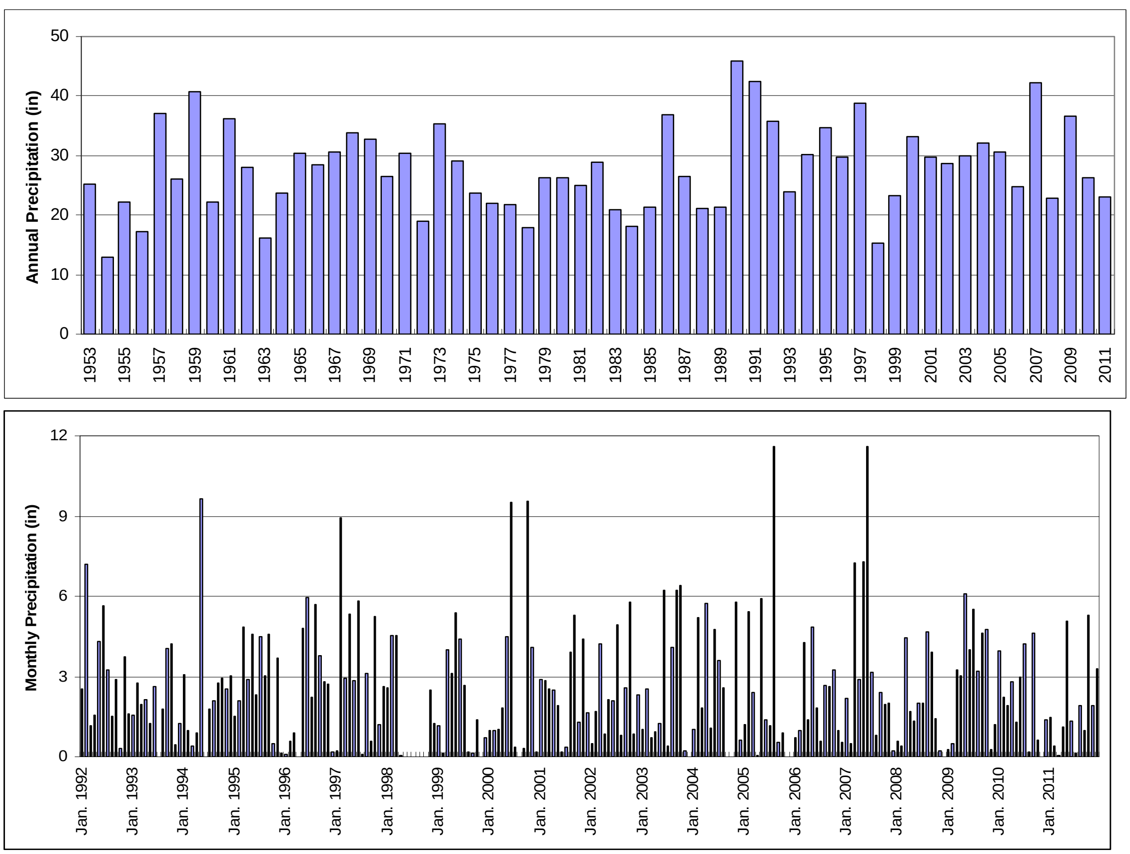


Figure 1. Brown and neighboring counties in north-central Texas.



Source: NOAA Brownwood station
Note: data gaps in monthly record translate into artificially low annuals.

Figure 2. (a) Annual and (b) monthly precipitation in the study area.

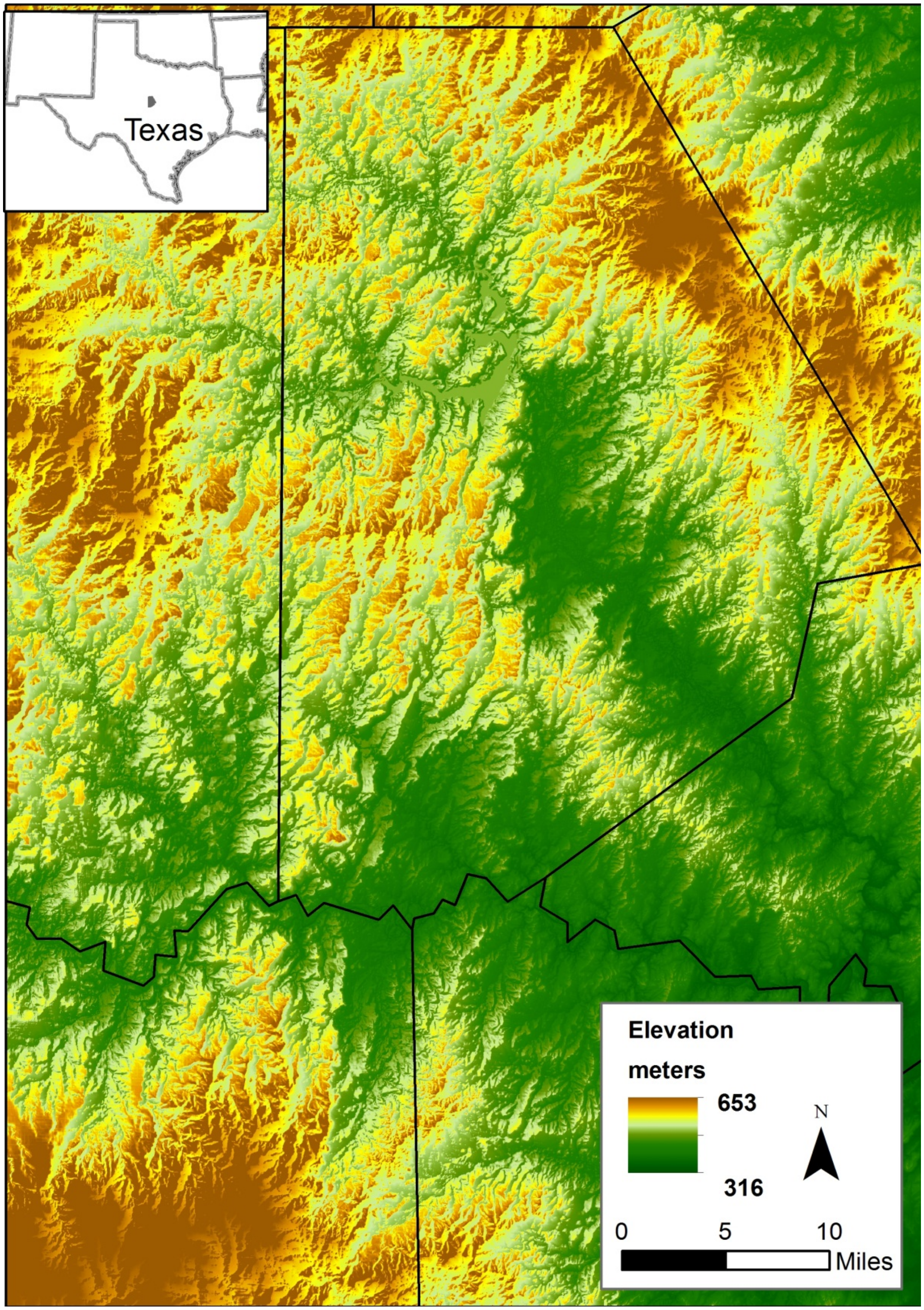
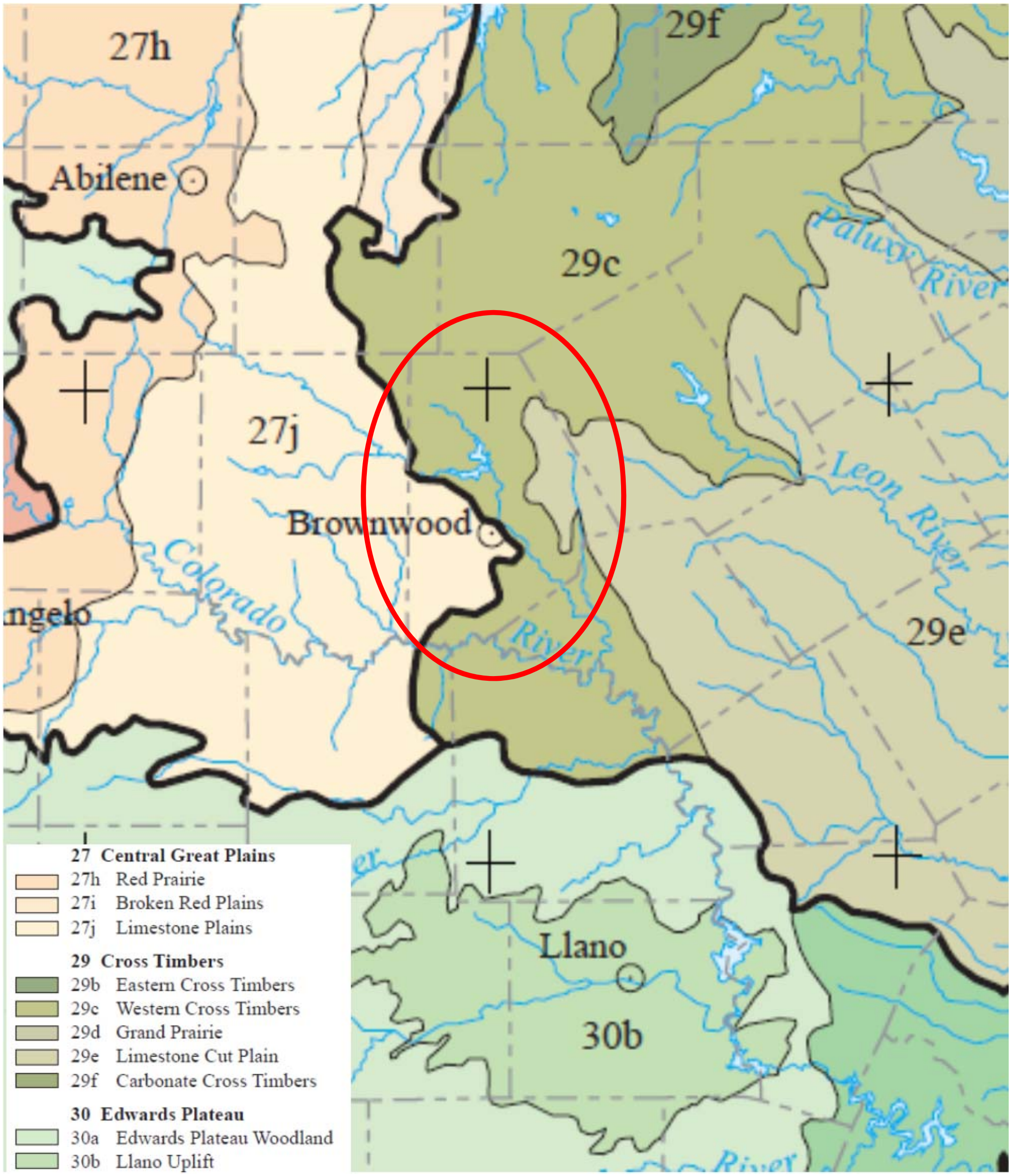


Figure 3. Regional land-surface elevation trend in Brown County–Llano Uplift region.



Source: Griffith et al. (2004); http://epa.gov/wed/pages/ecoregions/tx_eco.htm

Figure 4. Ecoregions near Brown County.

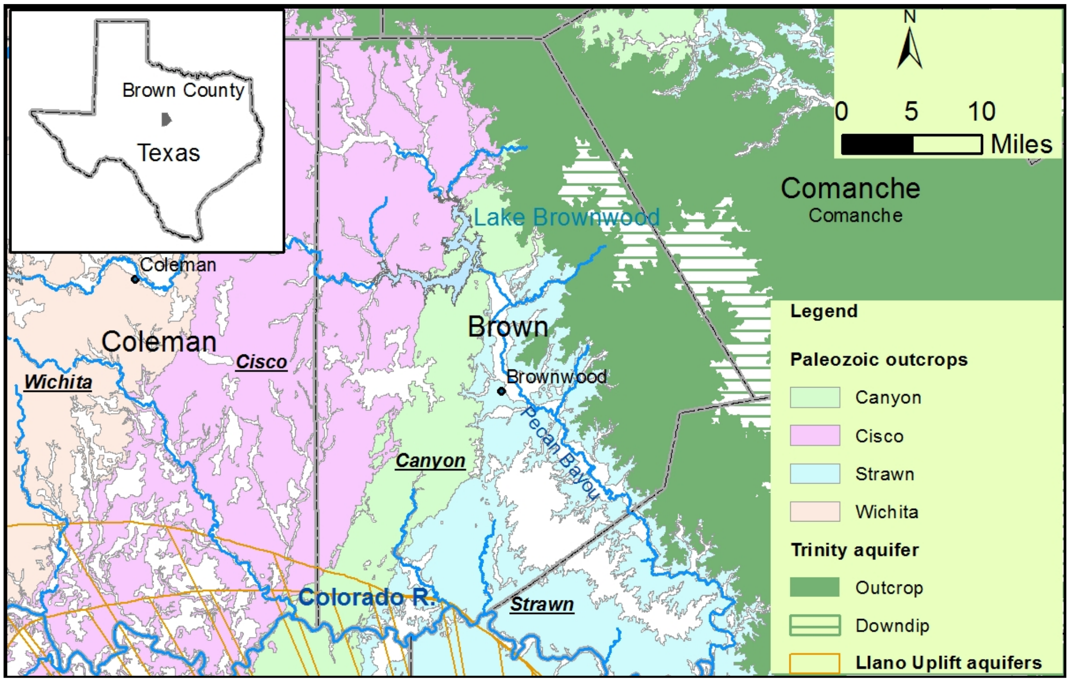
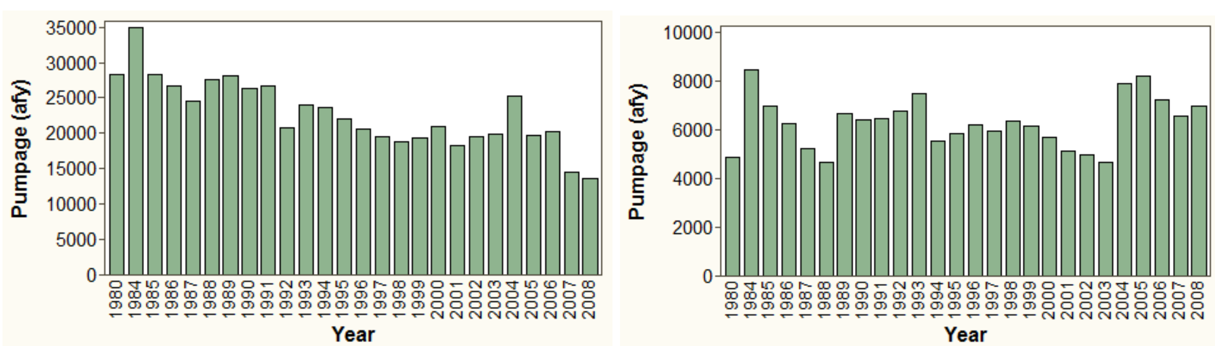


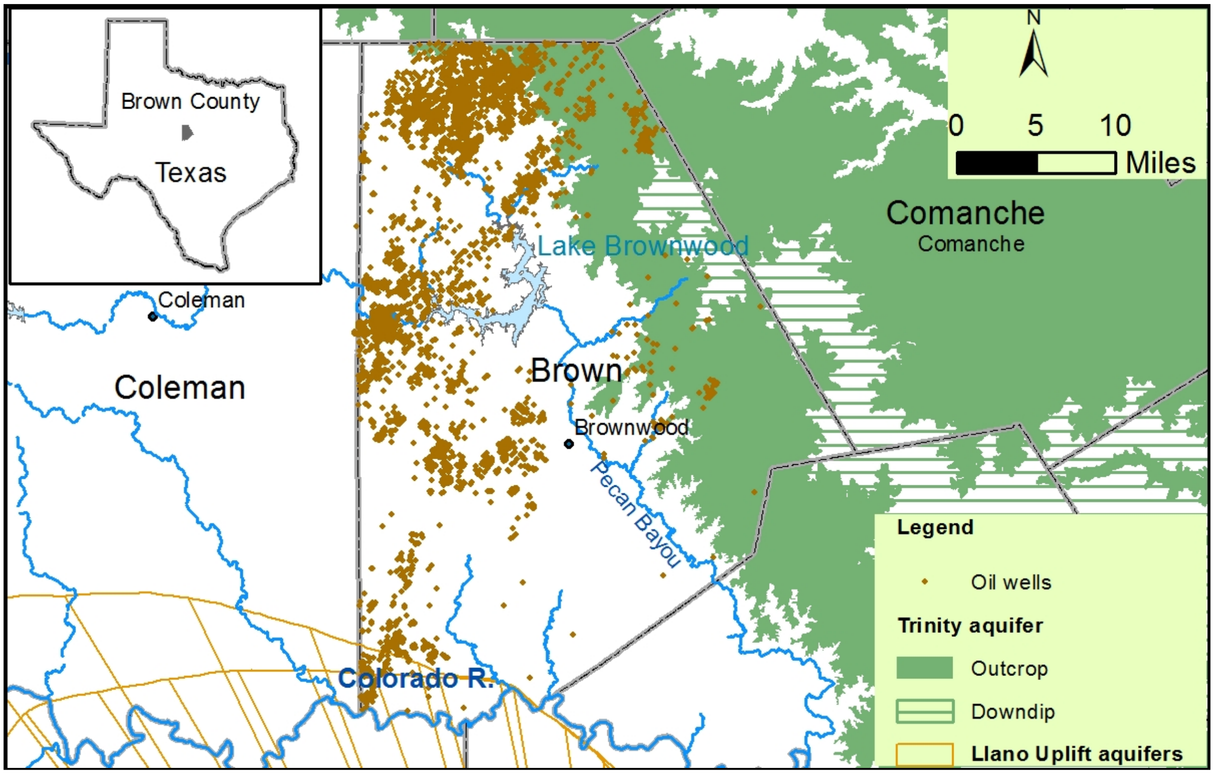
Figure 5. Simplified geological map of Brown County showing Paleozoic outcrops, Trinity aquifer, and northern extent of Llano Uplift aquifers.



Hickory Ellenburger

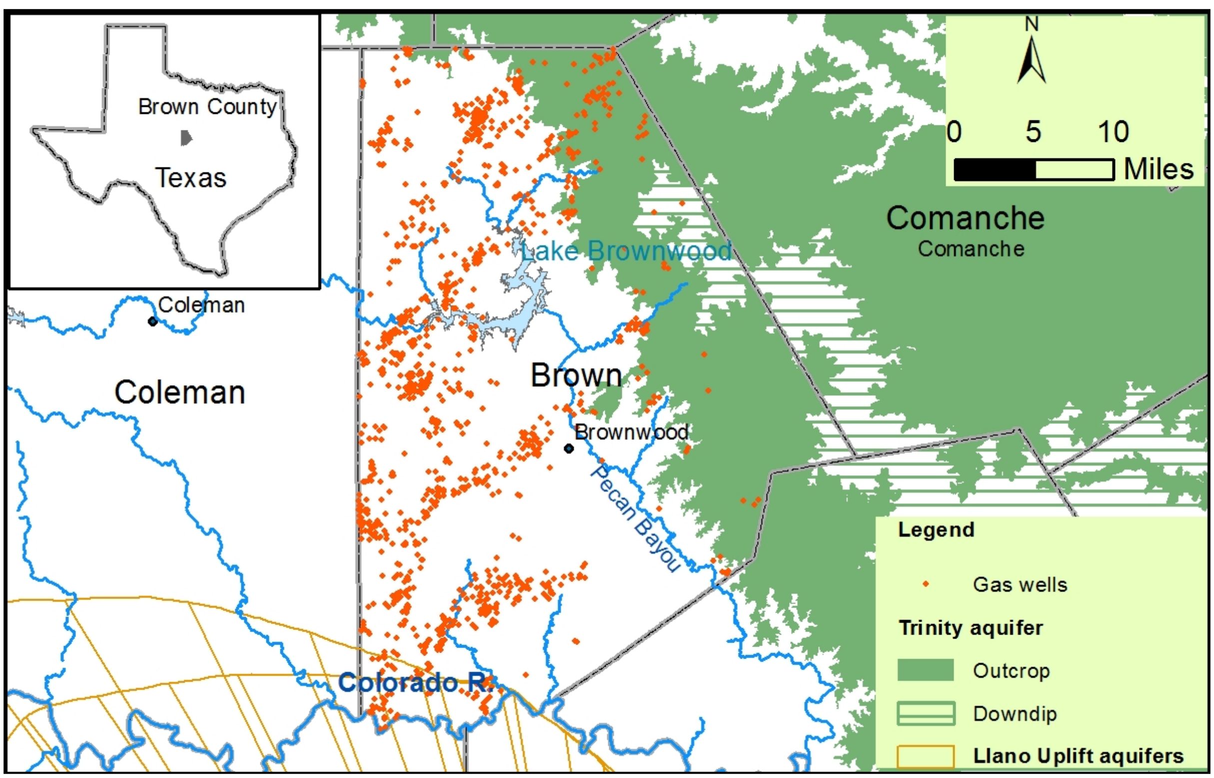
Note: note the difference in vertical scale (to 35,000 AF/yr for the Hickory aquifer and to 10,000 AF/yr for the Ellenburger aquifer)

Figure 6. Historical groundwater pumpage from Hickory and Ellenburger aquifers.



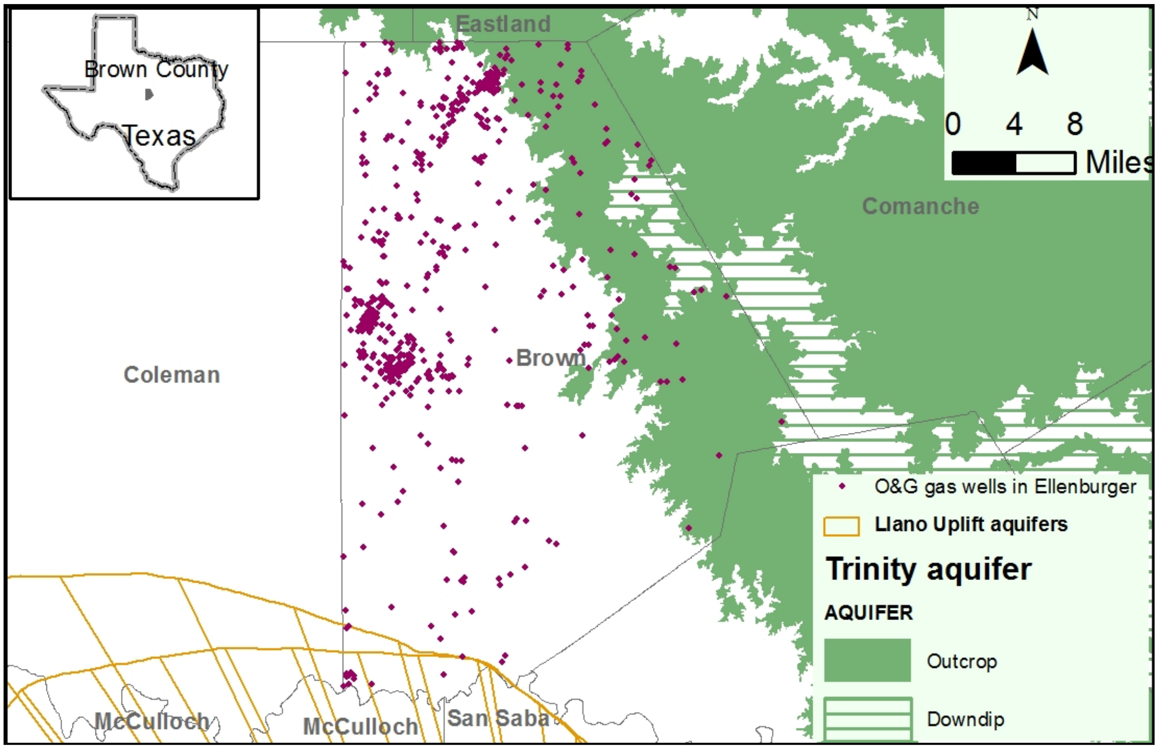
Source: IHS Enerdeq database for well locations

Figure 7. Oil-well spatial distribution in Brown County.



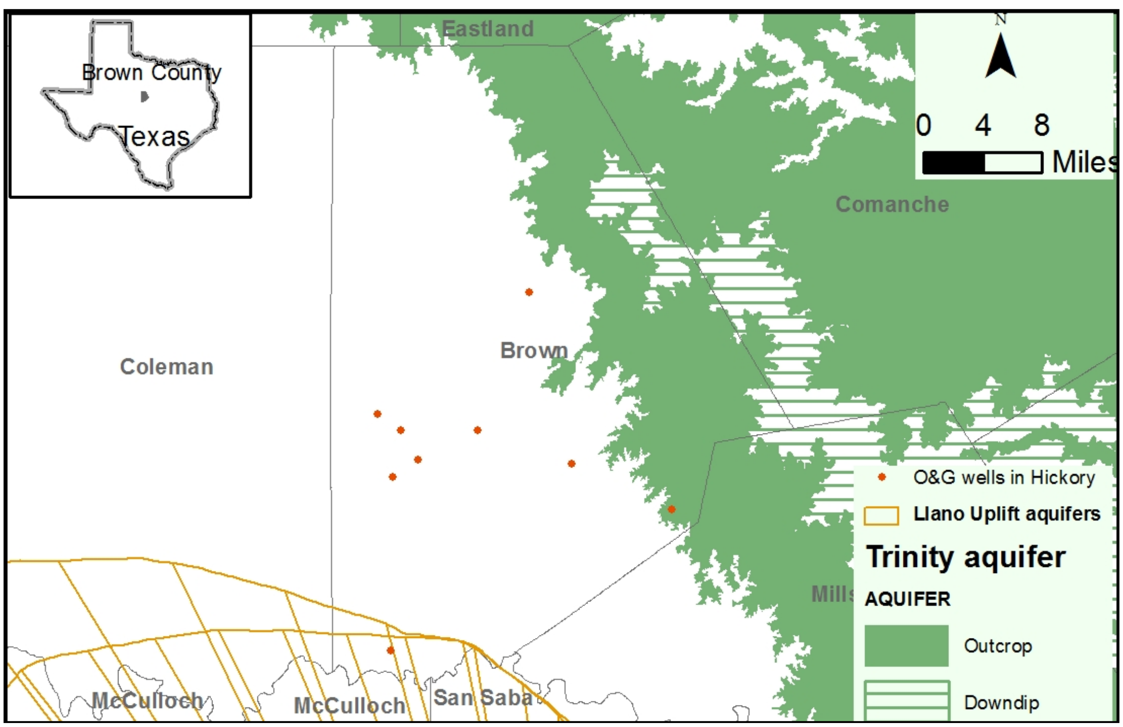
Source: IHS Enerdeq database for well locations

Figure 8. Gas-well spatial distribution in Brown County.



Source: IHS Enerdeq database for well locations

Figure 9. Oil and gas wells whose total depth penetrated top of Ellenburger Group.



Source: IHS Enerdeq database for well locations

Figure 10. Oil and gas wells whose total depth penetrated top of Hickory Sandstone.

III. Previous Studies

Groundwater resources of Brown County, or, more generally, of Central Texas, have drawn interest for many decades. Davis (1938) tabulated records of wells, driller' s logs, and water analyses in Brown County, including locally well known Hot Wells, which were drilled to a depth of 2,402 feet (an Ellenburger well; see Appendix A for more details). Commissioned by TWDB, Thompson (1967) conducted a groundwater study in Brown County by compiling information about occurrence and chemical quality of groundwater resources in each of the producing strata. They included rocks of the Ellenburger Group of Ordovician age; the Strawn, Canyon, and Cisco Groups of Pennsylvanian age; the Wichita Group of Permian age; the Trinity Group of Cretaceous age; and alluvium of Pleistocene to Recent age. He noted that only five water wells were known to be completed in the Ellenburger Group in Brown County, with well depth ranging from 1,436 to 4,522 feet. Three were flowing wells, and all were originally drilled for oil tests. Two were later used to supply water for petroleum secondary recovery, one was used as a swimming pool for a few years (Hot Wells, as mentioned earlier), and two others were used for domestic and livestock purposes. He also noted that Pennsylvanian and Permian rocks yield small amounts of groundwater of varying water quality that have been used for domestic and livestock purposes.

Mason (1961) conducted a groundwater study in McCulloch County (south of Brown County) that focused on the Hickory Sandstone Member of the Riley Formation, the principal aquifer in the county. The Hickory aquifer has supplied a large quantity of water with good quality (i.e., the water meets drinking-water standards), most municipal, industrial, and irrigation uses relying on the Hickory aquifer. There, the Ellenburger aquifer yields a small to moderate quantity of water for domestic and livestock uses in many places across the county.

Walker (1967) conducted a groundwater study in Coleman County (west of Brown County). Sediments there in the Trinity Group of Cretaceous age (remnants) supplied a larger portion (45%) of groundwater. Rocks in the Wichita and Clear Fork Groups of Permian age supplied 40% of the groundwater, and 15% was produced from sediments of the Canyon and Cisco Groups of Pennsylvanian age, alluvium, and the Ellenburger Group of Ordovician age. He noted that several Ellenburger wells in the north part of the county were used to provide water for secondary recovery of oil. Two Ellenburger wells near the southeast corner of the county supply water for livestock use (TDS 1360 and 4860 mg/L).

Preston et al. (1996) conducted a study of Paleozoic aquifers in central Texas with a focus on the Hickory, Ellenburger, Marble Falls, and Mid-Cambrian aquifers. The core area of their study is in the Llano Uplift, where the Paleozoic rocks are closer to land surface and located toward the south and southeast of Brown County (not including Brown County). He noted that those aquifers yield good-quality groundwater close to the outcrop and that water quality deteriorates downdip. In addition, he noted that owing to the complex geological structure, especially extensive faulting associated with the uplift, groundwater flow may be compartmentalized, presenting great challenges to quantitative studies.

Relevant geological features have also been studied by many authors, a few of which are listed here. Core Laboratories Inc. (1972) compiled saline and brackish groundwater resources in Texas, and structure, thickness, and salinity for the Pennsylvanian (Bend, Strawn, Canyon, Cisco, and Wolfcamp) and Ellenburger Formations were mapped. The isopach map of the Ellenburger includes the Cambrian Riley and Wilberns Formations in Central Texas.

Geology in north-central Texas (including Brown County) was discussed in Cheney (1940). Stafford (1960) and Terriere (1960) discussed the geology of the Pennsylvanian, Lower Permian, and Cretaceous systems in Brown and neighboring counties. Barnes and Bell (1977) presented a geological study of the lower Paleozoic rocks in Central Texas (mainly the Llano Uplift region south of Brown County). Kerans (1990) studied geology of the Ellenburger Group in West Texas, and McBride et al. (2002) studied the mineralogical and geochemical character of the Hickory sandstones by analyzing nine cores in the Llano Uplift region (south of Brown County). The latter workers also reconstructed the diagenetic history of the Hickory.

A list of recent TWDB reports discussing some aspect of Brown County hydrogeology:

- R046, Occurrence and Quality of Ground Water in Brown County, Texas, by D. R. Thompson, May 1967
- R195, Volume 1, Ground-Water Resources of Part of Central Texas with Emphasis on the Antlers and Travis Peak Formations, by William B. Klemt, Robert D. Perkins, and Henry J. Alvarez, November 1975
- R195,Volume 2, Ground-Water Resources of Part of Central Texas with Emphasis on the Antlers and Travis Peak Formations, by William B. Klemt, Robert D. Perkins, and Henry J. Alvarez, January 1976
- R298, Ground-Water Resources of the Antlers and Travis Peak Formations in the Outcrop Area of North-Central Texas, by Phillip L. Nordstrom, June 1987
- R319, Evaluation of Water Resources in Part of Central Texas, by Bernard Baker, Gail Duffin, Robert Flores, and Tad Lynch, January 1990
- R346, The Paleozoic and Related Aquifers of Central Texas, by Richard D. Preston, Dianne J. Pavlicek, Robert L. Bluntzer, and John Derton, March 1996
- R339, Evaluation of the Ground-Water Resources of the Paleozoic and Cretaceous Aquifers in the Hill Country of Central Texas, 1992

More recently, Standen and Ruggiero (2007) listed old and recent literature about the geological structure of the Llano Uplift. TWDB has also undertaken, in the past decade, a long-term study to better understand the groundwater resources of the state in a program called Groundwater Availability Models (GAM, http://www.twdb.state.tx.us/groundwater/models/). GAM models exist for the Trinity and Edwards-Trinity aquifers to the south, east, and north. The GAM model for the Llano Uplift aquifers has not been completed yet, and only the static geometry of the layers is available (Standen and Ruggiero, 2007), which focuses on lower Paleozoic aquifers (Hickory and Ellenburger aquifers). However, it does not appear that Brown County will be included in the Llano Uplift GAM (currently being developed internally by TWDB, http://www.twdb.state.tx.us/ groundwater/models/gam/llano/llano.asp; to be completed in 2015), and, to date, no model of lower Paleozoic aquifers in the county has been made public, if they exist at all. However, the State of Texas, through its funding and directives to the TWDB, has shown an interest in developing the brackish-water resources of the state (http://www.twdb.state.tx.us/innovativewater/bracs/).

As an illustration of their limited regional importance, no model of the upper Paleozoic aquifers between the Trinity aquifer to the east and the Ogallala and Dockum aquifers to the west exists to our knowledge, although Nicot et al. (2012, unpublished document) have recently concluded a multicounty study of upper Paleozoic aquifers of north-central Texas. No model of the Welge or Marble Falls aquifer has been developed so far either.

IV. Geological Setting

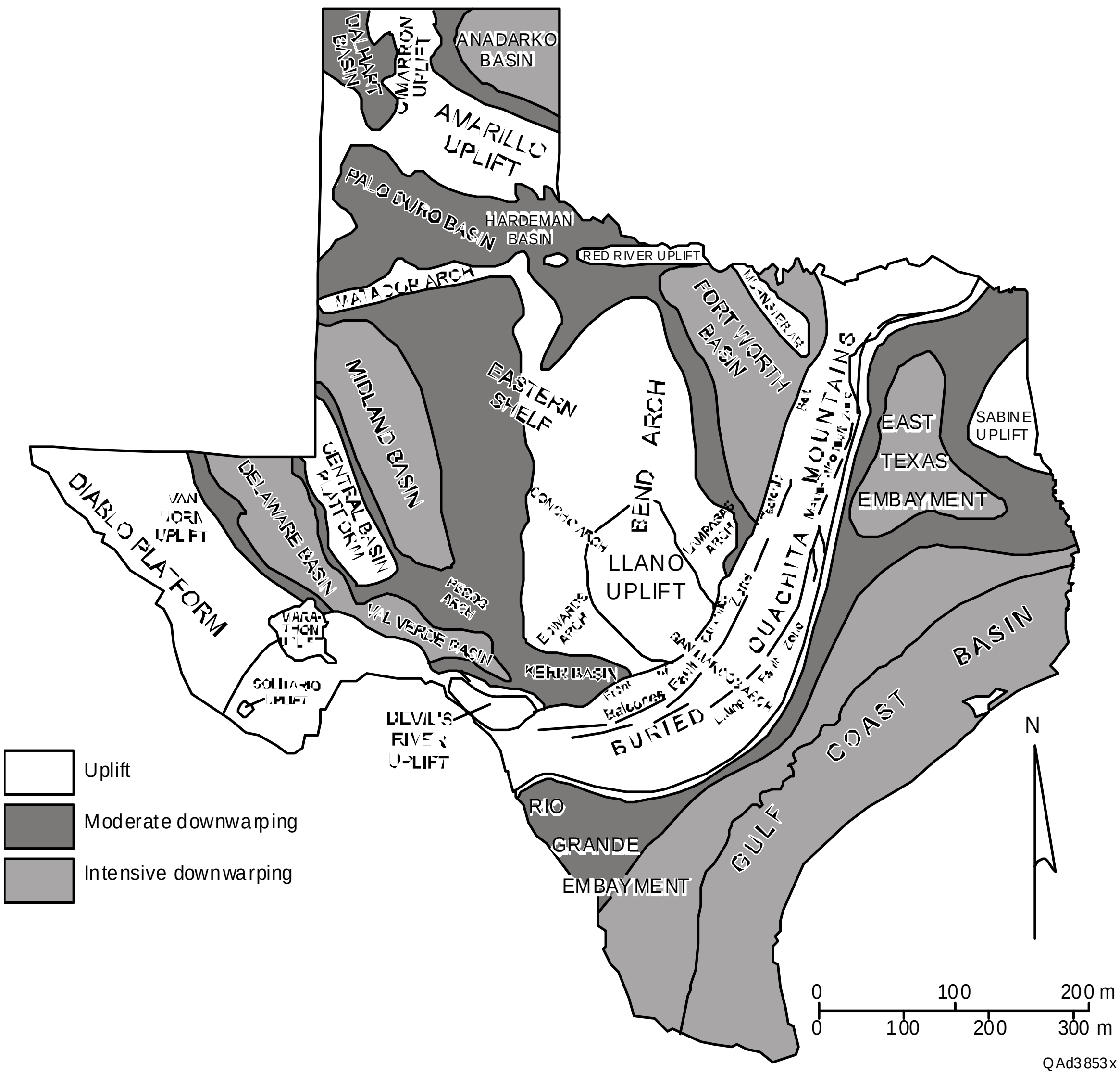
Brown County is located in Central Texas north of a prominent geological feature known as the Llano Uplift, where Precambrian rocks crop out. Regionally dipping away radially in all directions, including in the subsurface of Brown County, Paleozoic rocks of increasingly younger age are exposed around it. They are unconformably covered by Cretaceous sediments in the eastern half of the county. To the east of the uplift, a major structural feature, the Ouachita Front (or Ouachita Thrustbelt or Ouachita Mountains), divides the state into two major provinces and runs approximately from the Dallas-Fort Worth metroplex and farther east through Austin to San Antonio and beyond to the west (Figure 11). A summary of the geological history of Texas might help set the stage for arguments developed in subsequent sections.

IV-1. General Geology

The following section gives an overview of the relevant Texas geology summarized from Ewing (1991). Most of West and Central Texas is underlain by Precambrian rocks that crop out mostly in the Llano Uplift in Central Texas and locally in the Trans-Pecos area. Starting in the Cambrian period, ~550 million years ago, failed continental rifting resulted in widespread deposition of shelf sediments on a stable craton (e.g., Cambrian sediments, Ellenburger Group). Carbonate and clastic deposition continued until the Late Devonian, 350 million years ago. Thickness of the deposits varies, with a maximum in the ancestral Anadarko Basin and total removal by erosion of some formations along a broad arch oriented NW-SE on the Amarillo-Llano Uplift axis (Concho Arch). Beginning in the Mississippian Period (starting 350 million years ago), the passive-margin history of rifting and subsidence was replaced by extensive deep-marine sedimentation and tectonic convergence on the east flank of the continental margin. This convergence episode yielded the so-called Ouachita Mountains, now eroded and buried, whose trace approximately follows the current Balcones Fault Zone that runs west from San Antonio and northeast through Austin to the east of Dallas. Behind the orogenic belt, during and after the compressive event, sedimentation continued in and around several inland marine basins, north and west of the current Balcones Fault Zone. Sedimentation was thicker in the basins and thinner or absent on platforms and arches. During these Pennsylvanian and Permian times (320–270 million years ago), major subsidence and sediment accumulation, partly fed by erosion of the Ouachita Mountains, occurred in the Permian Basin. Farther north, the Anadarko Basin is separated from the Midland Basin by another basin and two structural highs. The Anadarko Basin also underwent abundant sedimentation during the Pennsylvanian and Permian and included coarse granitic detritus ("granite wash") from the Amarillo Uplift. The Fort Worth Basin (with Brown County at his south end) is also filled with Pennsylvanian and Permian sediments.

Beginning in Triassic time (250 million years ago), Texas was again subject to extension and volcanism, leading to Jurassic rifting of the continental margin and creation of the Gulf of Mexico and Atlantic Ocean. The focus of major geologic events shifted to the east part of the state. The small rift basins that initially formed were buried under abundant salt accumulation (Louann Salt). As the weight of sediments increased, the salt became unstable and started locally to move upward in diapirs, a phenomenon still active today. During the Cretaceous, sediments deposited from shallow inland seas formed broad continental shelves that covered most of Texas. Abundant sedimentation in the East Texas and Maverick Basins occurred during the Cretaceous. In the Tertiary (starting 65 million years ago), as the Rocky Mountains to the west started rising, large river systems flowed toward the Gulf of Mexico, carrying an abundant sediment load, in the fashion of today's Mississippi River. All the area west of the old Ouachita Mountain range was also lifted, generating a local sediment source, including erosional detritus from the multiple Tertiary volcanic centers in West Texas and Mexico. Six major progradation events, where the sedimentation built out into the Gulf Coast Basin, can be distinguished. The last one is still active.

This document focuses on Cambrian and Early Ordovician periods, during which the Hickory and Ellenburger sediments were deposited. However, later events, such as the building of the Ouachita Mountains and the widespread Cretaceous transgression are also relevant to the study. A simplified stratigraphic column is displayed in Figure 12.



Source: modified from Kreitler, 1989

Figure 11. Generalized tectonic map of Texas showing location of sedimentary basins.

Era	System	Group	Formation/Unit		Th. (ft)	Lithology	Hydrogeology
Cenozoic	Quaternary		Undivided		40	Alluvium and fluvial terrace	**Alluvium aquifers** Low yield
Mesozoic	Cretaceous	Fredericksburg	Undivided		240	Hard limestone, with thin clay and shale beds	Generally not saturated; no known production
		Trinity	Undivided		200+	Silt, sand, clay, and gravel	**Paluxy aquifer and Trinity Sand aquifer** Low to good yield
Paleozoic	Permian	Wichita	Undivided		190	Shale, limestone, and lenticular sandstone	**Multiple upper Paleozoic aquifers** Low yield; mostly confining units
	Pennsylvanian	Cisco	Undivided		325	Sandstone, thin limestone, and shale	
		Canyon	Undivided		560	Limestone, shale, and lenticular sandstone	
		Strawn	Undivided		1,200	Shale, limestone, and sandstone	
		Bend	Smithwick Fm. Marble Falls Limestone		500	Mudstone, sandstone, shale, and limestone	**Marble Falls aquifer**
	Mississippian Devonian		Barnett Fm. Chappel Fm. Houy Fm. Stribling Fm.				Confining unit
	Silurian		N/A		0		
	Ordovician	Ellenburger	Honeycut Fm. Gorman Fm. Tanyard Fm.		1000-1300	Limestone and dolomite, highly karstified	**Ellenburger aquifer** Low yield; slightly saline to very saline
	Cambrian	Moore Hollow	Wilberns Fm.	San Saba	300-450	Dolomite and mod. glauconitic limestone	**San Saba aquifer**
				Point Peak Shale	40-100	Calcareous shale, siltstone w/ stromatolitic bioherms	Confining unit
				Morgan Creek Limestone	110-120	Medium- to coarse-grained glauconitic limestone	
				Welge Sandstone	20-30	Brown, nonglauconitic sandstone	**Welge aquifer**
			Riley Fm.	Lion Mountain Sandstone	50-60	Quartzose glauconitic sandstone and limestone	
				Cap Mountain Limestone	0-50	Granular limestone	Confining unit
				Hickory Sandstone	150-350	Yellow, brown, and red sandstone; lenses of clay	**Hickory aquifer**
	Precambrian					Granite, schist, gneiss	**Regolith aquifer** Small yield

Based on Thompson (1967), Barnes and Bell (1977), Preston et al. (1996), and Hoh and Hunt (2004). Th. = approximate maximum thickness if there is only one number and thickness range if there are two numbers.

Figure 12. Stratigraphic columns showing nomenclature of geologic units in larger study area.

IV-2. Local Geology

IV-2-1 Precambrian and Cambrian (Hickory)

The following section gives an overview of the relevant strata near the Llano Uplift. Detailed information about the stratigraphy of the Lower Paleozoic can be found in Barnes and Bell (1977), Barnes and Cloud (1982), and Watson (1980) (up to the Marble Falls Formation). Note that, as will be discussed later, some of these strata do not exist or are of reduced thickness in Brown County. The Hickory Sandstone represents the base of the Riley Formation (Figure 12) and corresponds to the first transgression over the Precambrian basement, which is composed of NW-SE-trending gneiss, schists, and other metamorphic rocks intruded by postmetamorphic granitic plutons (Krause, 1996, p. 20; McBride et al., 2002, p. 5). The basement topography was probably irregular because actual islands persisted during Hickory deposition (McBride et al., 2002, p. 5)—and probably relatively similar to the current topography of Precambrian rocks on the Llano Uplift. Northwest-trending ridges with a relief of 200 to 250 m (600–800 ft) were inferred by Krause (1996) and Barnes et al. (1959), translating into variable thickness of the Hickory Sandstone across the area. Generation of generalized maps of the Hickory Sandstone (Figure 14, Figure 15, and Figure 17) is possible, but because of the low well density, such maps cannot capture all the thickness variations (hence their being called *generalized*). In other words, generalized thickness maps do not show locally reduced thickness because of the irregular Precambrian topography. For example, Cambrian time islands would eventually be covered by sediments but with a much smaller thicknesses than in the topographic lows around them. Because they use relatively few data points, generalized thickness maps are not necessarily fully consistent with one another (e.g., 300-ft contour line barely within Brown County in Figure 14 and clearly within it in Figure 15), although trends are similar, with a general thickness increase toward the south. Variable thickness following basement topography was described in San Saba County by Pettigrew (1991). Note that the future San Angelo well field at the convergence of Concho, McCulloch, and Menard Counties is located in an area where the Hickory Sandstone is considerably thicker (450 ft) than it is in Brown County, where generalized thicknesses range from 350 ft in the south to 150 ft to the north.

From a paleogeographic standpoint, sediments are understood to be coming from the north and northeast, where the proto-North-American craton was located at the time, transported by rivers and streams to the recently created ocean extending to the south (the Iapetus Ocean), and deposited there in a passive-margin environment. Figure 16 illustrates the transgressive nature of the Hickory Formation, starting with continental deposits, moving to estuary deposits, and then possibly shelf deposits (Cornish, 1975,'s interpretation). The transgression came from the south, and it is logical to expect that the continental deposits would be more preponderant to the north.

The Hickory is generally recognized as made up of three units: a lower unit used for hydraulic-fracturing sand exploited in quarries farther south (~100 ft but variable at the outcrop south of Brown County); a middle unit, sometimes more argillaceous (~270 ft at the outcrop); and an upper unit cemented by hematite and other iron-based material (~90 ft at the outcrop) (Kier et al., 1976; GAT sheet).

