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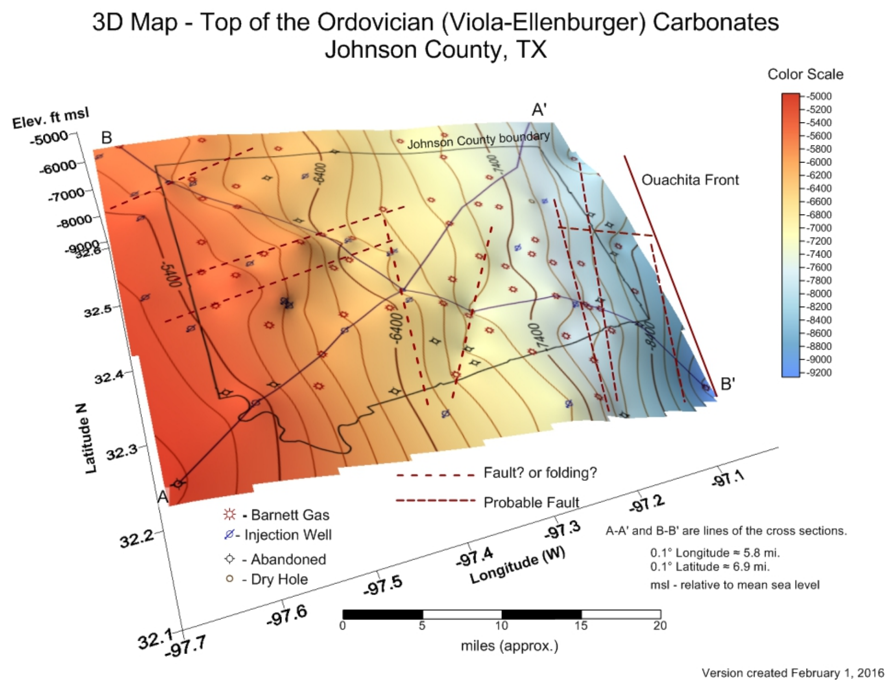

Geologic Characterization of Johnson County, Texas

14 December 2016

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NETL-TRS-17-2016

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Cover Illustration: 3D map of the surface of the Ordovician top (base of the Barnett), Johnson County, Texas, showing discontinuities (lineaments) that could represent faults. This surface is based on data from 103 wells.

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Geologic Characterization of Johnson County, Texas

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Acronyms, Abbreviations, and Symbols

Term	Description
3D	Three-dimensional
BEG	Bureau of Economic Geology
BWPM	Barrels of waste fluid per month
EDX	NETL's Energy Data eXchange
FWB	Fort Worth Basin
NAD83	North American Datum 1983 (1986)
RRC	Texas Railroad Commission
TRS	Technical Report Series
TVD	True vertical depths
WGS84	World Geodetic System 1984

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ABSTRACT

The Fort Worth Basin (FWB) in north-central Texas has seen a surge in shale-gas drilling and associated hydraulic fracturing in the Barnett shale. This basin is a structural basin bounded by the Ouachita Thrust Zone to the east and the Muenster Arch to the north. The fracturing (frac) fluids and subsequent produced water from the wells must be disposed of, and most of this disposal is into a deep carbonate formation, the Ellenburger Group dolomite, which underlies the Barnett shale. This disposal appears to be associated with seismic activity, earthquakes that can sometimes be felt by residents in the area. An attempt is being made to model the disposal of these fluids into the Ellenburger and develop methods to predict the most likely places of seismic activity. A working model could assist in mitigating the strength of seismic activity through providing optimum disposal rates, optimum disposal well siting, and prediction of potentially imminent seismic activity.

To develop models to simulate the disposal of frac fluids, a geologic framework of the area is required. This framework includes the distribution, thickness, and depth of major geologic units, and the distribution of existing fractures and faults in the area. This geologic framework is the basis of this report.

To develop this geologic framework data from nearly 300 wells within and adjacent to Johnson County were reviewed along with over 220 geophysical logs obtained from the Texas Railroad Commission (RRC) and IHS, a well information service. These data were compiled and evaluated using Surfer® and Strater® to provide structure contour maps of specific units of interest and cross-sections across the county.

The data compiled for this report show that the depth of major units generally increases eastward toward the Ouachita Thrust Zone, a major structure on the east side of Johnson County. This thickening is in agreement with all reports on the FWB geology (e.g. Montgomery et al., 2005; Turner, 1957). The principal unit of interest, the Ellenburger, ranges from 5,600 to 10,000 ft in depth and its thickness varies from about 2,400 ft to the northwest to 3,400 ft near the Ouachita Thrust Zone. This eastward thickening is, again, in agreement with the geologic literature. Overlying shales and sandstones include a unit termed the “Atoka” sandstone in this report. The cross-sections indicate that the Atoka is flatter across the county and that shales beneath the Atoka thicken considerably, from as little as 50 ft on the west to up to 3,000 ft to the east. The sands themselves vary considerably in thickness and appear to interfinger with shales and often pinch out in one area and reappear in another.

Geophysical logs to the basement rocks are rare. However, there are a few, and based on these logs and logs to the Cambrian, the Cambrian unit appears to be about 800 to 1,000 ft thick. The depth to the Cambrian varies from about 8,500 to 13,500 ft, increasing eastward. Also, based on the logs that intercept the Precambrian, the thickness of the Cambrian appears to increase from west to east from about 900 ft on the west to 1,000 ft on the east.

Structure contour maps in conjunction with the cross-sections were used to evaluate potential faulting and fracturing and relate this to published faulting in the literature. Potential fault zones appear to trend north-northeast near the Ouachita Thrust and east-northeast in the western part of the county. Some probable cross faults were noted, east-west near the thrust and northwest-

southeast to the west. The faults near the thrust correspond with faults in Frohlich et al. (2015), Ewing (1990) and Elebiju et al. (2010). The potential faults to the west more closely follow faulting presented in Turner (1957), which are slightly different from those presented by Frohlich and others.