The Cap Mountain Sandstone (Figure 12) conformably overlies the Hickory Sandstone and has a gradational contact that is mapped as the point at which the lime content of the formation exceeds the sand content. As a consequence, the upper Hickory Sandstone may contain lime-rich sands, and the lower Cap Mountain Limestone may contain sandy limestone beds (Smith, 2004). Its thickness seems to be maximum where the Llano Uplift currently stands (although the uplift did not exist at the time) at >500 ft in Menard and Kimble Counties and farther south and decreases toward the north, although it exists only mostly south of the Brown County area, where its thickness drops to 0 ft in the middle of the county from ~50 ft at the south edge of the county (Figure 18). The Cap Mountain Limestone consists mostly of carbonates and is considered a confining unit.

The Lion Mountain Sandstone (Figure 18), which forms the youngest of the three members of the Riley Formation, has a generalized thickness of approximately 50 ft (Figure 19). In the north half of Brown County, it rests directly on top of the Hickory, but it is distinguishable from it because of its glauconitic nature (greensand). It is also shaly in its upper part (Barnes and Schofield, 1964, p. 27). Some erosion on top of the Lion Mountain occurred before deposition of the Welge Sandstone, base unit of the Wilberns Formation (Figure 20). It is a nonglauconitic sandstone generally distinguishable from the underlying Lion Mountain Sandstone. Its thickness in Brown County is small (20–30 ft). In addition, calcite cement locally reduces its permeability (Barnes and Schofield, 1964, p. 28).

Overlying the Lion Mountain Sandstone, the Point Peak Shale and Morgan Creek Limestone can be found. The former is mostly a calcareous mudstone and siltstone (Figure 22), whereas the latter consists mostly of a glauconitic limestone (Figure 21). They form the aquitard separating the Cambrian sandstone aquifers from the overlying carbonate aquifers. Note that the Cambrian limestones have limited porosity and did not go through long emergence episodes as the Lower Ordovician carbonates of the Ellenburger Group did.

The last member of the Cambrian Wilberns Formation, the San Saba Limestone member (Figure 24), is attached to the Lower Ordovician Ellenburger Group because they are in hydraulic communication. Smith (2004) stated that the upper part of the San Saba is considered Ordovician, and the contact between the San Saba Limestone and the Ellenburger Group is conformable over most of its extent. Its generalized thickness in Brown County ranges from 350 ft in the north and west to 450 ft in the southeast corner of the county. The thicknesses of the four viable lower Paleozoic aquifers are compared in Figure 23.

Hickory Petrography

Hickory sediments have been described as marine by recent authors (e.g., McBride et al, 2002), although the general idea of topography-dominated deposition is still valid (Figure 16). Barnes and Bell (1977) described the Hickory Sandstone composition as poorly sorted sand, granules, finer materials, and some pebbles, some of which at the base of the member are wind abraded. McBride et al. (2002) noted the Hickory sandstones are relatively uniform in texture, composition, and degree of cementation. McBride et al. (2002) described the Hickory as chiefly marine sandstone with minor mudrock, conglomerate, limestone, and ironstone. They noted that although sediments were derived ultimately from the Precambrian basement, some were reworked from fluvial deposits and eolian dunes. Whereas McBride et al. (2002) recognized eight facies of the Hickory from their samples (Figure 13), Pettigrew (1991), in San Saba County, divided the sediment roughly into three facies. The lower facies is a fine- to coarse-grained, poorly sorted sand with rounded to subrounded grains and minor amounts of siltstone and shale. The middle facies interfingers with the lower facies and is composed of layers of coarse- to medium-grained sand interbedded with fine-grained sand, silt, and shale. The upper facies is medium- to coarse-grained, well rounded, hematitic sandstone. The Hickory is sometimes rich in iron cement and iron ooids ("ironstone" forms ~8% overall, McBride et al., 2002, p. 10) but consists mostly of sandstone (85%). Kim (1995, his Table 1) observed that the base was richer in feldspars, whereas iron-oxide ooids and hematitic cement were frequent at the top of the sandstone. Facies, rock type, and environmental interpretations by Cornish (1975) and Krause (1996) from their respective studies are shown in Figure 16.

McBride et al. (2002) noted that the Hickory sandstones have undergone a complex history of physical and chemical compaction, recrystallization, dissolution, oxidation, reduction, grain fracturing, and authigenic mineral generation. Diagenesis occurred through syndepositional events, burial events (compaction, grain deformation, cementation, dissolution, and precipitation), and events related to uplift and near-surface exposure. Concerns that deep basinal brines pushed by the Ouachita collision toward what is now Brown County would occlude pores, but it does not seem to have happened. The Hickory sandstones in the McBride et al. (2002) study area (south of Brown County, see Figure 15) have been sampled from cores and near-surface exposure and have demonstrated that shallow burial over a long time span did not impact porosity, which remains good as long as maximum burial depth did not reach 3000 feet. Kupecz and Land (1991, Fig. 5) demonstrated that the ~1000-ft-thick Ellenburger never had >1000 ft of overburden in the Llano Uplift area. It follows that Brown County Hickory Sandstones have experienced mostly similar histories (except for the lack of recent exposure) and most likely contain large rock volumes with good porosity.

IV-2-2 Ordovician (Ellenburger)

The Lower Ordovician is represented by a massive carbonate shelf, denoting a lack of clastic sediments from the North American craton (Mason, 1961; Thompson, 1967). The carbonate platform invaded the craton farther than the Cambrian seas did, resulting in Ellenburger deposits being in direct contact with the Precambrian—for example, in the Midland Basin of West Texas. The Ellenburger Group is composed of three formations, only two of which still exist in Brown County (Figure 12): the Tanyard and the Gorman Formations. The younger formation, the Honeycut Formation, was eroded in the Paleozoic era before deposition of the Pennsylvanian sediments. Tanyard and Gorman Formations can also be locally thinned by erosion (Figure 25, Figure 26, Figure 27). The Tanyard Formation (535–600 ft at the outcrop south of Brown County) and Gorman Formation (300–475 ft at the outcrop south of Brown County) have a combined thickness of 750 to 1000 feet in Brown County (Figure 25). The Honeycut Formation could be as much as 325 feet thick at the outcrop but is locally inexistent and was eroded before deposition of Mississippian sediments in the study area except, perhaps, in the extreme east of Brown County (Figure 26).

The Ellenburger consists chiefly of gray to yellowish-gray, fine- to coarse-grained limestone and dolomite, parts of which are vugular or porous. Kerans (1990), as illustrated by Kupecz and Land (1991) in Figure 28, recognized six depositional systems and corresponding sedimentary facies for the Ellenburger: (1) fan delta–marginal marine (litharenite), (2) lower tidal flat (mixed siliciclastic-carbonate packstone/grainstone), (3) high-energy restricted shelf (ooid and peloid grainstone), (4) low-energy restricted shelf (mottled–bioturbated mudstone), (5) upper tidal flat (laminated mudstone), and (6) open shallow-water shelf (gastropod–intraclast–peloid packstone/grainstone). Kerans (1990) noted that "the first four depositional systems are pervasively dolomitized, whereas the upper tidal-flat system is somewhat less dolomitized, and the open shallow-water shelf system displays minor patchy dolomite."

Ellenburger Petrography

Ellenburger sediments were deposited mostly as mudstones in a limestone-dominated, open shallow-water shelf (Figure 28). Early marine diagenesis (micritization, early rim cements) of deposits was followed by widespread blocky calcite cementation. Extensive replacement and cementation by dolomite in this predominantly mudstone sequence resulted in very low average interparticle and intercrystalline porosity. Kerans (1990) observed that nearly all porosity of the Ellenburger is of secondary origin. Dolomitization created vuggy and intercrystalline porosity. Karstification at the end of the Early Ordovician enhanced porosity development (details in a later section).

IV-2-3 Younger Paleozoic Formations

Silurian and Devonian deposits had been nearly completely eroded in the Llano Uplift area before deposition of Mississippian sediments. The Mississippian, including the well-known Barnett Shale, is present in Brown County, where its thickness ranges from ~150 ft in the north to ~50 ft in the south (Montgomery et al., 2005; Pollastro et al., 2007, Fig. 6) but is impacted by late action of the Ellenburger karstic features. The Marble Falls carbonate platform of the Bend Group of Early Pennsylvanian age (Kier, 1980) extends unconformably over the Barnett Shale and is generally not in direct contact with the Ellenburger Group in Brown County. The post-Marble Falls Early Pennsylvanian marks a transition in sediment type/nature/origin, from relatively steady regional environments producing relatively continuous deposits, to depositional systems heavily impacted by the Ouachita orogeny and more fragmented. This contrast in depositional context has obvious consequences in terms of hydrogeological behavior. Strawn, Canyon, and Cisco Groups of Pennsylvanian age in the Fort Worth Basin represent periods with sometimes abundant clastic sediments that were deposited in both transgressional and retrogressional shallow-sea environments but not of regional extent.

The Strawn Group is composed principally of alternating beds of sandstone and shale that represent nearshore deposits. The Canyon Group is composed of thick limestone with shale and little sandstone. The sandstone lenses in the Canyon Group represent valley-fill, channel-fill, and delta-front deposits. Local disconformities and channeling are apparent in Cisco strata, indicating that the shelf environment of late Canyon time became more and more deltaic locally during Cisco time. The Wichita Group, composed of marginal marine and marine facies of shale and sandstone, contains many channel deposits as well (Thompson, 1967; Cleaves and Erxleben, 1982; Hentz, 1988).

IV-2-4 Cretaceous and Younger Formations

The Llano Uplift area was not submerged during the Triassic and Jurassic periods, or, if it was, the sediments were thin and were removed by erosion before the large Cretaceous sea invasion. At that time, the ocean deposited siliciclastic and carbonate sediments over a large swath of Texas to form a major unconformity on the Paleozoic rocks. Cretaceous sediments were removed by erosion in most of Brown County, where the Trinity Group is present in the eastern third of the county having a thickness of >200 ft (Thompson, 1967, Table 2), as well as in remnants of various sizes across the county. In a process reminiscent of the deposition of the Hickory

Sandstone, the Hosston Sands at the base of the Trinity Formation were deposited on an uneven surface, and their thickness varies. The basal sands of the Cretaceous transgression exhibit a complex nomenclature and are variously called Antlers, Hosston, Sycamore, or Trinity (R.W. Harden & Associates, 2004, their Fig. 4.1; Figure 29), but they also make up the base of the Travis Peak Formation (known as the Twin Mountain Formation just north of Brownwood and beyond to the north). They are of mostly of fluvial or deltaic origin (Woodruff and McBride, 1979, p. 67). Farther east toward the Balcones Fault Zone and beyond, where the section is thicker and of lagoonal and shallow-marine origin, shaly calcareous horizons are present between the Antlers/Hosston and another sandy formation known as the Hensel Formation. Combined thickness of the Hosston and Hensel Formations is ~100 ft in Brown County (R.W. Harden & Associates, 2004, Figs. 4.12 and 4.15). The Trinity Group is topped by the Glen Rose Formation (thick series of limestones) and the Paluxy Formation (mostly sands). The Trinity Group is overlain by the limestone-dominated Fredericksburg Group (including the Edwards Limestone), capping the hills in the landscape. In Brown County, the Fredericksburg Group is mostly dry and part of the unsaturated zone. In an observation that could impact recharge to lower Paleozoic aquifers, note that, in Central Texas, the Trinity Sands are a dip-oriented aquifer; that is, zones of high-permeability-channeling flow tend to be along dip, i.e., along fluvial paleochannels. The Llano Uplift had clearly emerged by the time, probably feeding sediments to the fluvial system. Farther east, they become strike oriented because the main rock-type grain is now more or less parallel to the ancient shoreline. The Paluxy Sands in the Brown County area are mostly strandplain deposits (shoreline more or less E-W) with some fluvial influence (channels coming mostly from the north) (Woodruff and McBride, 1979, p. 98 and Fig. 66), but the major Paluxy depocenters are toward the east in East Texas. Paluxy Formation thickness is ~50 ft in Brown County (R.W. Harden & Associates, 2004, Fig.4.9).

In addition, Pecan Bayou River has mapped alluvium on the Brownwood GAT sheet (http://www.twdb.state.tx.us/groundwater/aquifer/GAT/). Thompson (1967, p. 10) described them as yielding only small amounts of water.

IV-2-5 Structural Features

An understanding of structural features and their history as they impact sediment deposition and, more broadly, current groundwater flow is important. Faults, in particular, can act as barriers to flow and channelize flow or can put in direct contact permeable layers that would otherwise be separated by aquitards. The wider Llano Uplift area has seen three main cycles of deformation: (1) an extended Precambrian phase dating back from ~1 billion years (Greenvillian orogeny) that produced schists, gneisses, and granitic bodies currently visible in the Llano area, followed by a long episode of peneplanation (i.e., erosion of the mountain range); the ocean invaded the continent during the Cambrian (~550 million years ago) to deposit sediments starting with the Hickory Sandstone; (2) a deformation of the accumulated sediments by the second major phase, the Ouachita Orogeny (~350 million years ago), which thrust a southern continent against the continent of which the Llano Uplift was a part to create the Ouachita front suture line and a mountain range that is now eroded and whose roots are buried; and (3) a final phase linked to the Mesozoic opening of the Gulf of Mexico (Triassic to Early Jurassic periods) and the later formation of the regional down-to-the-coast Miocene normal Balcones Fault System it later created (Balcones Fault Zone).

Very noticeable structural features are the NW-SE Precambrian grain being superposed by the NE-SW Ouachita-related fold orientation. The latter system is well expressed at the surface close to the Ouachita Front, but its density decreases toward the west (Figure 30). Consultation of the structural map of Texas by Ewing (1991) shows that, on an E-W profile starting in Bosque County to the east and continuing through Hamilton and Comanche Counties, the density of NE-SW-trending faults decreases into Brown County (sampling artifact due to depth?). The NE-SW fault system cuts through sediments up to the Marble Falls (Lower Pennsylvanian) but dies out in Strawn and Canyon sediments (Middle Pennsylvanian). The most active period of faulting occurs during the Middle Pennsylvanian Ouachita orogeny (McBride et al., 2002, p. 46), impacting both Hickory and Ellenburger Formations. Cretaceous rocks are not impacted by these almost vertical faults in Brown County (but they are farther east along the Balcones Escarpment, which can be considered a reactivation of older Ouachita faults). In the uplift proper, faults of both NW-down and SE-down displacements are well balanced, but toward the east, these are predominantly SE-down with large throws (Ewing, 2004, p. 29–30). They are mostly normal faults, and some NS-trending faults may have a significant strike-slip component (e.g., in the Llano area; they are, however, not present in Brown County, according to Ewing, 1991). Ewing (1991) called them collectively the Llano Fault Zone, which consists of a series of NE-SW-trending regional conjugate normal faults individualizing several grabens. Two are particularly noticeable on the geologic map (Llano GAT sheet, Barnes, 1981): the Mason Graben and the Riley Mountains Graben (Figure 31). Their throw can be >2000 ft, and no major faulted structure seems to exist west of the Mason Graben Fault Zone. The fault zone in the SE corner of Brown County appears in continuity with this zone, but it is a basement high rather than a graben. The Balcones Fault Zone, a system of high-angle, NNE-SSW-trending normal faults with downthrown blocks toward the Gulf of Mexico impacting Cretaceous and early Cenozoic layers, is most likely the latest manifestation of the Ouachita Front. It does not seem to have had a major impact on Brown County.

Gentler features also exist, such as the Bend Arch (or the Bend Flexure) extending north from the Llano Uplift through Brown County and north to the Red River Uplift. It consists of a gentle arching of the strata associated with the Ouachita Orogeny. Earlier strata, in particular, Hickory Sandstone, Ellenburger Group, and Marble Falls Limestone, are passively entrained by the arching, whereas thickness of Pennsylvanian sediments (Strawn to Cisco Groups) is reduced toward the arch. It came into existence during early or middle Strawn times (Pennsylvanian) as a result of the differential subsidence of the Midland Basin and the eastern Midland Shelf (Cheney, 1929; Thompson, 1967). Llano uplift is just the extreme manifestation of the Bend Arch of N-S orientation (Figure 32 and see Ewing, 1991, p. 9; Ewing, 2004, his Fig. 2). Another arch, the Concho Arch, had been active during the Ordovician through Devonian periods, perhaps impacting the deposition of Ellenburger sediments, but certainly impacting the amount eroded (including in Brown County).

Group	Formation/Unit		Rock type and depositional environment
Ellenburger Group	Honeycut Fm.* Gorman Fm.		An open, shallow-water, shelf depositional system containing bioturbated mudstone, peloidal and ooid grainstones, intraclastic breccias, cryptalgal laminated mudstones, and thin, quartz arenite beds
	Tanyard Fm.		Tidal-flat and high-energy restricted-shelf conditions (ooid shoals, intershoal bioturbated mudstones, supra-shoal cryptalgal laminites with silicified evaporite nodules)
Moore Hollow Group	Wilberns Fm.	San Saba	Limestone and dolomite, partly stromatolite bearing and glauconitic, but containing calcareous sandstone and sandy dolomite in the western uplift; laterally variable
		Point Peak	Terrigenous siltstone, silty and stromatolitic limestones, and flat-pebble conglomerate, 52 m thick
		Morgan Creek Limestone	Intertidal, shallow shelf and shoal oolitic, glauconitic, and stromatolitic limestone, 38 to 44 m thick
		Welge Sandstone	Medium-grained marine quartz sandstone , 3 to 9 m thick
	Riley Fm.	Lion Mountain Sandstone	A regressive, tidally dominated, progradational, argillaceous glauconite greensand with carbonate trilobite coquina lenses and beds, totaling 6 to 23 m in thickness
		Cap Mountain* Limestone	Progradational intertidal, subtidal, and shallow-shelf sandstone/siltstone and transgressive shallow-shelf and shoal-carbonate packstones and fossiliferous grainstones, with a total thickness of 0 to 150 m
		Hickory Sandstone	A mixture of red weathering, terrestrial (basal), and transgressive marine arkosic to quartz arenitic sandstone/siltstone, mudstone, and ironstone that is 0 to 153 m thick

*: Does not exist in most of Brown County
Source: Helper (2000)

Figure 13. Rock type and depositional environment for Moore Hollow (Upper Cambrian) and Ellenburger (Lower Ordovician) Groups.

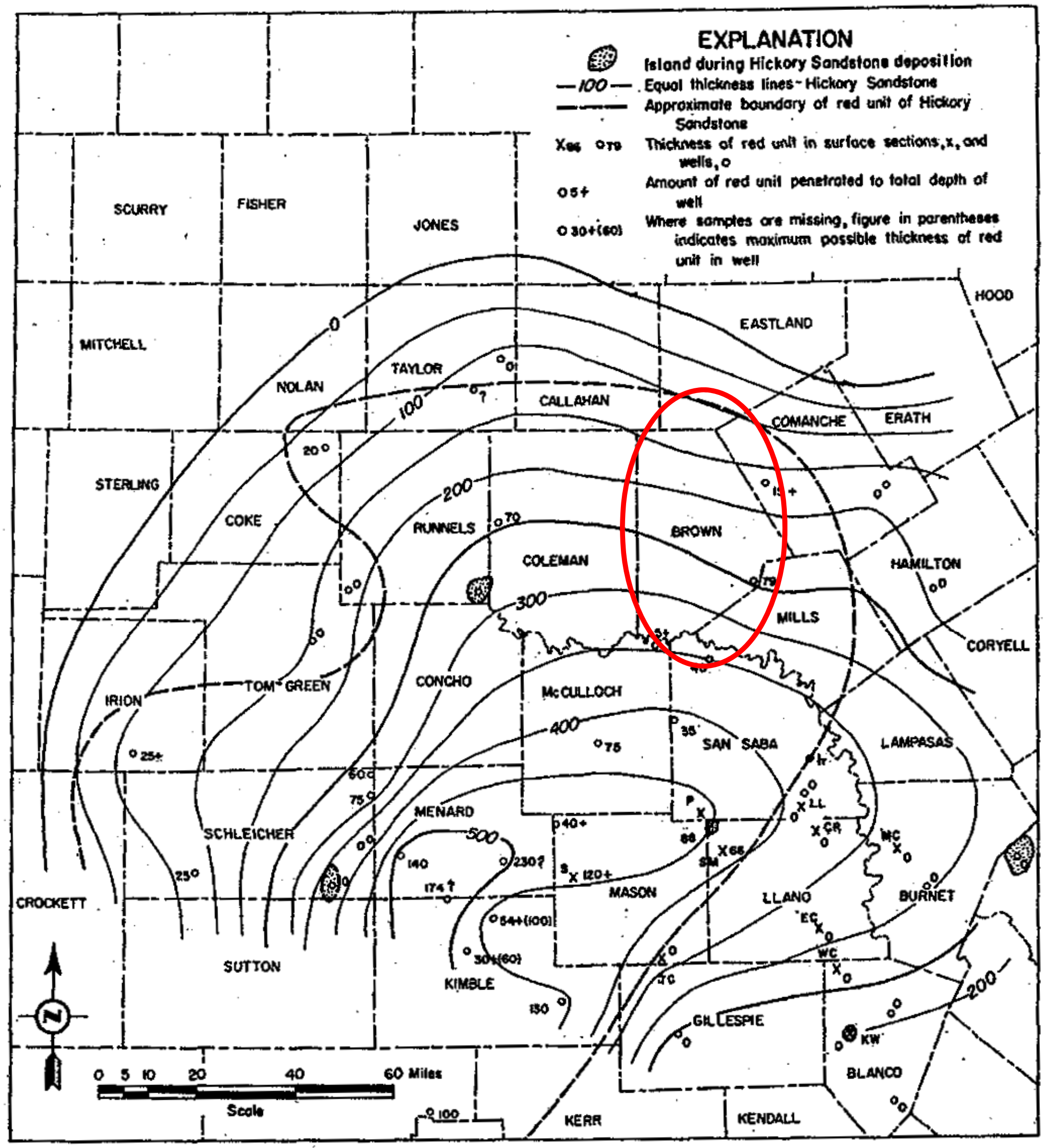


FIG. 2. Thickness map of Hickory sandstone in Texas showing distribution of red unit.
Surface sections: Carter ranch, CR; East Canyon, EC; Klett-Walker, KW; Little Llano River, LL; Morgan Creek, MC; Pontotoc, P; Slick Mountain, SM; Streeter, S; Threadgill Creek, TC; and White Creek, WC.

Source: Barnes and Schofield (1964)
Note: “Red unit” (in scanned legend) is top unit of Hickory Sandstone. Note paucity of well coverage in, for example, Concho County.
Note: thickness in feet

Figure 14. Generalized Hickory Sandstone thickness map (example 1).

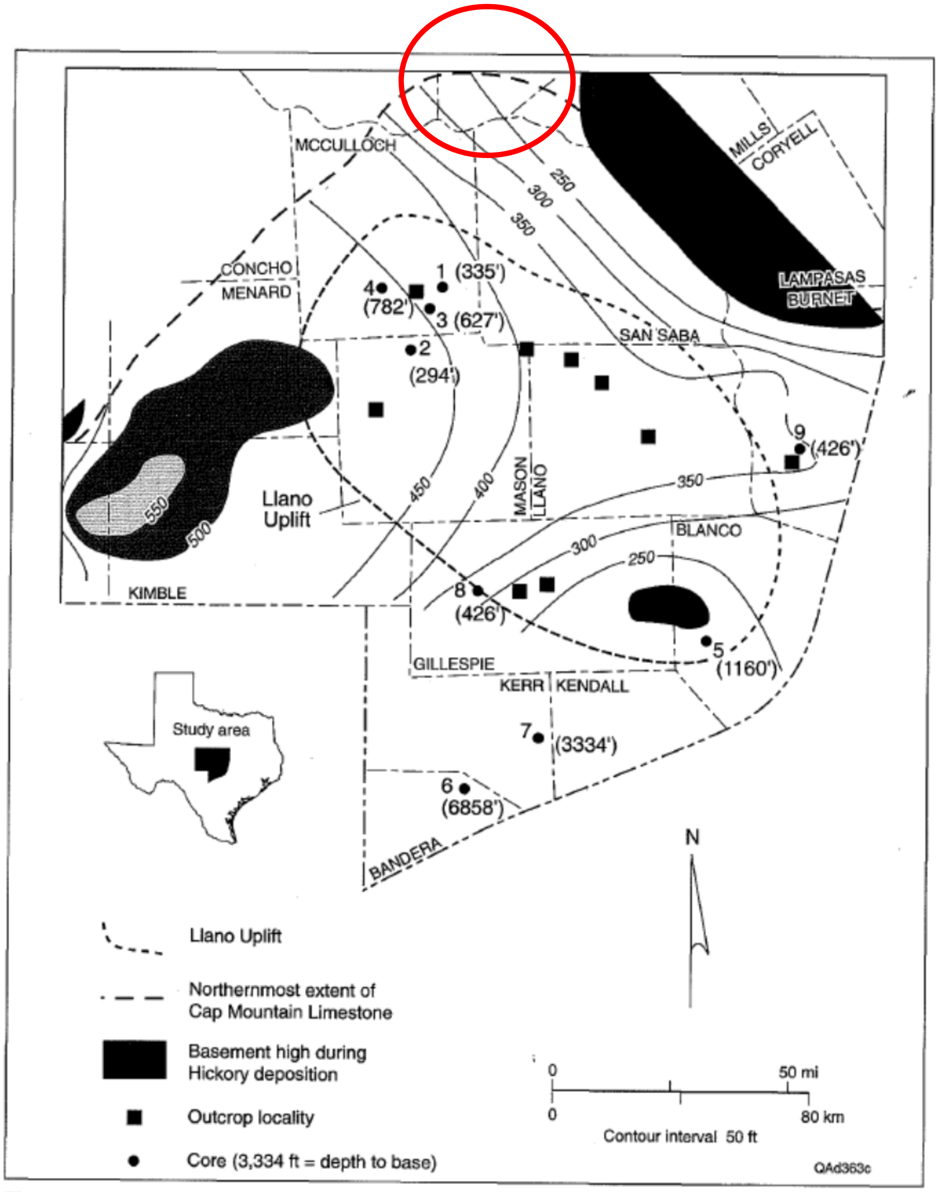


Figure 1. Map of study area. Numbered cores shown in figure 2. Isopach data for the Hickory are after Cornish (1975); hachured areas identify thickest part of formation.

Source McBride et al. (2002)
Note: thickness in feet

Figure 15. Generalized Hickory Sandstone thickness map (example 2).

Facies number	Facies name	Rock type	Cornish (1975)	Krause (1996)
8	Laminated sandstone	Sandstone, laminated, calcite cemented; grainstone lenses; 0 to 5 m thick	Shelf, storm dominated	Tidal flat and shoreface
7	Even-bedded sandstone	Sandstone, planar bedded; interbedded siltstone; 20 to 35 m thick	Shelf, storm dominated	Subtidal platform
6	Mudstone	Mudstone, laminated, gray-green; sand and pebble lenses; 12 m thick	Not seen	Lagoon
5	Ironstone	Sandstone with iron-oxide ooids; ferruginized fossils; grainstone lenses; to 35 m thick	Estuary channel and shoal	Shallow subtidal shoal
4	Siltstone	Sandstone and interbedded siltstone and minor claystone; 35 m thick	Estuary bar and channel fill	Shallow subtidal inner platform
3	Burrowed sandstone	Sandstone, crossbedded, bioturbated; interbedded siltstone and claystone; to 35 m thick	Tidal channel and tide flat	Shallow subtidal embayment marginal to sand flats
2	Basal crossbedded sandstone	Sandstone, crossbedded, trough and planar; channel fills; 0 to 50 m thick	Estuary channel and shoal	Estuarine channels and intertidal sand flat
1	Basal sandy conglomerate	Conglomerate; muddy conglomerate; crossbedded sandstone; lateritic paleosol; 0 to 60 m thick	Not seen	Alluvial fan and braided stream

Source: Adapted from McBride et al. (2002)

Figure 16. Facies and rock type of Hickory and environmental interpretation.

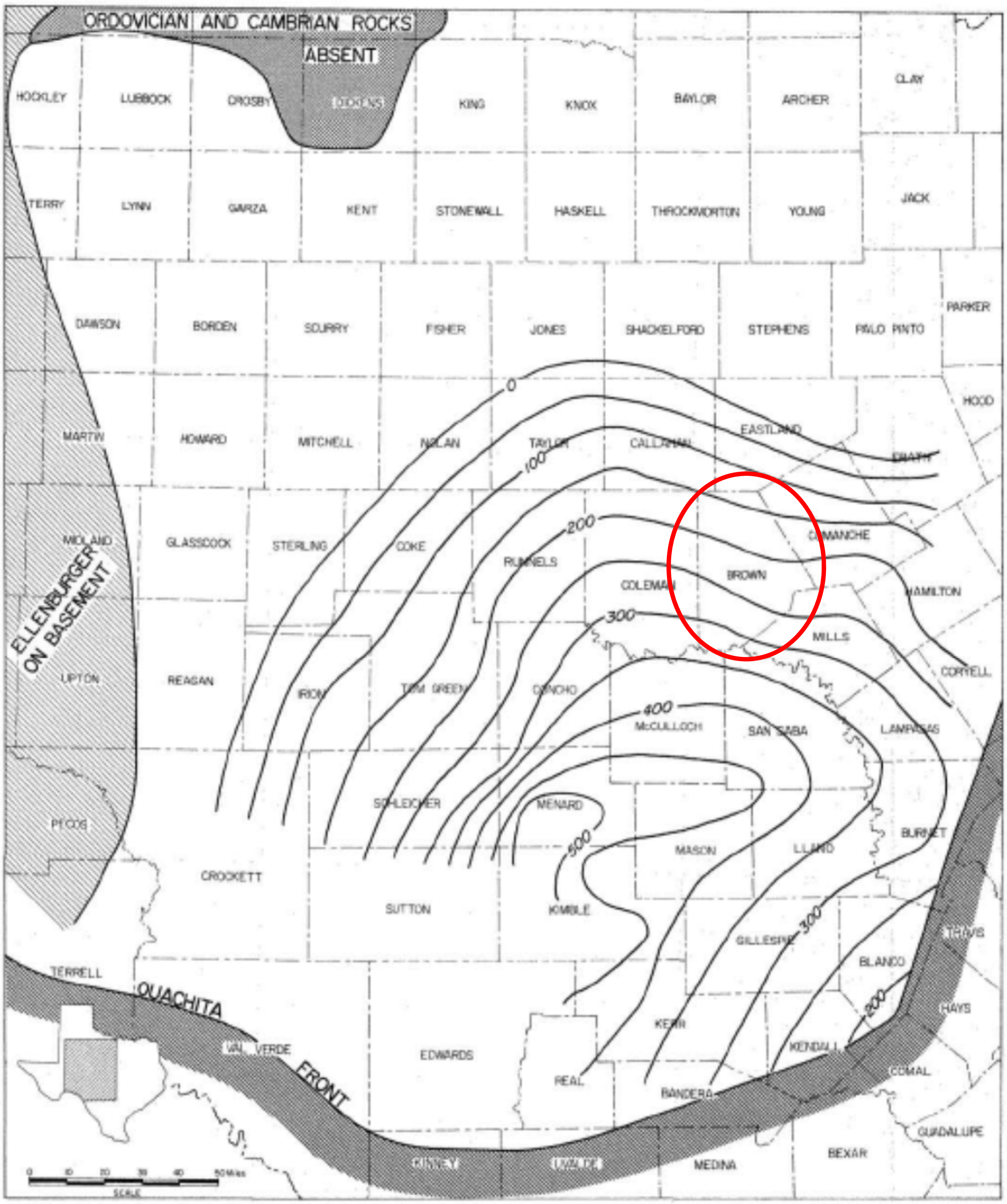


Figure 4. Isopach map of Hickory Sandstone Member of Riley Formation, Central Texas.

Source: Barnes and Bell (1977)
Note: thickness in feet

Figure 17. Generalized Hickory Sandstone thickness map (example 3).

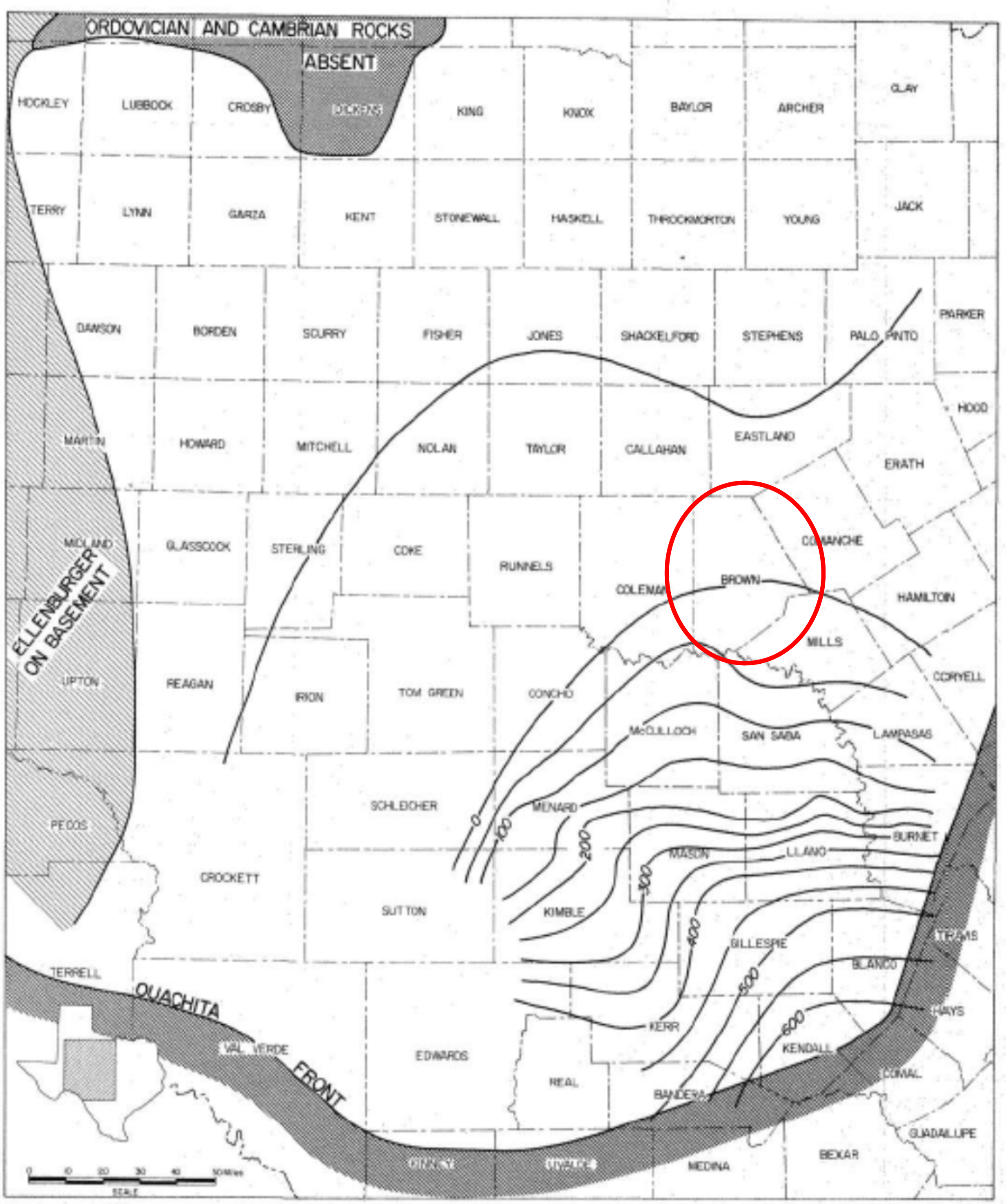


Figure 5. Isopach map of Cap Mountain Limestone Member of Riley Formation, Central Texas.

Source: Barnes and Bell (1977)
Note: thickness in feet

Figure 18. Generalized Cap Mountain Limestone thickness map.

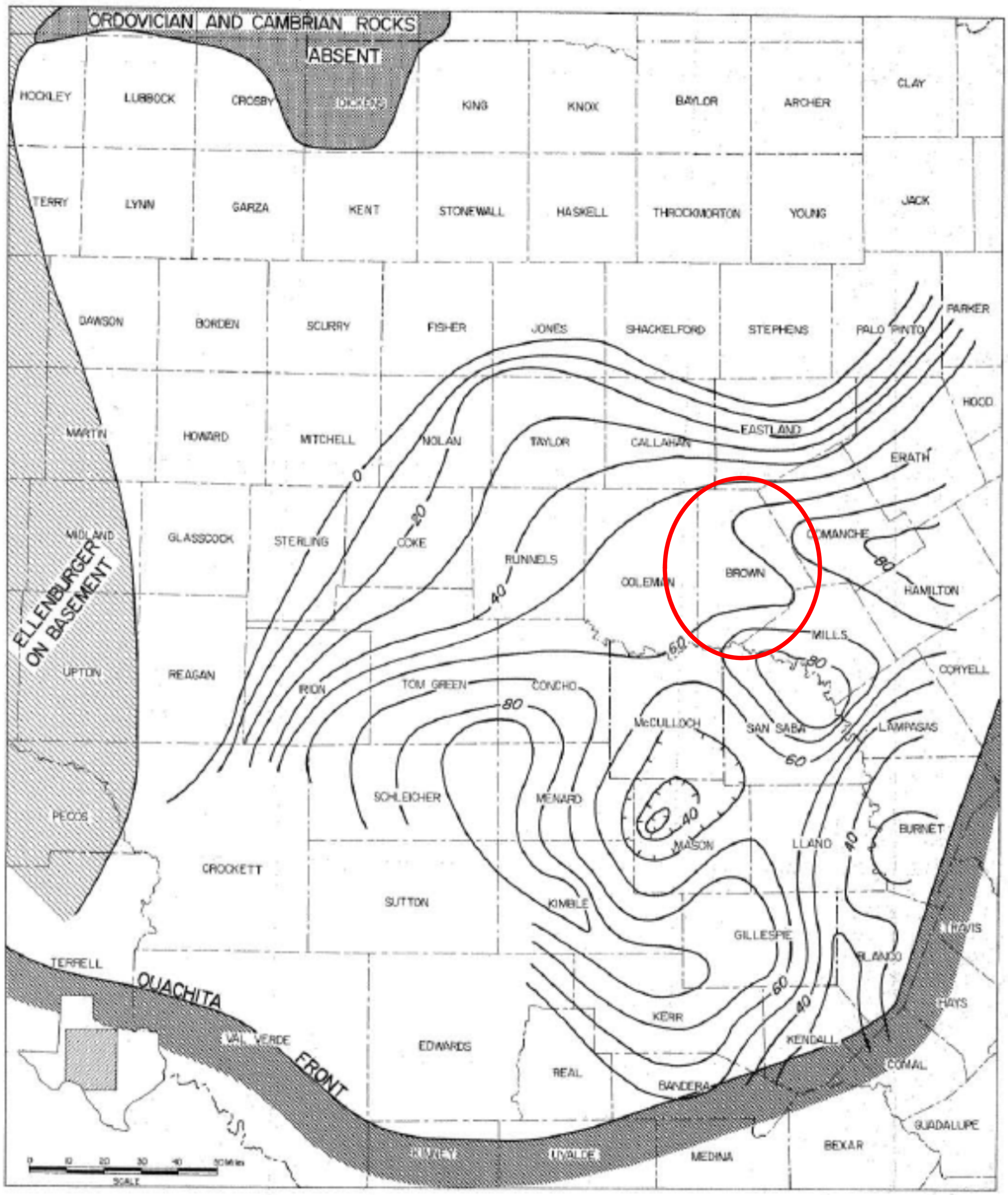


Figure 6. Isopach map of Lion Mountain Sandstone Member of Riley Formation, Central Texas.

Source: Barnes and Bell (1977)
Note: thickness in feet

Figure 19. Generalized Lion Mountain Sandstone thickness map.

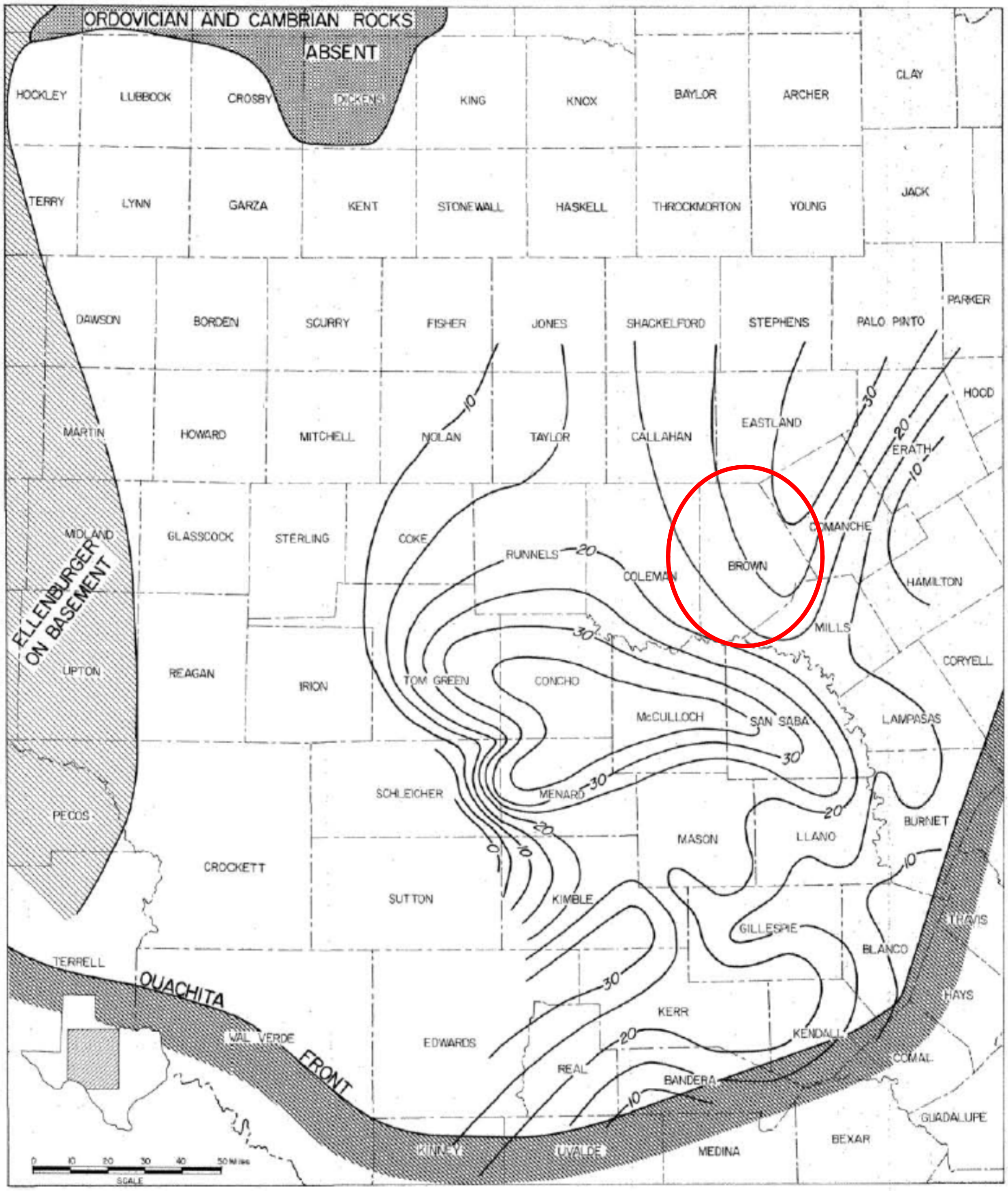


Figure 8. Isopach map of Welge Sandstone Member of Wilberns Formation, Central Texas.

Source: Barnes and Bell (1977)
Note: thickness in feet

Figure 20. Generalized Welge Sandstone thickness map.

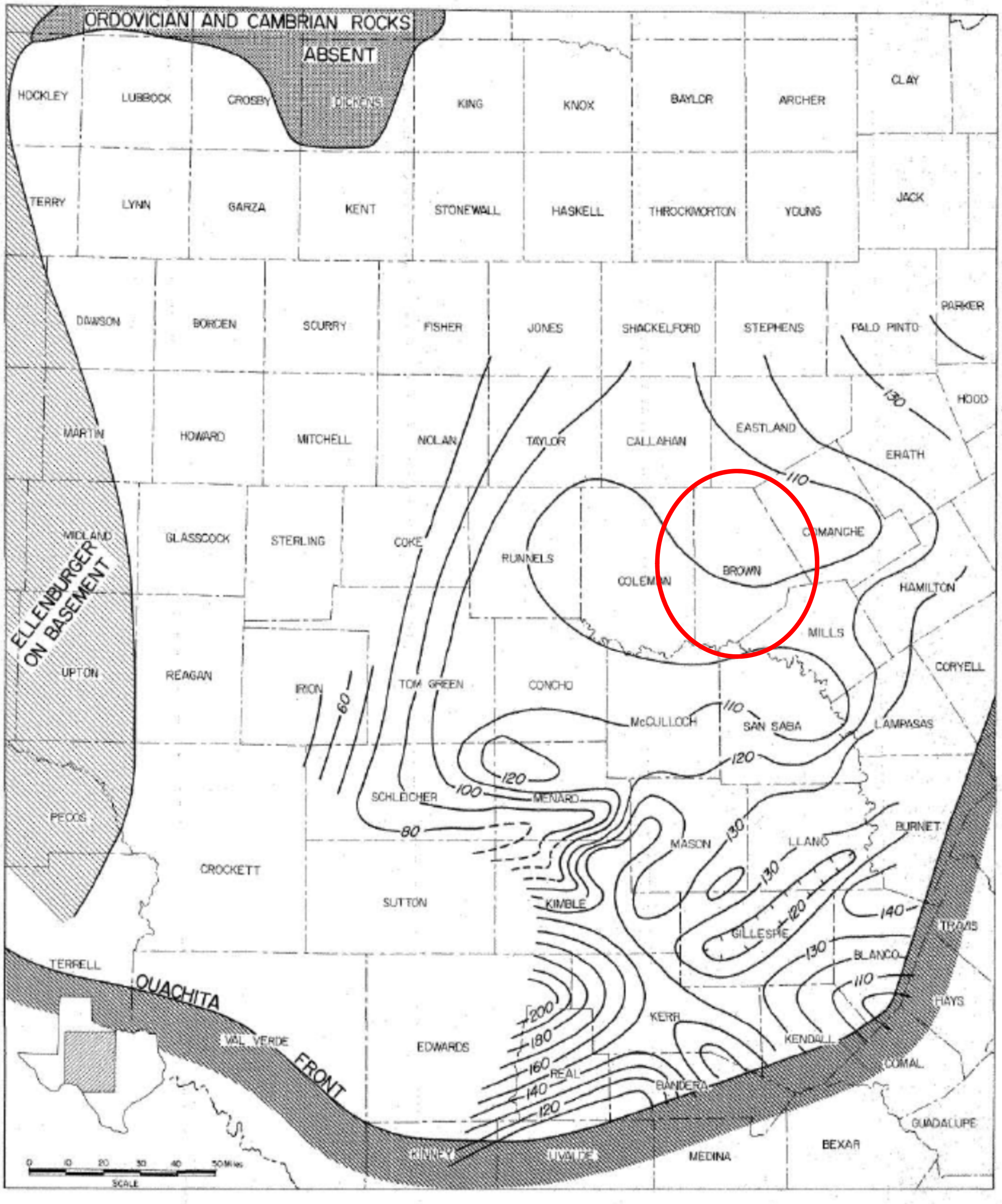


Figure 9. Isopach map of Morgan Creek Limestone Member of Wilberns Formation, Central Texas.