Despite the multitude of data, the apparent offset on these proposed faults and fractures is rarely over 100 ft. As such, variations on the structure contour maps are subtle and could be the result of folding rather than faulting. A review of additional wells in the area could further help to identify potential faults in and adjacent to Johnson County. A better method would be seismic surveys across potential faults in Johnson County, though such an effort is beyond the scope of this project. Still, the data compiled gives a starting point for modeling the injection of frac fluids and the potential effects of this on nearby faults and fractures. These data can be used to assist regulators in mitigating the effects of fluid disposal on seismic activity.

1. INTRODUCTION

Since the huge increase of shale-gas drilling and associated hydraulic fracturing in the Barnett shale in the Fort Worth Basin, Texas, there has been a significant increase in earthquake activity. Many of these earthquakes are M+3 or larger, which can generally be felt (Frohlich, 2012). The fracturing fluids and subsequent produced water from the wells must be disposed of, and the general method of disposal is to inject them into a relatively saline aquifer, the Ellenburger Formation, which lies beneath the productive gas horizon, the Barnett shale. Thousands of wells have been drilled within the basin and used to dispose of the produced water, hundreds of injection wells have been completed (Frohlich et al., 2011).

The induced seismic activity has been particularly common in Johnson County, Texas, south of the principal gas field, but still an area that is gas productive. A good correlation was found between this activity and injection wells in the county (Frohlich et al., 2011; Frohlich, 2012; Justinic et al., 2013). These wells may inject as much as 600,000 barrels of waste fluid per month (BWPM), averaging as much as 300,000 BWPM over several years (Justinic et al., 2013). The injection horizon, the Ellenburger Formation, is a relatively low-porosity carbonate unit, dominantly dolomite, that is already saturated with saline water. The injected water must go somewhere, as it is not likely that the Ellenburger will accept all of it without a significant increase in pore pressure to expand the pore space. This increased stress is manifested in earthquake activity, particularly in areas of existing weakness that in most cases are preexisting fractures and faults. Because of the excessive earthquake activity in Johnson County, it was selected as the area for this study of seismic activity resulting from wastewater injection.

Several studies of induced seismicity indicate that induced earthquakes generally occur along pre-existing fractures and faults rather than on newly created faults or fractures (Nicholson and Wesson, 1990; Frohlich et al., 2014; Skoumal et al., 2015). In the Fort Worth Basin, the area of greatest shale-gas development is north and northeast of Johnson County, yet much of the earthquake activity occurs in or near Johnson County. Many injection wells outside of this area have little associated earthquake activity (Frohlich, 2012; Justinic et al., 2013). It is apparent from these inconsistent relationships that there is a disconnect between seismic activity and many of the wastewater injection wells. Within Johnson County and adjacent areas (e.g. Tarrant County), the seismic activity tends to occur along linear trends or near some injection wells, but more distant from others, which emphasizes a likely association of the seismic activity with faulting irrespective of the location of nearby injection wells. Commonly, the seismic activity is along a north-south to northeast-southwest trend, which corresponds to the directions of some of the known faults within the area (Turner, 1957; Frohlich, 2012; Justinic et al., 2013).

To better understand the relationship between injection wells and seismic activity, an accurate flow and geomechanical model is needed for this region. This seismic model can provide insight as to why earthquake activity is higher in Johnson County than in other areas and could point the way toward mitigating earthquake activity through careful management of wastewater injection. Such a model is quite complex and is beyond the scope of this report.

The model will require a fairly comprehensive understanding of the subsurface geology within the county. Of particular interest are the extent, thickness, and depth relationships of the major geologic units. Different lithologies have different hydraulic and geomechanical properties and this information can improve the model’s accuracy. The deeper geologic unit characteristics are important as most of the earthquakes are in these deeper zones, particularly below the

Ellenburger where the wastewater is being injected. Unfortunately, data is sparse concerning these deep horizons so other avenues have been pursued to obtain this information.

1.1 SCOPE

This Technical Report Series (TRS) describes the methodology, assumptions, and extracted data used to develop a geologic characterization of the subsurface in Johnson County. The geologic data provide depths and elevations of formations used in the study and variations laterally in the geologic units. This geologic data are presented in cross-sections showing the stratigraphy of the lithologic (rock) units and structure maps (showing contours of the top elevation) of major geologic units. The scope was expanded for a few miles outside of Johnson County into neighboring counties to provide better interpretation of unit surfaces along the boundary of the county. The geology put forth in this report relies primarily on geophysical logs and well data reports filed by the petroleum industry with the Texas Railroad Commission (RRC). There is some interpretation of data to fit a lithologic model rather than a time-stratigraphic model of the region, as it is the lithology that is critical for analysis of seismicity.

1.2 PURPOSE

The purpose of this study is to provide a three-dimensional (3D) characterization of the subsurface geology for the modeling of fluid injection, geomechanics response, and the associated induced seismicity in Johnson County, Texas. Small earthquakes (M+1.0 to M+3.0) have been quite common in this county since 2008, within a year or two after the inception of hydraulic fracturing and fluid disposal using injection wells (Frohlich et al., 2011). With this geologic data, a better understanding of the earthquake data can be achieved and a connection can be made between earthquake activity and fluid injection.

This report describes the geologic units within the county, explains the research that was performed to obtain the geologic information, provides a compendium of this information, and discusses geologic cross-sections and elevation maps based on these data.