Source: Barnes and Bell (1977)
Note: thickness in feet

Figure 21. Generalized Morgan Creek Limestone thickness map.

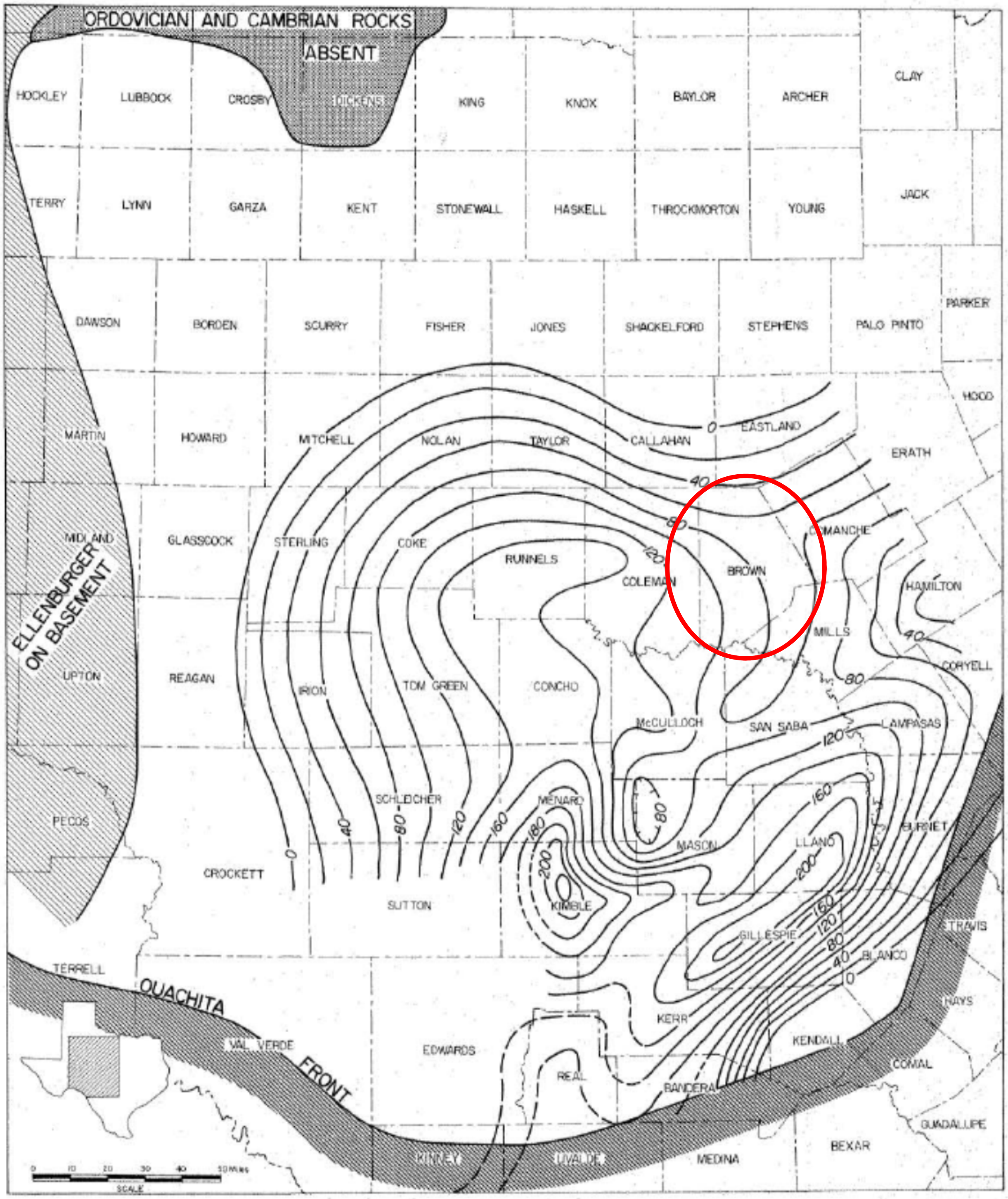
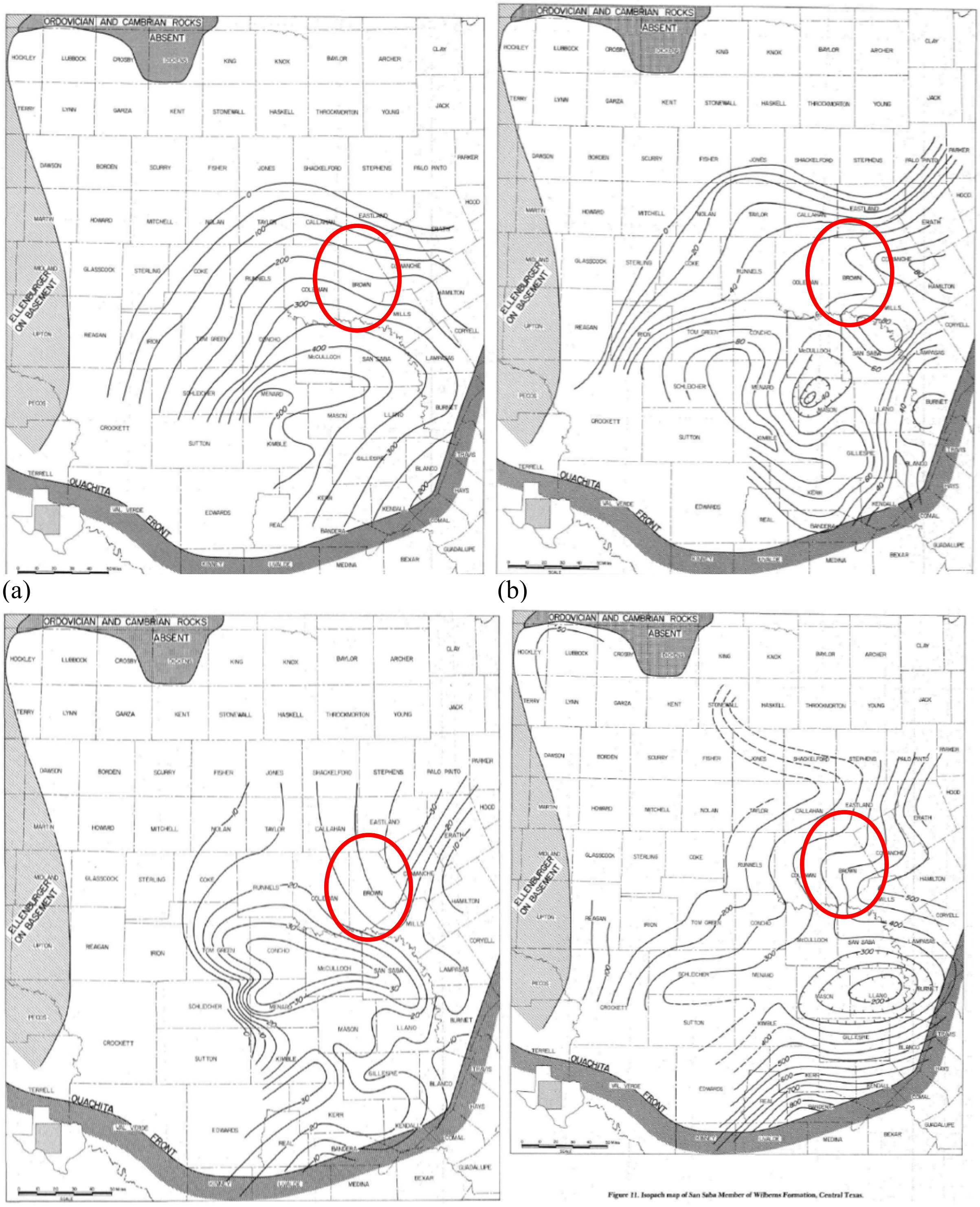


Figure 10. Isopach map of Point Peak Member of Wilberns Formation, Central Texas.

Source: Barnes and Bell (1977)
Note: thickness in feet

Figure 22. Generalized Point Peak Shale thickness map.



(a) (b) (c) (d)

Source: Barnes and Bell (1977)
Note: thickness in feet

Figure 23. Generalized thickness maps of water-bearing Cambrian units: (a) Hickory, (b) Lion Mountain, (c) Welge, (d) San Saba.

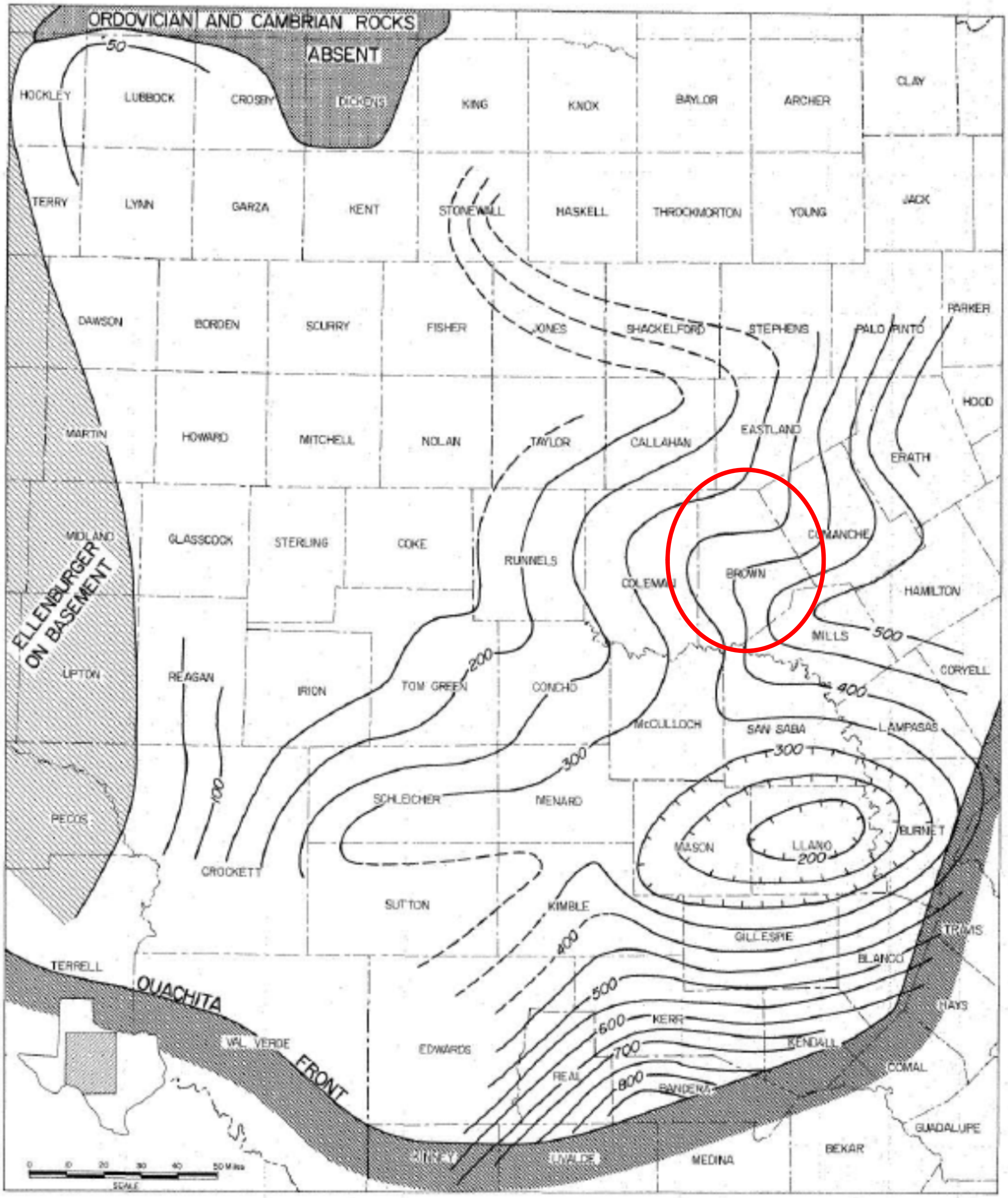
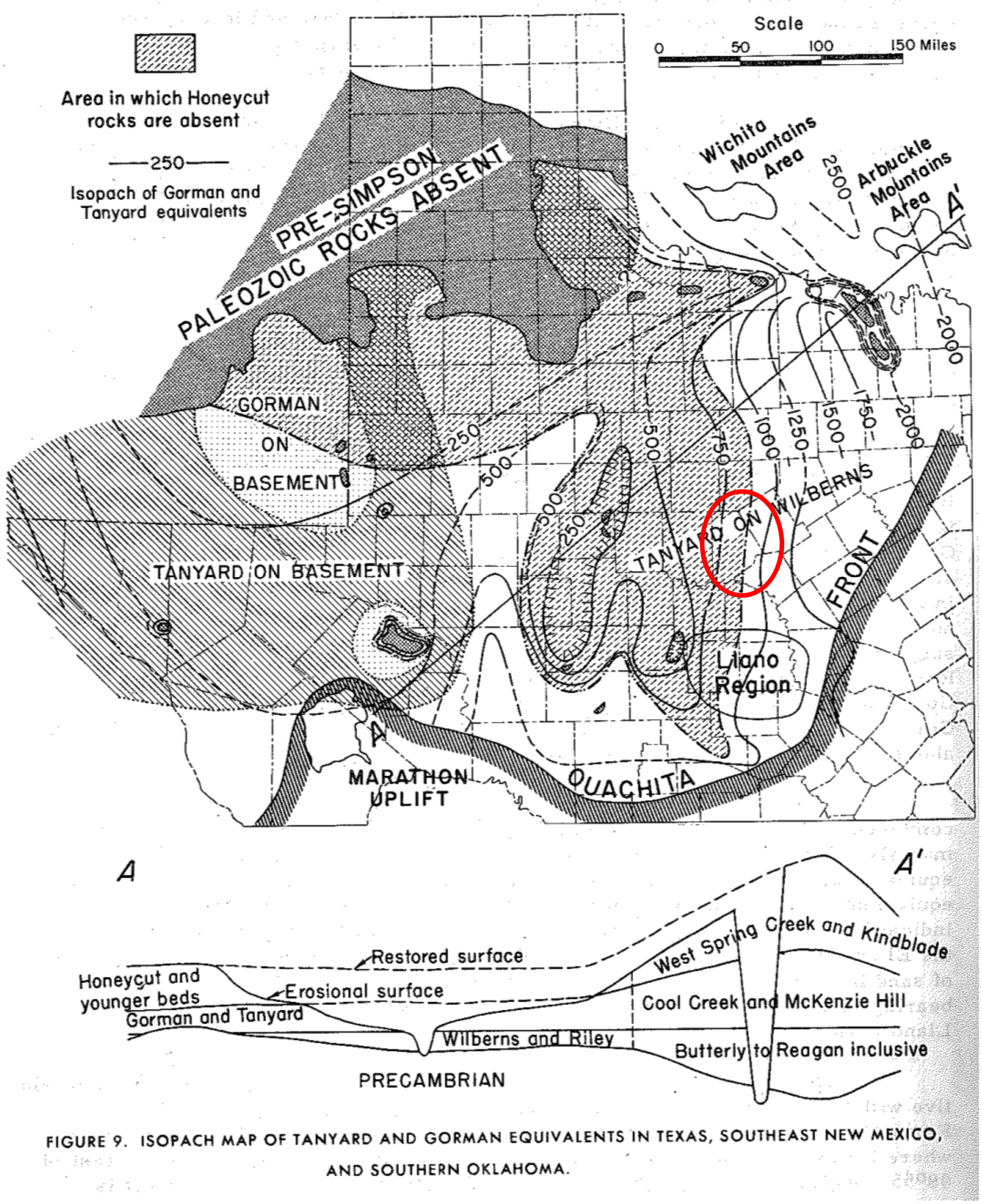


Figure 11. Isopach map of San Saba Member of Wilberns Formation, Central Texas.

Source: Barnes and Bell (1977)
Note: thickness in feet

Figure 24. Generalized thickness map of San Saba Limestone.



Source: Barnes and Cloud (1982)
Note: A-A′ section illustrates amount of material removed by erosion
Note: thickness in feet

Figure 25. Generalized thickness map of Tanyard and Gorman Formations of Ellenburger Group.

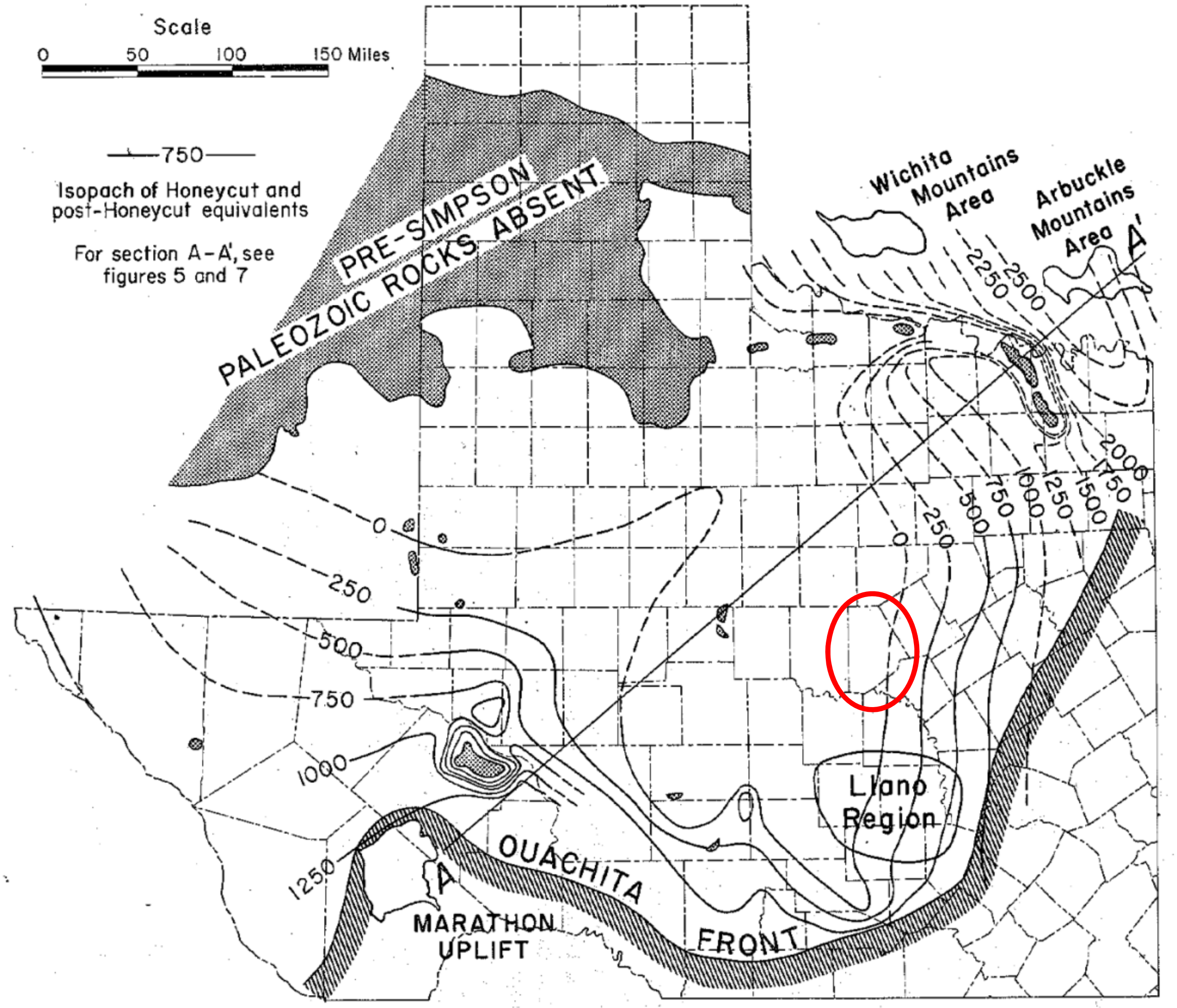


FIGURE 10. ISOPACH MAP OF HONEYCUT AND POST-HONEYCUT EQUIVALENTS IN TEXAS, SOUTHEAST NEW MEXICO, AND SOUTHERN OKLAHOMA.

Source: Barnes and Cloud (1982)
Note: Honeycut Formation barely exists in Brown County
Note: thickness in feet

Figure 26. Generalized thickness map of Honeycut Formation of Ellenburger Group.

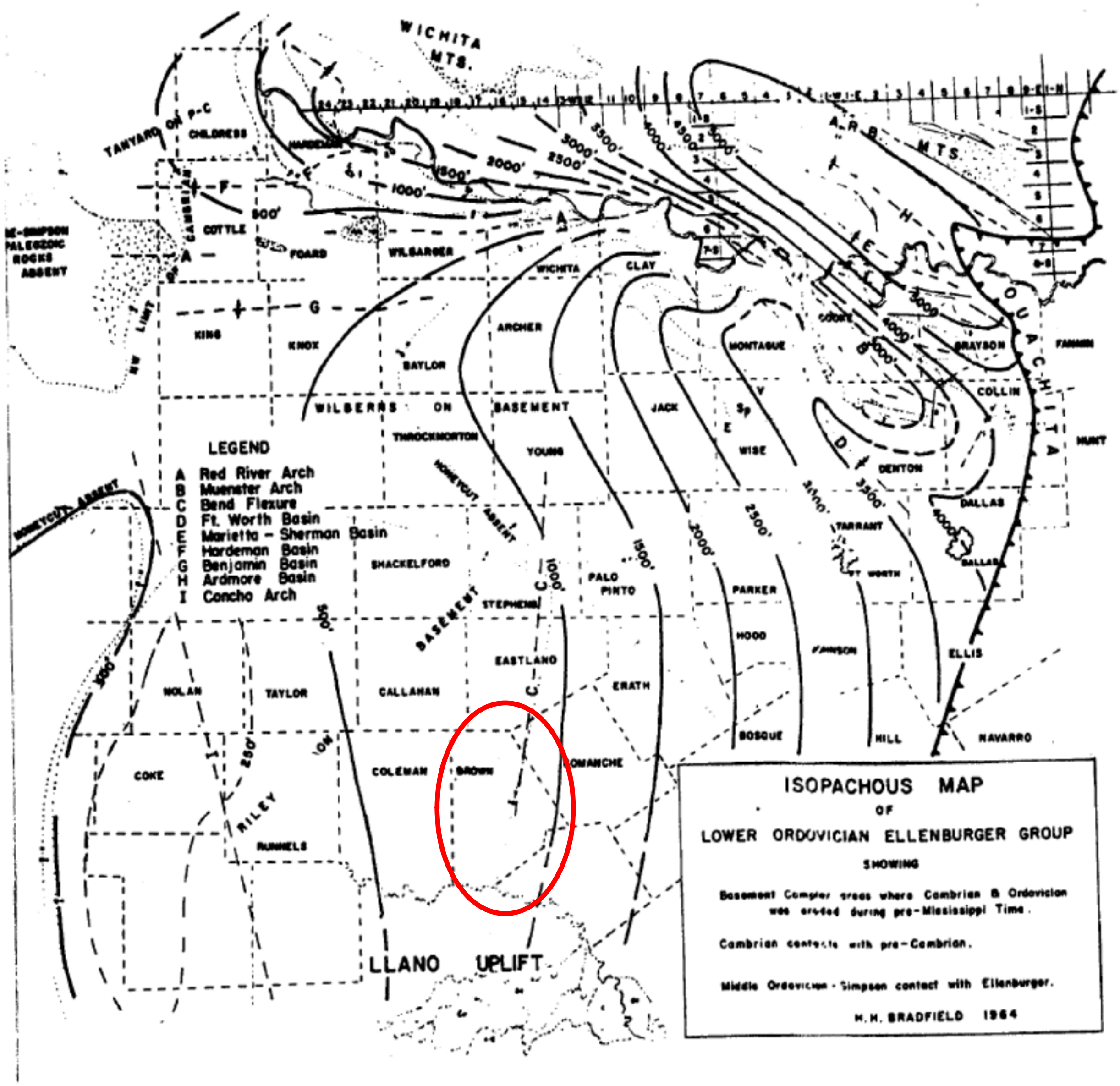
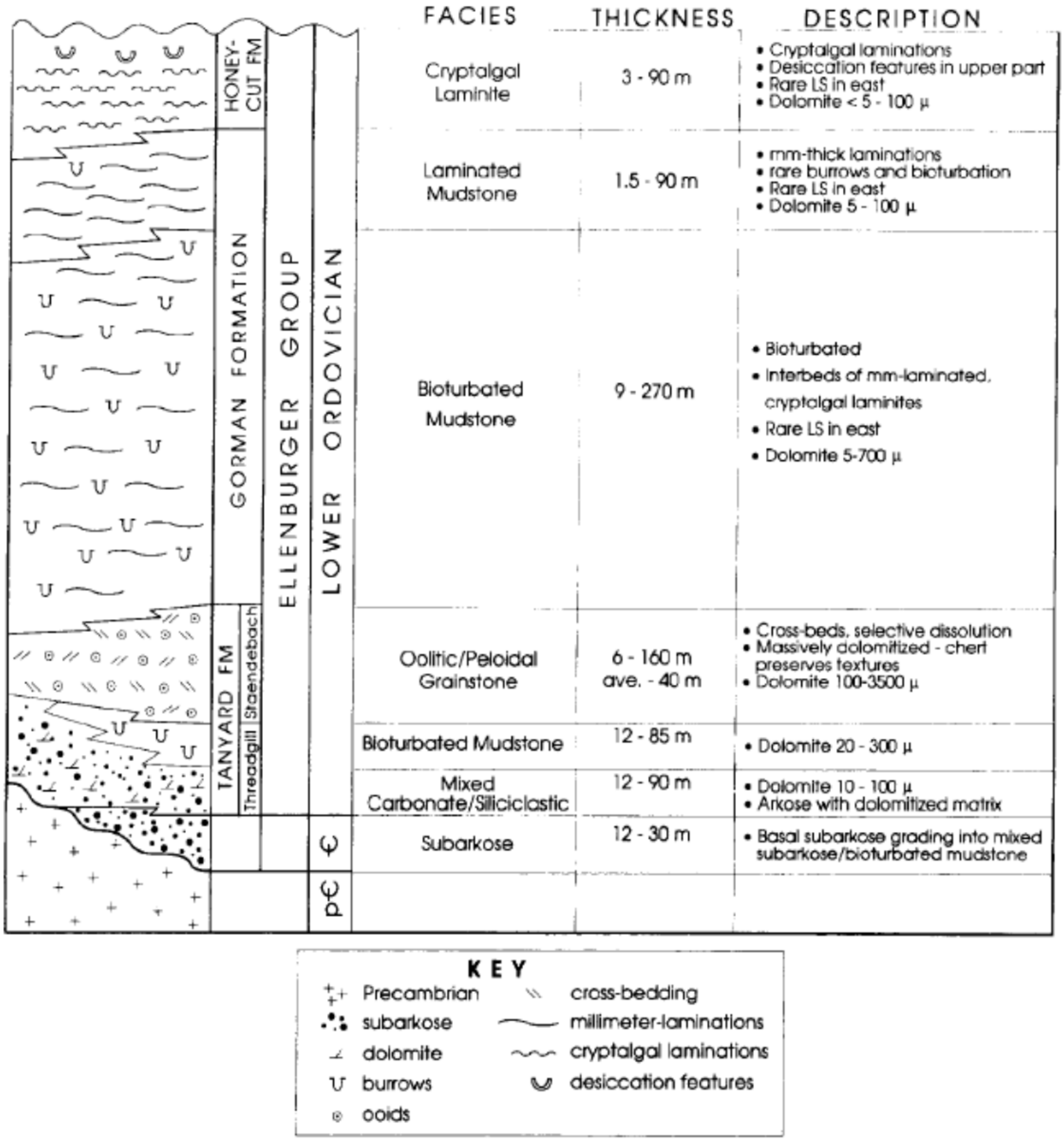


Figure 3. Isopach Map of Lower Ordovician Ellenburger Group (after Bradfield, 1964).

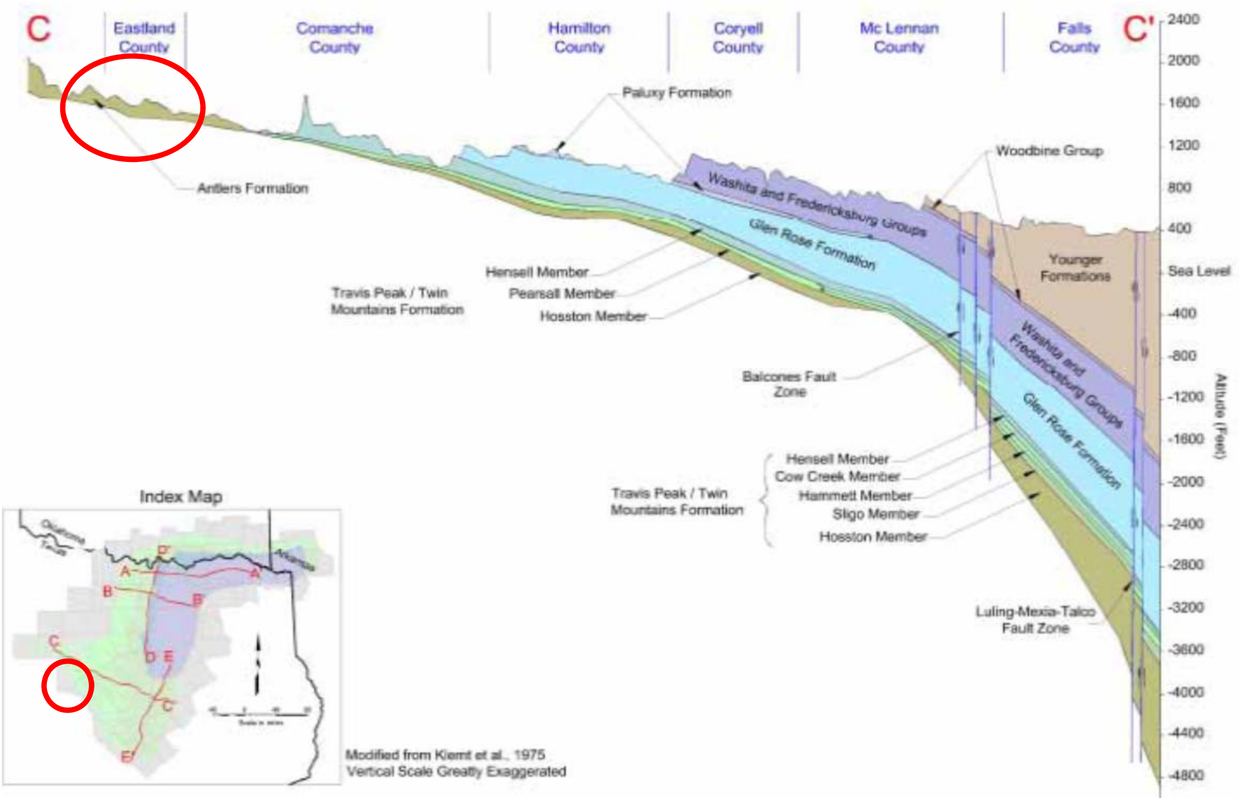
Source: Collier (1983)
Note: thickness in feet

Figure 27. Generalized thickness map of Ellenburger Group.



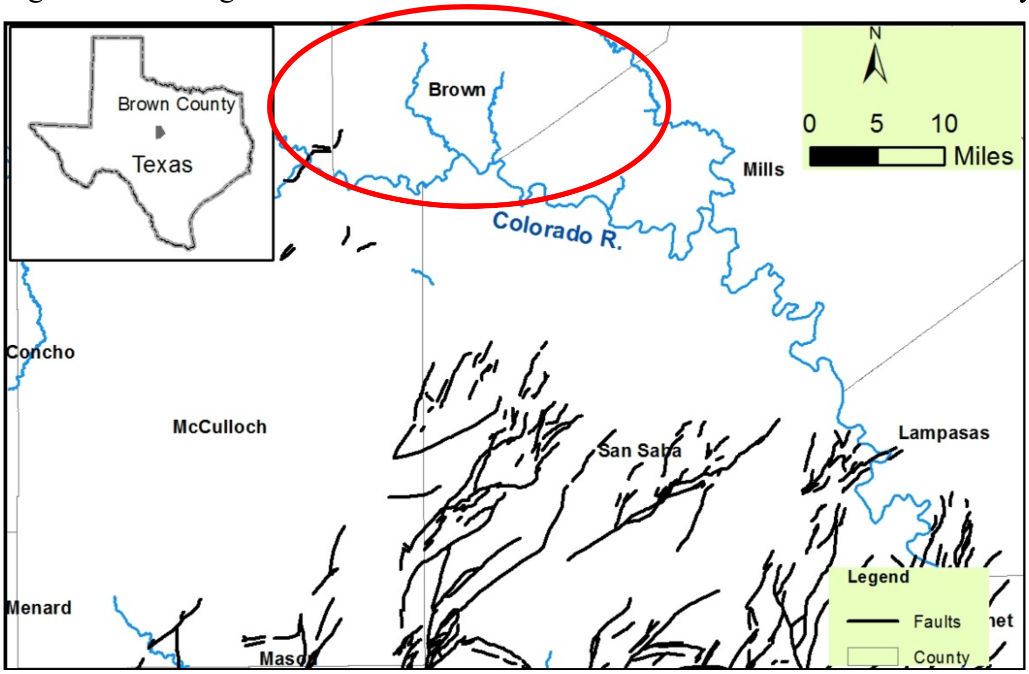
Source: Kupecz and Land (1991)
Note: Honeycut Formation has been removed by erosion in Brown County. Basal arkosic levels do not exist in Brown County but only father north and west, where Ellenburger sediments lie directly on the basement.

Figure 28. Generalized stratigraphic column, Ellenburger Group.



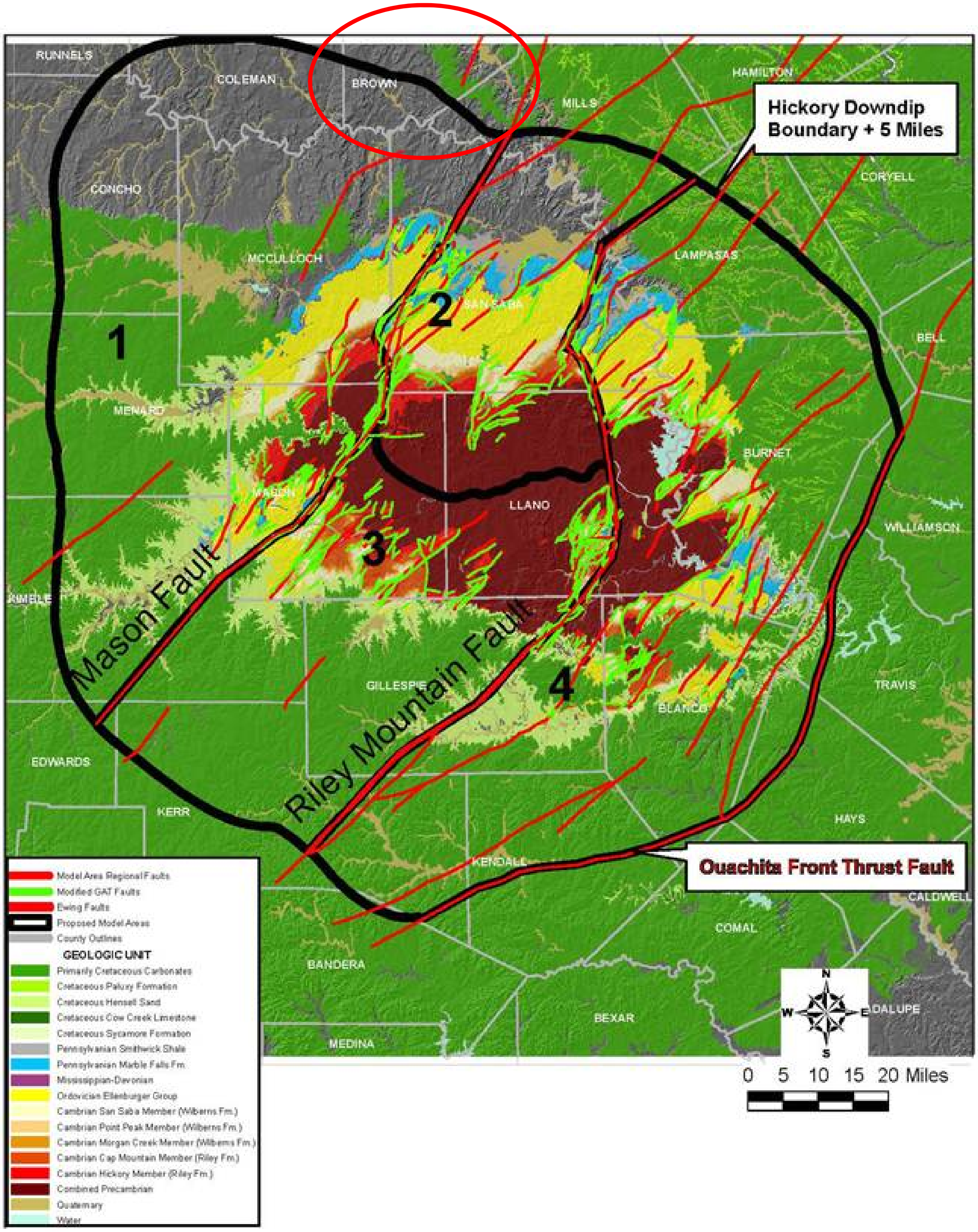
Source: R.W. Harden and Associates (2004, Fig. 2.16)
Note: Cross section starts in Callahan County and continues through Eastland County, just north of Brown County. In Brown County, Antlers/Hensel more confined than shown on profile.

Figure 29. Geologic cross section of Cretaceous north and east of Brown County.



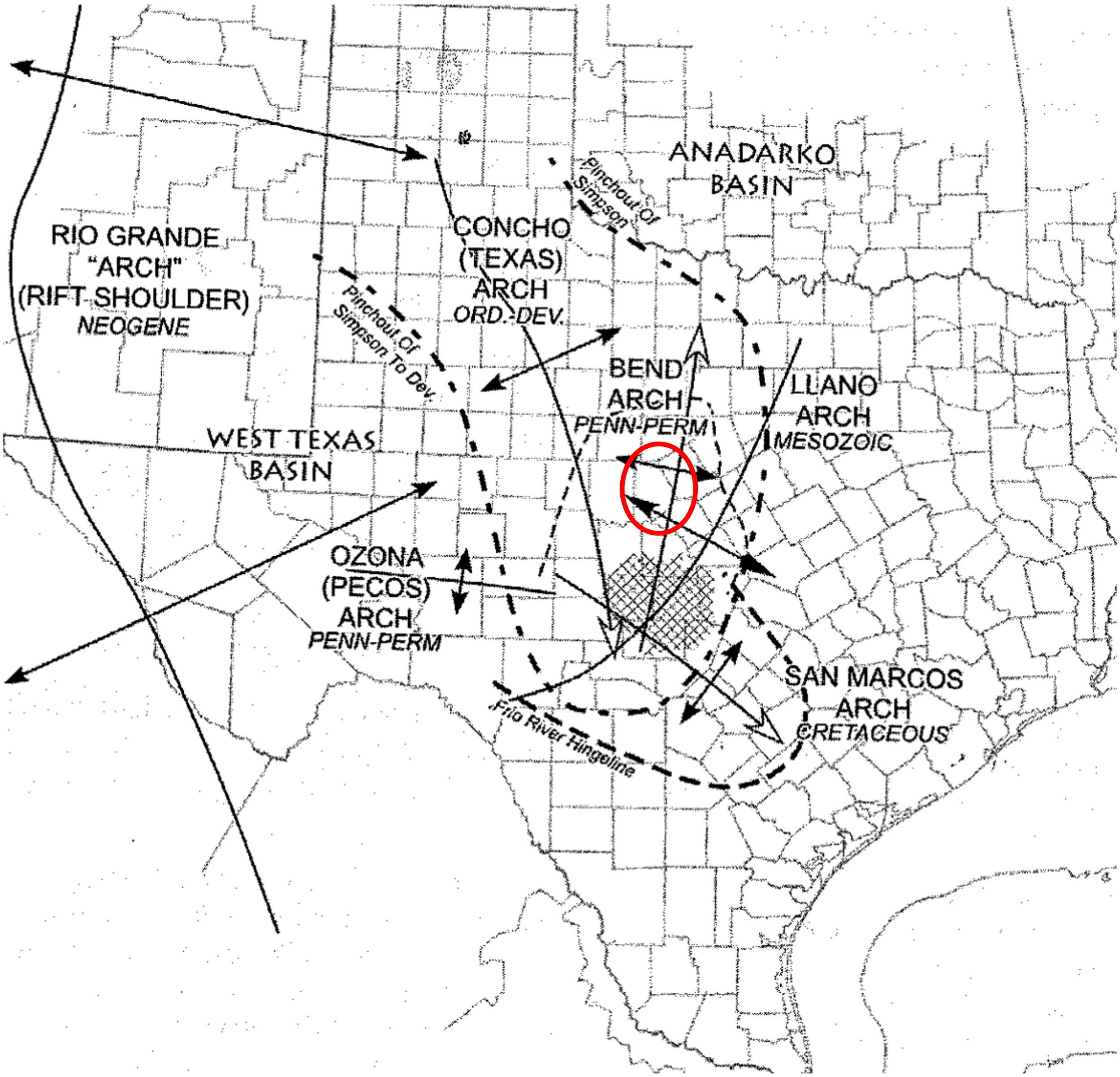
Source: Brownwood GAT Sheets (Kier et al., 1976)

Figure 30. Surface faults associated with Llano Uplift.



Source: Standen and Ruggiero (2007)—from Brownwood and Llano GAT sheets by Kier et al. (1976) and Barnes (1981)

Figure 31. Simplified geology of Llano Uplift; proposed independent groundwater flow compartments.



Source: Figure 2 of Ewing (2004)

Figure 32. Sketch map showing intersection of arches that created Llano Uplift.

IV-3. Hydrostratigraphy

From bottom to top of the stratigraphic column, several water-bearing strata can be identified (Figure 12): Hickory Sandstone, Lion Mountain Sandstone, Welge Sandstone, San Saba Limestone, Ellenburger Group, Marble Falls Limestone, upper Paleozoic aquifers, and Trinity aquifer. Because they are in hydraulic communication, several of these strata can be grouped together: the combined Lion Mountain and Welge aquifers is called the Welge aquifer or the Mid-Cambrian aquifer(UTBEG and Parsons, 2010, p. 3–12). For example, Mason (1961, p. 17) stated that they form a single aquifer in McCulloch County, although the two sandstones are distinguishable from one another on the outcrop. They are also likely to form a single aquifer in Brown County, where they might be in direct hydraulic communication with the Hickory aquifer because of the absence of the Cap Mountain aquitard. In addition, the Hickory aquifer may also be connected to the Precambrian basement, which may have some fracture permeability (Carrell, 2000, p. 14). The San Saba Limestone is generally appended to the Ellenburger formations with which it is in direct contact to form the Ellenburger-San Saba aquifer. The confining system between the base of the San Saba Formation and the top of the Welge Sandstone is made up of low-permeability limestones and siltstones of the Point Peak and Morgan Creek units. The Marble Falls aquifer, made up of the Marble Falls Limestone, is confined from below by Mississippian shales and limestones and from above by the Marble Falls Shale and Strawn low-permeability rocks. The Marble Falls aquifer is recognized to be distinct from the Ellenburger-San Saba in Brown County, but they could be locally in direct contact. The Trinity aquifer is generally defined as the system composed of three primary aquifers: Hosston, Hensell (sometimes combined as Antlers), and Paluxy aquifers.

South-north cross sections show a simplified hydrostratigraphic column and water quality (Figure 33). Moving from south to north, salinity in the Ellenburger and Hickory increases greatly to levels beyond 50,000 mg/L. Depth to the Ellenburger increases ~400 feet, and depth to the Hickory increases ~200 feet from the southwest tip of Brown County to the City of Brownwood.