2. GEOLOGY OF THE FORT WORTH BASIN, JOHNSON COUNTY, TEXAS

2.1 BACKGROUND

The geology of the Fort Worth Basin (FWB) has been delineated in a number of publications. Overviews of the geology include Turner (1957), Montgomery et al. (2005), Pollastro et al. (2007), and Bruner and Smosna (2011). In addition to these, there have been a number of articles on the Barnett shale itself, the overlying sandstones, shales, and limestones, and the underlying Ellenburger dolomite and limestone (e.g. Dallas Geologic Society, in Martin, 1982). Seismic evidence of the geology is largely unpublished, but a few helpful publications include Elebiju et al. (2008, 2010) and Khatiwada et al. (2013).

The primary source of specific geologic data is from well data reports and accompanying geophysical logs filed by oil and gas operators and fluid disposal companies with the Texas RRC. Another source of data includes geophysical logs obtained through IHS Enerdeq, a vendor in support of the petroleum industry. Some data was also obtained from other reports or was provided by staff at the Bureau of Economic Geology (BEG) at the University of Texas at Austin.

Unfortunately, much of the geologic data is from wells that do not penetrate below the primary production horizon, the Barnett shale, and locating wells that are deeper is a tedious process. Some wells do penetrate the injection layer but do not penetrate to the deepest, or basement, rocks where most of the earthquakes occur. Assumptions had to be made concerning these basement rocks, which are based on limited published data and seismic studies of nearby areas within the Fort Worth Basin.

2.2 GEOLOGIC FRAMEWORK

The Fort Worth Basin is a structural basin that formed during the late Paleozoic Era during the Ouachita Orogeny (Montgomery et al., 2005) and bounded by the Ouachita Thrust Front to the east and the Muenster and Red River Arches to the north. The basin is deepest near the thrust, shallowing westward toward the Bend Arch (Figure 1). Secondary faults within the basin trend subparallel to the thrust front. The Mineral Wells Fault, a normal fault with a strike-slip component, trends more to the northeast ending at a northwest structure subparallel to the Muenster Arch.

The pre-orogenic sediments range from Cambrian to Mississippian in age and include the Cambrian carbonates and sandstones and the Ellenburger Group carbonates. The orogeny began during late Mississippian time and continued into the Pennsylvanian Period (Montgomery and others, 2005). Inception of downwarping of the FWB resulted in deposition of the Barnett shale, a black shale, often limy, with intermittent limestones on an erosion surface on pre-existing carbonates. The Barnett was followed by the Marble Falls Limestone, primarily present in the western part of the county with shale being deposited to the east (Montgomery et al., 2005). Uplift to the north and east with continued downwarping along the Ouachita Thrust Front, due to the orogeny, resulted in increasing clastic deposition particularly in the eastern part of the basin (Turner, 1957; Brown, 1973). During this time the Atoka and Strawn clastic sequences and the Smithwick shale were deposited (Figure 2 and Table 1).

In later Pennsylvanian time, the Canyon and Cisco Groups, along with younger units, were deposited. These units are a sequence of shale and limestone with some interbedded sandstone beds that do not occur in the Johnson County area (Turner, 1957). The Pennsylvanian sequence was folded and uplifted during the late Permian through Jurassic Periods (Flippin, 1982) creating an erosional surface that removed the younger units from the Johnson County area. Following this uplift, Cretaceous sediments were deposited in a sequence of sandstone, shale, and limestone (Turner, 1957). Both the erosional surface and the Cretaceous sediments persist across the Ouachita Thrust Front.