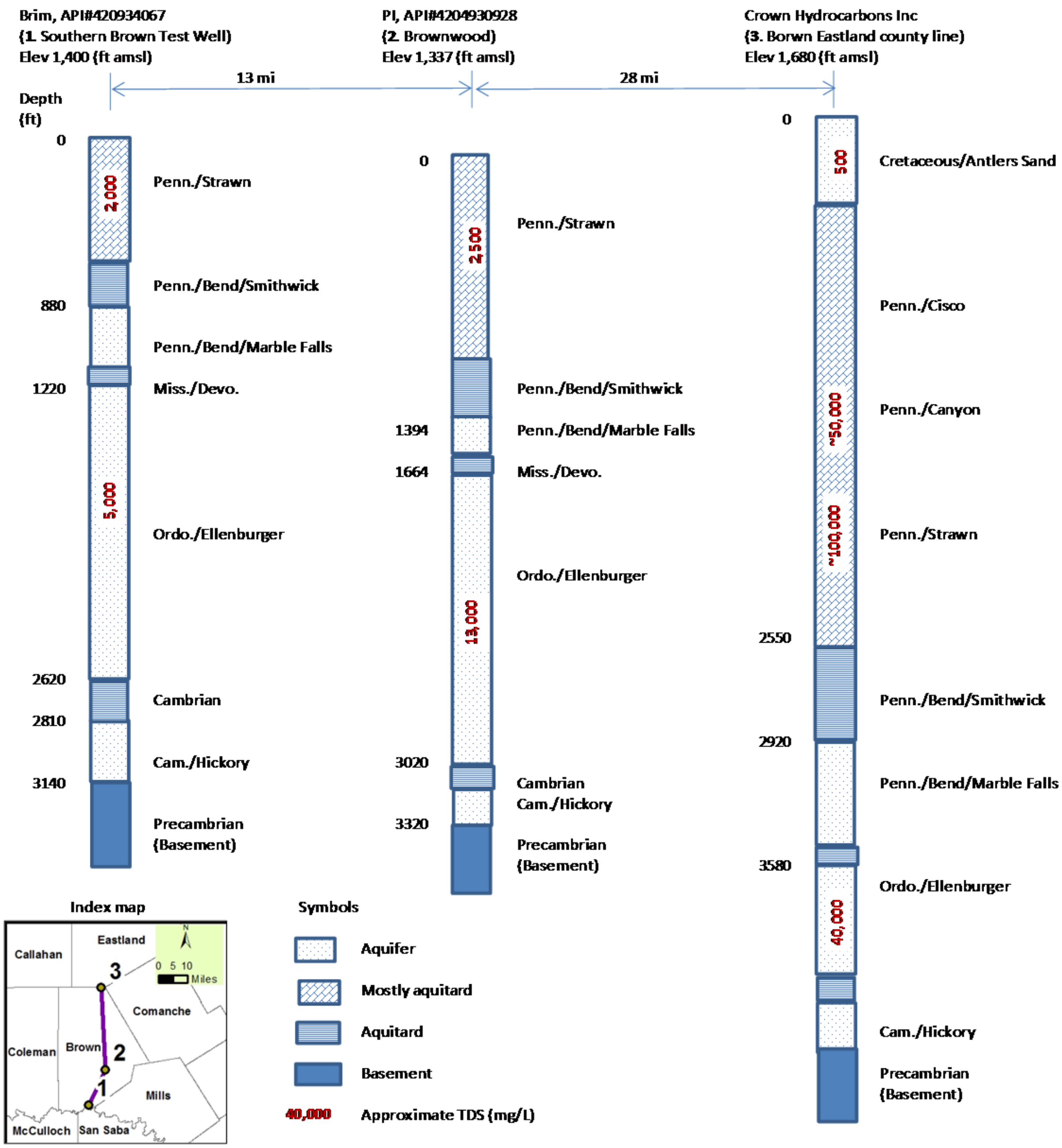


Figure 33. South-north cross sections showing simplified hydrostratigraphic column and water quality.

IV-4. Hydrogeological Implications

Hickory

The irregular base of the Hickory Sandstone has important hydrogeological implications: paleovalleys are likely to contain thicker Hickory sediments, and the base is likely to be more conglomeratic (that is, have higher permeability). This is a model that has been reproduced for Cretaceous times (Trinity Group), and again for Ogallala times, with the important difference being that the Hickory Sandstone is mostly marine and the Trinity Group and Ogallala sediments are continental. Before deposition of the Hickory Sandstone, the exposed basement topography was aligned along NW-SE-trending folds intruded by granitic plutons (somewhat similar to the current topography) (Figure 34). During the Cambrian transgression, the ocean coming from the south progressively invaded the basement (Figure 35) and reworked sediments whose source was toward the north. Field observations of paleocurrent features in the Hickory also strongly suggest a NW-SE control matching the basement structural direction (Krause, 1996, p. 25). That the generalized thickness of the Hickory Sandstone decreases toward the north suggests that sediments brought by rivers from farther inland were transported away from the shore, where they accumulated in larger thicknesses. It also suggests that the impact of the basement on the thickness of the sandstone becomes more important toward the north and that the chances of hitting a reduced thickness (i.e., smaller than the generalized thickness map suggests) increases from south to north in Brown County. As a general rule, the deeper a formation is buried at some point of its history, the more likely porosity will be somehow occluded, which does not seem to be the case for the Hickory Sandstone (McBride et al., 2002).

Can the Hickory Sandstone be considered a single hydrological unit? Clearly not, Mason (1961, p. 16) noted that clay stringers are frequent in the Hickory, especially at its top, suggesting a limited vertical permeability between the most permeable unit at the base of the Hickory. Zhurina (2003, p.21) also observed that some beds in the lower middle Hickory on a small site just south of the Mason-McCulloch County line acted as an aquitard between the upper and lower Hickory Sandstone. Mason (1961, Table 1) mentioned that Point Peak Shale and Morgan Creek Limestone yield small amounts of water in McCulloch County, suggesting that the aquitard between the Hickory and Mid-Cambrian aquifers can be considered leaky.

The Hickory aquifer has been described as compartmentalized because of the presence of numerous NW-SE-trending faults. However, how much of a barrier to flow they are remains unclear. Large faults with throws larger than the aquifer thickness (<350 ft for Hickory and <1000 ft for Ellenburger) are likely not conductive transversally. Many smaller faults are en echelon, letting flow between compartments (see, e.g., Carrell, 2000) in San Saba County, but they may still deflect general groundwater flow that has been described as more or less parallel to the general direction of faults. Few studies have determined the actual impact of faulting on regional flow in the Hickory. Locally in Brown County, the Bend Flexure is the most prominent geological structure that could affect groundwater flow.

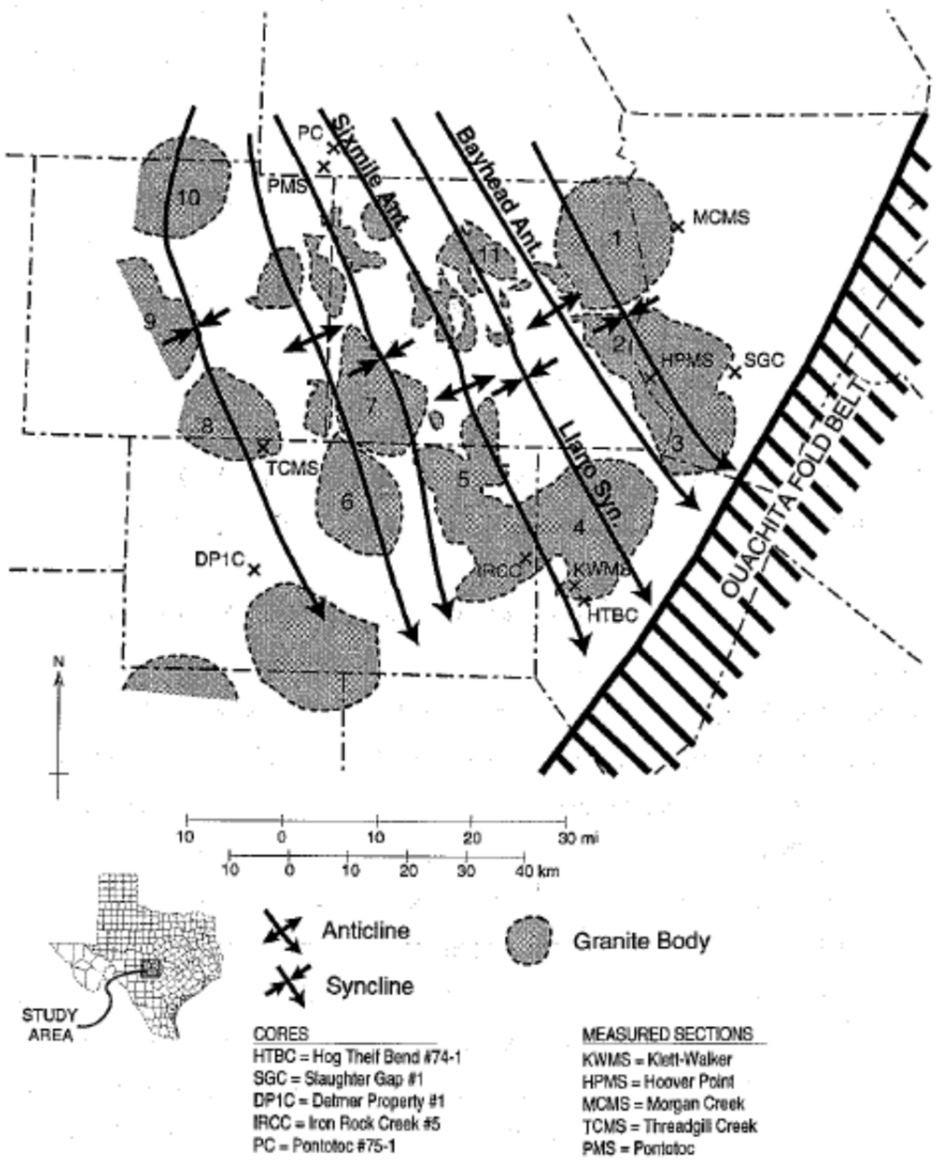


Figure 2.3. Precambrian structure within study area. Older NW to SE trending folds of gneiss and schist are overprinted by younger intrusive granites (compiled from Stenzel, 1934; Barnes and Romberg, 1956; and Muehlberger, et al., 1967). (Plutons; 1. Lone Grove, 2. Kingsland, 3. Marble Falls, 4. Grape Creek, 5. Legion Creek, 6. Bear Mtn, 7. Enchanted Rock, 8. Hilda, 9. Grit, 10. Katemcy, 11. Wolf Mtn.)

Source: Krause (1996)

Figure 34. Precambrian basement structure in counties south of Brown County.

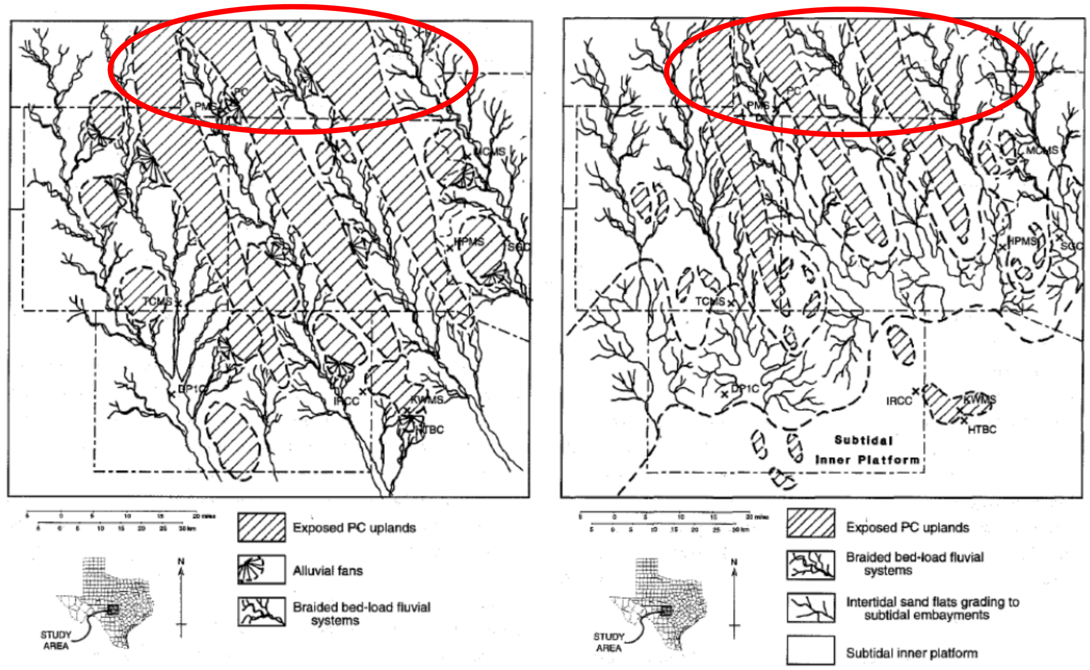


Figure 5.1. Generalized early Hickory Sandstone paleogeography. Subaerial exposure and alluvial and fluvial sytems dominate. A ridge-and-swale topography puncuated by resistant granite peaks had up to 200 hundred meters of relief. Isolated eolian dune fields may have been present within valleys but are not preserved.

Figure 5.2. Generalized middle Hickory Sandstone paleogeography. Marine transgression results in the backstepping of fluvial environments and the formation of broad, embayed sand flats along an open, northeast-trending coastline.

Source: Krause (1996)
Note: south of San Saba County circled in red

Figure 35. Speculative interpretation from Krause (1996) displaying hypothetical Precambrian valleys in which Hickory sediments were deposited.

V. What We Know

In Section V we present results of work done for this project beyond the bibliographic analysis presented earlier: (1) more detailed structure maps that go beyond regional generalized thickness maps already presented and (2) aquifer properties of current groundwater wells in Brown County.

V-1. Structure

In Section V-1, we display results of our analysis of the structure of formations of interest. We present the depth to top of various formation (useful for determining drilling depth) and the elevation of the top of the same formations (favored format for examining water flow). The latter, which is independent of surface topography, is all that can be used to analyze structure maps. We present the following surfaces: top of the basement (base of Hickory), which is the most uncertain owing to the paucity of well data points; top of the Hickory Sandstone; top of the Welge Sandstone; top of the Ellenburger; and top of the Marble Falls Limestone (not including Marble Falls Shale). We also collected data points for the Strawn Caddo Limestone. Although the influence of faults and other structural features is visible on the structural maps, we did not try to integrate them into the drawing of the contour lines. The lines should be considered a general indication rather than an accurate depiction of the depth and elevation of layer boundaries.

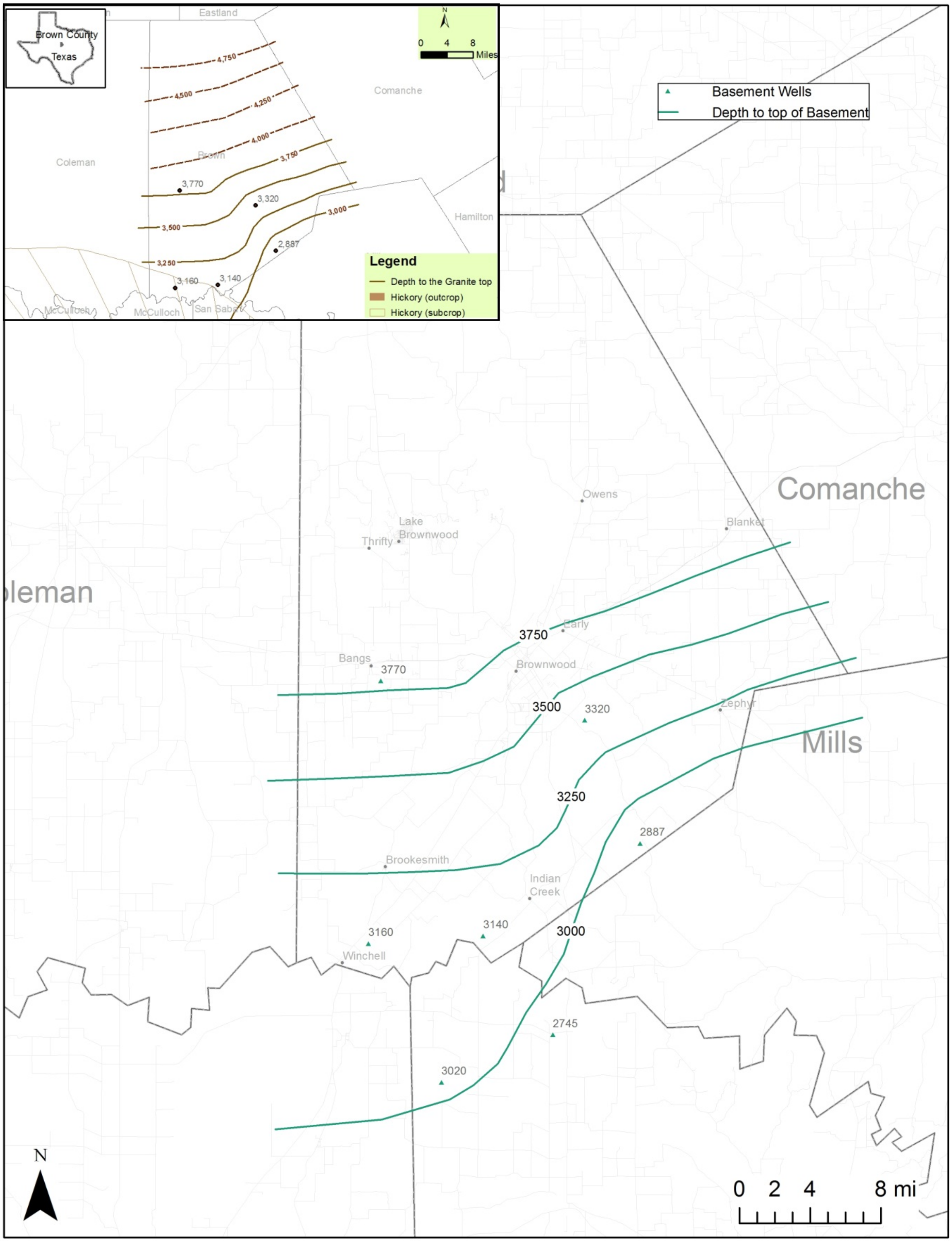
V-1-1 Data for Structure Maps

To develop structure maps of Brown County, we undertook an extensive search of well logs of wells reaching the Ellenburger formations and/or the Hickory Sandstone following an approach similar to that of Standen and Ruggiero (2007). Construction of the subsurface stratigraphy was accomplished by integrating numerous types of publically available data sources from the BEG. Surface geology for the study area was obtained from the Geologic Atlas of Texas (GAT) Brownwood Sheet, which has a scale of 1:250,000 and is available in map or digital formats. A total of 101 subsurface and surface data points were compiled to complete this analysis, which includes 40 detailed lithologic descriptions from cable-tool driller's reports from the 1920's through the 1960's, a total of 29 oil and gas exploration scout tickets (formation top picks), 1 oil and gas mud logger's description (lithology), 21 oil service company database formation top picks, and 10 locations from the GAT surface geology (see Appendix B). These data were compiled and integrated so as to construct shapefiles in ESRI ArcGIS 10.2 software. Depth to the top of the formation from land surface and top elevation (relative to sea level) contour shapefiles were constructed for the Pennsylvanian Strawn Caddo, the Pennsylvanian Bend Marble Falls, the Ordovician Ellenburger, the top Cambrian Sand, the Cambrian Hickory, and the top of the Precambrian basement. Top and base surface outcrop picks for the Pennsylvanian-age Cisco Thrifty and Graham Formations (potential low-yield and brackish-water-producing sand formations) in the western third of the county were also included in the GIS package.

V-1-2 Structure Results and Discussion

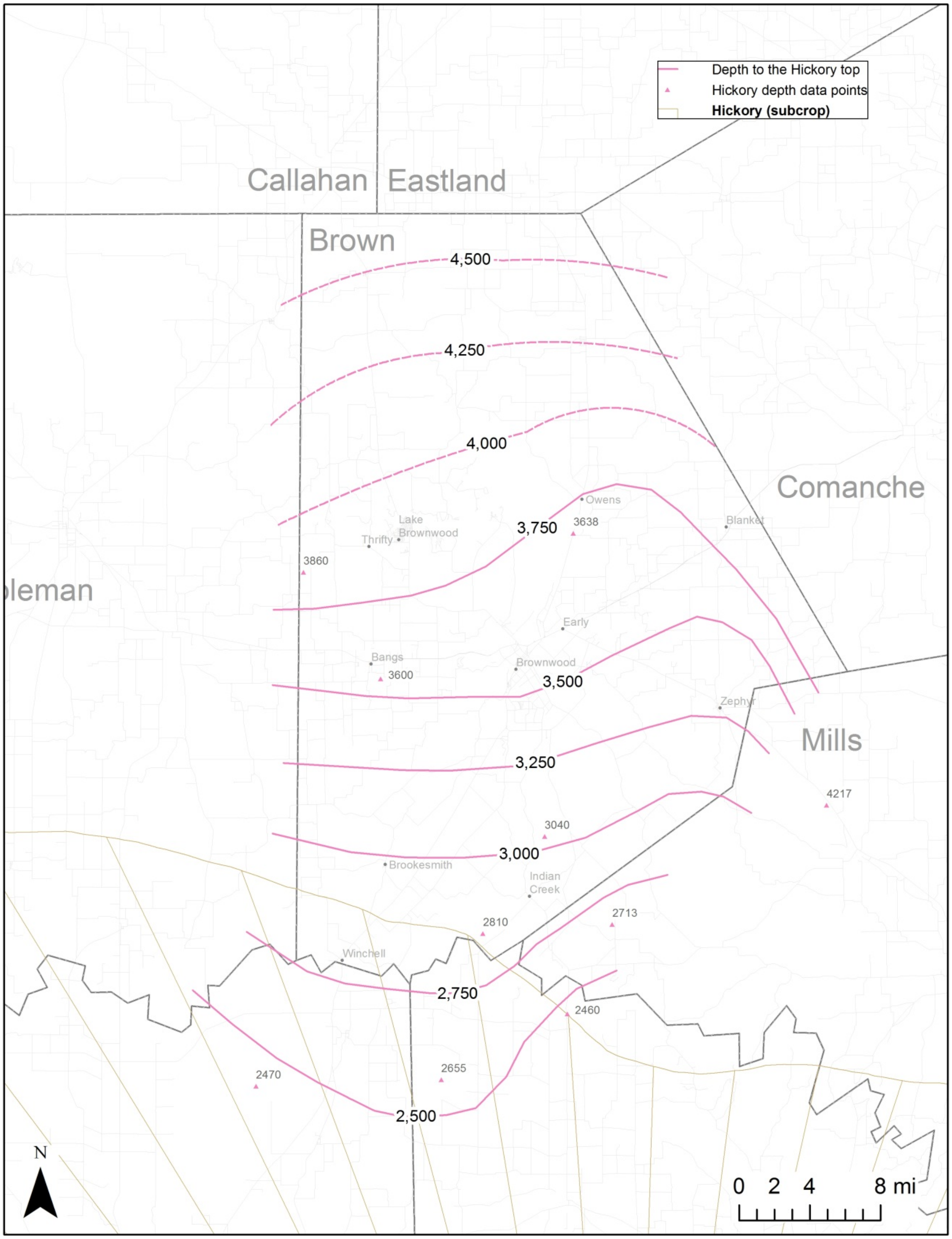
Generalized depth to the top of the Precambrian basement was based on well logs (Figure 36). The depth ranges from ~3000 feet in the south part to ~5000 feet in the north part of Brown County. Depth to the top of the Hickory is shown in Figure 37. The depth ranges from ~2,800 feet in the south to ~4800 feet in the north. Figure 38 illustrates the depth to the top of the Welge/Mid-Cambrian aquifer from 2500 to 4500 feet in the south and north parts of the county, respectively. Depth to the top of the Ellenburger is shown in Figure 39. The depth ranges from ~1,200 feet in the south part to ~3,500 feet in the north. Thickness of the Ellenburger in Brown County ranges from ~750 to1000 feet, whereas thickness of the Hickory in Brown County ranges from ~150 feet in the north to 350 feet in the south. However, local thickness could be different—a difference that cannot be captured in the regional trend. Depth to the top of the Marble Falls Limestone ranges from ~850 feet in the south part of the county to 3,000 feet in the north (Figure 40). As mentioned earlier, the Strawn Group represents the early phase of a sediment package different from that of the lower Paleozoic to the Marble Falls, which is also transparent in the general dip of the formations—toward the NW for the Caddo Limestone (Figure 41). Maps of elevation of formation tops show a similar pattern (Figure 42–Figure 47). The general dip is toward the north (even if thickness variation can be E-W). Some layers are clearly impacted by the Bend Arch Flexure, which stands out as a NS-trending feature. The known basement high at the southeast end of the county is also noticeable when it deflects contour lines. Note that the lines should be interrupted against a fault or group of faults, which is not shown.

Depth to tops:



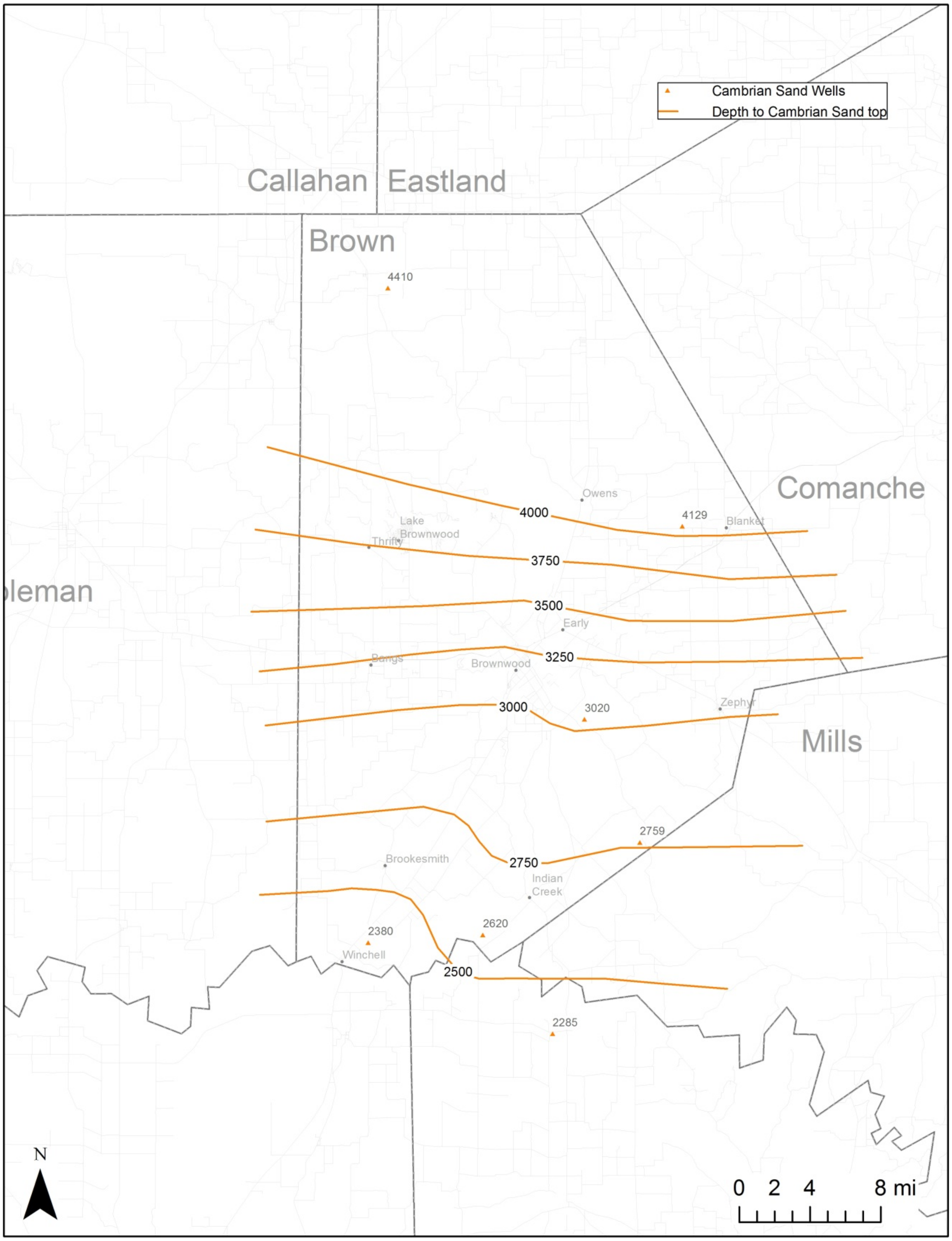
Note: presented contour lines only indicate true contour lines because fault interruptions unaccounted for.

Figure 36. Generalized map of depth to top of Precambrian basement in Brown County (ft).



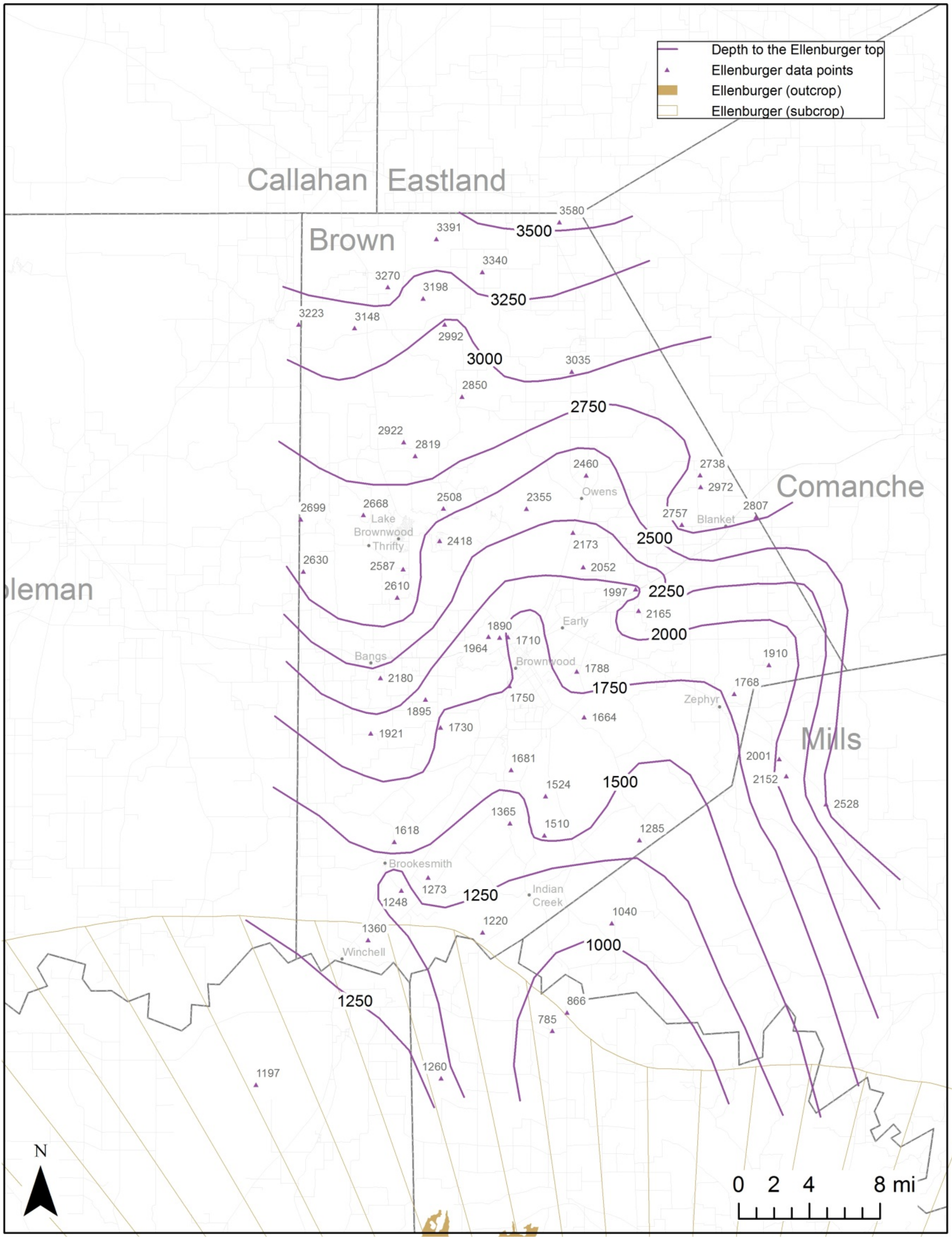
Note: presented contour lines only indicate true contour lines because fault interruptions unaccounted for.

Figure 37. Generalized map of depth to top of Hickory Sandstone in Brown County (ft).



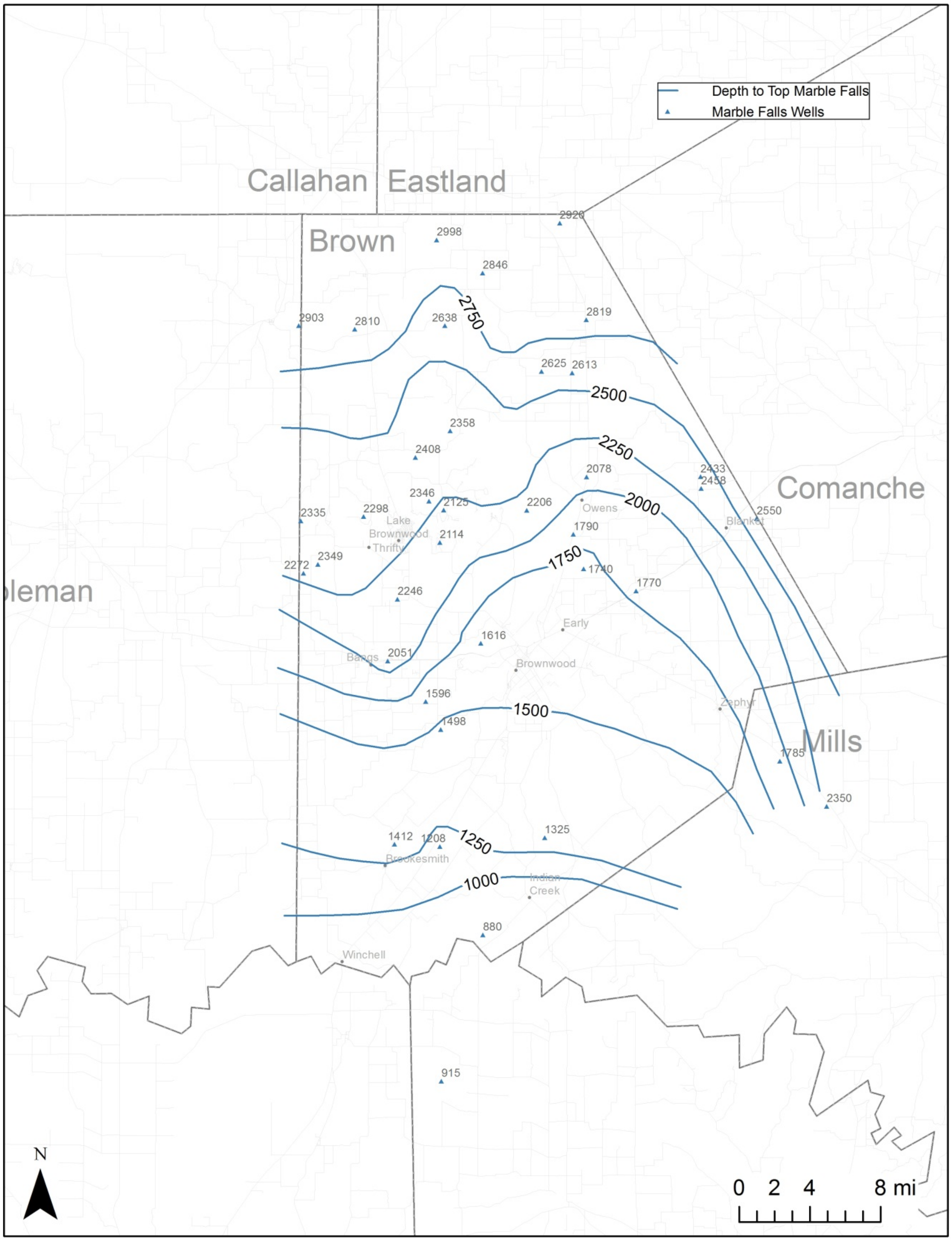
Note: presented contour lines only indicate true contour lines because fault interruptions unaccounted for.

Figure 38. Generalized map of depth to top of Mid-Cambrian sandstones in Brown County (ft).



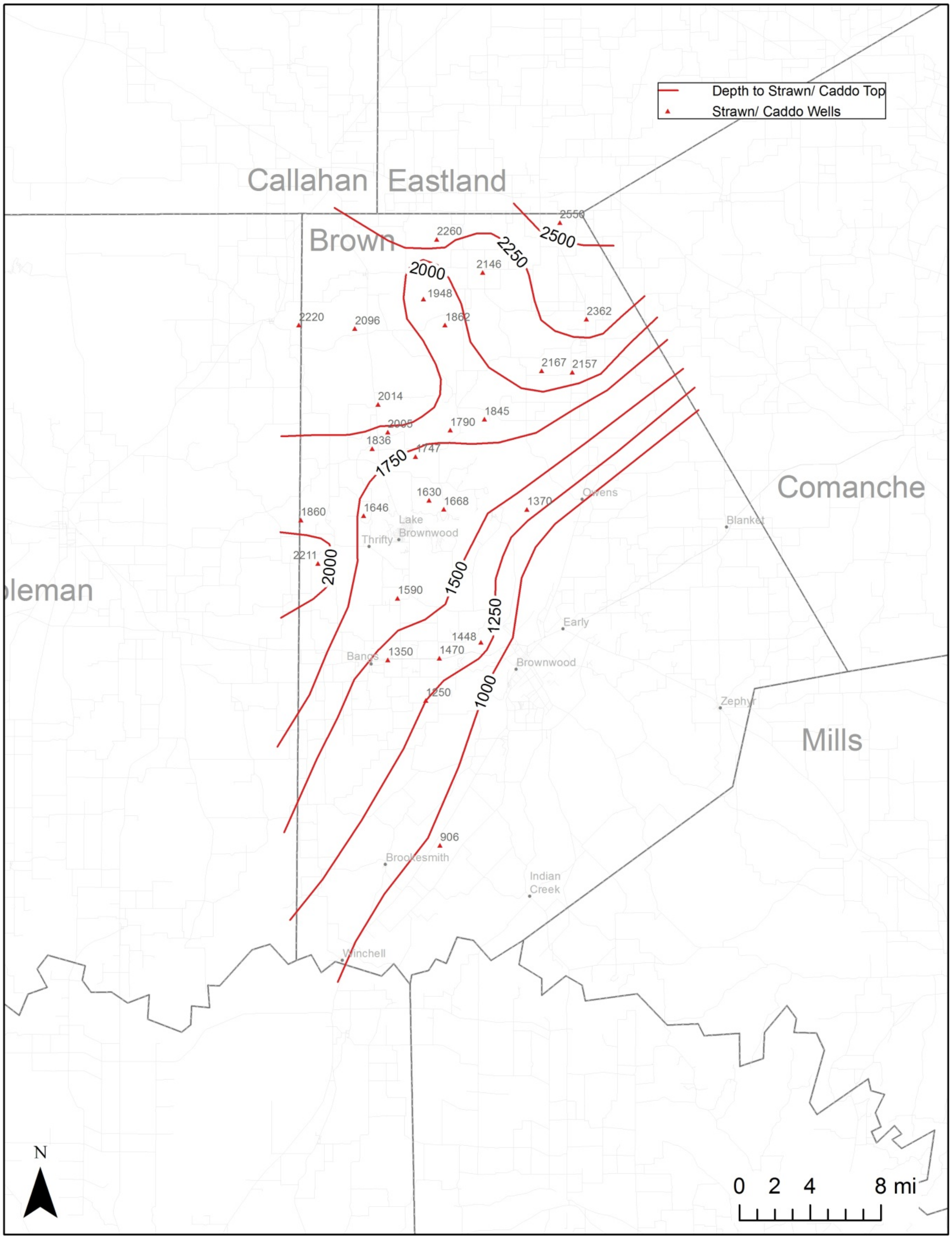
Note: presented contour lines only indicate true contour lines because fault interruptions unaccounted for.

Figure 39. Generalized map of depth to top of Ellenburger Group in Brown County (ft).



Note: presented contour lines only indicate true contour lines because fault interruptions unaccounted for.

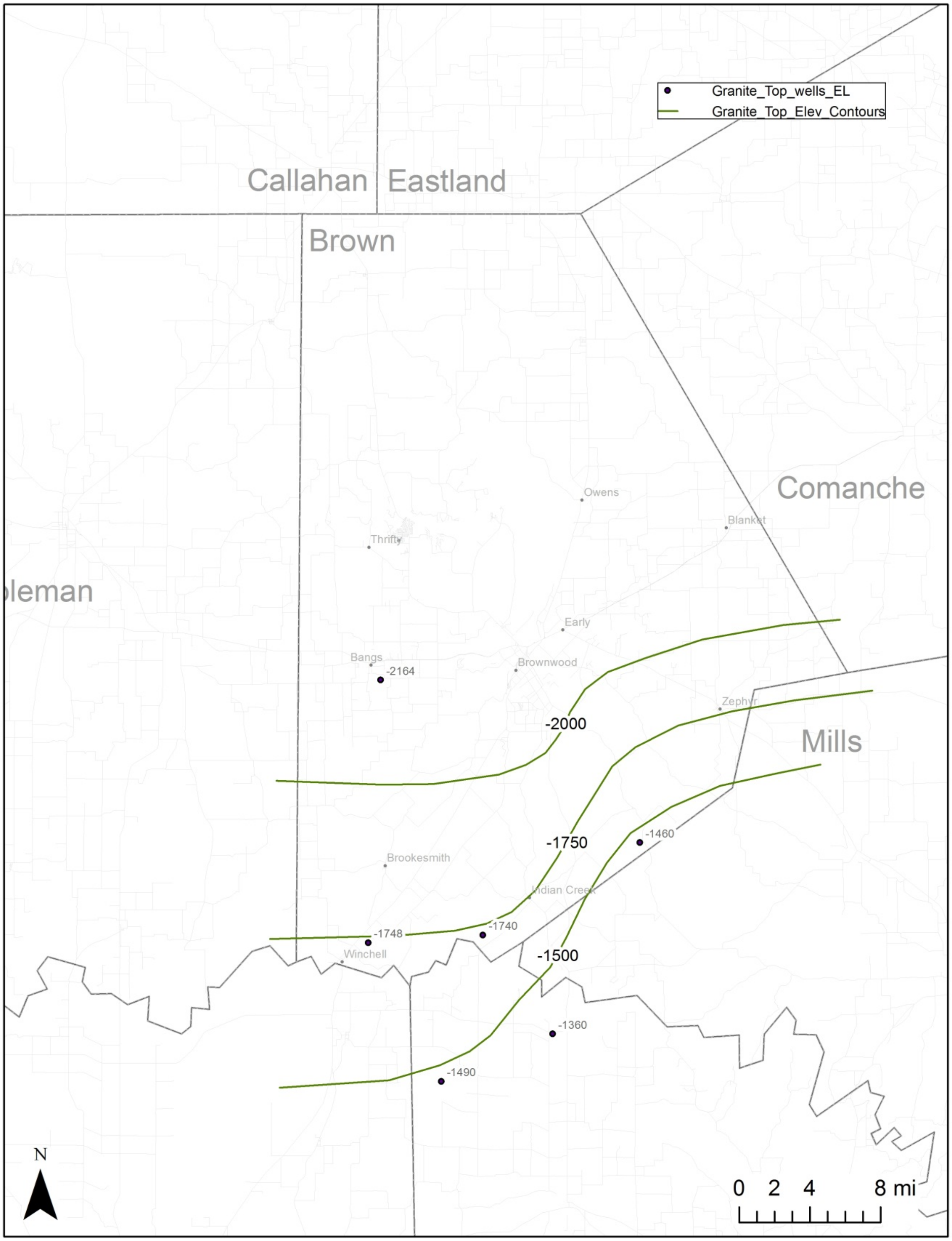
Figure 40. Generalized map of depth to top of Marble Falls Limestone in Brown County (ft).



Note: presented contour lines only indicate true contour lines because fault interruptions unaccounted for.

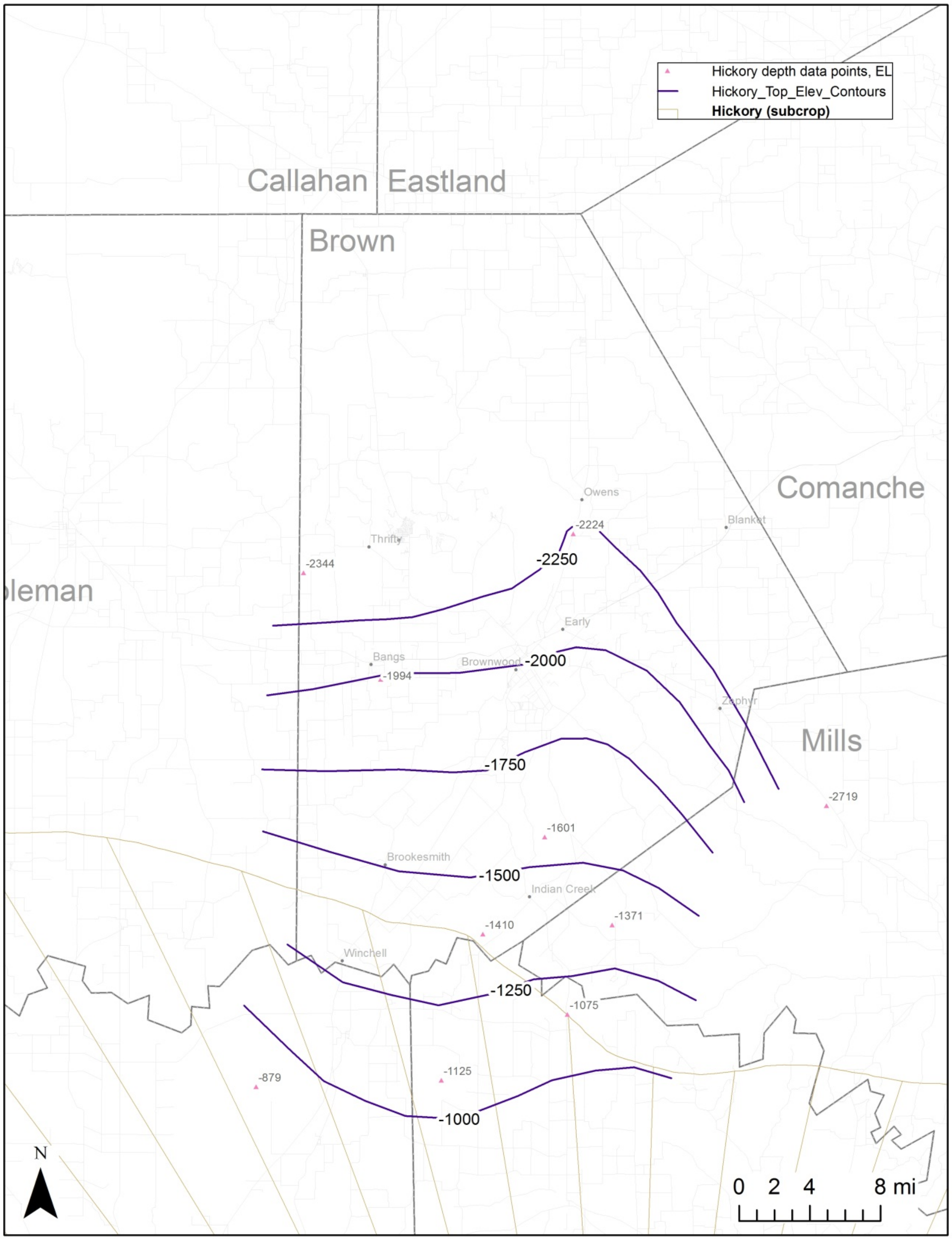
Figure 41. Generalized map of depth to top of Caddo Limestone (Strawn) in Brown County (ft).