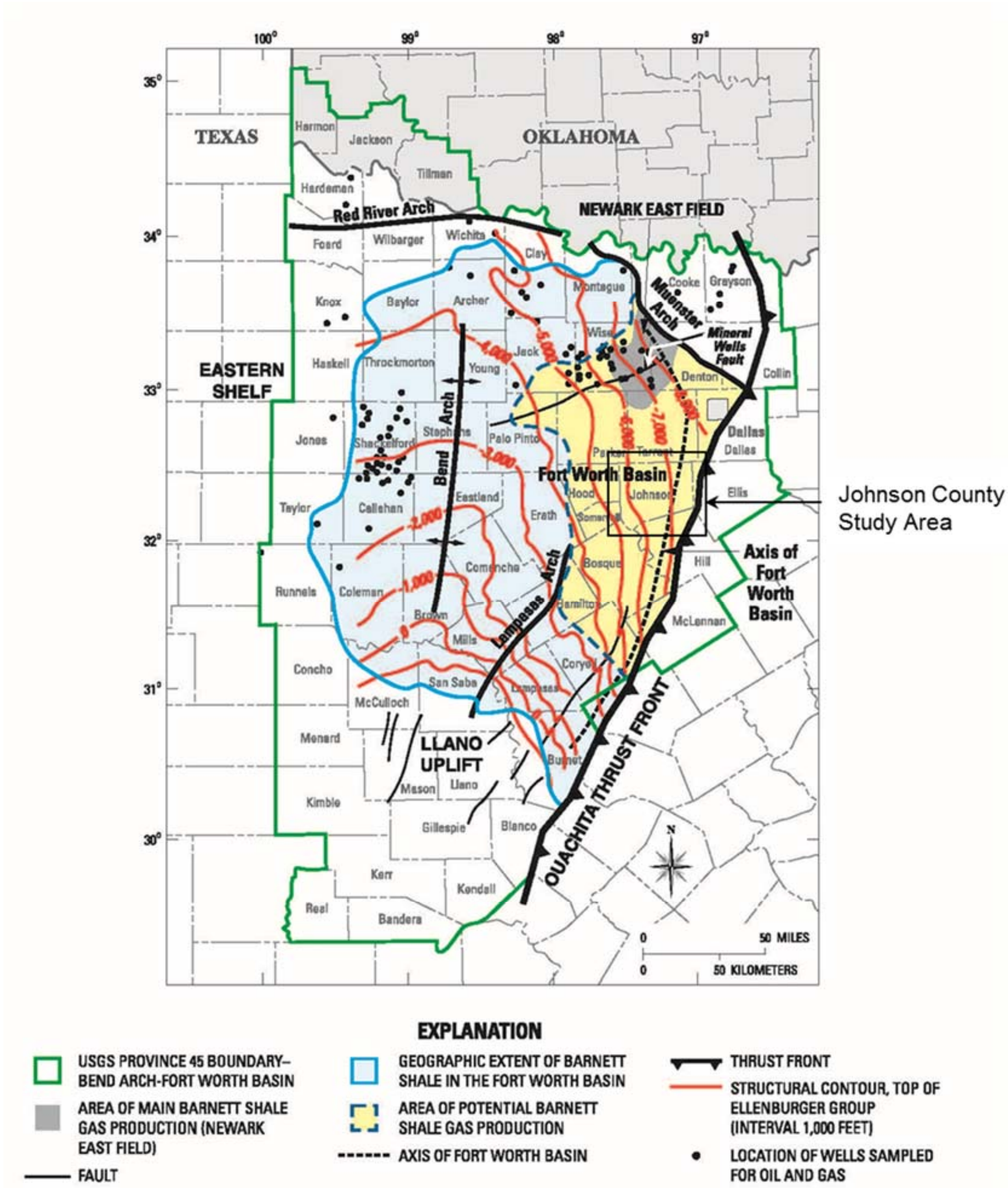

Figure 1: Areal extent of the Barnett shale in the Fort Worth Basin, with relevant geologic features (folding, faulting) showing the elevation on top of the Ellenburger Group (modified after Montgomery et al., 2005).

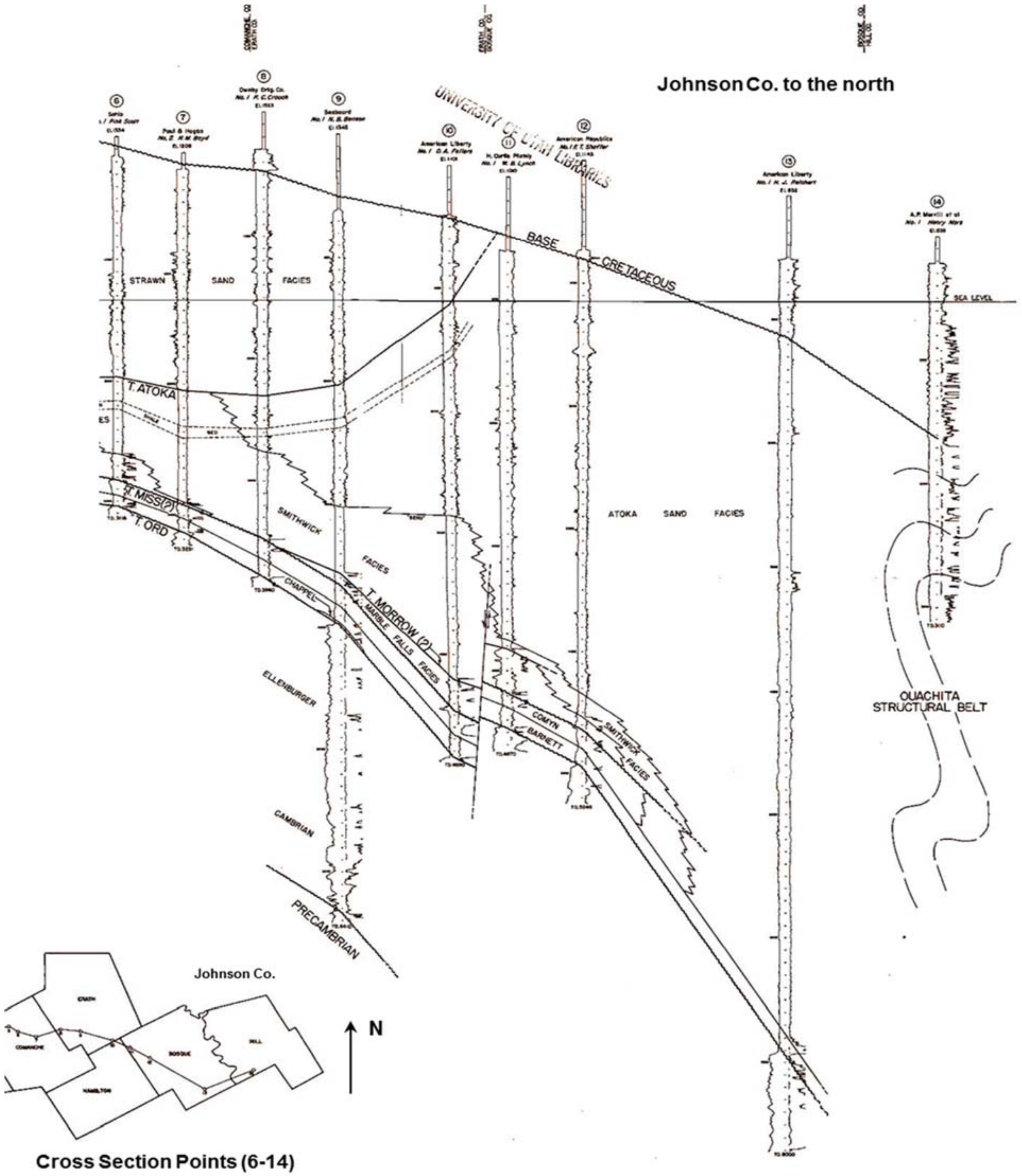

Figure 2: Cross-section through the eastern portion of the Fort Worth Basin, passing south of Johnson County, Texas (after Turner, 1957). Geophysical logs are gamma ray or spontaneous potential and resistivity.

The geologic units described in this section that underlie Johnson County are given in Table 1, and those specific units used in the cross-sections and provided for seismic modeling are listed in Table 2.

Table 1: Geologic units that underlie Johnson County, Texas, and surrounding areas. Many of these units are used in the cross-sections.

Group	Unit	Description
	Cretaceous	Sandstone, shale, and limestone beds. Unconformable contact with deeper units.
Strawn	Upper shale	Pennsylvanian shale unit with thin sandstones, limited extent.
	Strawn sandstone	Pennsylvanian, sandstone dominant, usually with significant interbedded shale. Appears to be thicker at the eastern edge of the county and absent to the southwest. To the east, the sandstone may be Atokan in age.
	Strawn-Caddo	Pennsylvanian, intermittent limestone unit (principally to the west). This unit is thin and not broken out.
Atokan Stage	Upper Penn. shale	Pennsylvanian, shale dominant unit with sparse, thin sands and limestone, often called part of the Smithwick shale.
Atoka or Bend Group	Upper Atoka sands	Pennsylvanian, sandstone units of variable thickness and extent and commonly with interbedded shale. These units are at varying depth above the Atoka Sandstone indicated below.
	Middle Penn. shale	Pennsylvanian, shale unit below the Upper Atoka Sandstone with sparse thin sandstone beds. This unit may be thin.
	Atoka sandstone	Pennsylvanian, sandstone, conglomerate, with interbedded shale beds. Good marker horizon, almost everywhere present. This unit may be absent or thin to the east. This unit is sometimes included with the Grant sandstone.
	Smithwick shale (upper)	Pennsylvanian, shale dominant unit that appears to be sandy or silty in part. This unit can be fairly thick, but thins to the west.
	Grant sandstone	Pennsylvanian, sandstone dominant unit in the Atoka Group. Present over only a part of the area, and may merge with the Atoka sandstone.
	Smithwick shale (middle)	Pennsylvanian, usually present where the Grant sandstone is present. Usually included in the above Smithwick shale where the Grant is absent.
	Bend conglomerate	Pennsylvanian, sandstone and conglomerate, with occasional limestone. Often present where the Grant sandstone is not, but there is usually, but not necessarily, more shale between the Bend conglomerate and the Atoka sandstone.
	Smithwick shale (lower)	Pennsylvanian, shale unit below the Bend conglomerate where present, usually thinner than the shale above the conglomerate.
	Big saline	Pennsylvanian, lower limestone and sandstone with interbedded shale. Sometimes considered a part of the Bend conglomerate unit but it is generally beneath the Bend.
	Hood sandstone	Pennsylvanian, sandstone, conglomerate, and limestone, more common in the western part of the county. Similar stratigraphically to the Big saline.
	Lower Smithwick shale	Pennsylvanian, lowest shale unit of the Smithwick. Variable thickness and above the Marble Falls. This unit may contain thin sandstone and/or limestone beds. Thins westward.
Marble Falls	Marble Falls limestone	Upper Mississippian to basal Pennsylvanian-age limestone and shale. The shale component increases eastward to where it is up to 80% shale. The lower Marble Falls limestone directly above the Barnett shale is equivalent to the Comyn limestone (Flippen, 1982).

Table 1: Geologic units that underlie Johnson County, Texas, and surrounding areas (cont.)

Group	Unit	Description
Barnett	Upper Barnett shale	Mississippian shale, with some limestone and sandstone. The top of this unit is difficult to determine, but is at or up to 50 ft above the first high gamma radiation reading.
	Forestburg	Intermittent limestone unit within the Barnett.
	Lower Barnett	Shale as above, often limy.
Ov	Viola limestone	Ordovician carbonates. Present only in eastern Johnson County.
Os	Simpson Formation	Ordovician carbonates and sandstone, often with significant shale. Present only in eastern Johnson County.
Oe	Ellenburger Group	Ordovician limestone and dolomite, dolomite-dominant.
Camb.	Cambrian	Cambrian carbonates and sandstone units.
pC	PreCambrian	Precambrian granitic and metamorphic rocks.

These units are represented in the following stratigraphic section (Figure 3).

Table 2: Units provided for modeling

Formation or Group	Description
Cretaceous	Sandstone, shale, and limestone beds.
Strawn-Atoka	Pennsylvanian, shale dominant with an upper sandstone-shale layer.
Atoka	Pennsylvanian sandstone and shale, sometimes with limestone and conglomerate beds. Includes the Grant sandstone and/or Bend conglomerate where the intervening shale is thin.
Smithwick	Shale with local sandstone, conglomerate, and limestone beds.
Marble Falls	Upper Mississippian to basal Pennsylvanian-age limestone and shale. Includes the Big Saline limestone and sandstone directly above the Marble Falls unit where the intervening shale is thin. This unit may be up to 80% shale in eastern Johnson County.
Barnett shale	Mississippian shale, with limestone and may contain sand units.
Ellenburger and Viola-Simpson	Ordovician limestone and dolomite.
Cambrian	Cambrian carbonates and sandstone units.
PreCambrian	Precambrian granitic and metamorphic rocks.

2.3 METHODOLOGY

2.3.1 Data Sources

Several methods were used to interpret subsurface unit thicknesses, depths, and lithology. The first method was the literature research indicated in prior sections (Sections 2.1 and 2.2). Geologic data for the Barnett shale and overlying units were found in most articles researched, particularly for the Barnett shale and the overlying Marble Falls limestone. The top of the Ellenburger carbonates was defined in some of these articles, but otherwise, the data limited. Information on overlying units, such as the Atoka, Strawn, and Cretaceous sediments was more common but often suspect, as the Atoka and Strawn are difficult to differentiate (Turner, 1957).