Elevations:



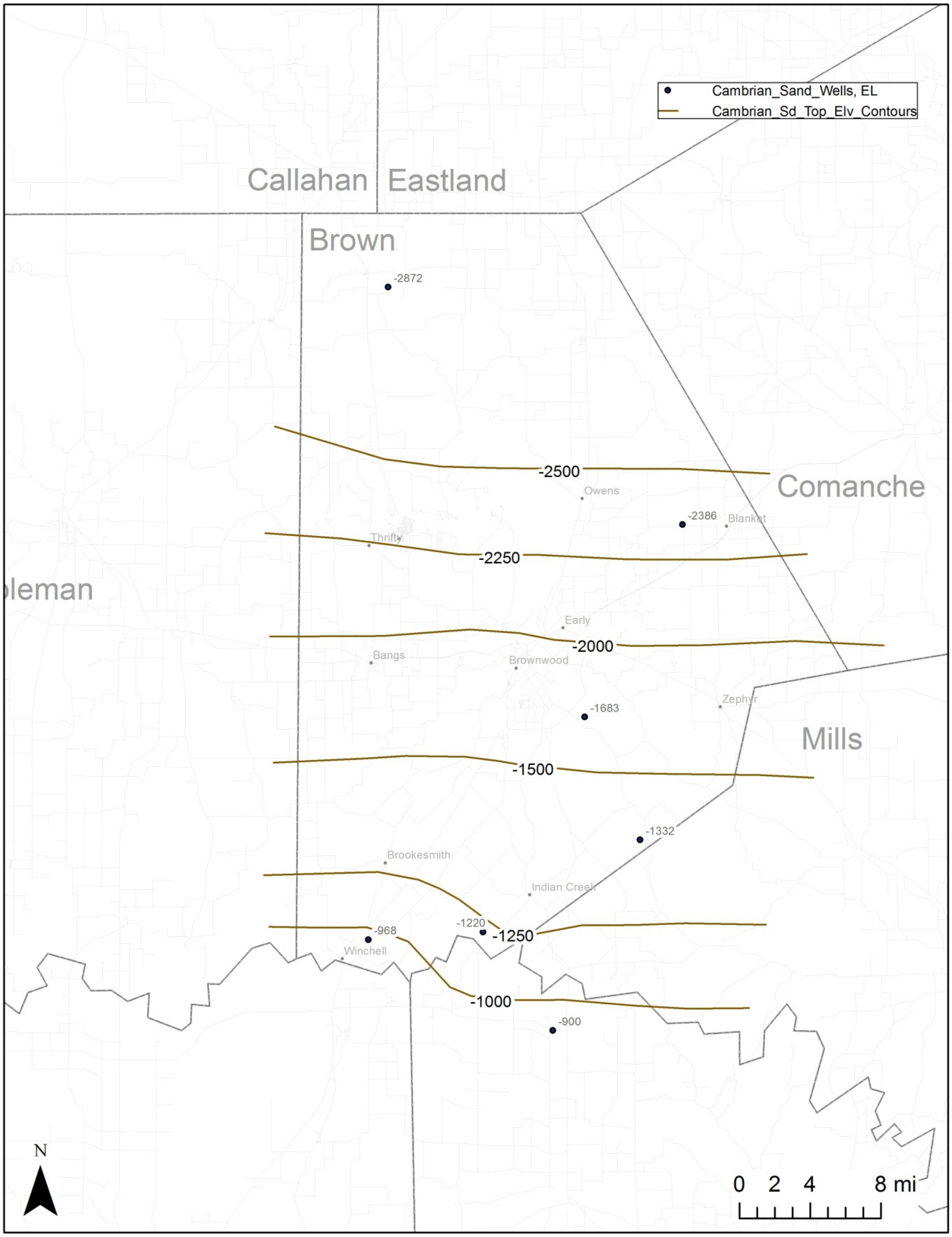
Note: presented contour lines are only indicate true contour lines because fault interruptions unaccounted for.
Note: datum is mean sea level

Figure 42. Generalized map of elevation of top of Precambrian basement in Brown County (ft).



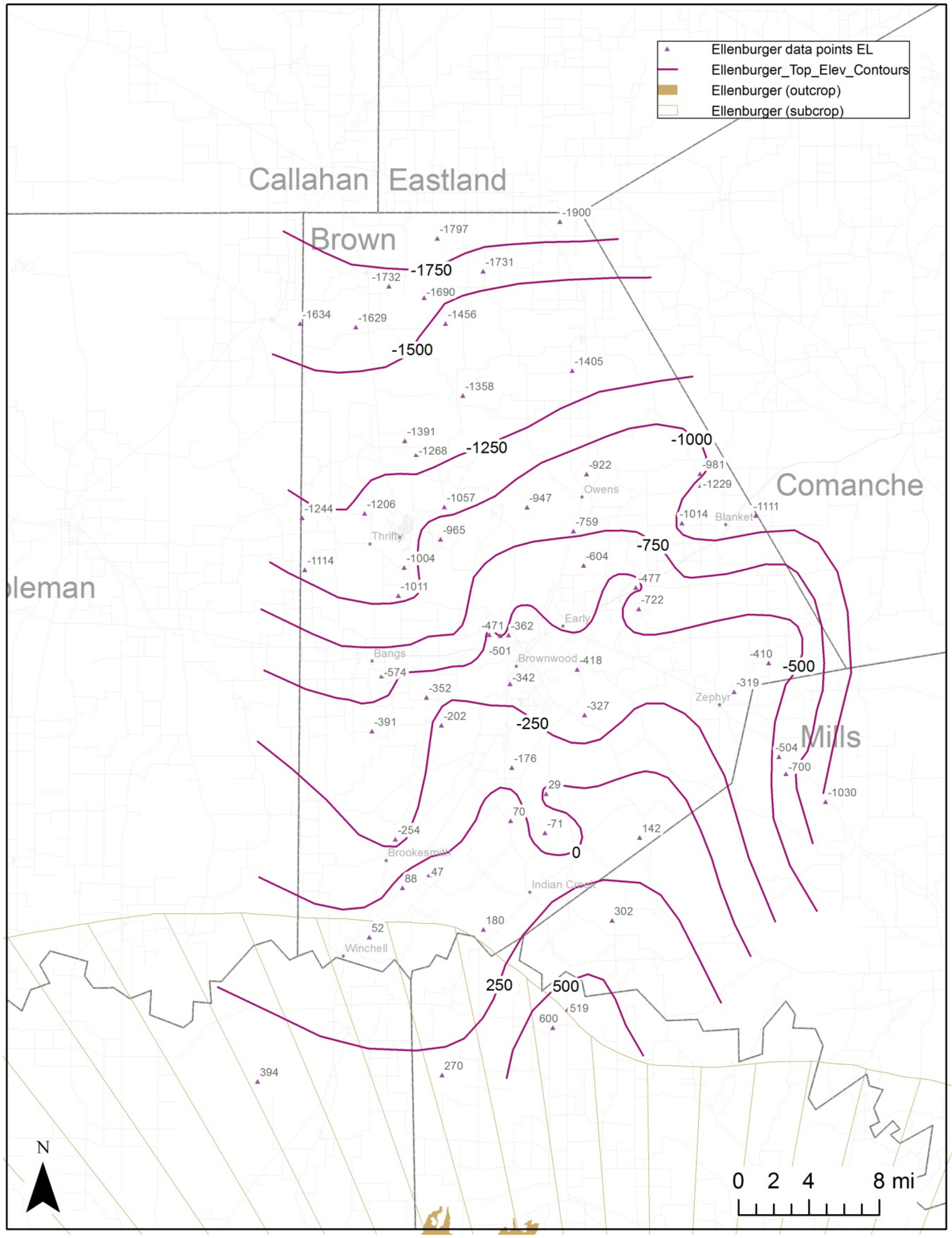
Note: presented contour lines only indicate true contour lines because fault interruptions unaccounted for.
Note: datum is mean sea level

Figure 43. Generalized map of elevation of top of Hickory Sandstone in Brown County (ft).



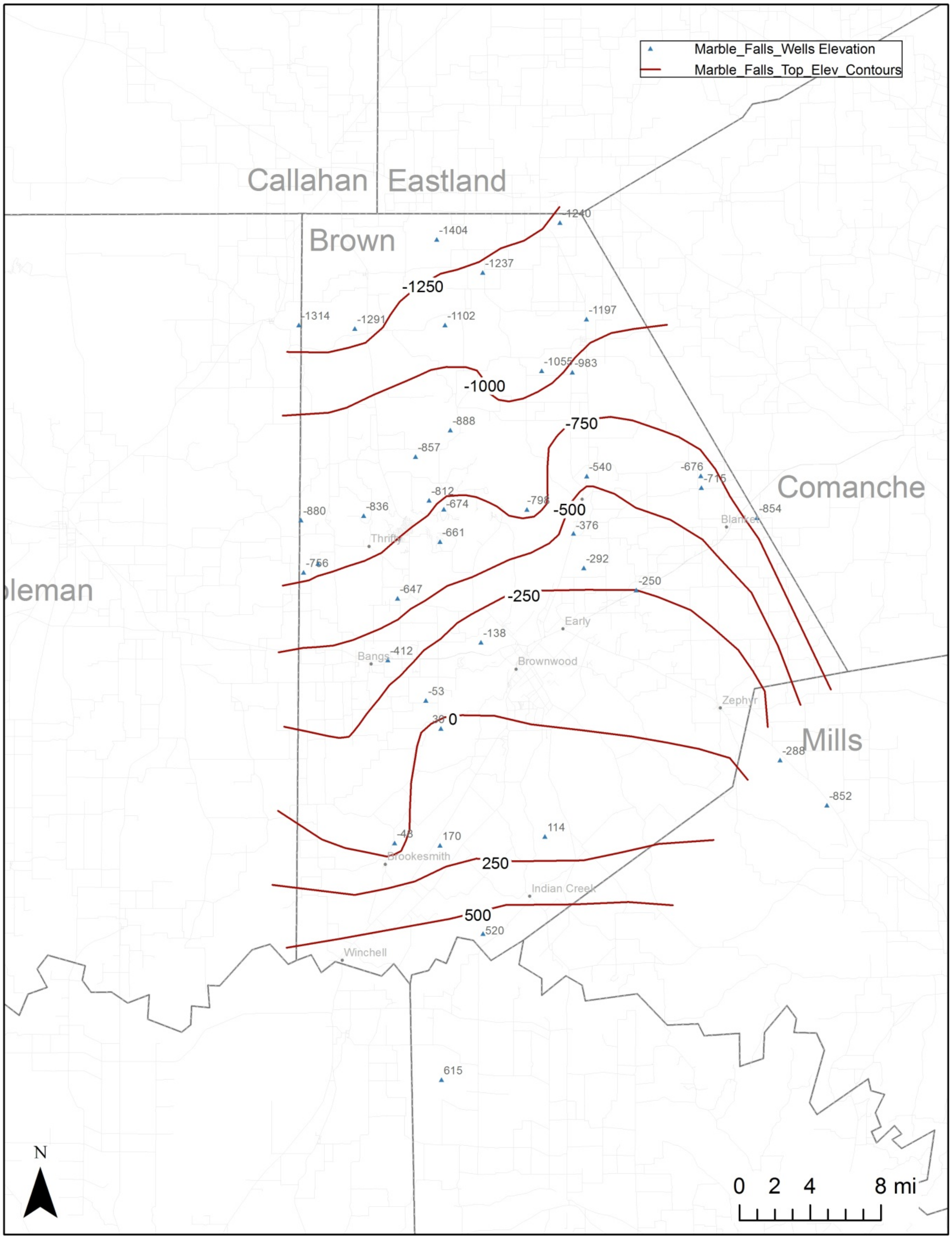
Note: presented contour lines only indicate true contour lines because fault interruptions unaccounted for.
Note: datum is mean sea level

Figure 44. Generalized map of elevation of top of Mid-Cambrian Sandstone in Brown County (ft).



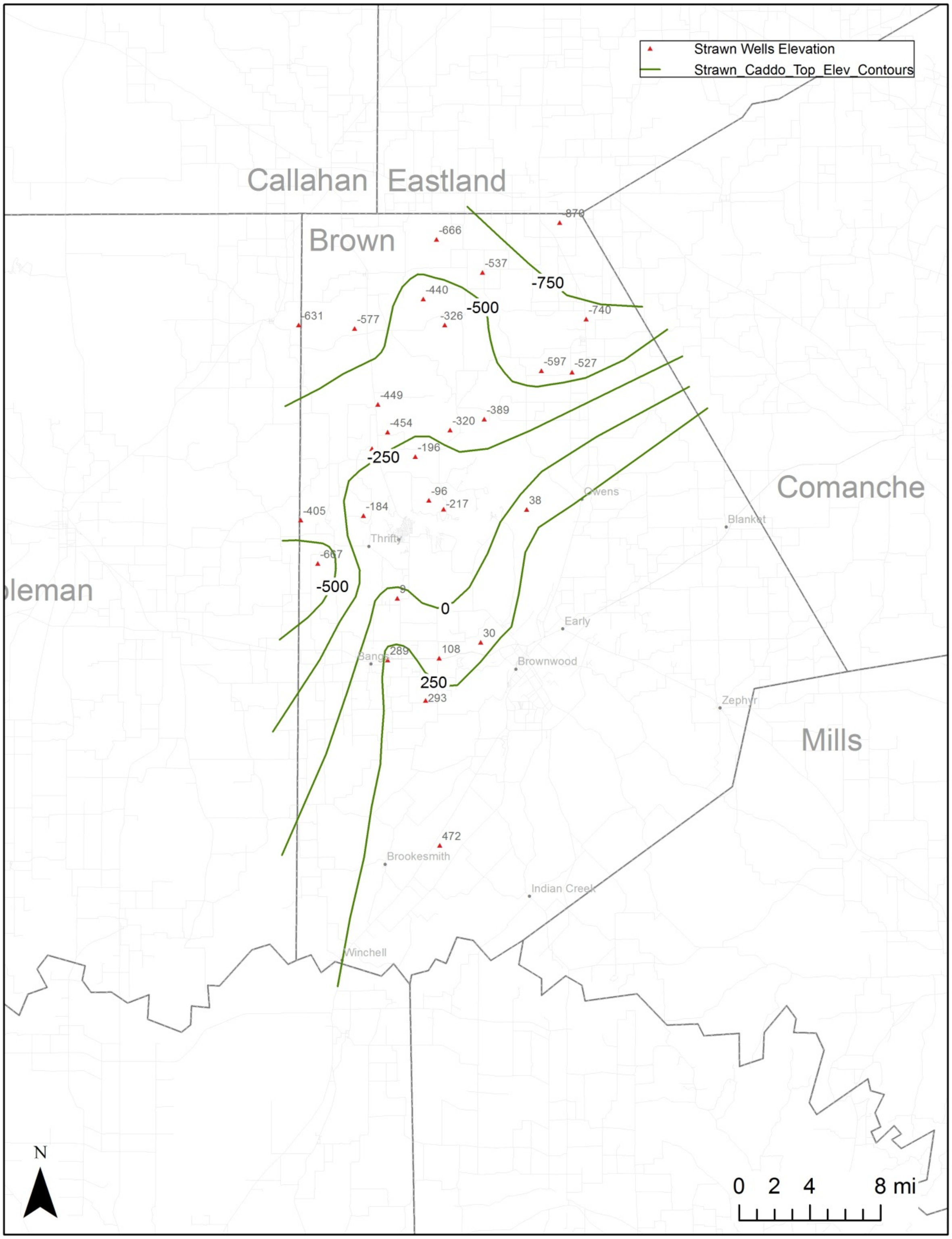
Note: presented contour lines only indicate true contour lines because fault interruptions unaccounted for.
Note: datum is mean sea level

Figure 45. Generalized map of elevation of top of Ellenburger Group in Brown County (ft).



Note: presented contour lines only indicate true contour lines because fault interruptions unaccounted for.
Note: datum is mean sea level

Figure 46. Generalized map of elevation of top of Marble Falls Limestone in Brown County (ft).



Note: presented contour lines only indicate true contour lines because fault interruptions unaccounted for.
Note: datum is mean sea level

Figure 47. Generalized map of elevation of top of Caddo Limestone (Strawn) in Brown County (ft).

V-2. Aquifer Hydraulic Properties

V-2-1 Active Water-Producing Formations in Brown County

To set the stage for a better understanding of water resources in Brown County, we compiled information about all productive strata in the county. Then, to acquire their aquifer hydraulic properties, we researched water-well driller's reports from TCEQ and TWDB. Well-completion reports from TCEQ, with completion dates prior to 5 February 2001, are in scanned PDF format, whereas those from TWDB, with completion dates after 5 February 2001 are in an electronic database format. We digitized data from scanned PDFs to spreadsheets for 1125 wells in Brown County, with about a 10-mile buffer to the south and west of the county (Figure 48). A total of 497 well data were downloaded from TWDB. Because well casing and screen information were lumped into one field in the TWDB database, considerable editing and reorganization were required to put the data into a usable format. Most wells in the study area are small, domestic and livestock-supply wells. Although both data sets include latitude and longitude, as well locations, these data were found to be unreliable for plotting. Instead, we used the center of 2.5-minute quadrangles to approximate well locations. Trinity wells were excluded if the wells plotted in quadrangles that intercept the Trinity aquifer. Formations in which the wells were completed were unavailable in both data sets. In this study, we did not differentiate wells within the Pennsylvanian and younger rocks (e.g., Strawn, Canyon, and Cisco). Attributes of the well and performance tests were then summarized. An analytical approach was used to derive transmissivity from specific capacity on the basis of Mace (2001) for wells having well-test data. The aquifers were assumed to be unconfined, and a storativity value of 0.15 was used in transmissivity calculations. Hydraulic conductivity was calculated by dividing transmissivity by the total length of screen intervals. Average and maximum discharge rate, transmissivity, and hydraulic conductivity for each 2.5-minute quadrangle were also computed.

Attributes of wells and performance tests were compiled from TCEQ and TWDB databases (Table 2). Spatial distribution of average and maximum discharge rate, transmissivity, and hydraulic conductivity are shown in Figure 49, Figure 50, and Figure 51. Histograms of well depth, depth to water, and discharge rate are shown in Figure 52. About 90% wells are <300 ft in depth. About 90% discharge rates in well-performance tests are <30 gpm. Histograms of transmissivity and hydraulic conductivity are shown in Figure 53. About 90% of tests have transmissivity values of <400 ft^2/day. About 90% of hydraulic conductivity values are <18 ft/day.

V-2-2 Hickory, Ellenburger, and Other Lower Paleozoic Aquifers

Data about hydraulic parameters of the Hickory and Ellenburger aquifers are not numerous. Myers (1969) compiled pumping-test data in Texas, and no data points were found for Brown County. We can increase information about likely values of hydraulic parameters in Brown County by widening the search to neighboring counties and farther out.

Two data points with transmissivity estimates were found for the Ellenburger aquifer in southern Gillespie County—~12,200 and ~12,800 ft^2/day. Hydraulic-conductivity values were unavailable, but one well provided total screen footage, and hydraulic conductivity could be estimated to be ~74 ft/day. Core Laboratories (1972) discussed the Ellenburger as a whole and mentioned permeability of 0.1 to 200 md (1 d=1000 md=2.8 ft/day) and porosity of 2 to 12%.

BEG oil and gas atlases also provide similar ranges of values. Kosters et al. (1989, p. 94-96) listed a range of <0.1 to 300 md, with most data points (out of 24 gas fields in the Permian Basin, each with a single point) in the 1- to 50-md range; average porosity ranges from 1 to 6 % (as high as 25%). Galloway et al. (1983) (using 29 oil fields in the Permian Basin) mentioned an average permeability ranging from 2 to 300 md (100 md on average), with most values in the 2- to 50-md range. Average porosity is 3% (1–6%). Note that oil and gas atlas values are most likely biased toward high because they were taken from oil and gas reservoirs. Given the type of secondary fracture-related porosity, conductivity is probably very variable and changes can be abrupt. Smith (2004) noted that the Ellenburger-San Saba aquifer yields very small to very large quantities of fresh to slightly saline water. If a well bore intersects fractures or other cavities, then groundwater production can be prolific (as much as 1,000 gpm). However, if no such features are encountered, then yields will be small (<5 gpm). When limestone (calcium carbonate) is encountered, yields can be significantly increased by acidization of the well bore. The production rate from public-water-supply wells are used as an indicator for well (or well-field) yields. Public-supply wells have well yields of as much as 1,000 gpm in the Ellenburger aquifer (Figure 55).

Smith (2004) reported that Marble Falls wells have not been used for public supply. Yields of rural domestic and livestock wells range from 1 to 100 gpm, and irrigation wells are reported to produce from 100 to 200 gpm.

Smith (2004) mentioned that groundwater production from the Welge aquifer is generally small, with average yields of 20 gpm, but a public-supply test well in south-central Gillespie County produced 60 gpm.

In Mason, McCulloch, and Gillespie Counties, 12 data points were found for transmissivity estimates for the Hickory aquifer (Figure 54). Transmissivity from that summary ranges from 668 to 5,882 ft^2/day, and hydraulic conductivity ranges from 3 to 14 ft/day. Discharge rate during the test ranges from 70 to 915 gpm. Smith (2004) reported that well yields from public-supply wells vary from 200 to 790 gpm and irrigation wells have production rates of 25 to 325 gpm. Three data points have storativity values of 0.0001, 0.00004, and 0.00009. UTBEG and Parsons (2010) related information about well #1 in San Saba County with a yield of 70 gpm. Public-supply wells have well yields of as much as 1,150 gpm from the Hickory aquifer (Figure 56).

Table 2. Attributes of wells and performance tests compiled from TCEQ and TWDB databases.

Parameter	No. of samples	Min	Mean	Max	10th Pctl	90th Pctl
Well depth (ft)	777	7.5	132	640	23	280
Depth to water (ft)	498	0	53	280	10	112
Discharge rate (gpm)	448	0.25	11	100	1	25
Drawdown (ft)	129	0	36	303	0	100
Test time (hr)	127	0.05	2	24	0.5	2
Specific capacity (ft^2/d)	107	0.16	321	6468	4	579
Transmissivity (ft^2/d)	89	0.06	240	4907	5	388
Conductivity (ft/d)	79	0.02	8	140	0.2	19

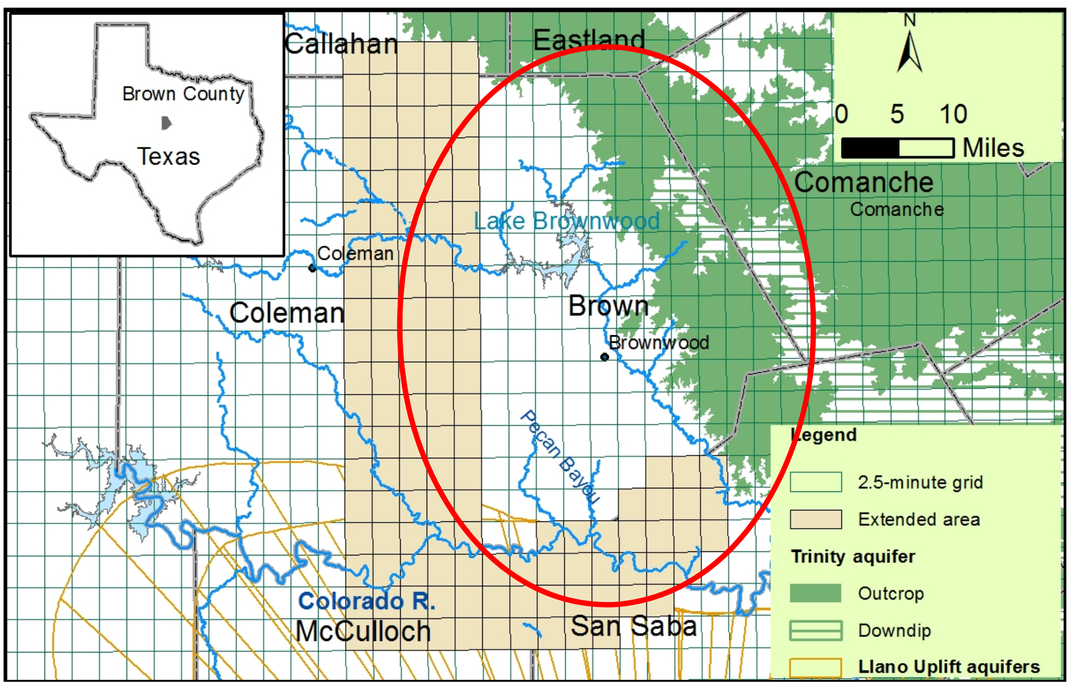
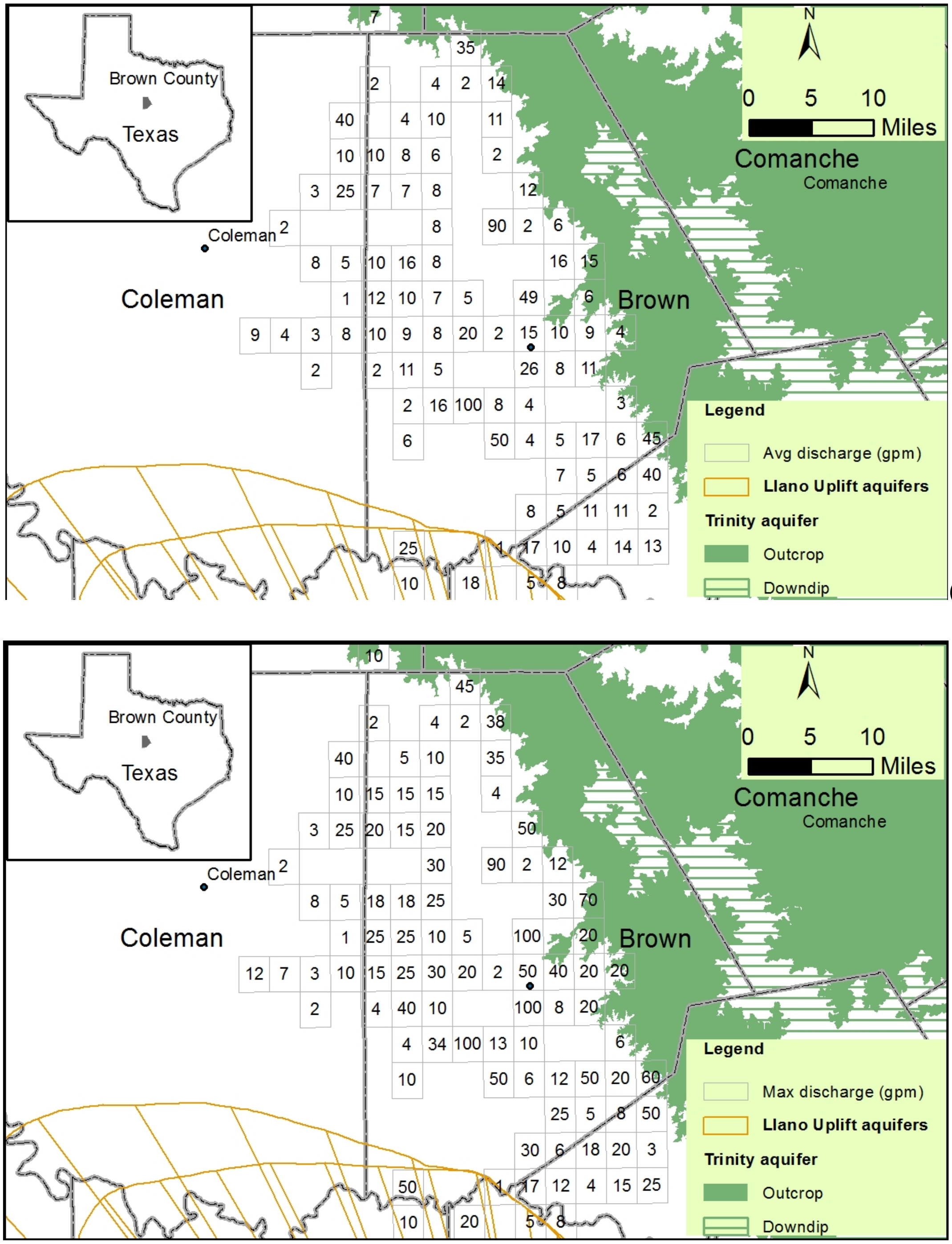


Figure 48. Extended area with 2.5-minute grid in which TCEQ and TWDB wells were digitized/processed for transmissivity calculations.



(a)

(b)

Figure 49. Spatial distributions of (a) average and (b) maximum discharge rate (gpm).

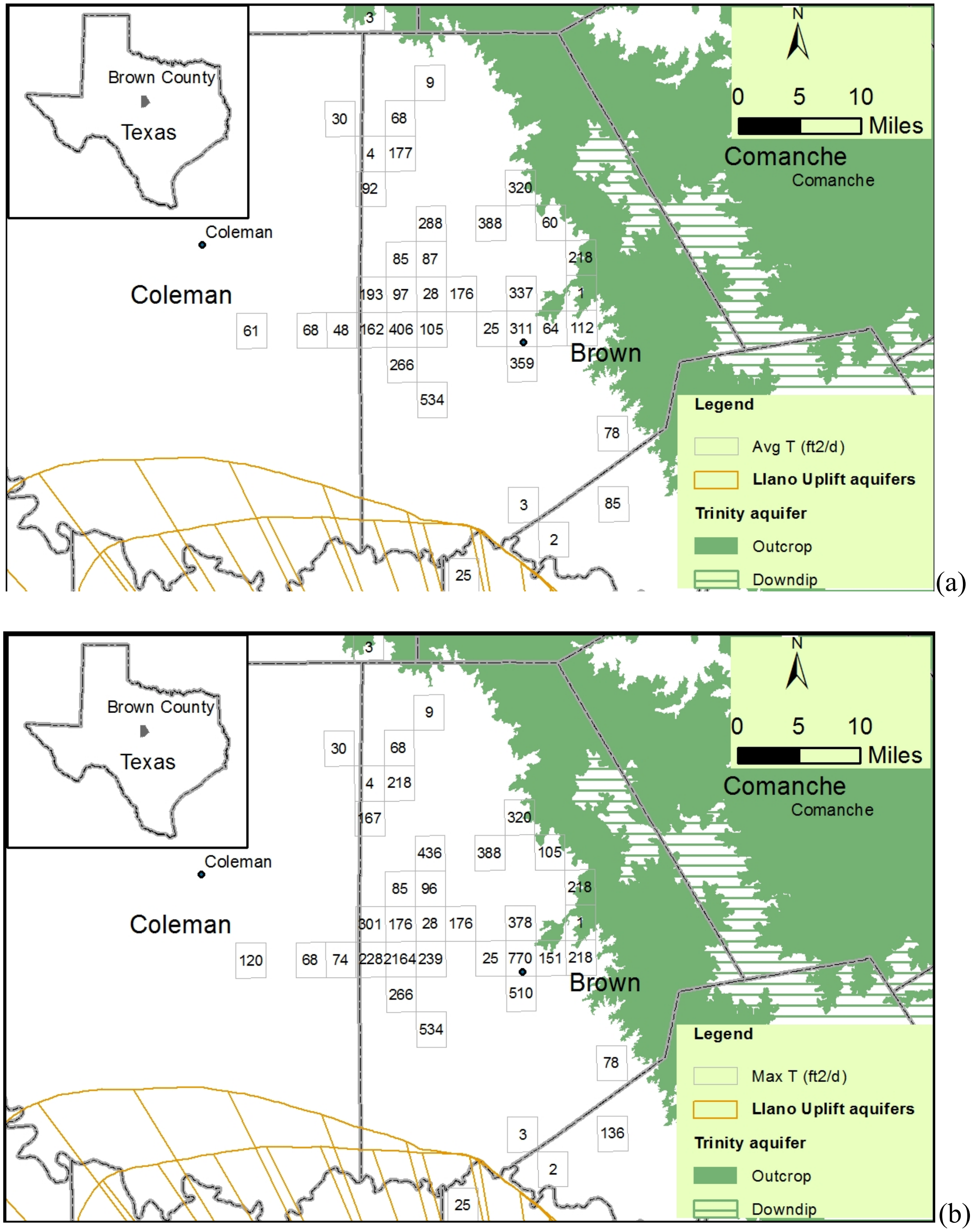


Figure 50. Spatial distributions of (a) average and (b) maximum transmissivity (ft^2/day).

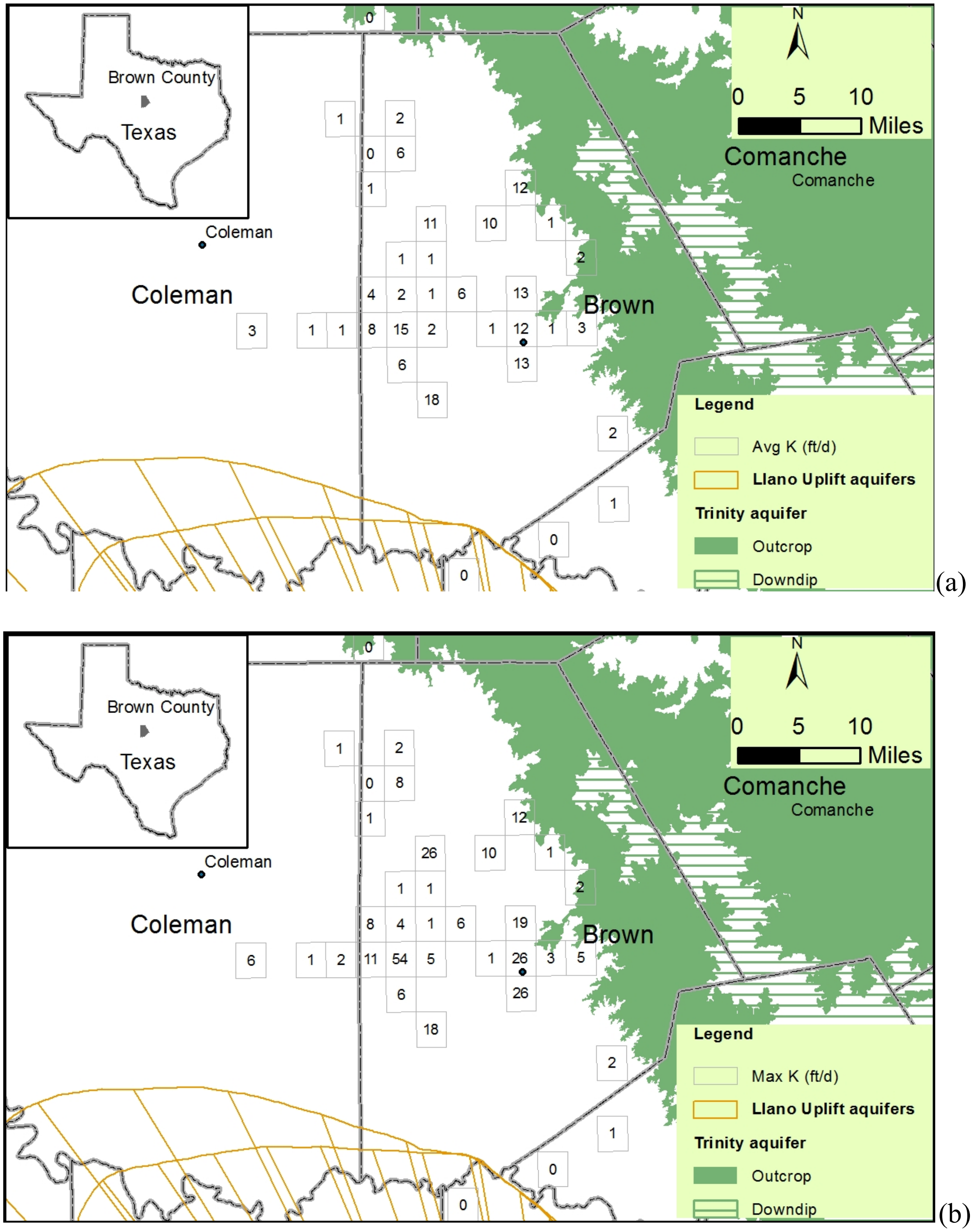


Figure 51. Spatial distributions of (a) average and (b) maximum hydraulic conductivity (ft/day).

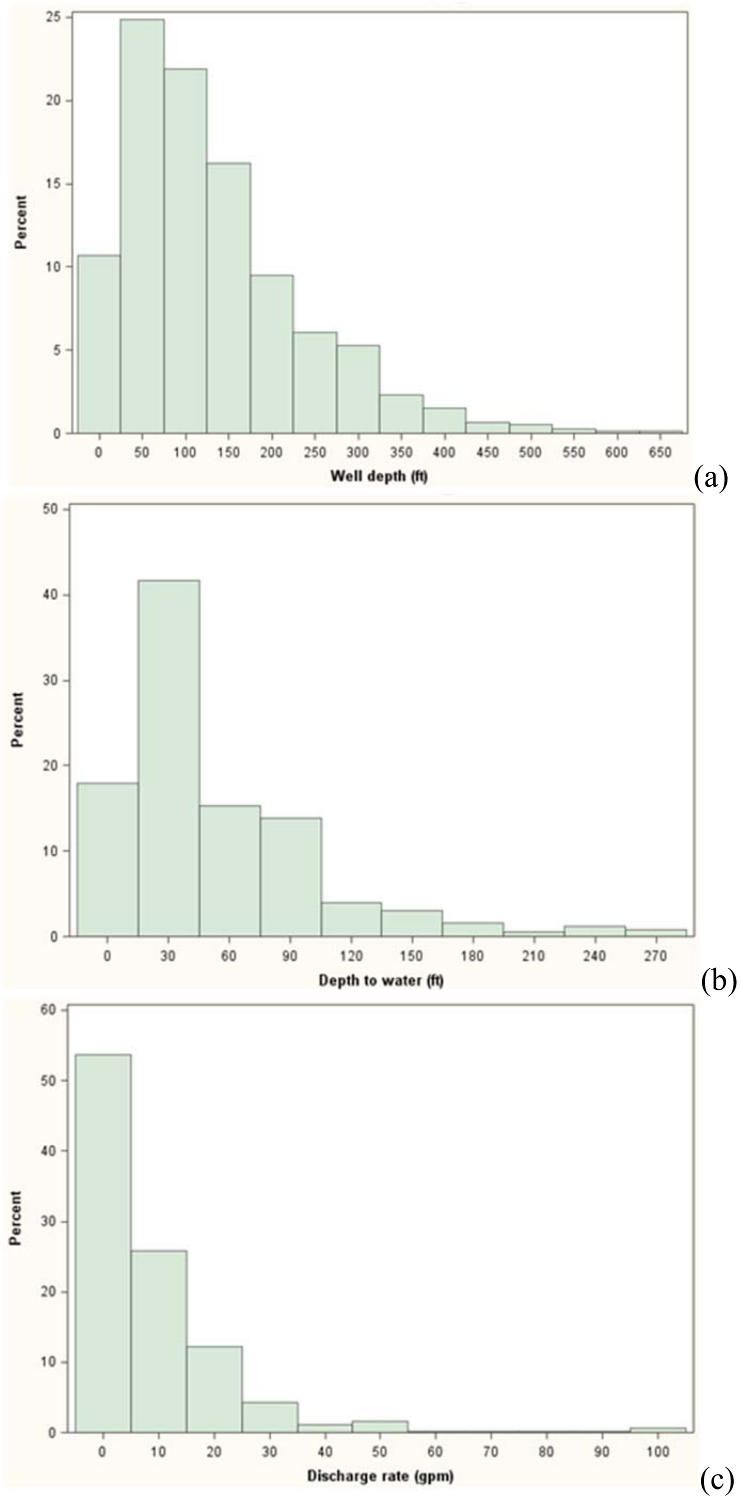
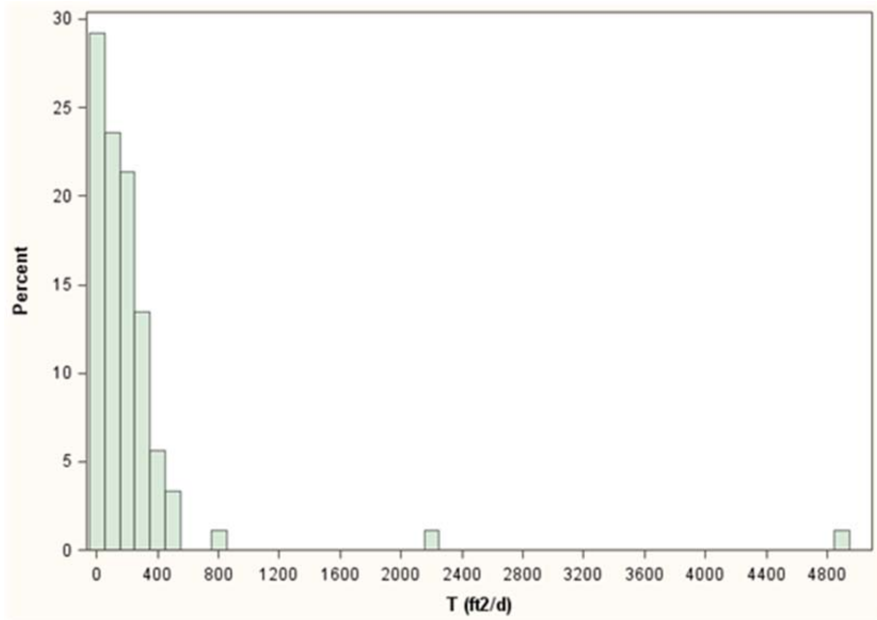
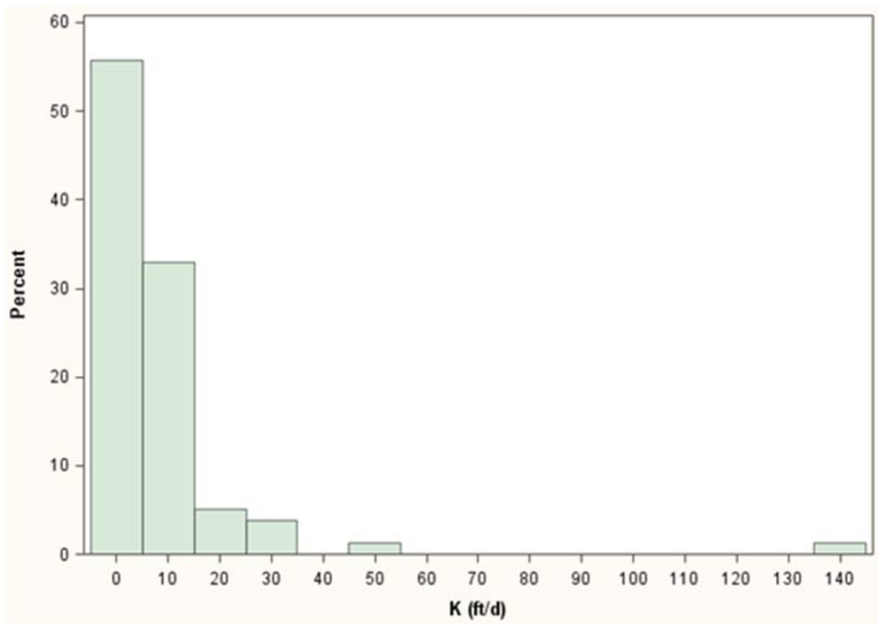


Figure 52. Statistical distribution of (a) well depth, (b) depth to water, and (c) well-test discharge rate.



(a)



(b)

Figure 53. Statistical distribution of (a) transmissivity and (b) hydraulic conductivity (b)

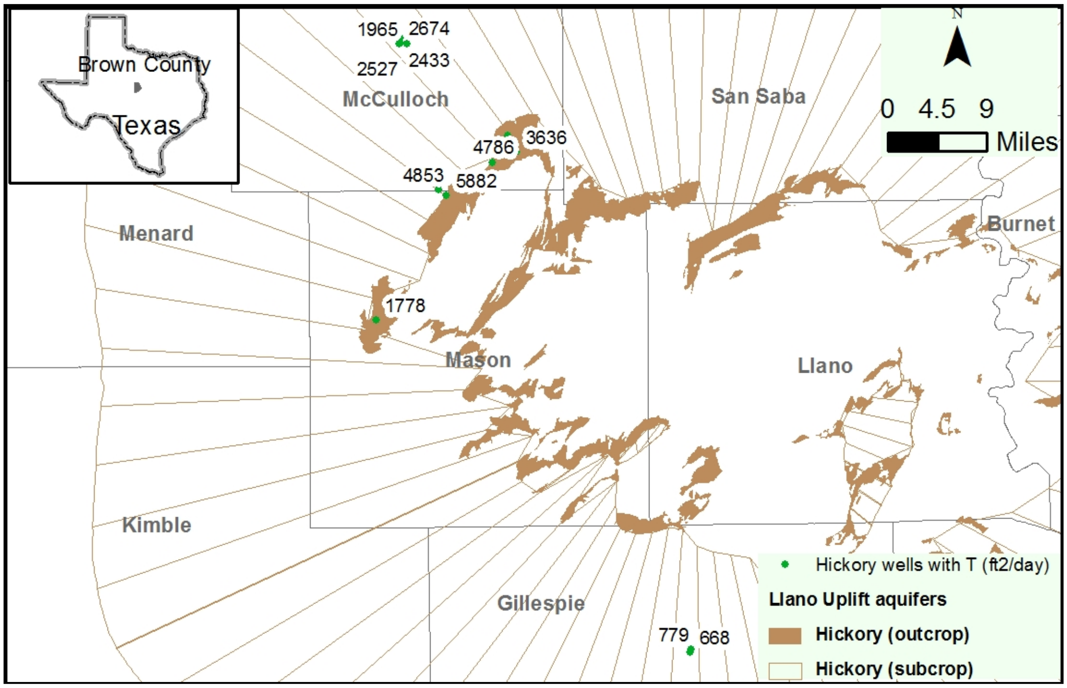


Figure 54. Transmissivity values in the Hickory aquifer from Myers (1969).