Seismic data were considered the best source of information, but publicly available seismic data for the Johnson County area were almost non-existent.

A major source of information was the drilling reports filed with the Texas Railroad Commission (RRC, 2015). These reports are filed for all wells drilled in Texas after a confidentiality period, and include injection wells. Most of these reports were obtained for Johnson County and adjacent areas to fill out the formation depths between cross-sections (Appendix). The locations of the cross-sections are shown on Figure 4.

A third and significant source of information are the geophysical logs commonly filed with the RRC in conjunction with the data reports. Not all data reports are associated with geophysical logs, and many of these logs are incomplete (including only the horizontal portion of the well, the vertical part of the well ending above the Barnett shale, or in the case of injection wells, only the part below the Barnett shale). The reason for the latter is often that the well was drilled in two stages or a dry hole was deepened for an injection well. There may have been no geophysical log filed for the dry hole. In addition to these geophysical logs, a number of logs and related well information were obtained from IHS Enerdeq (2015). Of all the data, the geophysical logs proved to be the most useful.

Finally, there were a couple of geophysical logs provided by the BEG at the University of Texas at Austin. One of these logs (the Gage well) penetrated the Cambrian sediments and to the basement. This log is from “8 miles west of Cleburne” in Johnson County, but a more precise location could not be determined.

2.3.2 <u>Data Compilation</u>

Over 290 well data reports (reports filed by the well operator) were obtained from the Texas RRC in which data on formation depths were provided. Geophysical logs were obtained from about 200 wells (Table 3) either from Texas RRC or from IHS. Of these, 20 were injection wells that have useful data on the subsurface geology. The well locations are shown in Figure 7 along with the lines of cross-sections. Nearly all of the well data reports give the depth to the Barnett shale, many give the depth to the Marble Falls, and a significant number provided depths to the top of the “Atoka”. Some give the depth to the Ellenburger carbonates, including most of the injection well drilling reports. At least ten wells provide a depth to the Cambrian, and four wells (API No’s 25130385, 25131305, 25132402, and 22130983) appear to have penetrated the Precambrian basement. Where possible, all of these depths were converted to vertical depth using the reported well survey, and the reported depths were checked with geophysical logs of the wells when available. If unit depths in the data reports could not be verified by geophysical logs or log depths in nearby wells, these depths were deleted from the database.

The depth data from the RRC data reports and IHS database were compiled into a spreadsheet with multiple pages. The primary page lists the well name, location, comment on data quality, operator, district and lease, well type, whether a geophysical log was available, surface elevation, vertical depth, and depth to each unit noted in the report. In some cases, calculated vertical depths are given in the data reports. Depths determined from geophysical logs were checked with well surveys in the data reports to provide true vertical depths (TVD).

Due to the county-wide area, all well locations were entered in latitude-longitude coordinates. All well locations were checked using Google Earth®, which provides coordinates using the WGS84 system. As long as the well location could be located in the satellite view, the location noted using Google Earth® usually coincided within a few feet of the NAD83 location (when available) in the data report. (The difference between NAD83 and WGS84 is usually less than one meter (three feet), Wikipedia.org (2016).) Note that well deviation with depth is typically 100 ft or more from the surface location, so that a more precise location is not important for the subsurface depth of a geologic unit. No attempt was made to precisely locate the horizontal position of the penetration point of subsurface units.

The geologic formations and depths were commonly listed in the well data reports and were compiled in a spreadsheet. Geophysical log data were compiled on a separate sheet to verify the depths given in the report, provide depths to units not listed in the report, and determine the actual top of persistent units within the section, such as the top of the Atoka sandstone. Detailed data were compiled from the geophysical logs and then combined with data from data reports in a third spreadsheet to provide depths to the major geologic units.

Some units, such as the top of Atoka sandstone were difficult to evaluate due to the heterogeneity of the formation, consisting of sandstone lenses within thick sequences of shale, occasional limestone beds, and a conglomerate. As such, the top of the Atoka sandstone and other Pennsylvanian sandstones, as provided in this report, must be taken as tentative for each of the wells where they are given, particularly in wells near the Ouachita Thrust. The Atoka sandstone is not the top of the Atoka-age sediments, but a significant marker horizon within the Atoka Series (Turner, 1957). In Turner (1957) the Strawn is absent over much of Johnson County, yet the well data reports list it as present in most of the wells where depths to the Atoka are given. As such, this study has instead, divided the Atoka into sandstone-rich and shale-rich units, which are more appropriate for the detailed models of fluid migration and associated geomechanical response required to understand where induced seismicity may occur.

Table 3: List of all wells used to determine unit depth and layer thicknesses in Johnson County, Texas

Well API #	Latitude	Longitude	Well Type	Refr. Elev. (ft)	Elev. Refr	Surface Elev. (ft)	Total Vert. Depth (ft)	Gph Log
36734085	32.59130	-97.68418	Injection	1,084	KB	1,138	9,408	YesC
36734467	32.58623	-97.68049	Injection	1,144	KB	1,132	8,800	NA
03530102	32.12425	-97.66884	Abandoned	831	KB	817	5,985	YesE
36733841	32.58392	-97.66543	Gas	1,084	KB	1,066	6,435	Yes
36733836	32.58389	-97.66535	Gas	1,084	KB	1,066	6,526	Yes
22130984	32.34382	-97.66478	Gas	670	KB	652	5,725	Yes
22130946	32.48670	-97.66440	Abandoned	930	KB	920	5,711	Inc1
22130983	32.33861	-97.66211	Injection	687	GR	687	9,691	Gamma-C
22131331	32.49147	-97.65532	Gas	957	GR	957	6,259	Inc2
36733480	32.59926	-97.65393	Gas	989	KB	975	6,908	YesE
22131311	32.49248	-97.65385	Gas	1,020	KB	998	6,241	Gamma
22131219	32.47621	-97.65254	Gas	965	KB	950	6,710	YesE
22131206	32.50808	-97.64854	Injection	990	KB	990	9,100	Gamma-E
22131364	32.45765	-97.64850	Injection	850	GR	850	9,295	NA
36733776	32.64093	-97.63617	Gas	987	KB	971	6,634	Inc1
42530200	32.28923	-97.62916	Injection	788	KB	776	8,990	YesE
22131093	32.33956	-97.62804	Gas	971	KB	952	8,221	Yes
22131051	32.37802	-97.62595	Gas	785	KB	766	5,933	Yes
42530113	32.21046	-97.62447	Gas	650	KB	650	5,725	Gamma
42530122	32.29255	-97.62400	Injection	770	GR	770	9,850	NA
22131158	32.48957	-97.61890	Gas	979	KB	971	6,655	YesE
22131217	32.38278	-97.61867	Gas	802	KB	783	5,942	Gamma
42530192	32.25513	-97.61826	Gas	816	KB	803	6,003	Inc2
36733618	32.56411	-97.61803	Abandoned	980	KB	966	6,722	Yes
25131509	32.44820	-97.61522	Gas	864	KB	843	6,601	Yes
25132379	32.48241	-97.60871	Gas	966	KB	945	6,379	Inc2
25132969	32.50944	-97.60825	Gas	1,032	KB	1,011	6,383	Yes
25130846	32.21010	-97.60744	Abandoned	728	KB	715	6,300	YesE
25131782	32.53682	-97.60503	Gas	1,055	KB	1,035	6,588	Yes
25130385	32.52062	-97.60485	Injection	1,012	GR	1,012	11,000	NA
25130489	32.52221	-97.60355	Injection	1,030	KB	1,019	9,775	NA
03530110	32.09288	-97.60342	Abandoned	846	KB	822	6,123	YesE
25130360	32.36841	-97.59824	Gas	759	KB	742	6,551	YesE
25130762	32.31230	-97.59660	Gas	839	KB	821	6,231	Inc1

Table 3: List of all wells used to determine unit depth and layer thicknesses in Johnson County, Texas (cont.)

Well API #	Latitude	Longitude	Well Type	Refr. Elev. (ft)	Elev. Refr	Surface Elev. (ft)	Total Vert. Depth (ft)	Gph Log
25130302	32.32090	-97.59397	Gas	955	KB	937	8,270	YesE
36733547	32.56844	-97.59302	Gas	966	KB	950	6,631	Yes
25133146	32.41133	-97.58918	Gas	952	KB	939	6,751.7	YesE
25130303	32.44310	-97.58436	Gas	933	KB	912	6,449	Yes
25131443	32.19119	-97.58295	Injection	636	GR	636	9,260	NA
25130957	32.23579	-97.58198	Gas	751	KB	733	6,047	Yes
25131918	32.28199	-97.58066	Gas	943	KB	929	6,360	Inc2
36733645	32.56309	-97.57908	Gas	982	KB	965	6,596	Inc2
25130428	32.51760	-97.57780	Injection	968	GR	968	9,631	NA
25130364	32.52424	-97.57772	Gas	982	KB	968	7,150	Yes
25130396	32.37664	-97.57510	Gas	942	KB	925	6,360	Inc2
25130232	32.48898	-97.57282	Gas	1,040	KB	1,025	7,055	YesE
36734496	32.56076	-97.56837	Gas	966	KB	953	6,498	NA
25131375	32.17824	-97.56441	Gas	689	KB	668	6,200	Inc2
25130195	32.35103	-97.56400	Gas	942	KB	925	6,670	YesE
25131749	32.21447	-97.56051	Abandoned	627	KB	610	6,731	YesE
25130839	32.17698	-97.55330	Gas	685	KB	671	6,170	Inc2
43931262	32.58992	-97.55145	Gas	809	KB	795	6,715	YesE
25130840	32.18931	-97.54565	Abandoned	744	KB	727	6,216	Inc2
25134177	32.28760	-97.54504	Gas	903	KB	881	7,075	YesE
25130249	32.37434	-97.54317	Injection	950	GR	950	9,523	NA
25132586	32.46599	-97.53515	Gas	1,002	KB	989	6,600	Yes
25133189	32.37471	-97.53445	Injection	967	KB	954	8,579	YesE
25130432	32.41253	-97.53157	Gas	1,015	KB	1,005	6,579	Inc2
25133088	32.50965	-97.52725	Gas	984	KB	966	7,195	YesE
25133092	32.50964	-97.52712	Gas	984	KB	966	7,220	Yes
Gage	32.38400	-97.52500	Gas	872	GR	872	9,584	Yes
25130509	32.31480	-97.52087	Injection	934	KB	917	9,800	YesC
25131770	32.42316	-97.52010	Gas	957	KB	938	6,583	NA
25131182	32.14383	-97.51858	Abandoned	602	KB	583	6,481	Inc2
25130696	32.31191	-97.51687	Injection	893	KB	880	10,036	YesC
25132625	32.20956	-97.51667	Gas	832	KB	819	6,918	YesE
43932146	32.58455	-97.51258	Gas	876	KB	861	6,686	NA

Table 3: List of all wells used to determine unit depth and layer thicknesses in Johnson County, Texas (cont.)