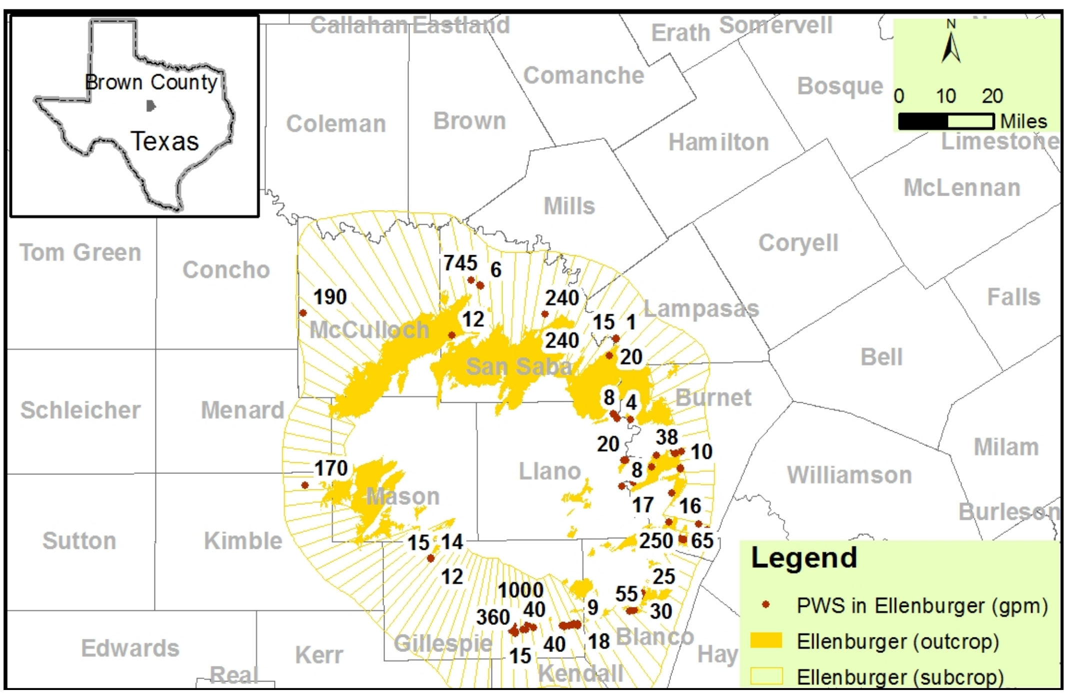


Figure 55. Production rate from public-water-supply (PWS) systems in the Ellenburger aquifer.

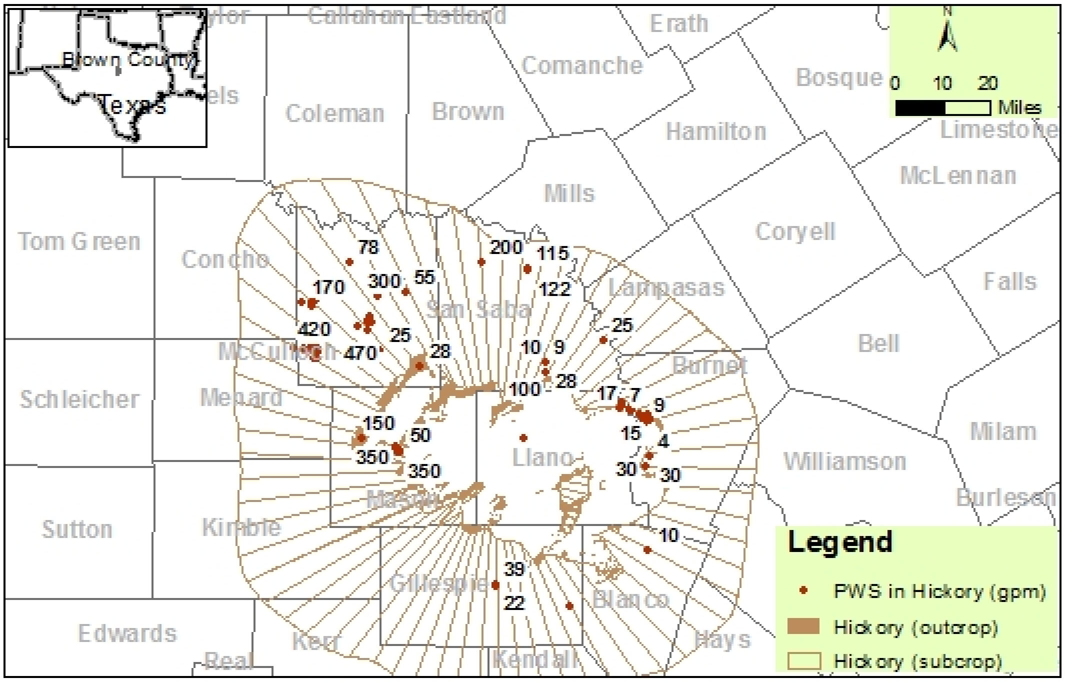
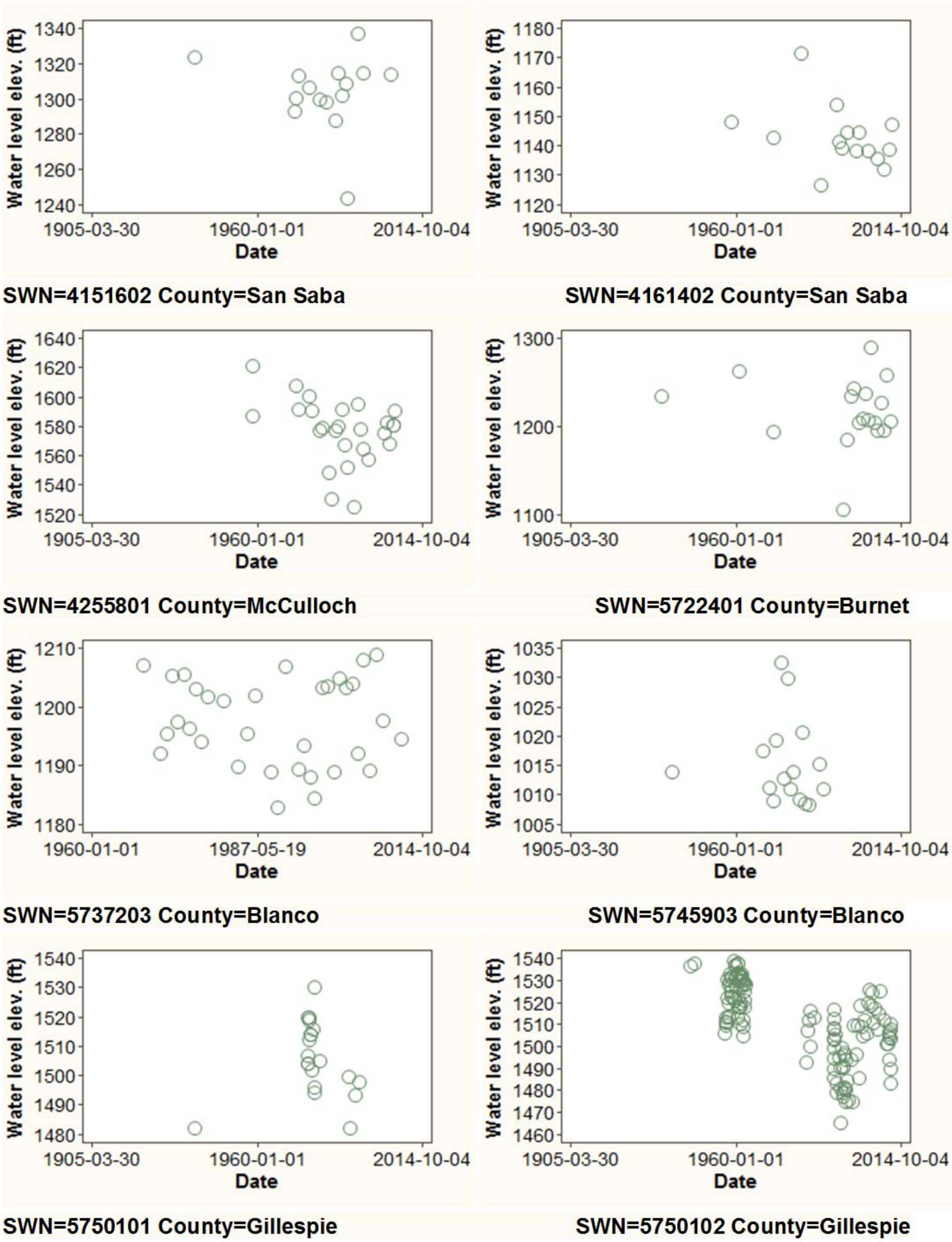


Figure 56. Production rate from public-water-supply (PWS) systems in the Hickory aquifer.

V-3. Water Levels in Hickory and Ellenburger Aquifers

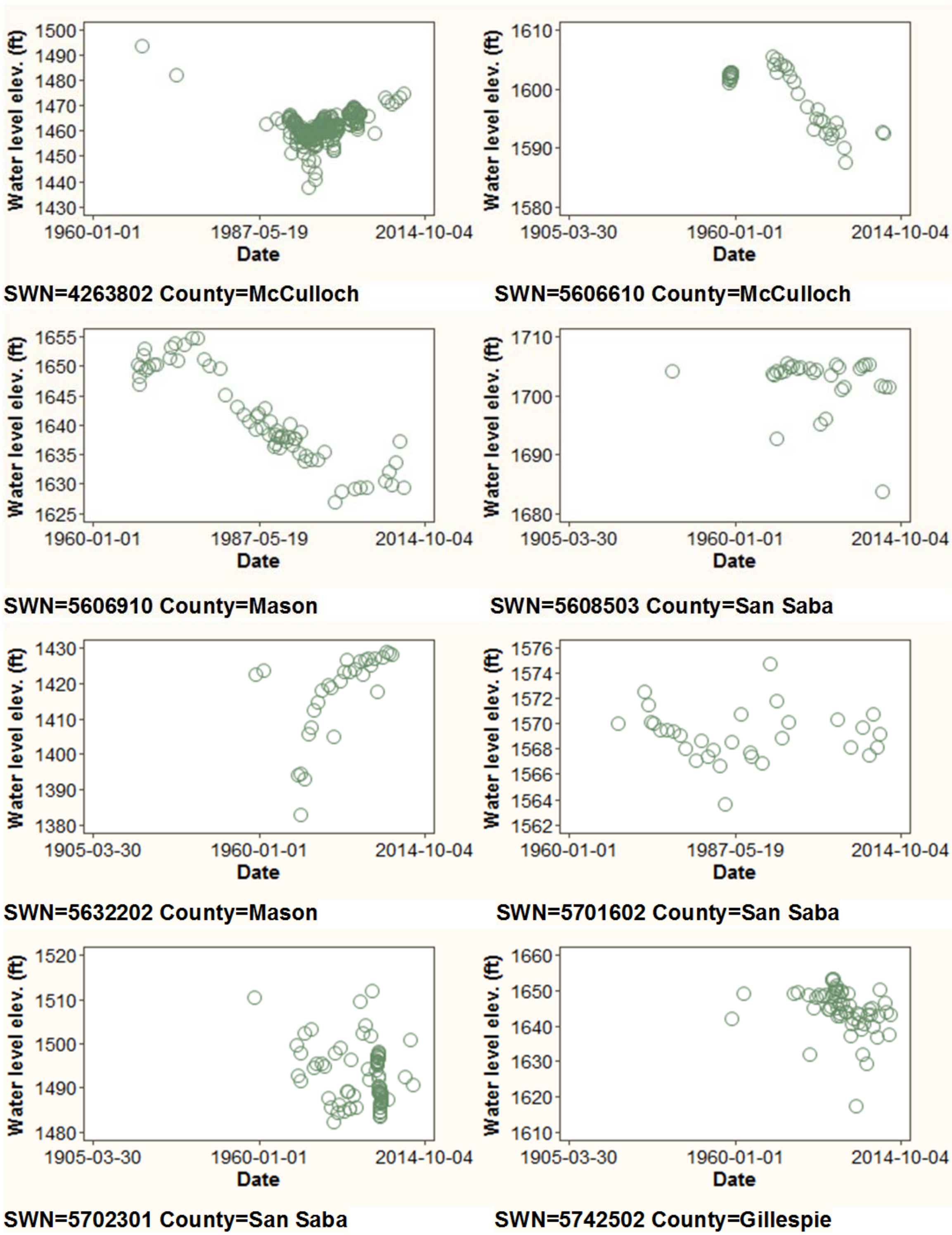
Both Hickory and Ellenburger aquifers are confined aquifers in Brown County, with well-water level rising above the top of the formation and sometimes above ground in some documented cases (e.g., Hot Wells; see Appendix A). However, overall, few head data are available. Figure 57 and Figure 58 show water-level changes over time in the Ellenburger and Hickory aquifers in selected wells. The wells were selected if the number of observations were >15 and the time range of the observation spanned at least 40 years. Systematic head changes through time are lacking in the Ellenburger aquifer. Some wells showed significant drawdown, whereas most others showed no systematic changes. In San Saba and McCulloch Counties, due south of Brown County, water-level histories are noisy but do show neither significant decrease nor systematic decrease, except for in one Hickory well in McCulloch County, which had a small drop of <20 ft.

Spatial distribution of water-level elevations is shown in Figure 59 and Figure 60 for Ellenburger and Hickory aquifers for pre-1970 conditions and year 2000 conditions. Water levels in the aquifer are influenced by topography, geological faults, and surface drainage, exhibiting a complex pattern, although overall they do show no major head drop. The regional flow direction in Brown County can be estimated if water levels in the Brown County part of the aquifer could be obtained. This quick analysis would suggest that both Hickory and Ellenburger aquifers have seen only minor production relative to contained water volumes.



Note: vertical axes have variable scales

Figure 57. Changes in water levels through time in Ellenburger wells.



Note: vertical axes have variable scales

Figure 58. Changes in water levels through time in Hickory wells.

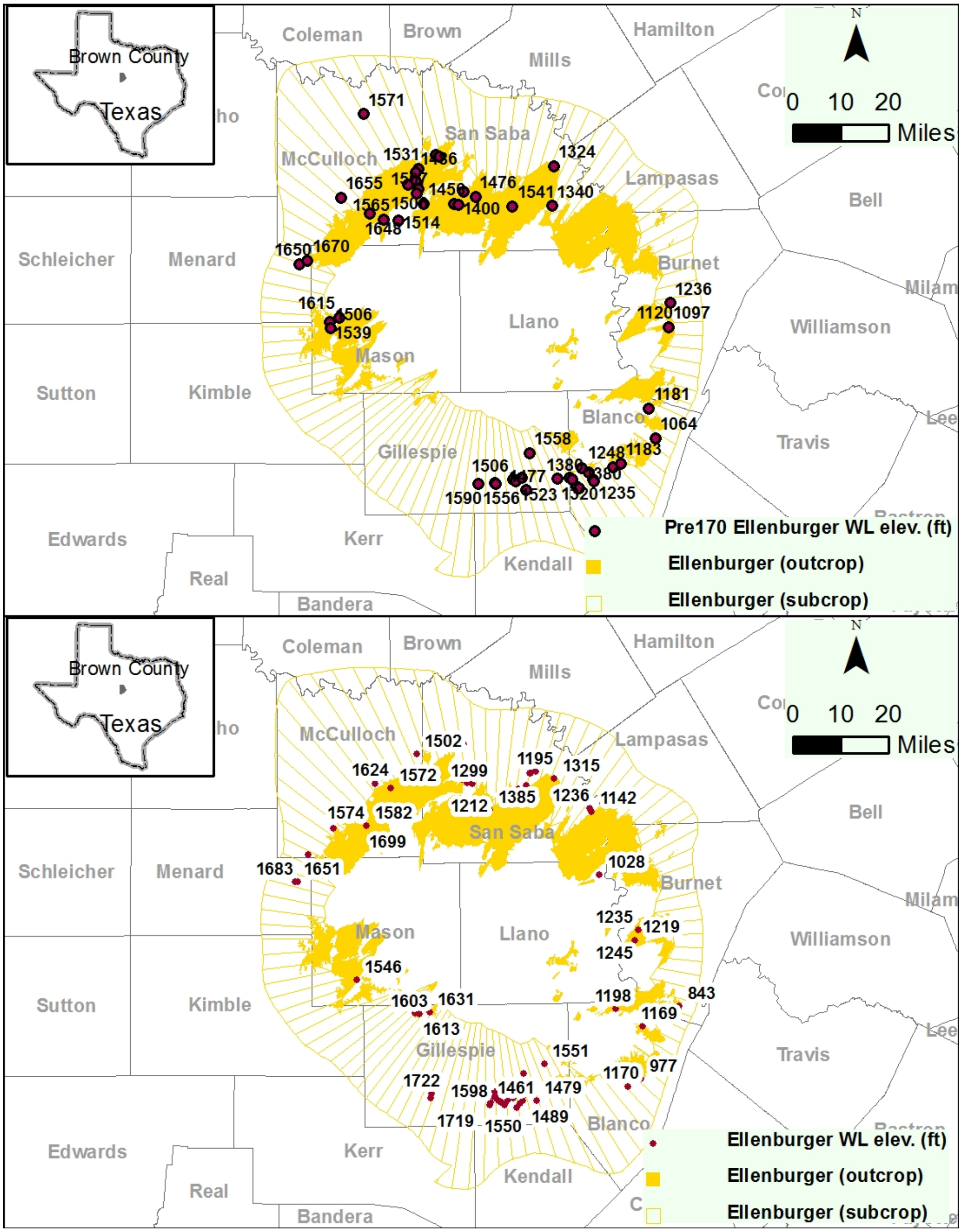


Figure 59. Water-level elevations in Ellenburger aquifer showing (a) pre-1970 conditions and (b) conditions around 2000.

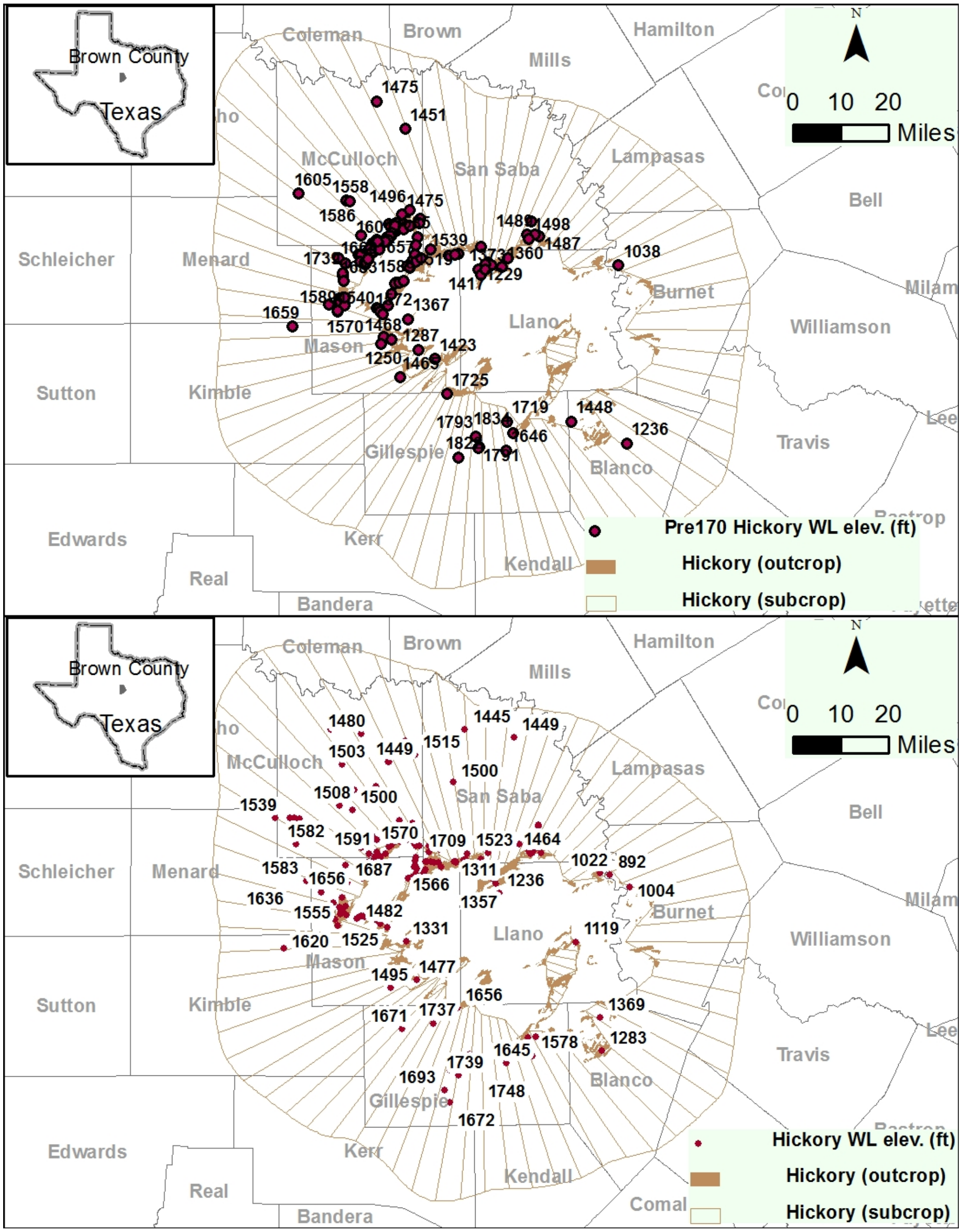


Figure 60. Water-level elevations in Hickory aquifer, showing (a) pre-1970 conditions and (b) conditions around 2000.

V-4. Hydrogeochemistry and Water Quality

As a general rule, shallow groundwater recharged by rain is of good quality, which is the case for lower Paleozoic aquifers where they crop out around the Precambrian basement window. However, Thompson (1967) noted that water quality in shallower upper Paleozoic aquifers varied greatly. He also expressed concerns about water-quality alteration by brine disposal in historical oil and gas production. Mason (1961) noted that groundwater quality from the Hickory in McCulloch County meets drinking-water standards. In the 23 samples from 18 wells tapping the Hickory, except for 1 well that might have leaking water from the overlying Paleozoic rocks, TDS values were <500 mg/L.

A total of 392 major-constituent water-quality samples from 377 Paleozoic wells in Brown County were obtained from the TWDB well database (most wells only have one measurement) (Figure 61). A summary of chloride, fluoride, sulfate, nitrate, and TDS is displayed in Table 3. Chloride concentration is much higher in the Ellenburger and Canyon Groups than in other groups but for different reasons. Fluoride is mostly within the limit of the maximum contaminant level (MCL; 4 mg/L). Sulfate concentration is relatively lower than the secondary MCL (250 mg/L). Nitrate concentration is high in some wells except in the Ellenburger, indicating likely anthropogenic contamination. In the Strawn, Canyon, Cisco, and Wichita, ~85% of samples have TDS values of <3,000 mg/L, and 42% of samples have TDS values of <1,000 mg/L.

To evaluate regional trends, we analyzed TDS measurements in the Ellenburger and Hickory aquifers. Well location and the latest TDS values were plotted, and extrapolation of the TDS trend was indicated by contour lines (Figure 62, Figure 63, Figure 64, and Figure 65). Note that TDS values for four Ellenburger wells in Brown County are 1270; 4810; 13,172; and 41,134 mg/L (Figure 63). In Brown County, salinity of the Ellenburger aquifer varies from ~3000 mg/L at the southern tip of the county to ~50,000 mg/L on the Eastland County line. No new sampling point was found—our map looks like that published by TWDB in 1972 (Core Laboratories, 1972). The Hot Wells location, which has been drilled to the upper part of the Ellenburger, has a salinity of ~13,000 mg/L. Such salinity gradation is common and expected. Why the 1931 Brownwood Chamber of Commerce document displays a salinity 10 times lower than the actual one with an unusual chemical composition is unclear (see Appendix A). The Hickory aquifer has no salinity data in Brown County, although its gradient is likely steeper than that of the Ellenburger aquifer. From these measurements, we can infer that TDS increases faster in the Hickory than in the Ellenburger aquifer.

Trace-element iron and manganese samples were also available for Brown County. Dissolved iron concentrations were 10 ug/L for all six samples from the Cisco, iron being a chemical listed in the secondary MCL (0.3 mg/L). Total manganese concentrations (ug/L) for three samples were 30 for the Cisco, 2500 for the Strawn, and 10 for the Ellenburger. Manganese is a chemical listed in the secondary MCL (50 ug/L).

Preston et al. (1996) noted some incidents of naturally occurring high radioactivity in water from a few Paleozoic wells and springs in Central Texas. These radioactive constituents include gross alpha, gross beta, radium-226, radium-228, and radon gas. UTBEG and Parsons (2010) conducted a feasibility evaluation of water-supply alternatives for the North San Saba Water Supply Corporation. Two groundwater wells completed in the Hickory aquifer were used to supply a community water system in north San Saba County. From July 1998 through December

2008, gross alpha values and combined radium (226 and 228) recorded in their wells were above MCL, causing potential compliance issues under drinking-water standards.

Kim (1995) suggested that uranium and its decay products are mobilized, particularly from intervals in which concentrations of shaly laminae, phosphatic materials, or hematitic cement are high. The study includes 114 core samples from two wells (located 7 mi south of the City of Brady and in Fredericksburg).

Analysis of the most recent, combined radium measurements from 30 wells in the Ellenburger aquifer indicates that 17% of wells had combined radium activity levels higher than the MCL (5 pCi/L). These measurements range from 0.7 to 28 pCi/L, and measurement dates span from 1990 through 2008. No clear spatial pattern of wells exceeded the MCL (Figure 66). From the combined radium activity measurements in 95 wells in the Hickory aquifer, ~65% had levels higher than the MCL. Measurements range from 0.4 to 105 pCi/L. Spatial distribution of combined Radium activity in the Hickory aquifer is shown in Figure 67.

Figure 68 shows spatial distribution of gross alpha from 153 wells in the Ellenburger aquifer, gross alpha activity measurements ranging from 1 to 605 pCi/L. About 14% of these wells had measurements higher than the MCL (15 pCi/L). Figure 69 shows spatial distribution of gross alpha from 226 wells in the Hickory aquifer, gross alpha activity measurements ranging from 1.3 to 95 pCi/L. About 30% of the wells had measurements higher than the MCL (15 pCi/L), and dates range from 1977 through 2009. UTBEG and Parsons (2010) also noted that MCL for radium and gross alpha are sometimes exceeded for a well located in north San Saba County. This recent report (Section 3.2) provides detailed statistical information about the contaminants of concern.

Table 3. Summary of concentrations in water-well samples from Paleozoic aquifers.

Aquifer	Constituent	No. of Samples	Minimum	Median	90^{th} Pctl	Maximum
Wichita	Chloride	24	4	175	1490	2090
Cisco	Chloride	139	7.2	262	1090	6908
Canyon	Chloride	133	1.8	424	1692	7388
Strawn	Chloride	91	2.1	205	851	3144
Ellenburger	Chloride	5	523	7692	24,817	24,817
Wichita	Fluoride	24	0.1	0.4	2.1	3.6
Cisco	Fluoride	139	0.1	0.5	2.5	7
Canyon	Fluoride	133	0.1	1.1	3	6
Strawn	Fluoride	91	0.1	0.7	1.8	3.3
Ellenburger	Fluoride	5	2.4	4.5	8.4	8.4
Wichita	Sulfate	24	4.4	196	798	1180
Cisco	Sulfate	139	3.2	162	782	1950
Canyon	Sulfate	133	1	133	766	1701
Strawn	Sulfate	91	4.3	106	365	597
Ellenburger	Sulfate	5	3	14	242	242
Wichita	Nitrate	24	0	1.5	104	219
Cisco	Nitrate	139	0	4.8	212	2640
Canyon	Nitrate	133	0	0.8	46	1107
Strawn	Nitrate	91	0.09	4.2	37	409
Ellenburger	Nitrate	5	0.4	0.4	0.4	0.4
Wichita	TDS	24	86	1218	3513	4515
Cisco	TDS	139	106	1198	3493	11139
Canyon	TDS	133	65	1588	4372	14078
Strawn	TDS	91	104	879	2153	5593
Ellenburger	TDS	5	1270	13,172	41,134	41,134

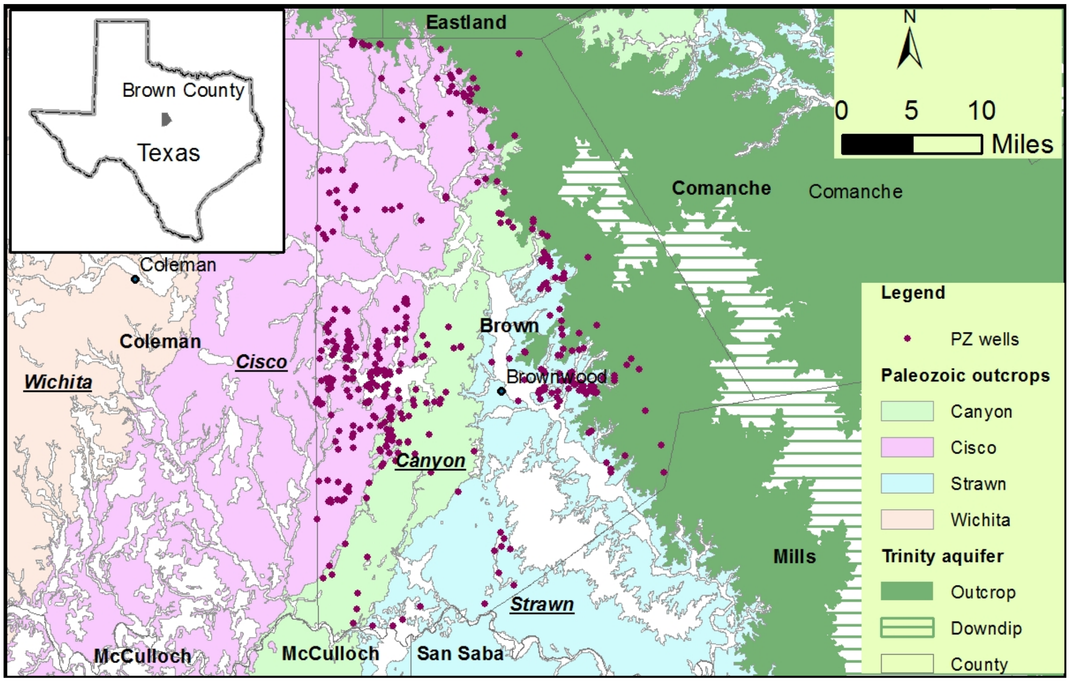
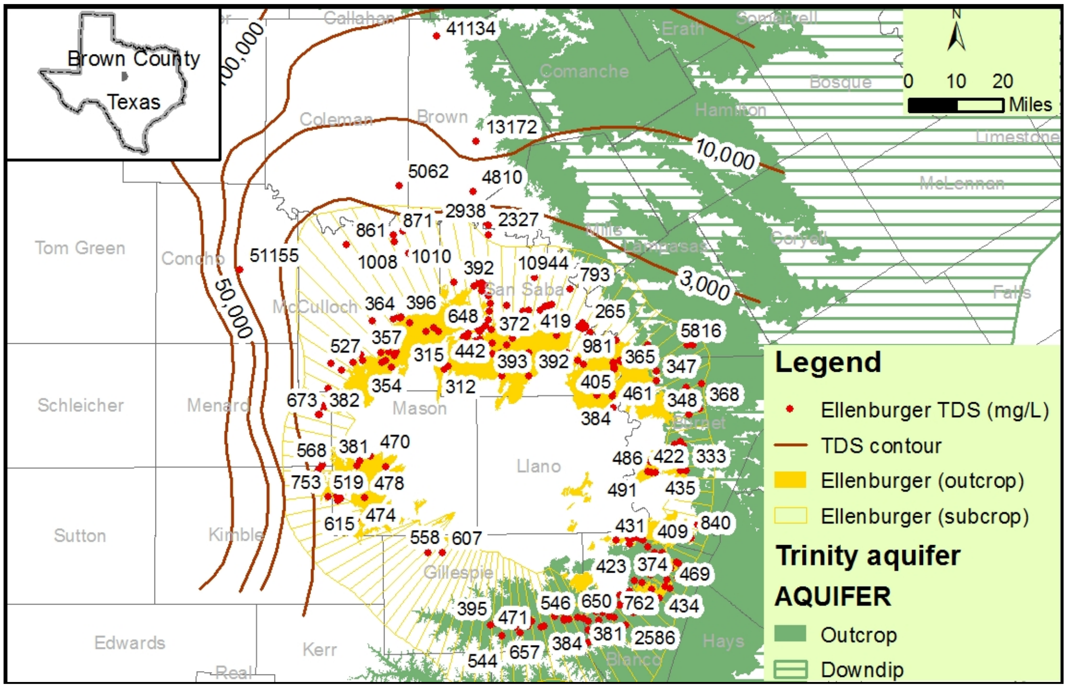
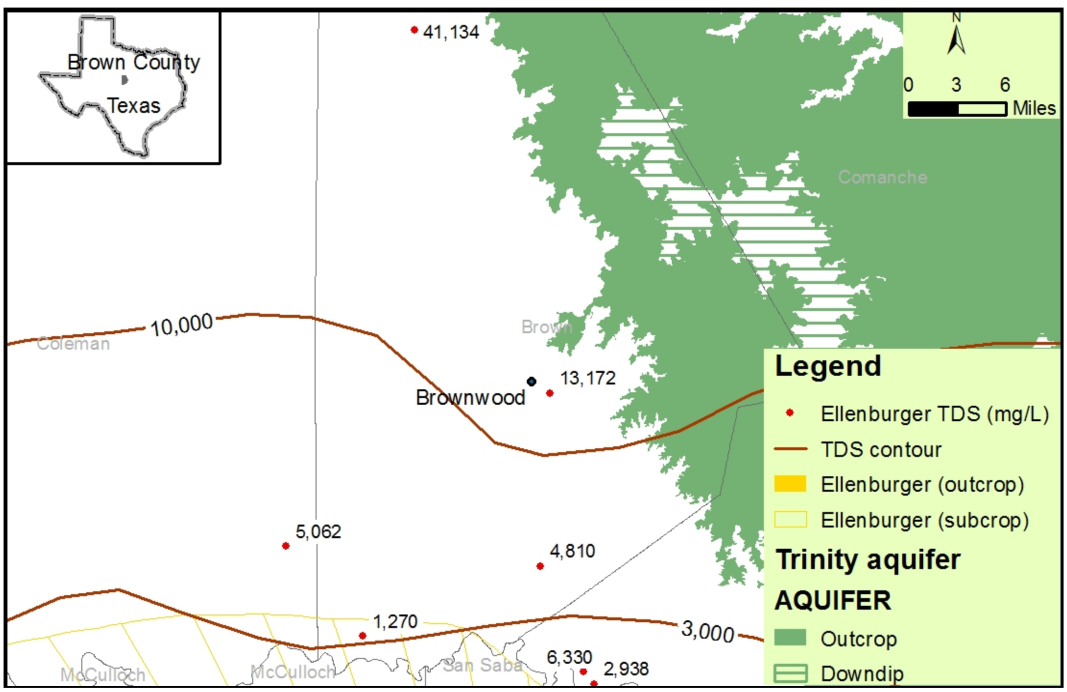


Figure 61. Location of Brown County upper Paleozoic wells with major constituent water-quality samples.



Source: TDS contours from Core Laboratories (1972)

Figure 62. Ellenburger wells and their TDS measurements from TWDB groundwater database.



Note: Ellenburger well near Brownwood—so-called Hot Wells.

Figure 63. Ellenburger wells in Brown County and their TDS measurements from TWDB groundwater database.

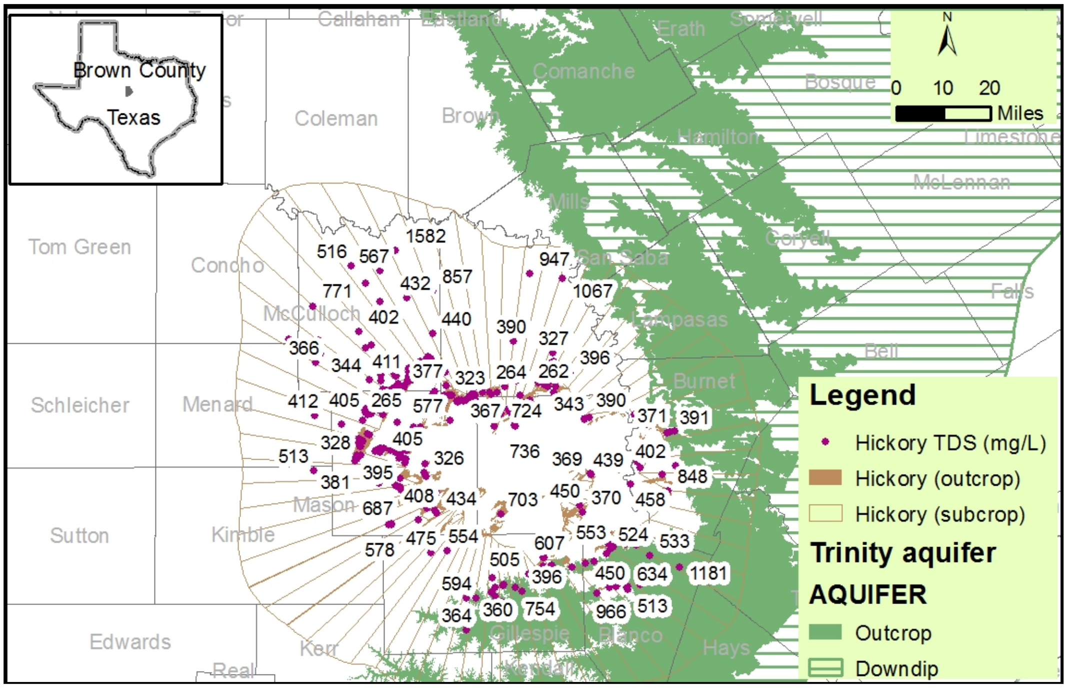
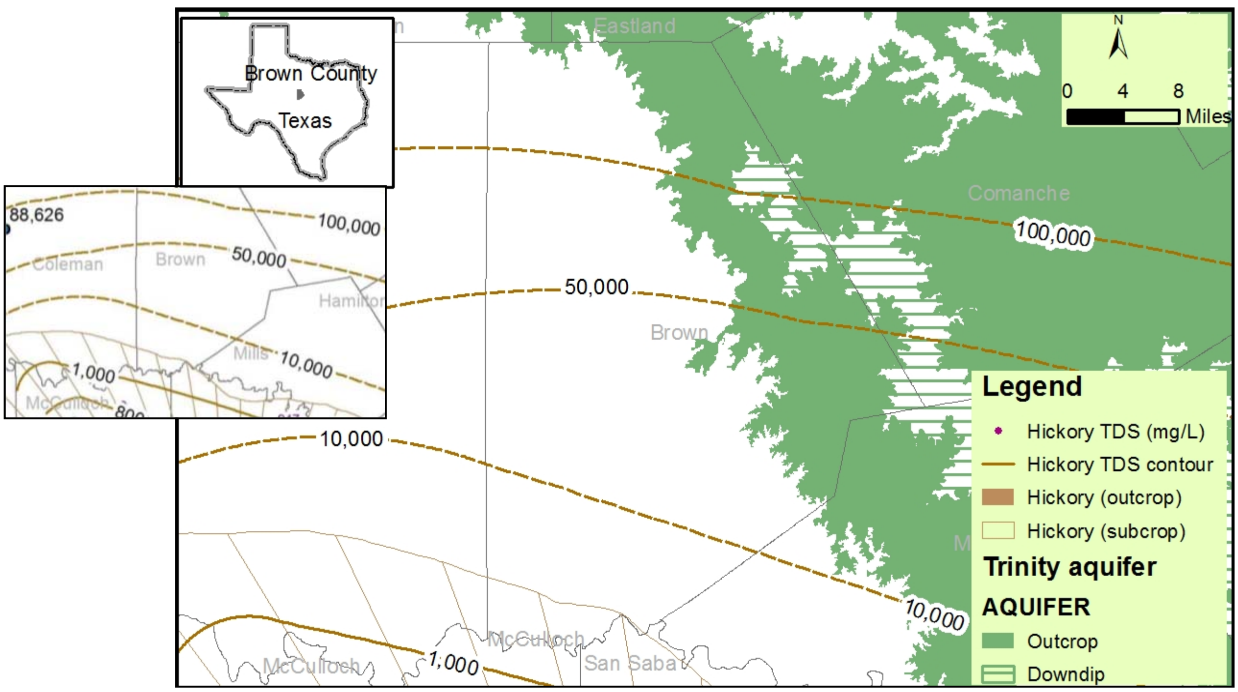


Figure 64. Hickory wells and their TDS measurements from TWDB groundwater database.



Note: one data point in Coleman County helped in drawing salinity contour lines

Figure 65. Hickory TDS contour lines in Brown County. Dashed contour lines indicate extrapolation.

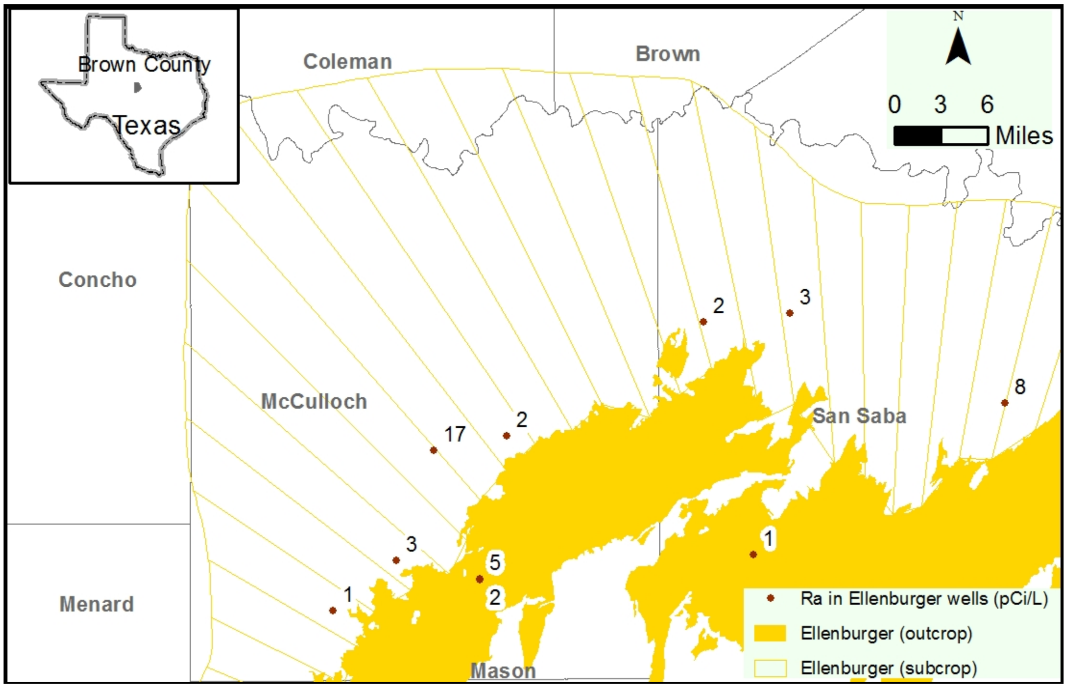


Figure 66. Spatial distribution of combined radium activity in Ellenburger aquifer (MCL: 5 pCi/L).

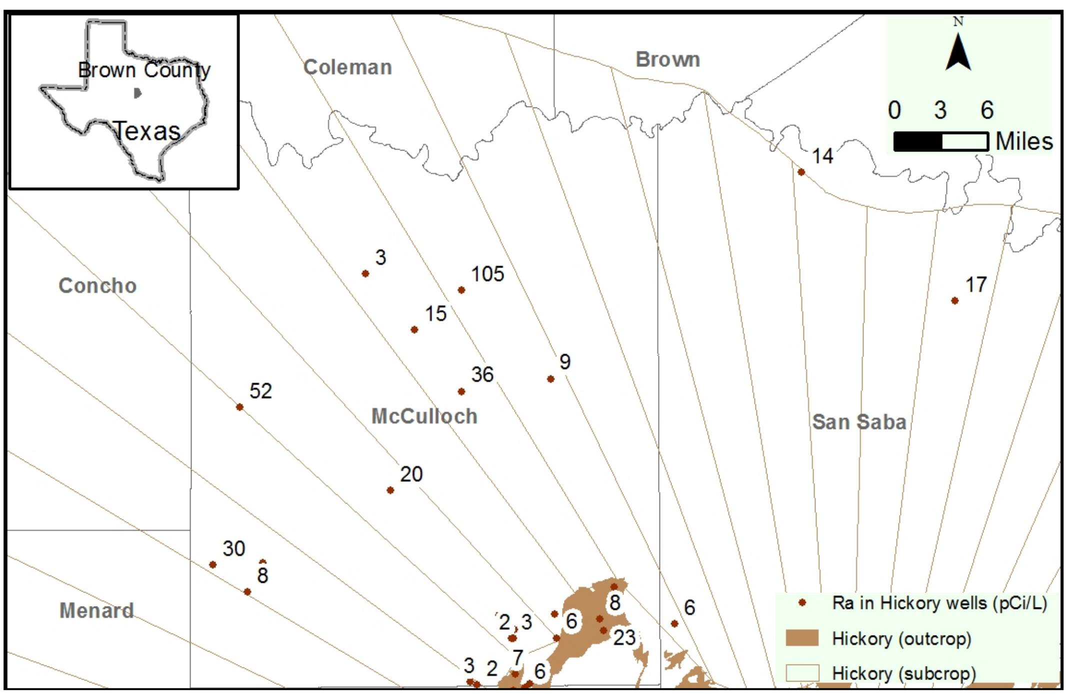


Figure 67. Spatial distribution of combined radium activity in Hickory aquifer (MCL: 5 pCi/L).

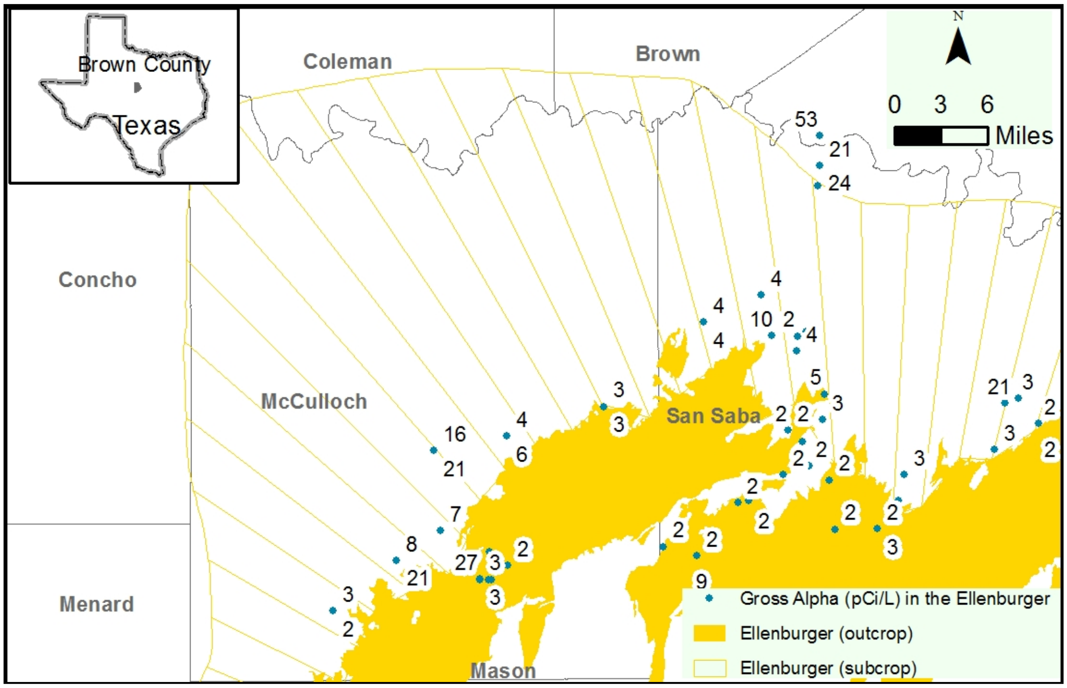


Figure 68. Spatial distribution of gross alpha in Ellenburger aquifers (MCL: 15 pCi/L).

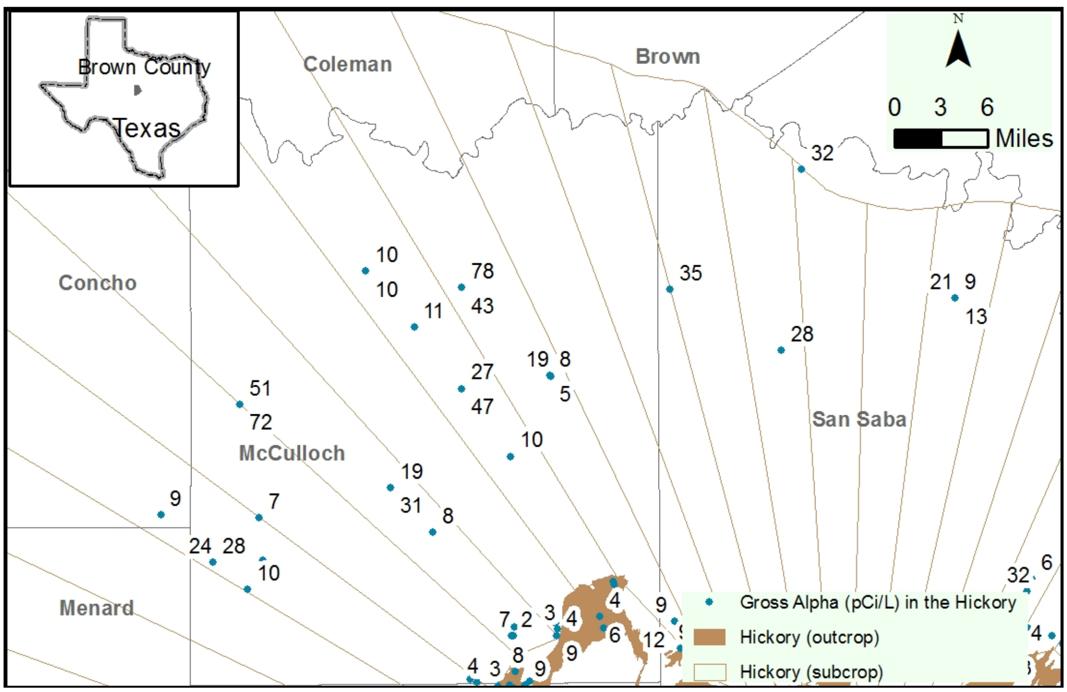


Figure 69. Spatial distribution of gross alpha in Hickory aquifers (MCL: 15 pCi/L)

VI. Results

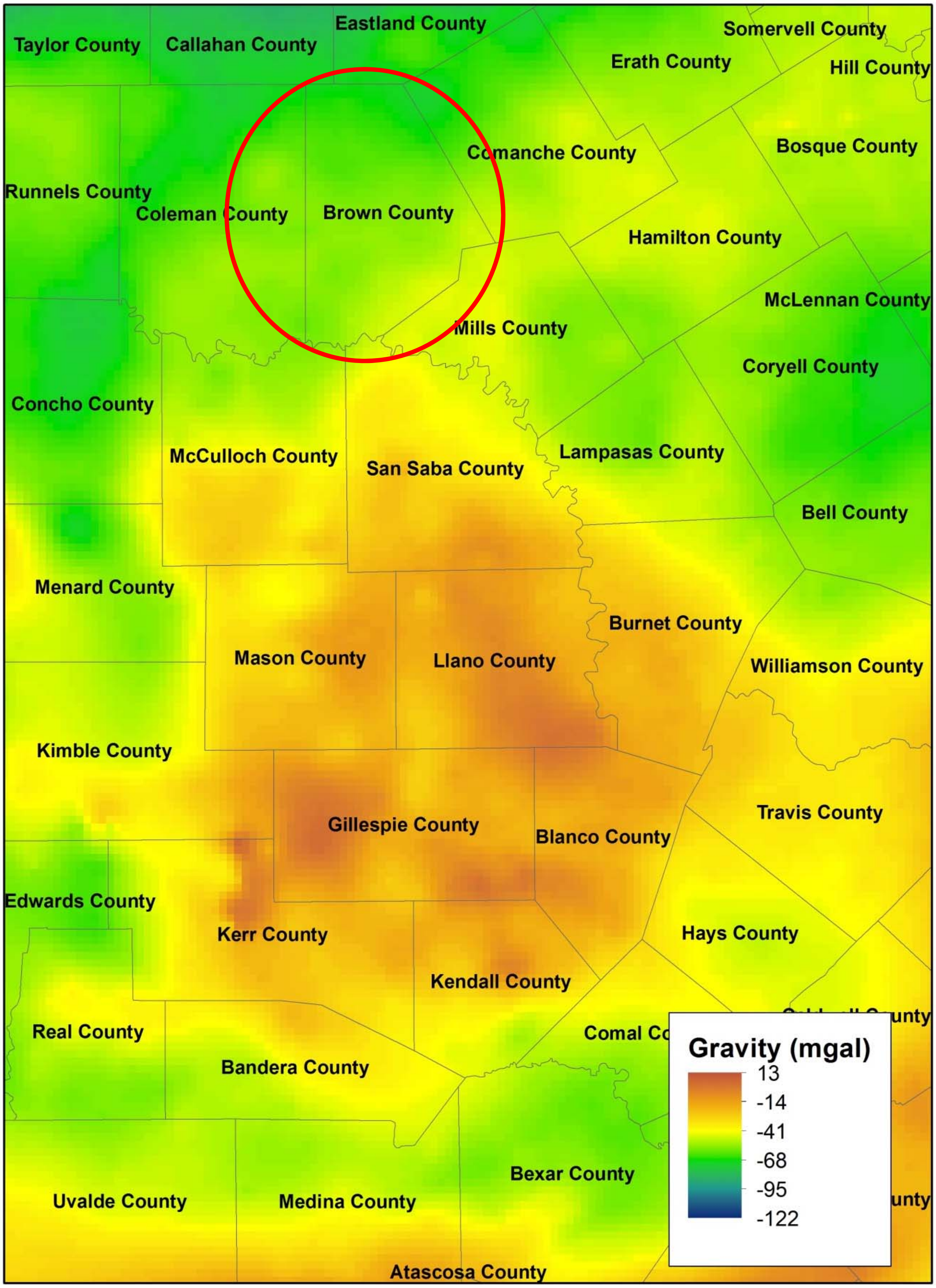
In this section, we analyze specific features that will help locate wells in the Hickory (paleotopography) and Ellenburger (karstic events) aquifers.

VI-1. Assessment of Paleoreliefs of the Precambrian Basement: Gravimetric Study

Assessing paleorelief information is important so as to site a well field tapping the Hickory Sandstone correctly. Paleochannels in the Hickory Sandstone would be thicker and probably more permeable, such as in the Ogallala when sediments were deposited on uneven topography of Cretaceous strata. Unfortunately, little information is available to locate them. We examined an older BEG Bulletin dedicated to Precambrian rocks with no success (Flawn, 1956, p. 53ff + plate 1), the resolution of the map is too low, and only a few additional wells reaching the basement have been drilled since. Owing to the lack of direct information, and because well density is so low and only generalized thickness maps can be drawn, we decided to rely on the next-best option, that is, geophysical information. We are unaware of any public-domain seismic data set that would be of use in solving the problem at hand. There are, however, public-domain geophysical data of a nonseismic nature. USGS regularly undertakes regional collection of ground gravimetric data (>76,000 gravity stations for Texas), as well as aeromagnetic regional data. We interpreted the most recent gravity data set (Bankey, 2006) to try to increase our information on the topography of the top of the Precambrian basement (which is also the base of the Hickory Sandstone). Gravity maps, also known as Bouguer anomaly maps, are available through the USGS website (http://pubs.usgs.gov/ds/2006/232/). Aeromagnetic data are, however, less straightforward to interpret

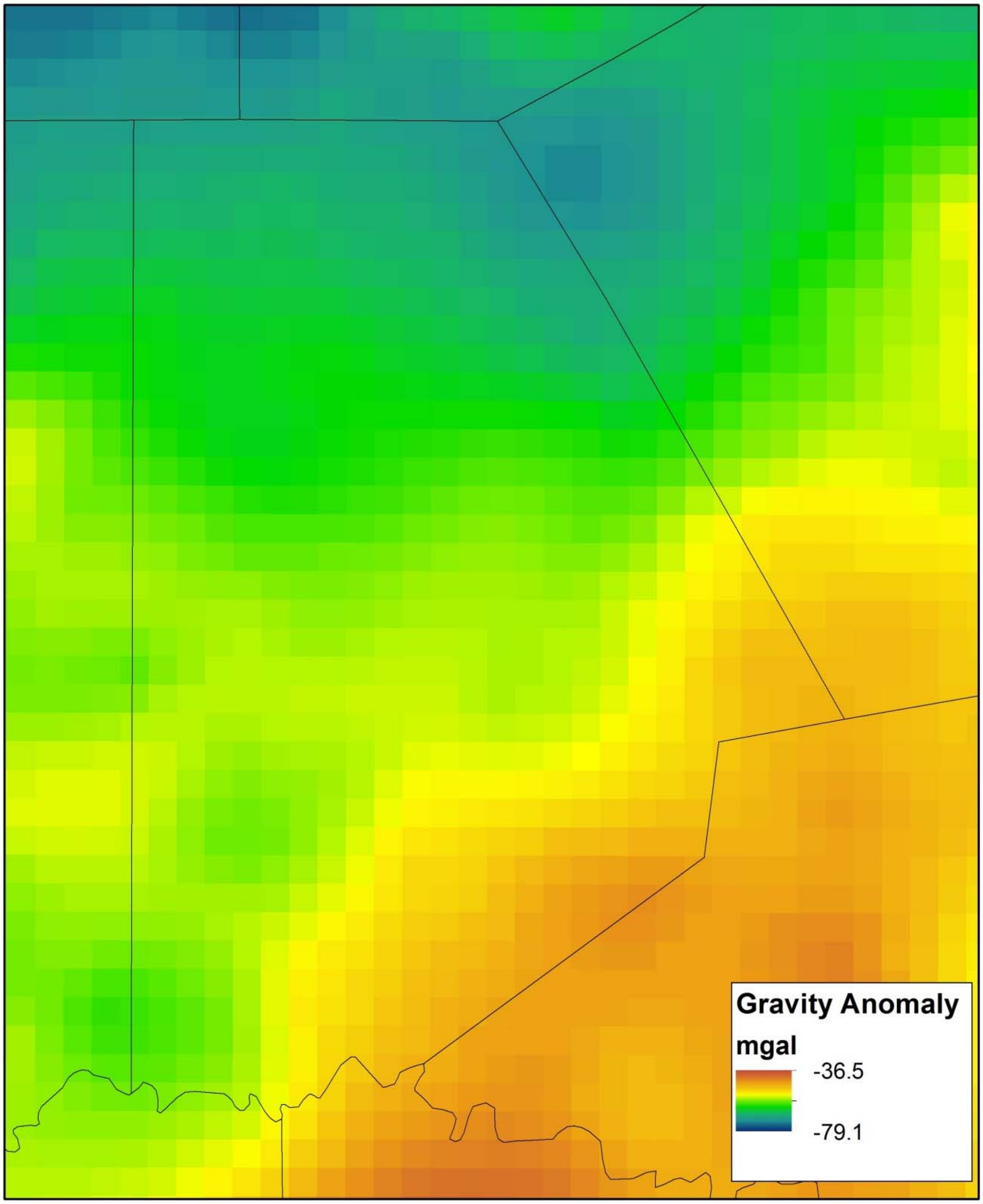
Gravimetric data illuminate mass deficit or excess relative to some average. For example, granite or schist having little porosity will be seen as contributing an excess mass to local gravimetric measurements because their density is in the 2.5- to 2.6-g/cm^3 range, as opposed to a sandstone or a limestone with porosity of say 20% filled with water (resulting in a density of 2.2–2.3 g/cm^3). The relevant unit for a gravimetric survey is the milligal or mgal (acceleration of gravity g is 980,000 mgal). Note that each measurement is the average of the impact of all rocks broadly located beneath the instrument, with a close volume of rock having more impact than the same volume farther away. Producing a map of the boundary between heavier (basement in this case) and lighter (sandstone, limestone, and shale in this case) is a complicated process and one that may not yield a unique solution, even guided by geological knowledge. Here we have attempted to extract information qualitatively, in particular in an attempt to identify locations where the basement is deeper than its surroundings. A first inspection of gravity data (Figure 70) illustrates that the Llano Uplift does produce an excess mass (red on the figure). However, in addition to this regional trend represented by a large central anomaly fading away radially, many spatially more constrained variations are also visible, illustrating the impact of faults, thickness variations, and various rock types.

For Brown County (Figure 71), variations are also noticeable, but within a much smaller range (40 mgal instead of 130 mgal). Variations in density are clearly visible, with the regional trend superimposed on local variations. Note that smooth variations are inherent to gravity maps because the same rock volumes contribute to several gravity-measurement stations. We then used filters (1) to remove large-scale variations (high-pass filter), that is, the general dipping trend, and keep only small variations, or (2) to remove small-scale variations that can be considered noise (low-pass filter). We did so using the Erdas Imagine 2011 software (http://geospatial.intergraph.com/ products/erdasimagine/erdasimagine/details.aspx). A rough approximation for better visualization of high-pass filter maps is that 10 mgal is equivalent to 300 ft. Note that this approximation should not be relied upon to estimate depth, but simply to get a visual sense of the topography illuminated by the gravimetric survey. A high-pass filter map of Brown County shows a checkered pattern controlled by the influence of two features: NE-SW faulting related to the Ouachita front and NW-SE faulting/basement paleotopography (Figure 72). To better understand the impact of faults, we broadened treatment of the gravity data to surrounding counties (Figure 73). The general trends are roughly NNE-SSW-trending lows, which could be interpreted either as valleys incised into the granitic basement filled with Hickory or down-dropped fault blocks. A NE-SW-trending graben (a downthrown block between two normal faults) is visible at the bottom of the figure between two areas with a stronger gravity signal (redder). This is the feature that has been described as *Mason Graben* on some maps (Figure 74). Although many factors can impact gravity response, we made four assumptions for the map to be interpreted: (1) only the NE-SW Ouachita-related faults can create a large contrast in Bouguer anomaly, (2) variations in the NE-SW direction along fault strike correspond to basement paleotopography (itself related to a NW-SE Precambrian structural direction), (3) the NW-SE structural grain was not much reactivated after deposition of the Hickory Sandstone, and (4) thickness variations in the Hickory are larger than thickness variations in the Ellenburger (whose top was eroded). Using this reasoning, and considering other factors, the extreme SW corner of the county is the most favorable, with the option of two probably thicker Hickory areas (black ellipse in Figure 74).



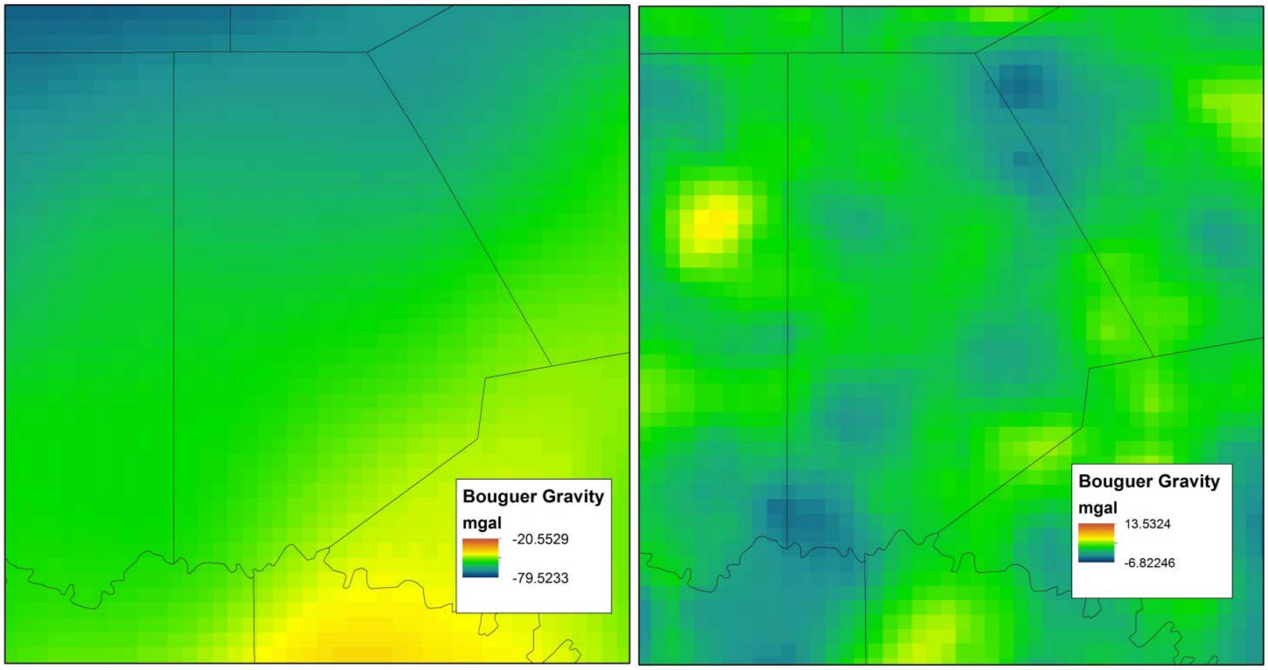
Source of data: Bankey (2006)

Figure 70. Gravity/Bouguer anomaly map of Brown and surrounding counties.



Source of data: Bankey (2006)

Figure 71. Gravity/Bouguer anomaly map of Brown County.

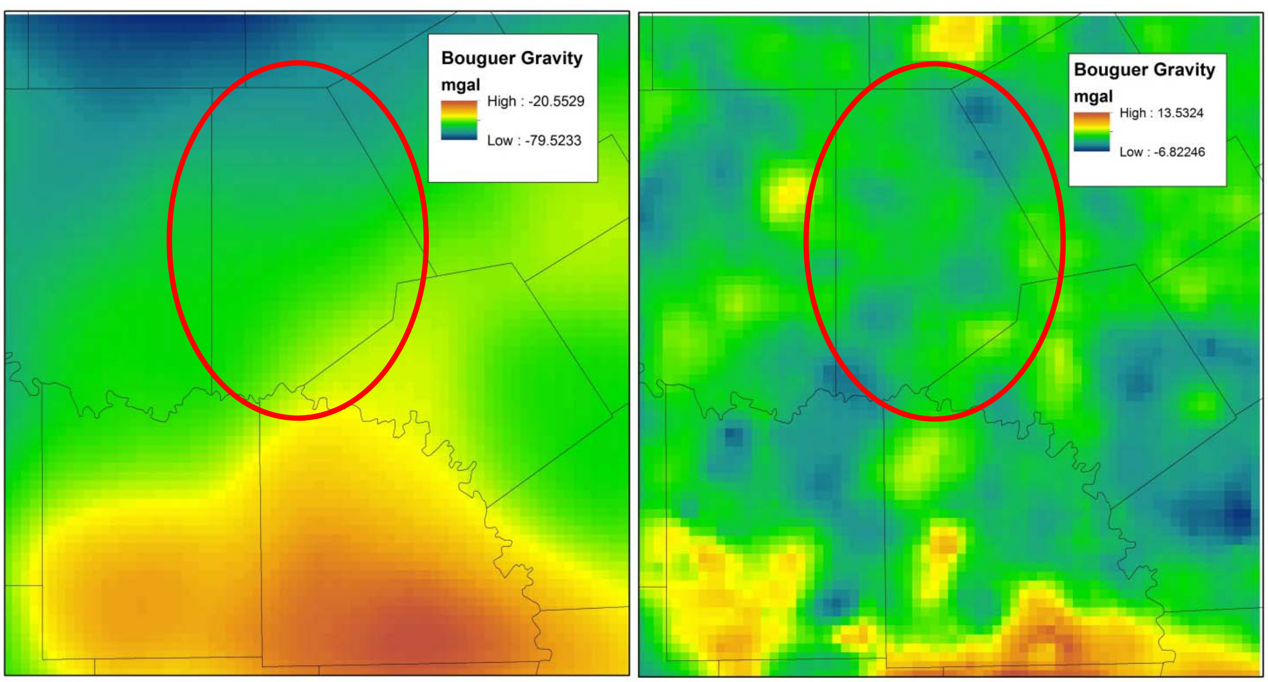


Regional Bouguer Gravity - Low Pass Filter Butterworth 50   Local Bouguer Gravity - High Pass Filter Butterworth 50

Source: processed from Bankey (2006)

Note: low-pass filter shows regional variations, whereas high-pass filter removes regional trend to keep only local variations.

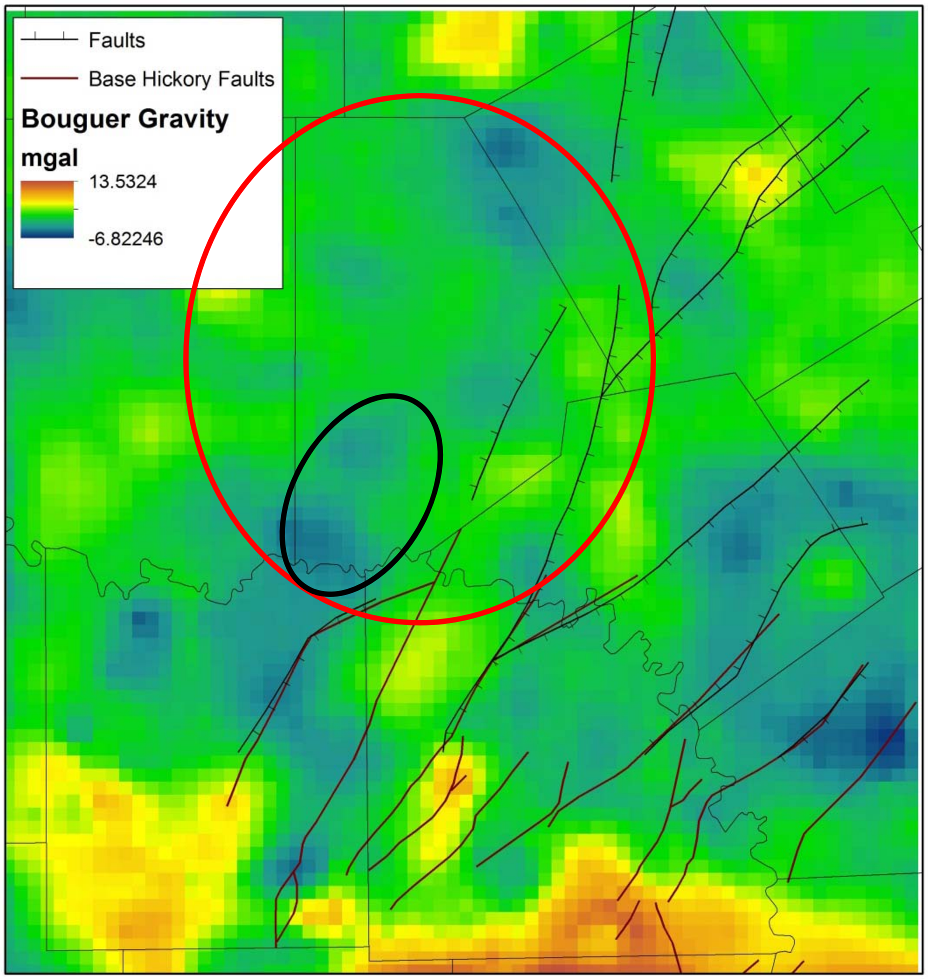
Figure 72. Low-pass/high-pass gravity/Bouguer anomaly map of Brown County.



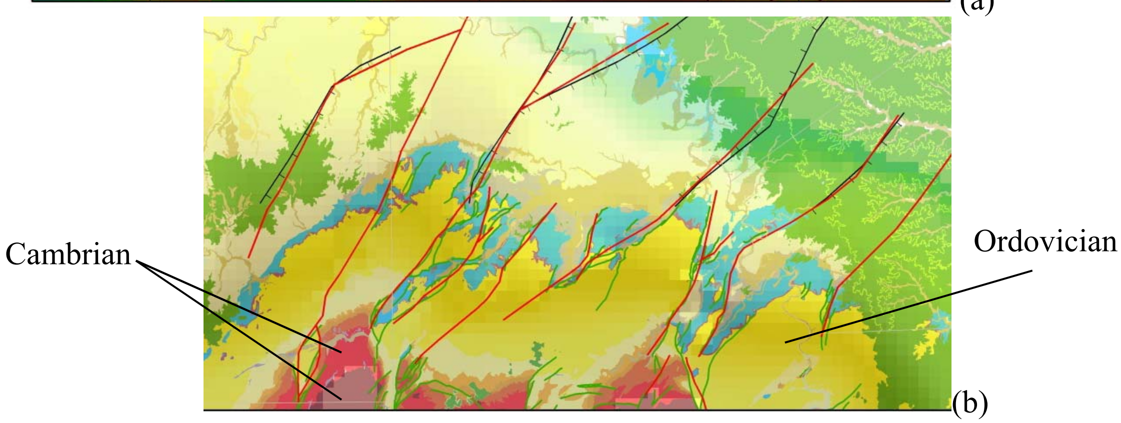
Regional Bouguer Gravity - Low Pass Filter Butterworth 50   Local Bouguer Gravity - High Pass Filter Butterworth 50

Source: processed from Bankey (2006)

Figure 73. Low-pass / high-pass gravity/Bouguer anomaly map of Brown and surrounding counties.



(a)



(b)

Source: (a) processed from Bankey (2006); (b) Texas geologic map (http://mrdata.usgs.gov/geology/state/state.php?state=TX)
Note: tick marks show downthrown side

Figure 74. Gravimetric anomalies and faults north of Llano Uplift.

VI-2. Assessment of Paleokarstic Features of Ellenburger Carbonates

Understanding paleokarstic feature distribution is important because these features provide the needed well productivity to sustain a well field. Two interrelated elements are at play: (1) establishment of karstic features and (2) interconnection of karstic features. There is no information about karstic features in the Ellenburger Group in Brown County, but they have been described at every location in which Ellenburger carbonates are known. Loucks et al. (2004) and McMechan et al. (1998) studied a paleocave between Burnet and Marble Falls in the Tanyard Formation (Ellenburger Group). They were also observed in outcrops in Far West Texas (Lucia, 1995), in the subsurface of the Permian Basin (Kerans, 1988), in the Val Verde Basin north of Del Rio (Canter et al., 1993), and in the Fort Worth Basin (Hardage et al., 1996; McDonnell et al., 2007).

Physical Description

Karstic features are typically created at the interface of the unsaturated/vadose zone and the water table, where groundwater and meteoric recharge meet and mix. This mixing area is generally recognized as the best area for extensive cave development. Ellenburger-time cave systems may be thought of a system similar to the current Edwards Aquifer system. However, the paleokarstic features are not generally caverns as open as they might be in the Edwards Aquifer. On the contrary, most caves are collapsed, with the collapse occurring millions of years after deposition of the Ellenberger sediments. The nature of the flow network is different in recent, current karst systems. In these cases, water flows through conduits and a fracture network. Collapsed paleocaves engage a larger volume of the formation, disturbing previously intact, overlying beds, even if the cavities proper are filled with breccia and sometimes low-permeability sediments (Loucks and Mescher, 2002, p. 5; Loucks, 2004, p. 1816). Collapsed zones extend hundreds of feet (Loucks, 2004, Table 1, items 15–16, 28–35) and enhance the overall permeability of the system, including vertical permeability. In the Franklin Mountain outcrops of the El Paso area (Lucia, 1995), the measured lateral dimensions of collapsed features correspond to the diameters of several of the disrupted zones observed in the 3D seismic image by Hardage et al. (1996) (Figure 75). The outcrop features and the seismically imaged collapses have extensive vertical dimensions, with some of these outcrop collapses extending vertically for at least 1200 ft in the larger outcrop exposures. Loucks (1999) noted that paleocave systems that form large hydrocarbon reservoirs are not a product of the collapse of isolated cave passages only meters across and tens to hundreds of meters long, but instead are a product of coalesced, collapsed-cave systems hundreds to several thousands of meters across, thousands of meters long, and tens of meters to >100 m thick (330 ft). That some of these caverns are still, at least partly, open and have not entirely collapsed is possible. Numerous bit drops during drilling for oil in West Texas suggest that open caverns are not uncommon (Loucks, p. 1816, 2004). The relatively shallow depth of burial of the Ellenburger in Brown County also suggests that open caverns could be present. So far, such collapse features have not been described in Brown County, most likely because nobody looked for them.

Kerans (1990) stated that, of the >10,000 ft (3,050 m) of core examined in his study in West Texas, >3,000 ft (915 m), or 30 %, is either brecciated dolostone or limestone, dolostone being by far the more abundant. However, note that the sample might be biased because hydrocarbon accumulation would occur where permeability is unusually high. Nevertheless, it represents a significant amount of brecciated material that does not include fractured halo around the collapsed zones.

Permeability in the Ellenburger aquifer is from fracture and karstic dissolution (collapse features), but the aquifer has subunits because not all layers have dissolution features and some act as confining layers.

Timing

Lucia (1995) discussed time occurrences and time durations of the subaerial exposures of Ellenburger rocks. These extensive vertical collapse zones are interpreted to be the result of post-Ellenburger carbonate-solution weathering, which occurred during periods of subaerial exposure, with a major karsting occurring during the Middle Ordovician, clearly before the Ouachita Orogeny. According to Hardage et al. (1996), the collapse features followed this timing:

(1) Post-Ellenburger/pre-Bend Conglomerate basement faults trending NNW;

(2) Karst solution weathering, particularly along vertical fractures related to NW-trending faults, where water seepage was enhanced—a process in which large caverns in some carbonate units were produced;

(3) Mississippian and Pennsylvanian sediment accumulation and sediment loading, causing these karst-induced caverns to collapse; Lucia (1995) suggested that 1000 to 2000 ft of sediments seem to be needed for collapse and that major collapses in Far West Texas happened earlier during the Silurian period;

(4) The presence of the resultant collapse structures, which influenced the distribution of younger sediments;

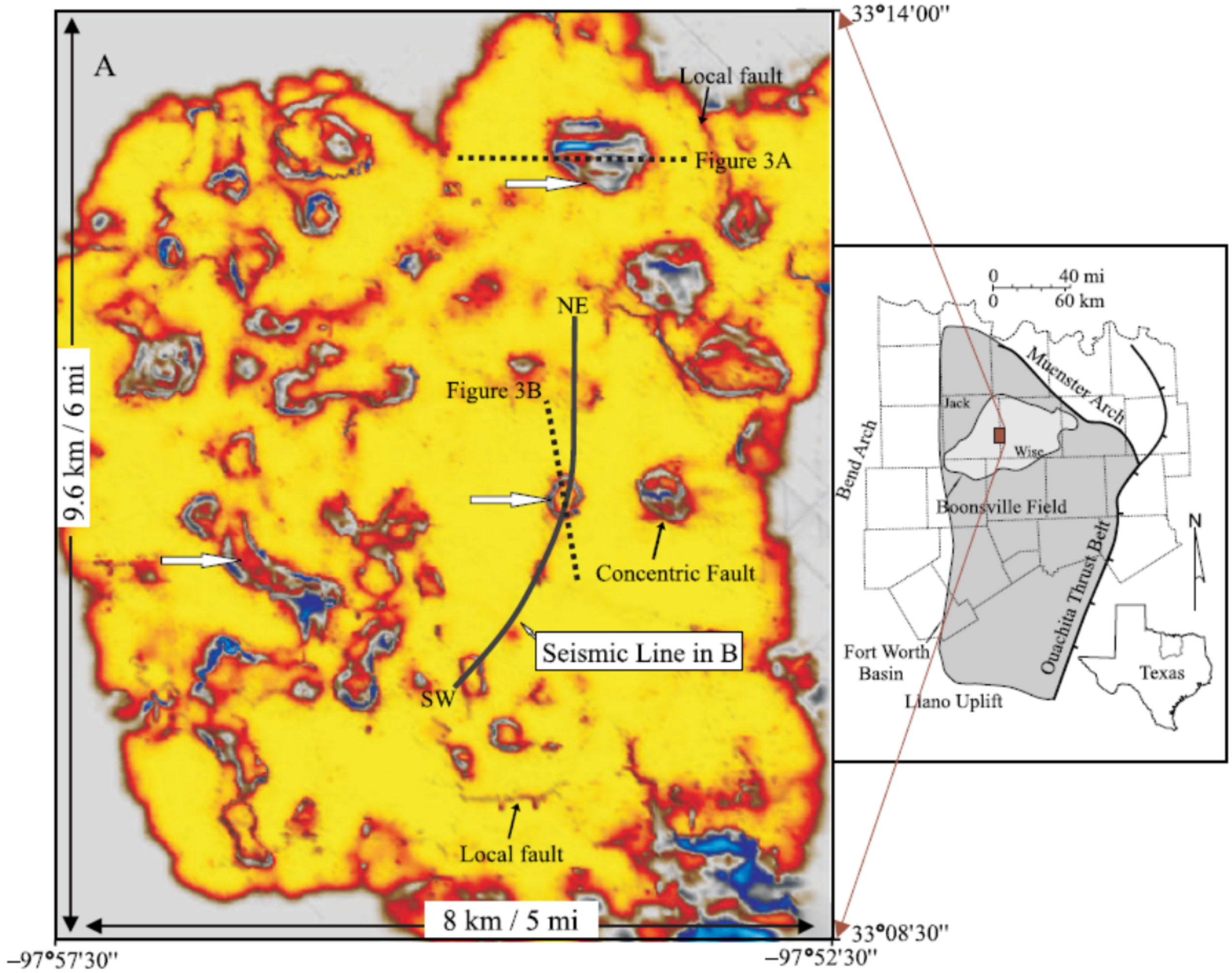
(6) Episodes of collapse that probably continued until most of the solution caverns had collapsed and filled from above, resulting in displacement of overlying strata.

Kerans (1990, p. 26) stated that the upper few hundred feet of the Ellenburger documents the main period of karst development, which occurred in the early Middle Ordovician. Important thickness of the Ellenburger was also eroded during this emergence event. Exposure events resulting in less significant erosion (although perhaps representing equal time) occurred during the Silurian, Devonian, Mississippian, and Pennsylvanian Periods. Canter et al. (1993, p. 96) proposed that the Ellenburger karst system was a product of at least five karst events, ranging from after Ellenburger deposition to the Early Pennsylvanian (less developed but clear, according to Kerans, 1990, p. 45). In contrast to Kerans (1990), Sullivan et al. (2006) noted that karst formation was likely more intense below the Mississippian unconformity than below the Middle Ordovician unconformity. They observed that in other Fort Worth Basin 3D surveys that Lower Ordovician Ellenburger carbonates overlain by Upper Ordovician carbonates appear to contain a lower density of sinkholelike features than do Ellenburger carbonates overlain directly by Mississippian shales.

In addition to this extensive paleokarsting, outcrops of Ellenburger formations and of other lower Paleozoic limestones are currently undergoing modern karstic processes (with the caveat that dolomite is less reactive than limestone) superimposed on the paleokarst.

Geometry and Orientation of Karst Features

McDonnell et al. (2007, p. 1316) stated that “a subtle northwest-southeast, northeast-southwest rectilinear structural grain in the Ellenburger Group, best developed in the northeastern corner of the data set [Wise-Jack county line], is interpreted as a fracture trend that was preferentially exploited by karst-forming waters, with deeper vertical cavern development where these joint and fracture trends intersect." Hardage et al. (1996, p. 1340) indicated groups of karst collapse features sometimes occur along linear northwest-southeast trends, suggesting some type of a genetic relationship between these structural depressions and basement faults. Canter et al. (1993), discussing paleocave-contained gas reservoirs located in the Val Verde Basin at the junction of Terrell, Val Verde, and Crockett Counties stated that"… the main portion of the paleo-cave network to extend … in a west-northwesterly direction, paralleling the principal bounding faults. The caves are thickest (up to 70′) and best developed adjacent to, but not necessarily coincident with the crests of the structures. It is interpreted that the maximum cave development was localized along the main basement fault zones which acted as secondary conduits for fluid flow."



Source: McDonnell et al. (2007)

Note: karstic features appear in gray in the figure; note dimensions of map (6×5 miles^2)

Figure 75. Example of buried and collapsed karstic features in Fort Worth Basin.

VII. Discussion and Conclusions

Subsurface-related important criteria for well siting include well yield/hydraulic conductivity of aquifer, water quality, current and after pumping starts, amount of water, and impact of and on boundaries (leakage from confining layers, impact on fresh-water section). Before suggestions for well locations are made, general behavior of the aquifer(s) is important to understand.

VII-1. Preliminary Conceptual Model of Flow through Hickory and Ellenburger Formations

The most conductive formations to groundwater of regional extent in Brown County are the Cambrian Hickory, Ordovician Ellenburger, and Cretaceous Trinity aquifers. The upper Paleozoic formations contain only local sandstone and limestone aquifers of limited extent. In the context of installing a well field, its feasibility should be evaluated by assessing its behavior in future decades. A seemingly good well in a closed compartment will have a limited life. The following discussion is conjectural because of the lack of data; however, it may guide further data gathering to prove or disprove the points discussed. Here we focus on the compartment numbered #1 in Standen and Ruggiero (2007) (Figure 31).

A general steady-state flow model for a dipping sandstone aquifer such as the Hickory aquifer consists of (1) an unconfined section receiving recharge (Figure 76a), most of it being discharged back to streams and springs in a shallow flow system (Figure 77) and (2) a downdip confined section receiving limited recharge (*deep recharge*), discharging through low-permeability layers and shallower aquifers to rivers or through other boundary features (faults). Clearly, in a steady state model, all water entering the aquifer must exit because of conservation of mass. In actual aquifers, only the balance would move upward, and locally the confined section of an aquifer could be recharged by the overlying aquifer. Recharge to the confined section of the Hickory aquifer from the Ellenburger through faults and other features is a possibility (head measurement lacking to confirm or inform this statement). The outcrop of Ellenburger formations in (mostly) McCulloch County is much larger than that of the Hickory Sandstone suggesting that more recharge could enter the Hickory-Ellenburger system through the Ellenburger outcrop. Discharge to the San Saba River and Brady Creek in McCulloch County and their subsidiaries is also likely, but less likely or of a smaller amount to the Colorado River at the southern county line of Brown County (base-flow studies are needed to assess the statement). The extent of the confined downdip section is controlled by precipitation on the outcrop; conductivity, transmissivity, and geometry of the formation; and location of discharge features. In the case of the Hickory aquifer, deep recharge is most likely directed to the thicker sections of the aquifer toward Menard and Concho Counties. Deep recharge is probably more limited toward the north and Brown County because of the limited thickness of the aquifer and because of (1) pinchout of the Hickory Formation in Eastland and Callahan Counties, creating a relative stagnation zone, and (2) the NW-SE general direction of the buried paleovalleys. This probability is confirmed by the observation that water becomes relatively quickly brackish toward Brown County (much faster than in the Ellenburger aquifer, which does not pinch out) and illustrated by the bulge of the 3,000-mg/L boundary on TWDB GAM maps toward Concho County.

The compartmentalization that exists farther east closer to the Ouachita front does not seem to be as widespread on this side of the Llano Uplift. In this context the Hickory aquifer can be considered a sheet aquifer. This assumption is not valid when the overall thickness of the aquifer decreases to a value in which paleotopographic features matter, such as in Brown County, in which case the aquifer becomes more of a “strip” aquifer, in which basement and Ouachita faults can exacerbate drawdown.

Recharge typically occurs through formation outcrops (unconfined section). Broadly speaking, recharge can be classified as either distributed or focused/discrete (e.g., playas for the Ogallala or losing streams in South Texas or for the Edwards aquifer). Recharge to the Hickory is more likely distributed and occurring through its sandy outcrops. Preston et al. (1996, p. 20) suggested that losing streams could also contribute to Hickory recharge but without providing much evidence for it. They cited (p. 21) gain-loss studies performed by Pavlicek and Hayes (1994) and other studies that discuss a mix of gain and loss reaches. The additional recharge mechanism of leakage through the much larger Ellenburger outcrop may play an important role. Although currently unknown, inspection of recharge to nearby aquifers provides some insight into recharge volumes. Through unsaturated-zone modeling, Keese et al. (2005) estimated that diffuse recharge in the study area was ~0.4 to 1.2 inch/yr. In the northern Trinity groundwater availability model (GAM; Bené and Harden, 2004), average recharge-rate input into the model is ~1.4 inch/yr with most of the area <1 inch/yr. In the Seymour GAM (Ewing et al., 2004), recharge distribution averaged 1.9 inch/yr in Seymour and ranged from 0.8 to 2.5 inches/yr among Seymour pods.

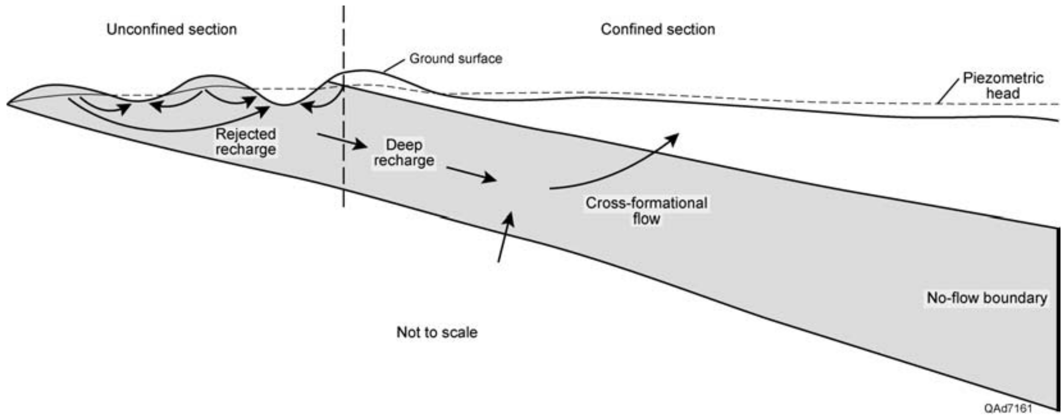
The Ellenburger aquifer follows a similar conceptual model. Its recharge area is larger because the aquifer is thicker, although the recharge might be more focused because of the generally low conductivity of the formations outside the fracture zones and modern karstic features. Losing streams (at least in some reaches) could significantly contribute to recharge. The thickness of the aquifer, although decreasing toward the west, does not show the sharp thickness decrease seen for the Hickory aquifer. The shape of the 3000-mg/L TDS line also suggests that deep recharge is regionally more evenly distributed in all directions (west, north, and southwest). The many springs in San Saba County (Brune, 1989) confirm a vigorous shallow groundwater system (to be further confirmed by flow and temperature studies if available). On the other hand, the presence of radium and radionuclides may suggest that some Hickory water is moving upward (further analyses would need to determine when the radium entered the Ellenburger, during sediment diagenesis or later).

Upper Paleozoic aquifers in Brown County are relatively small and seemingly irregularly distributed in a generally low-permeability Pennsylvanian section. They are, however, less impacted by faulting than the lower Paleozoic aquifers. The observation that the water becomes brackish quickly downdip also suggests very little deep recharge and that most of the recharge discharges through shallow flow paths (to Pecan Bayou and its tributaries and the Colorado River to which it drains). We analyzed well pairs (head measurements taken approximately at the same time in two closely spaced wells tapping two different strata) to understand the general flow direction in the upper Paleozoic aquifers (Figure 78 and Figure 79). Vertical flow gradient is analyzed by selecting wells clustered together but that have different depths. The well-pair head measurements suggest that flow is mostly down, and no well pair that included an Ellenburger head measurement was available. The direction of vertical flow is determined on the basis of water-level measurements in a pair of wells relative to well depth. About 23 pairs were identified, and all the wells belong to Strawn, Canyon, or Cisco Groups. The distance between wells in a pair is <2,000 ft, half of the pairs have measurements on the same date, and ~80% of the pairs have measurements in the same month. All pairs have measurements in the same year, and all measurements for selected wells were taken between 1962 and 1964. Among 23 pairs, 18 (80%) showed a downward gradient and 5 showed an upward gradient (Figure 78). In addition, upward-gradient pairs are weaker than most downward-gradient pairs (Figure 79). Such an observation is consistent with work by Nicot et al. (2012, unpublished document) on upper Paleozoic aquifers of north-central counties farther north, with a weaker regional system imprinting the shallow local system that discharges to larger rivers (Brazos River) and their tributaries farther north, following the average surface topographic slope (in essence, the larger the river, the farther away the recharge area of the base flow can be). With the general gradient down, the question is whether upper Paleozoic aquifers recharge Marble Falls and Ellenburger aquifers. No measurement pair between upper Paleozoic and Marble Falls/Ellenburger/San Saba aquifers and between Ellenburger and Hickory aquifers is available. Pettigrew (1991, Fig. 25), focusing on San Saba County, proposed a similar model for the Hickory, with a recharge zone in the outcrop and a discharge zone through the Ellenburger to the San Saba River, and no upward flow when covered by Strawn and other Pennsylvanian shales in a zone he called the *stagnation zone*.

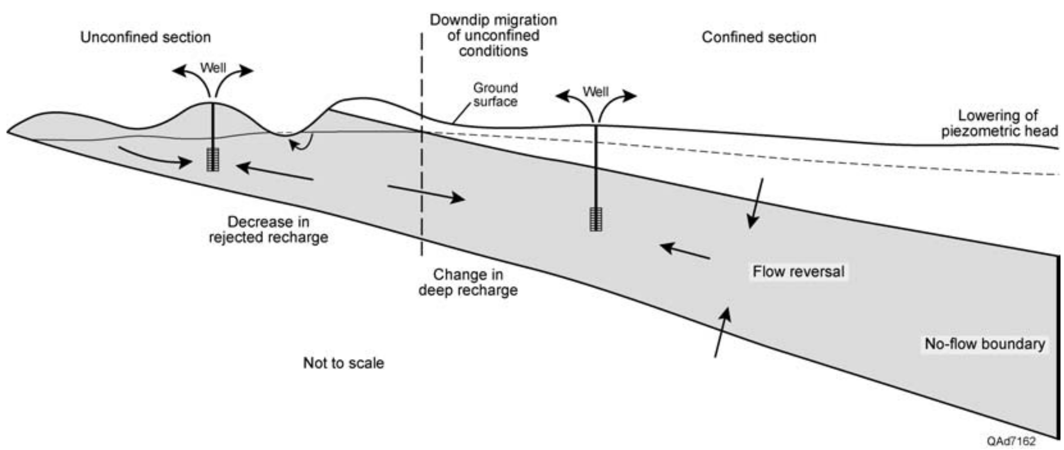
We propose a conceptual flow model (Figure 80). The Hickory aquifer is recharged through its outcrop and also likely through downward leakage from the outcrop of the Ellenburger formations and slowly discharges from its confined section through the overlying sediments with upward flow somewhat focused toward the gaining streams of the area (and maybe down in-between streams as seen in the upper Paleozoic of Brown County, however flow exchanges between Hickory and Ellenburger have not been thoroughly examined in this document) or along faults. Flow is conceptualized as decreasing in all directions away from the outcrop following the decrease in aquifer thickness. The arrow size is thought to be a function of the transmissivity of the aquifer.

We did not focus on the Trinity aquifer in this study, but Smith (2004) suggested that the lower Paleozoic aquifers are recharged by the Trinity aquifer, where they are overlain by it, but he did not provide more information. Bluntzer (1992, p. 26), discussing the southern flank of the Llano Uplift, commented that basal Cretaceous sands are in hydraulic communication with Hickory sandstones and Ellenburger and other lower Paleozoic limestones, and he added (p. 27) that the Trinity aquifer recharges the Paleozoic aquifers in his study area. However, this situation seems to be less true on the west side of the uplift. Lupton (2009) studied the connection between the Trinity aquifer and the Ellenburger aquifer south of the Llano Uplift aquifer, where natural discharge of groundwater occurs at springs and seeps along the Pedernales River valley. In Brown County, the Trinity can recharge only upper Paleozoic aquifers. Recharge through the Trinity aquifer to the upper Paleozoic is most likely controlled by the dip-oriented aquifer and regional EW/NW-SE-trending channels (Woodruff et al, 1979, their Fig. 51), although the proximity of the Llano Uplift may locally alter the direction of the fluvial channels.

How much faults are sealing remains a big unknown, as is whether all aquifers are vertically connected through large faults. Faults can be vertically transmissive but not allow lateral flow, and large and smaller faults may behave differently. For example, Zhurina (2003) studied the impact of a small fault zone with a normal throw of ~50 ft in Mason County just south of the county line with McCulloch County. She showed evidence that at least some faults do impede lateral flow but still permit it, although this particular fault had conductive Hickory sandstone vs. Hickory sandstone.



(a)



(b)

Source: Reedy et al. (2009)
Note: inspired by Carrizo aquifer of Central Texas

Figure 76. Conceptual model of flow in a dipping aquifer with outcrop (a) before and (b) after development.

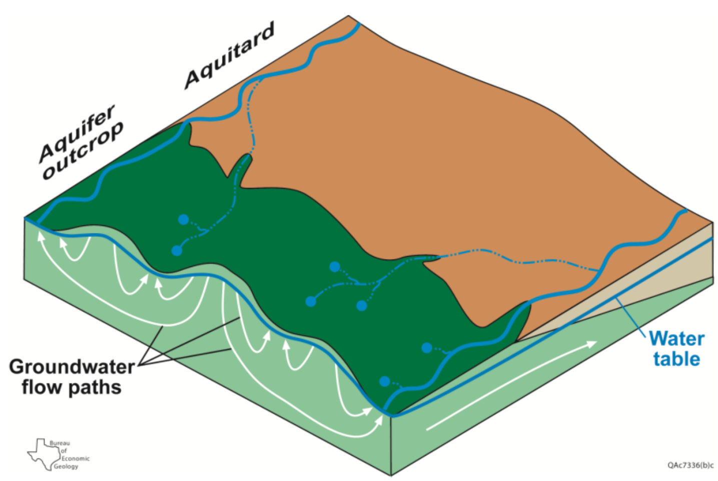


Figure 77. Conceptual model of flow in a hilly terrain .

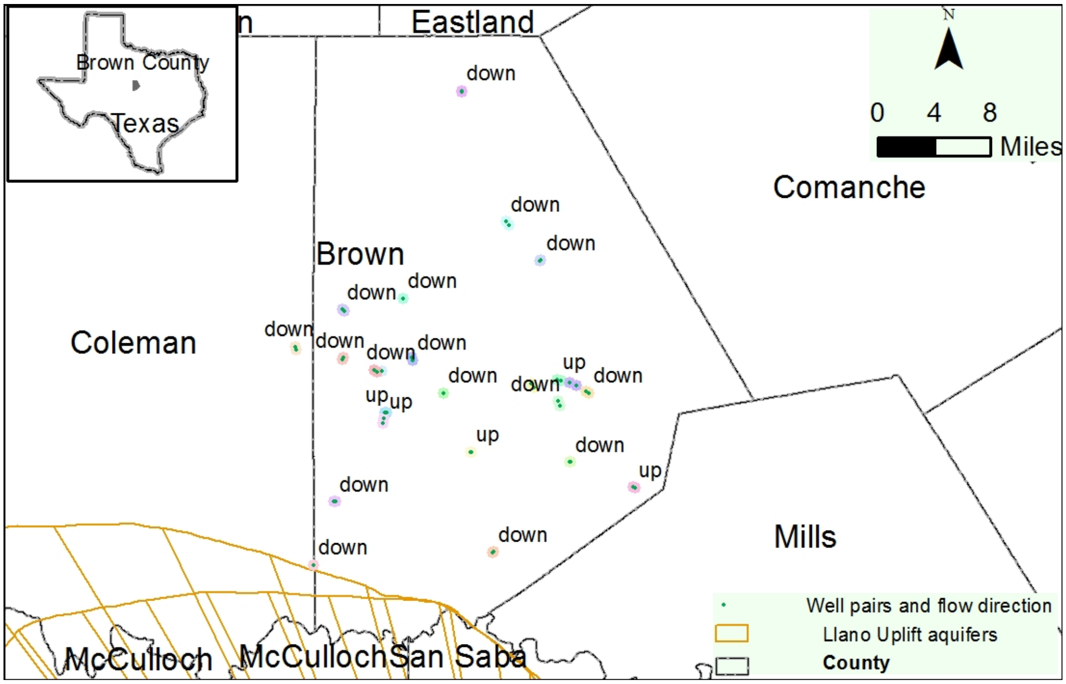
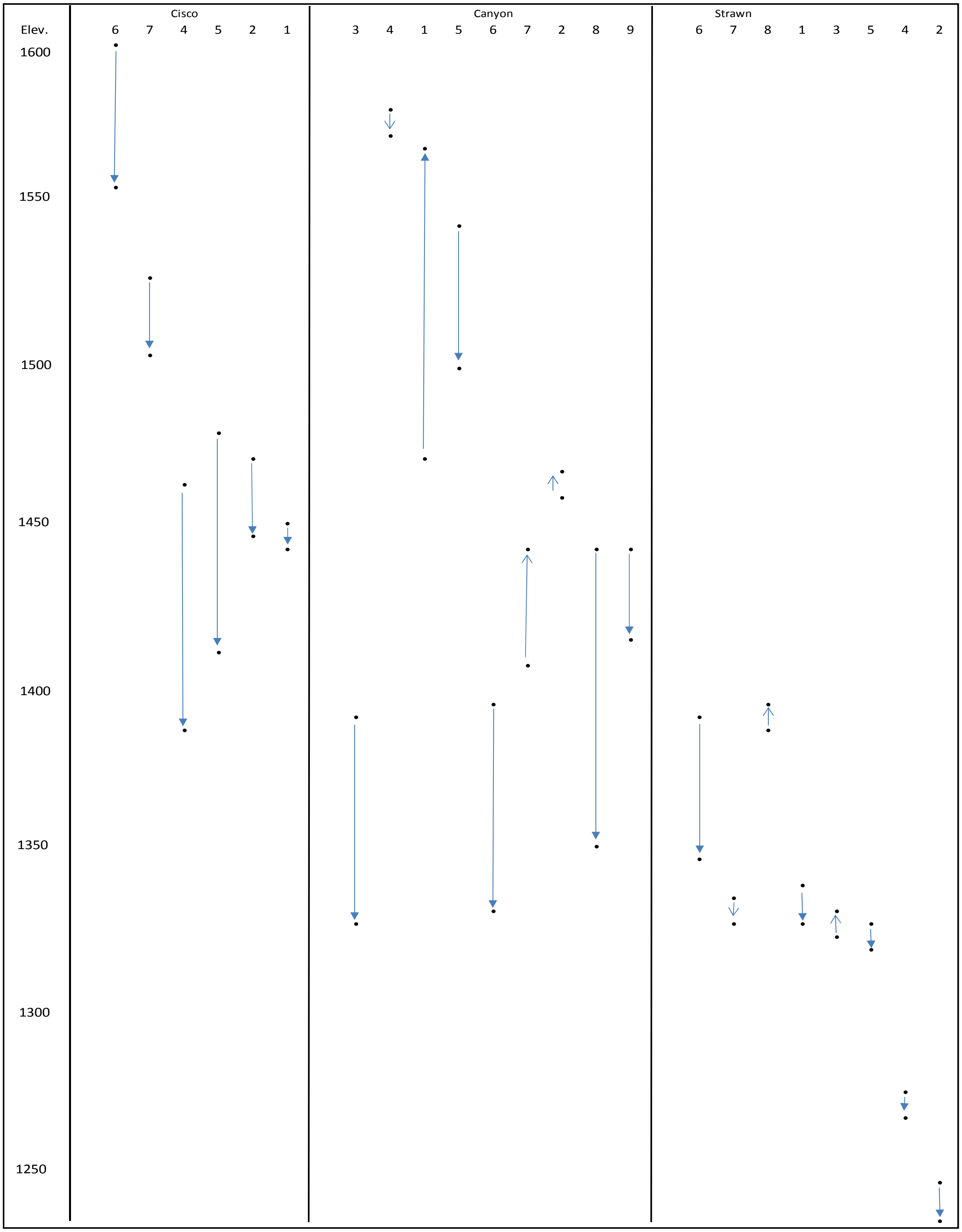
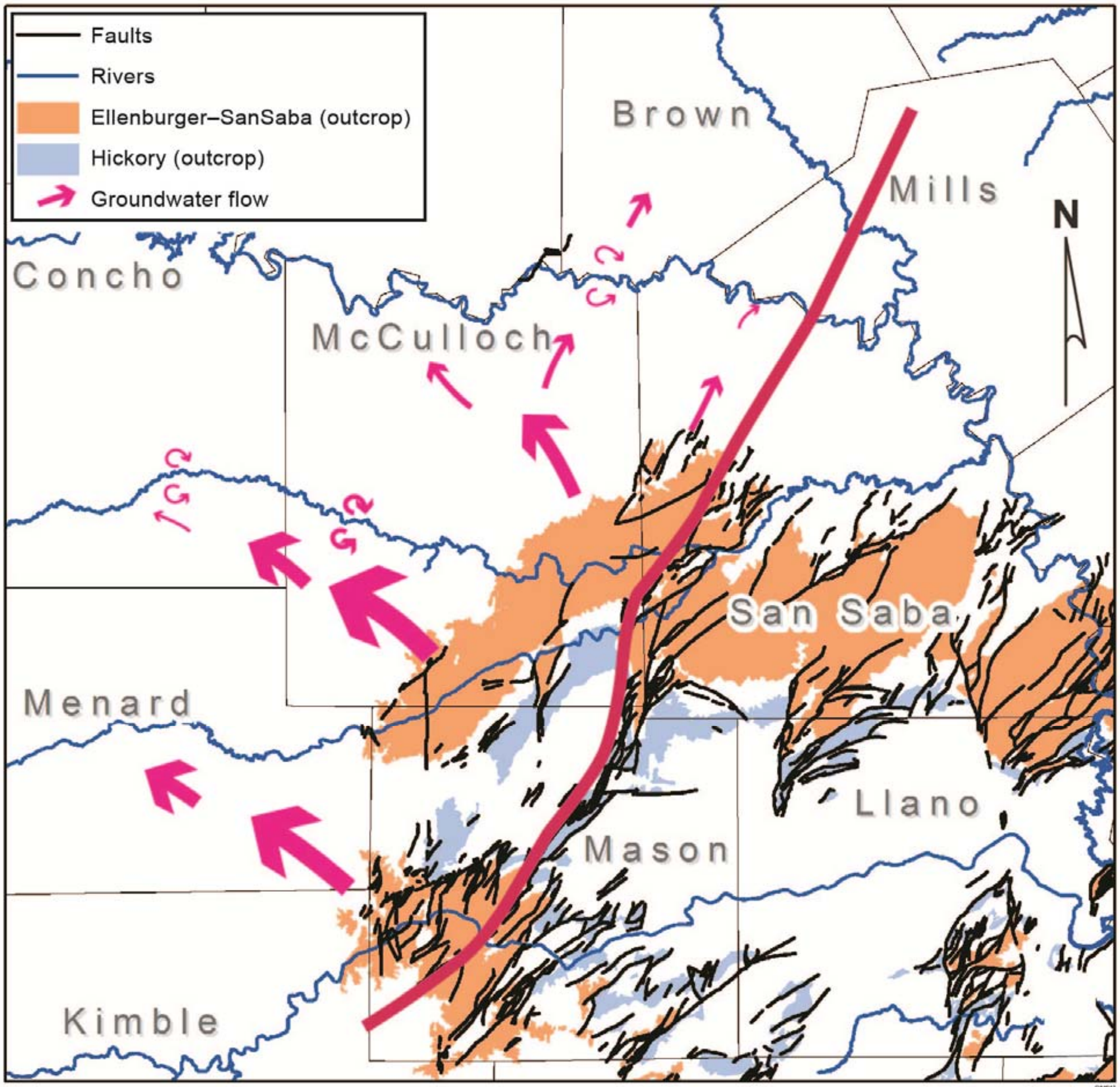


Figure 78. Indication of vertical flow direction from water-level measurements in well pairs.



Note: Numbering on top represents pairs in each group from west to east; arrow boldness increases with head gradient

Figure 79. Vertical interval within pairs and gradient direction.



Note: arrow size is approximately proportional to the amount of water flowing through the aquifer

Figure 80. Conceptual flow model of the western section of the Hickory Aquifer

VII-2. Recommendations for Exploratory Wells

We recommend two locations for siting the exploratory wells (Figure 82): well 1 in southwestern Brown County to test both the Ellenburger and Hickory aquifers. Expected total depth of well 1 is 3500 ft, and well 2 targeting the Ellenburger aquifer west of Brownwood should be drilled to the basement as well (expected total depth of 3200 ft). The rationale for these choices follows. There is a general tradeoff between distance to the City of Brownwood vs. water quality. Water quality is expected to degrade from the county line to the south to the city and will most likely require a more expensive treatment option. On the other hand, the closer the well field are to the city, the less substantial the conveyance issues. If the decision is made to drill only one well, well 1 location is preferred.

Well 1 targeting of the Hickory aquifer is chosen for

- The lowest TDS (TDS decreases to the south)
- The thickest Hickory Sandstone (thickness increases toward the south; in addition, to the north, basement highs not recorded on the generalized thickness map are more likely) (Figure 81)
- It being farthest from faults so as to limit drawdown issues and maximize drainage volume (should be restricted to west of the Mason Graben in order to tap a larger compartment). The analysis tends to support a smaller fault density at the chosen location, but whether the lack of mapped faults is real or due to limited well data remains unclear.

This location balances the risk of having the Hickory dropped between the Precambrian block (if the fault is post-Hickory) or having a greater Hickory thickness if the block boundaries were created prior to Hickory deposition. The most likely productive interval is at the bottom of the Hickory aquifer, with no well screen in more shaly intervals that could bring in radionuclides needed, a problem that may not go away through simple blending. In essence, radium and gross alpha could be handled downhole by screening and restricting production only to selected intervals after use of a multilevel sampler (available at BEG) once the well has been drilled (i.e., acquire information on the water in addition to the rock that will be obtained through regular logging).

Well 2 targeting of the Ellenburger Aquifer is chosen for

- Its proximity to the city
- Its location at the intersection of a NE-SW-trending Ouachita fault and a NW-SE-trending basement fault (as far as we can tell from the data available), near but west of the Mason Graben to tap a larger compartment.

The most likely productive interval is in the upper half of the Ellenburger aquifer (although karstified at several occasions, the upper part is more likely to hold kart-related features; tensile stress on the Bend Arch more likely to keep fractures open).

Note that ideally, Hickory wells would be located in the middle of a large fault-delimited compartment, whereas an Ellenburger well would be located at the intersection of multiple faults and the boundary of those compartments.

The following additional work would be useful for a better delineation of the final location of the well field.

- Thorough seismic analysis for better detection of faults (purchase of 2D seismic lines). Detection of faults and their geometry through well log correlation only is difficult.
- Denser analysis of existing oil and gas wells for structure and salinity (with the help of appropriate well logs, could help in determining salinity).
- Construction of a numerical model to assess the consistency of data with conjectural groundwater flow system

Precautions must also be taken when drilling to the basement in Brown County because several strata contain economic and uneconomic oil and gas accumulations. Another issue is disposal of the concentrate of any desalination plant. Deep-well injection is a well-regarded possibility for relatively large plants. However, options for disposal are limited. At the well 1 location, community long-term interest is to protect Hickory and Ellenburger aquifers—formations with the highest conductivity values in the southwestern tip of Brown County that are already protected by federal law (Safe Drinking Water Act, 10,000-mg/L limit). The most viable option would be to use depleted oil and gas reservoirs and inject the concentrate through Class II wells into the multiple inactive horizons (although their capacity is still to be determined). Well 2's location may not have this possibility available because most oil and gas activity occurs in the west half of the county. Moreover, the concentrate volume is likely to be larger because of the TDS level being four to five times higher than at the well 1 location.

Table 4. Summary of proposed drilling locations

	Well 1	**Well 2**
Target	Hickory/Welge/Ellenburger	Ellenburger
Total depth	3500 ft	3200 ft
Expected thickness	350 ft (Hick) – 800 ft (Ell)	<200 ft (Hick) – 900 (Ell.)
Expected TDS	~3,000 mg/L	10,000–15,000 mg/L
Expected yield	>300 gpm	<100 – >500 gpm
Expected temperature	105°F – 95°F	100°F
Approximate distance to Brownwood	20 miles	3 miles

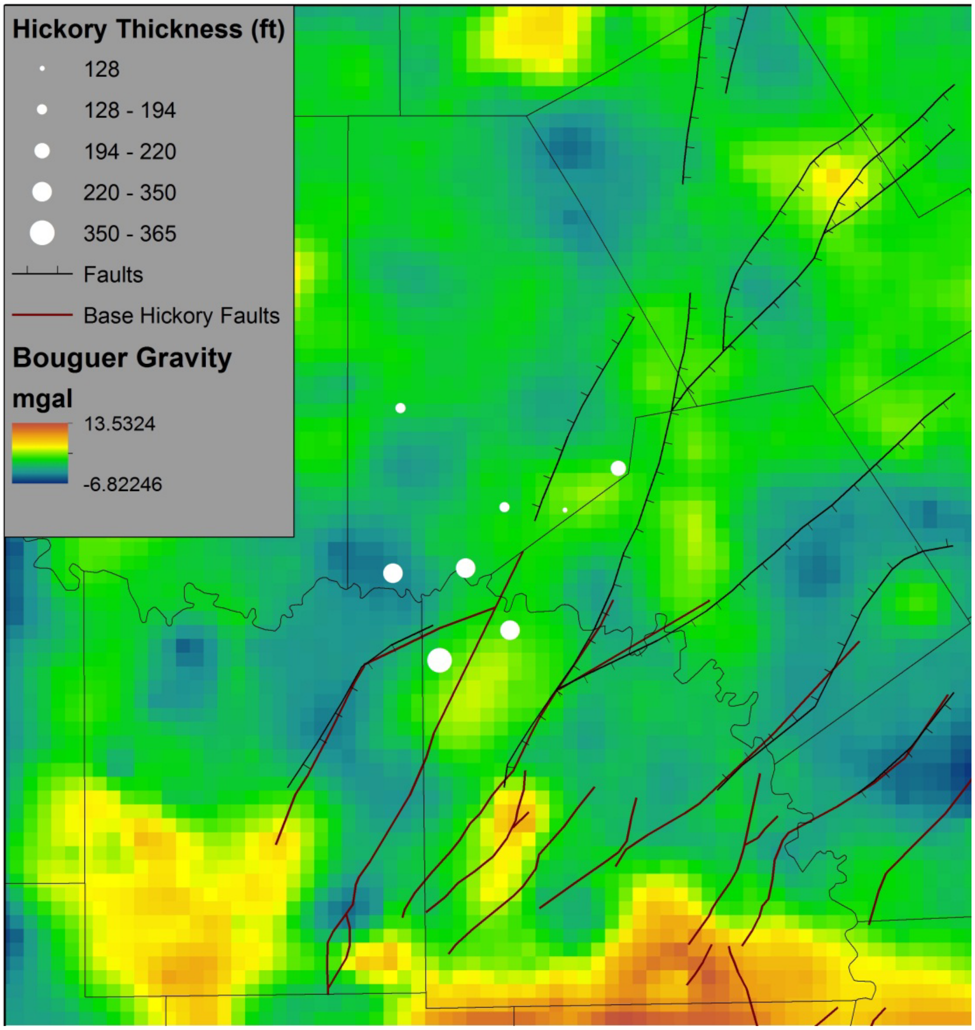


Figure 81. Gravimetric anomalies and Hickory Sandstone thickness.

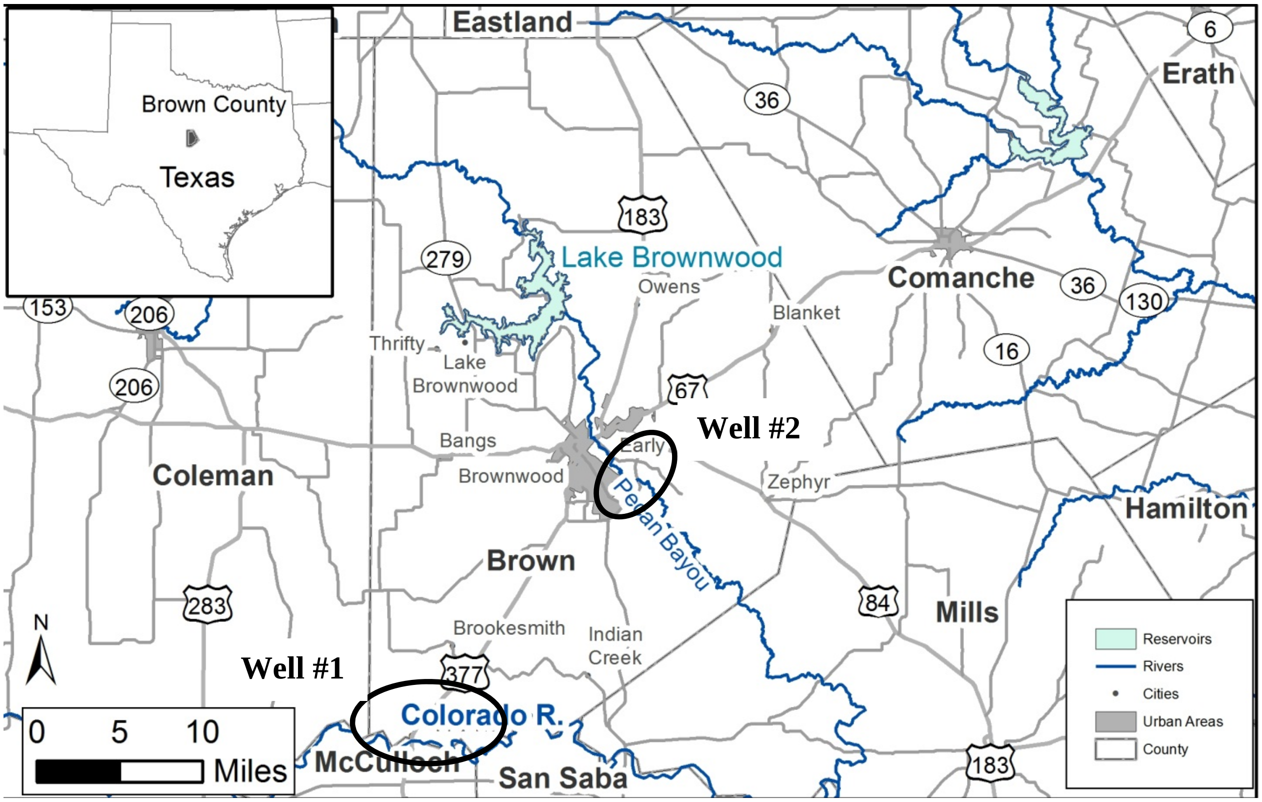


Figure 82. Proposed drilling locations.

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IX. Appendix A: Brown County Hot Wells

It has been reported by the local population and documented in diverse publications (Brownwood Chamber of Commerce [BCC], 1931; Davis, 1938) that, west of Brownwood, at least one well, most likely tapping the Ellenburger, has produced at a high flow rate for years. Davis (1938, p. 5) described it as well#53 located 2 miles SE of the city and drilled to a depth of 2,402 ft in 1916. Thompson (1967, p. 9) also described it, using the current numbering system, as well 41-17-502. Other wells at similar depth are #43 located 9.5 miles NE of Brownwood and reaching a depth of 2,340 ft, #48 (7.5 miles NE of Brownwood, 2,216 ft deep, and completed in 1929), and #58 (5 miles W of Brownwood, 2,100 ft deep). All these wells resulted from oil and gas exploration drilling. Davis (1938, p.23) mentioned that a sample taken at an unknown date had a TDS of 13,718 ppm. BCC (1931) referred to a well completed to a depth of 2,402 ft and located 2 miles from Brownwood, most likely well #53 referenced earlier. However, chemical analyses provided in the brochure (Figure 83) are not consistent with the Davis (1938) analysis (Figure 84), with a generally accepted understanding of the geochemistry of groundwater. The date is relatively consistent (1931–12 = 1919), and temperature is also consistent but on the high side when compared with local generalized geothermal gradient: 1 to 1.25°F/100 feet (Woodruff et al., 1984) with an average annual temperature of 65°F. The well that flowed at 25,000 bbl/day (730 gpm) most likely stopped because it was no longer artesian. Thompson (1967, p. 9) mentioned that the well was artesian but not used and that it flowed at a rate of 12 to 16 gpm (presumably at the time of the report). It could be inferred that the well went from artesian to nonartesian and then to artesian again after shut-in, suggesting good communication between compartments in the aquifer, but descriptions are too partial to jump to such a conclusion.

HOT WELLS

The Hot Wells are a great summer resort, situated about two miles out of the city of Brownwood. There are two large swimming pools in which thousands of people go bathing. There is also equipment at the wells for hot tub baths.

We had hoped by this time to have the water from the Hot Wells piped into the city where we could get these baths at our hotels, but we are not quite ready to announce this; however, we are still working on it, and think within a short time we will have this arrangement perfected.

This is a wonderful mineral water, and the analysis given by the State Chemist is as follows:

Sodium Chloride	11.08
Potassium Chloride	230.05
Calcium Chloride	48.05
Calcium Bicarbonate	454.00
Calcium Sulphate	49.05
Magnesium Sulphate	329.00
Silica	30.00
Iron Bicarbonate	66.03

These wells were drilled 12 years ago for oil. They are 2,402 feet deep, and produce 25,000 barrls of water daily, coming out of the ground at a mean temperature of 112 degrees. The flow of water has not diminished since the wells were drilled in; and you can see from the above analysis the real value of the water.

Figure 83. Excerpt from Brownwood Chamber of Commerce (BCC, 1931) publication.

Partial analyses of water from wells in Brown County--Continued
Results are in parts per million.

Well No.	Owner	Depth of well (ft.)	Date of collection	Total dissolved solids (calculated)	Calcium (Ca)	Magnesium (Mg)	Sodium and Potassium (Na + K) (calculated)	Bicarbonate (HCO_3)	Sulphate (SO_4)	Chloride (Cl)	Nitrate (NO_3)	Total hardness as $CaCO_3$ (calculated)
46	L. W. Reagan	147	Feb. 2, 1938	407	69	48	20	421	59	4	a/	369
47	J. W. Richmond	98	do.	888	-	-	-	451	117	225	a/	-
49	Oliver Steel	39	do.	2,078	270	173	243	628	197	820	61	1,387
50	Mrs. Hugh Davis	50	do.	3,155	366	279	340	293	456	1,520	50	2,162
51	M. E. Malone	125	Dec. 1, 1937	1,051	44	-	354	262	151	340	30	110
52	Bob Parker	49	Feb. [illegible], 1938	2,571	215	122	554	464	501	950	a/	1,041
53	A. C. Snyder	2,402	--	13,178	196	49	4,905	384	14	7,520	a/	690

Source: Davis (1938)

Figure 84. Hot-well chemical analysis from TWDB 1938 report.

X. Appendix B: Stratigraphic-Pick Well Dataset

The stratigraphic picks listed in Table 5 were used to develop maps of tops of formations of interest.

Table 5. List of wells for stratigraphic picks.

Track No	POINT_X	POINT_Y	Land_Elv	Source	County	Operator	Date_Drill	TD
1	-99.063983	32.061955	1594	BEG_Scout_Ticket	Brown	Palo Petroleum	11/03/78	3430
2	-98.921191	31.866985	1538	BEG_Scout_Ticket	Brown	W.W. Connell Inc.	08/31/47	2621
3	-99.05948	31.840825	1451	BEG_Scout_Ticket	Brown	E. D. Harris	10/05/47	2625
4	-98.924911	31.791813	1448	BEG_Scout_Ticket	Brown	Elray Oil Inc.	11/16/77	2081
5	-98.934404	31.820111	1414	BEG_Scout_Ticket	Brown	A. L. Andree	05/13/54	3635
6	-99.143783	31.98939	1519	BEG_Scout_Ticket	Brown	Southeastern Resources Corp	03/29/82	3181
7	-99.197928	31.992602	1589	BEG_Scout_Ticket	Brown	Hickok-Reynolds Royalty	11/20/53	3317
8	-99.078384	31.684355	1543	BEG_Scout_Ticket	Brown	R. L. Gohlke	02/18/74	1928
9	-99.111523	32.022745	1538	BEG_Scout_Ticket	Brown	Ambassador Oil Corp	12/23/56	4522
11	-98.944769	32.074798	1680	BEG_Scout_Ticket	Brown	Crown Hydrocarbons Inc	02/21/79	3635
13	-98.964873	31.572182	1439	BEG_Scout_Ticket	Brown	J. M. Johnson	03/01/54	3213
14	-99.063941	31.661453	1528	BEG_Scout_Ticket	Brown	Delray Oil Inc.	09/28/76	1797
15	-99.019776	32.034495	1609	BEG_Scout_Ticket	Brown	Southeastern Resources Corp.	06/22/84	3379
16	-99.086181	31.884193	1551	BEG_Scout_Ticket	Brown	Sioux Natural Gas Corp	05/26/79	2900
17	-99.065854	31.565625	1378	BEG_Scout_Ticket	Brown	Conquistador Petroleum	05/23/84	1307
18	-98.811135	31.866155	1757	BEG_Scout_Ticket	Brown	Tom A. Edgell	10/12/47	2883
19	-99.136812	31.836059	1462	BEG_Scout_Ticket	Brown	Needmoore Oil & Gas	09/01/82	2740
20	-99.056656	31.991702	1536	BEG_Scout_Ticket	Brown	KLH Oil & Gas Inc	05/11/82	3113
21	-98.919888	31.995433	1622	BEG_Scout_Ticket	Brown	Chapman Oil Co.	12/09/59	2979
22	-98.963781	31.953672	1570	BEG_Scout_Ticket	Brown	Belmont Oil Co.	02/25/76	3138
23	-99.024637	31.731573	1478	BEG_Scout_Ticket	Brown	Brownwood Dome Production	11/04/77	1890
24	-99.052516	31.905623	1470	BEG_Scout_Ticket	Brown	Clifford H. Brown	05/02/78	2650
25	-99.07363	31.848271	1534	BEG_Scout_Ticket	Brown	F. L. Hafner	11/16/53	2412
27	-99.063401	31.814439	1453	BEG_Scout_Ticket	Brown	Anzec Oil Corp.	01/27/53	2418
28	-99.097345	31.89563	1531	BEG_Cable_Tool	Brown	Bailey		2922
29	-99.158867	32.04989	1693	BEG_Cable_Tool	Brown	Brown Hancock Oil Co.	09/29/36	3160
30	-99.054946	32.000822	1514	BEG_Cable_Tool	Brown	Paul Gardner	04/20/49	2923

Track No	POINT_X	POINT_Y	Land_Elv	Source	County	Operator	Date_Drill	TD
31	-98.871881	31.755547	1443	BEG_Cable_Tool	Brown	R. F. Konea	07/21/22	2165
32	-99.077455	32.013286	1508	BEG_Cable_Tool	Brown	Hickok & Reynolds Royalty Co.	10/30/53	3248
33	-99.040479	31.932511	1492	BEG_Cable_Tool	Brown	Humble Oil Co.		2850
34	-98.941677	31.843859	1436	BEG_Cable_Tool	Brown	Texas Company		2841
35	-98.810752	31.856434	1743	BEG_Cable_Tool	Brown	United North & South Dev. Co.	12/11/48	3025
36	-99.109572	31.567841	1364	BEG_Cable_Tool	Brown	James L. White	03/27/47	1790
37	-99.019807	31.627111	1560	BEG_Cable_Tool	Brown	Horace E. White et al	06/26/49	1785
38	-99.019681	31.696907	1520	BEG_Cable_Tool	Brown	B. A. Houston	12/18/38	1528
39	-99.079856	31.670041	1527	BEG_Cable_Tool	Brown	T. G. Shaw	10/22/50	3347
40	-98.987657	31.686599	1360	BEG_Cable_Tool	Brown	Neil K Shaw et al	08/18/49	1764
41	-98.847716	31.710484	1498	BEG_Cable_Tool	Brown	A. J. Rife Construction Co.	09/08/43	1927
42	-98.97921	31.840133	1408	BEG_Cable_Tool	Brown	McClean-Roberts	05/22/51	2355
43	-98.983655	31.64175	1505	BEG_Cable_Tool	Brown	Graham, Thomas & Ludflow		2610
44	-99.09879	31.791436	1583	BEG_Cable_Tool	Brown	Kingwood Oil Co.	12/16/26	2767
45	-99.104592	31.768329	1599	BEG_Scout_Ticket	Brown	Atlanta Drilling Co	08/24/75	2680
46	-99.017122	31.735562	1493	BEG_Cable_Tool	Brown	B. R. W. Oil Company	07/20/47	2151
47	-98.746496	31.710036	1500	BEG_Cable_Tool	Brown	G. C. English	12/12/47	2420
48	-99.064919	31.718989	1578	BEG_Cable_Tool	Brown	Derrick & Boyer	06/29/39	2128
49	-99.197436	31.832937	1455	BEG_Cable_Tool	Brown	Dean Bros. & Chapman Oil Co.	11/04/49	2699
50	-98.874437	31.773254	1520	BEG_Cable_Tool	Brown	Lorenna Ball Busbee Trustee	09/14/51	2004
51	-98.82928	31.825683	1743	BEG_Cable_Tool	Brown	Hightower Oil & Refining Co.	11/15/35	4144
52	-98.904057	31.774821	1465	BEG_Cable_Tool	Brown	S. C. Herring	04/04/34	1927
53	-99.114473	31.717798	1639	BEG_Cable_Tool	Brown	Texas Southern Inc.	10/10/59	2051
54	-99.18688	31.774895	1557	BEG_Cable_Tool	Brown	J. A. Turner Co.	04/02/54	1324
55	-99.035916	31.764208	1540	BEG_Cable_Tool	Brown	Worth Thomason	07/15/49	2220
56	-98.757383	31.831329	1696	BEG_Cable_Tool	Brown	Martin H. Braun	12/19/54	2807
57	-99.019421	31.914241	1456	BEG_Cable_Tool	Brown	Brown & Gardner et al	08/29/38	2457
58	-99.132825	31.917924	1542	BEG_Cable_Tool	Brown	Hickok & Reynolds Inc.	03/30/40	3083

Track No	POINT_X	POINT_Y	Land_Elv	Source	County	Operator	Date_Drill	TD
59	-98.934157	31.952187	1630	BEG_Cable_Tool	Brown	Lone Star Producing Co.	12/14/49	3105
60	-98.985974	31.99105	1592	BEG_Cable_Tool	Brown	J. B. Roberts Co.	11/01/37	2773
61	-99.127894	31.891059	1555	BEG_Cable_Tool	Brown	Harry Trentman Jr. Inc	10/19/38	2600
62	-99.065794	32.010997	1533	BEG_Cable_Tool	Brown	Hilok & Reynolds Royalty	10/16/55	3148
63	-99.160081	31.904229	1574	BEG_Cable_Tool	Brown	Oil State Petroleum Co.		3160
64	-98.856098	31.868915	1618	BEG_Cable_Tool	Brown	George F. Mulkey & R P Baldwin	02/25/50	2851
65	-99.181296	31.797332	1544	BEG_Cable_Tool	Brown	Great Expectations Oil Corp	02/26/58	2349
66	-99.122126	31.927271	1565	BEG_Cable_Tool	Brown	Goldvick et al		3110
67	-98.960214	31.590522	1544	BEG_Scout_Ticket	Brown	Delray Oil Co.	08/11/77	1366
68	-99.112895	31.904506	1551	BEG_Cable_Tool	Brown	Geo. E. Lamb & Superior Oil Co	08/11/29	3585
69	-98.976833	31.734749	1332	Jim Brim, Cable Tool	Brown	J. E. Whiteside	01/10/41	1488
70	-98.731218	31.618725	1452	BEG_Scout_Ticket	Mills	A. W. Adkisson	02/05/52	2330
71	-98.737757	31.632838	1497	BEG_Scout_Ticket	Mills	The Pure Oil Co.	03/04/51	2124
72	-98.693	31.595404	1498	BEG_Scout_&_Cable	Mills	A. W. Sandy	05/16/46	4230
75	-99.066319	31.37375	1530	BEG_Scout_Ticket	San Saba	H. O. Newman	09/13/49	3023
87	-99.13553	31.487659	1412	PI, API# 4204900048	Brown	Deaton Oil & Gas Co	08/15/55	3200
88	-98.873379	31.5675	1427	PI, API# 4204900083	Brown	Trout L. E.	06/09/54	3014
90	-99.195293	31.790158	1516	PI, API# 4204908074	Brown	Miles Production Co.	06/20/68	3920
92	-98.925369	31.668683	1337	PI, API# 4204930928	Brown	Delray Oil Inc.	09/22/76	3360
93	-99.131215	31.657065	1530	PI, API# 4204931846	Brown	Vista Resources Inc	10/31/81	3518
94	-99.12147	31.702294	1606	PI, API# 4204935548	Brown	C E I Operating	01/13/95	3870
95	-98.996355	31.626028	1505	PI, API# 4204901279	Brown	Dietz, W	07/10/57	1720
96	-98.997197	31.694891	1408	PI, API# 4204903156	Brown	Neil K Shaw	12/12/49	1764
97	-99.102948	31.528043	1336	PI, API# 4204903774	Brown	J. G. Walker, et al	06/20/59	1265
98	-98.997996	31.582259	1435	PI, API# 4204904216	Brown	Ratner, Lee	08/24/58	1395
100	-99.077206	31.538338	1320	PI, API# 4204904437	Brown	Brearly, W R	03/30/55	1295
101	-98.932223	31.706264	1370	PI, API# 4204905199	Brown	Lone Star Prod Comp	05/12/47	1841
103	-98.780572	31.686552	1449	PI, API# 4204905976	Brown	Bonwell C E	08/02/30	1785

Track No	POINT_X	POINT_Y	Land_Elv	Source	County	Operator	Date_Drill	TD
105	-98.963195	31.604347	1553	PI, API# 4204931059	Brown	Delray Oil Co.	02/07/77	1629
107	-99.00618	31.734714	1389	PI, API# 4204931494	Brown	Brim, #1	08/09/77	2025
109	-98.998164	31.734966	1348	PI, API# 4204934756	Brown	Brim Jim, #7	01/06/87	1855
110	-99.025045	31.493164	1400	Brim, API# 4204934067	Brown	J & M Operating	07/20/84	3500
111	-98.900627	31.499677	1342	PI, API# 4233300061	Mills	Slavin, Pat	09/10/56	3009
113	-98.944702	31.426676	1385	PI, API# 4241100013	San Saba	Griggs, F	03/09/54	2785
114	-98.959053	31.411683	1385	PI, API# 4241100032	San Saba	Shaw, T G	09/05/55	2755
117	-99.244422	31.369627	1591	PI, API# 4230700009	McCulloch	Briggs J & Williams G	09/20/48	2600
200	-99.048509	32.01348	1609	Top, Cisco Thrifty & Graham Forms	Brown	GAT sheet outcrop top & base		
201	-99.104834	31.919182	1539	Top, Cisco Thrifty & Graham Forms	Brown	GAT sheet outcrop top & base		
202	-99.1474	31.845843	1533	Top, Cisco Thrifty & Graham Forms	Brown	GAT sheet outcrop top & base		
203	-99.176808	31.765573	1611	Top, Cisco Thrifty & Graham Forms	Brown	GAT sheet outcrop top & base		
205	-98.983437	31.939548	1551	Base, Cisco Thrifty & Graham Forms	Brown	GAT sheet outcrop top & base		
206	-99.045519	31.861332	1436	Base, Cisco Thrifty & Graham Forms	Brown	GAT sheet outcrop top & base		
207	-99.071203	31.803337	1450	Base, Cisco Thrifty & Graham Forms	Brown	GAT sheet outcrop top & base		
208	-99.100408	31.694671	1606	Base, Cisco Thrifty & Graham Forms	Brown	GAT sheet outcrop top & base		
209	-99.148928	31.604373	1472	Base, Cisco Thrifty & Graham Forms	Brown	GAT sheet outcrop top & base		
210	-99.195475	31.528988	1479	Base, Cisco Thrifty & Graham Forms	Brown	GAT sheet outcrop top & base		

XI. Appendix C: GIS Files and ArcReader

The attached CD contains the information presented in this document in two sets of files: (1) one, more complete, readable with ArcGIS software and (2) a second, standalone, file set to access coverages without using the conventional ArcGIS software. The interested reader would need to Install ArcReader 10, which is free:
(http://www.esri.com/software/arcgis/arcreader/download),

Brown County coverages accessible through ArcReader are listed below:

Brown_County_Final_Well_Dataset_5_6_2012 – Brown County Well Dataset
Brown_County_Study_Area_GAT – Brown County Geologic Atlas of Texas
Cambrian_Sand_Wells – Cambrian Sand Wells
Cambrian_Sd_Top_Depth_Contours – Cambrian Sand Top Depth Contours
Cambrian_Sd_Top_Elv_Contours – Cambrian Sand Top Elevation Contours
Ellenburger_Top_Depth_Contours – Ellenburger Top Depth Contours
Ellenburger_Top_Elev_Contours – Ellenburger Top Elevation Contours
Granite_Top_Depth_Contours – Granite Top Depth Contours
Granite_Top_Elevation_Contours – Granite Top Elevation Contours
Granite_Top_Wells – Granite Top Wells
Hickory_Top_Depth_Contours – Hickory Top Depth Contours
Hickory_Top_Elev_Contours – Hickory Top Elevation Contours
Marble_Falls_Top_Contours – Marble Falls Top Contours
Marble_Falls_Top_Elev_Contours – Marble Falls Top Elevation Contours
Marble_Falls_Wells – Marble Falls Wells
Penn_Strawn_Caddo_LS_Wells – Strawn/ Caddo Wells
Strawn_Caddo_Top_Depth_Contours – Strawn/ Caddo Top Depth Contours
Strawn_Caddo_Top_Elev_Contours – Strawn/Caddo Top Elevation Contours
D2Htop_extrap - Hickory Top Elevation extrapolation
Depth2_Hick_pts – Hickory well points
Llano_Uplift_aquifers – Llano Uplift aquifer boundaries
TDS_cont_Hick_extrap – Hickory Salinity Contours extrapolation
wq_latest_avgYr_ellenbHick – Ellenburger and Hickory Salinity Points
ESalinity_28 – Ellenburger Salinity Contours
TexasCounties – Texas Counties
Ci18my12 – Brown County cities and towns
Y01f_og_wells – Oil and Gas Wells
TxDOT_Roadways – Texas Roads
Aquifer_Trinity_TWDB – Trinity Aquifer Boundaries

XII. Appendix D: Updates to First Release

In addition to fixing the title of the document and several minor typos in the text, the main changes consist in providing a better land-surface elevation map (Figure 3), in updating Figure 56 (delete a “1150 gpm” data that does not exist), and adding some elements to the discussion on the conceptual flow model in the Hickory (Section VII-1) which is also complemented by the new Figure 80.