Well API #	Latitude	Longitude	Well Type	Refr. Elev. (ft)	Elev. Refr	Surface Elev. (ft)	Total Vert. Depth (ft)	Gph Log
43931846	32.57883	-97.51249	Gas	889	KB	871	6,682	Inc2
25130630	32.37582	-97.51141	Dry Hole	853	KB	838	6,458	Inc1
25130366	32.42469	-97.50871	Gas	903	KB	886	6,581	Inc2
25132067	32.22610	-97.50794	Gas	781	KB	763	6,675	Yes
25131116	32.17380	-97.50594	Gas	702	KB	682	6,479	Inc2
25130518	32.48944	-97.50320	Abandoned	994	KB	980	6,894	Inc2
25130109	32.50264	-97.50169	Injection	937	KB	925	7,370	YesE
03530138	32.14796	-97.50143	Gas	644	KB	632	6,602	Yes
25130899	32.17571	-97.50085	Injection	795	KB	775	6,876	YesE
25130348	32.24890	-97.50075	Gas	823	KB	795	6,864	Yes
25130347	32.25981	-97.49099	Gas	874	KB	863	6,824	Yes
43931548	32.57714	-97.48949	Gas	758	KB	758	6,627	NA
25131893	32.33972	-97.48788	Gas	866	KB	850	6,520	Inc2
25130136	32.51692	-97.48591	Abandoned	934	KB	918	7,258	YesE
25130399	32.39326	-97.47942	Gas	830	KB	808	6,399	Inc2
25130114	32.42149	-97.47376	Abandoned	884	KB	870	7,880	YesE
25130881	32.32248	-97.47327	Gas	828	KB	806	6,492	Inc2
43933462	32.55979	-97.47219	Gas	853	KB	836	6,771	Inc2
25130314	32.47705	-97.46838	Gas	986	KB	966	7,015	Inc1
25130895	32.27424	-97.46788	Injection	860	KB	844	9,810	NA
25130143	32.44498	-97.46757	Abandoned	915	KB	905	7,355	YesE
25131367	32.28498	-97.46594	Abandoned	860	KB	844	6,822	Yes
25132211	32.52955	-97.46285	Gas	919	KB	897	6,842	NA
25132143	32.35242	-97.46281	Gas	793	KB	776	6,653	NA
25130108	32.29681	-97.46166	Gas	818	KB	799	10,009	YesC
25130852	32.32609	-97.46079	Gas	768	GR	768	6,676	Gamma
25131596	32.20431	-97.45844	Gas	832	KB	814	6,926	Inc2
25130139	32.39072	-97.45834	Gas	904	KB	886	7,124	YesE
25132633	32.18826	-97.45792	Gas	751	KB	729	6,842	NA
43931662	32.57014	-97.45722	Gas	804	GR	804	7,210	YesE
25132362	32.53492	-97.45459	Gas	874	KB	851	6,909	Inc2
25130157	32.36461	-97.45036	Gas	845	KB	835	7,420	YesE
25131441	32.32652	-97.44914	Gas	776	KB	754	6,682	Inc2
25130806	32.21059	-97.44768	Gas	803	KB	788	7,053	Inc1

Table 3: List of all wells used to determine unit depth and layer thicknesses in Johnson County, Texas (cont.)

Well API #	Latitude	Longitude	Well Type	Refr. Elev. (ft)	Elev. Refr	Surface Elev. (ft)	Total Vert. Depth (ft)	Gph Log
25130184	32.41970	-97.44646	Gas	881	KB	865	7,360	Yes
25130111	32.19759	-97.44091	Abandoned	801	KB	789	7,305	YesE
25131079	32.47636	-97.44054	Gas	894	KB	882	7,200	Yes
25130319	32.28592	-97.43867	Gas	755	KB	738	5,475	Inc1
25133335	32.51419	-97.43759	Injection	850	GR	850	9,806	NA
25130805	32.45632	-97.43443	Gas	944	KB	926	7,082	Inc2
25132417	32.52857	-97.43315	Gas	856	KB	843	6,897	Yes
25130155	32.23055	-97.43293	Gas	747	KB	731	7,213	YesE
25132248	32.37838	-97.43013	Gas	865	KB	843	7,249	Inc1
25130864	32.23012	-97.42753	Gas	751	KB	729	7,010	Inc2
43931158	32.57321	-97.42744	Gas	800	KB	785	7,285	YesE
25130144	32.37882	-97.42720	Gas	863	KB	850	7,506	YesE
25132059	32.53413	-97.42703	Injection	844	GR	844	10,830	Yes
25131102	32.45068	-97.42413	Gas	915	KB	903	7,350	NA
25130196	32.41006	-97.42113	Gas	871	KB	853	7,401	Yes
43931817	32.56732	-97.41945	Gas	846	KB	824	7,007	Inc1
25130127	32.40401	-97.41916	Injection	864	KB	851	9,134	YesE
25130799	32.50666	-97.41889	Gas	872	KB	854	7,400	YesE
25132181	32.37289	-97.41510	Gas	847	KB	831	7,117	Inc1
25130861	32.20383	-97.41322	Abandoned	700	KB	681	7,402	Inc2
25130250	32.41085	-97.41163	Gas	858	KB	848	7,537	YesE
25132039	32.36473	-97.41137	Gas	840	KB	820	7,206	Inc1
21730408	32.18725	-97.40883	Gas	722	KB	702	7,321	Inc2
25130461	32.29636	-97.40857	Gas	763	KB	738	7,200	YesE
25130936	32.23020	-97.40520	Abandoned	690	KB	670	7,172	Inc1
25131344	32.28138	-97.40274	Gas	705	KB	685	6,925	Inc1
25130219	32.39551	-97.40116	Injection	852	KB	836	9,071	YesE
25130643	32.39730	-97.39987	Gas	818	GR	818	7,188	Inc2
21730452	32.16671	-97.39870	Injection	727	GR	727	10,340	YesE
25130293	32.27456	-97.39844	Gas	772	KB	758	7,370	Gamma

Table 3: List of all wells used to determine unit depth and layer thicknesses in Johnson County, Texas (cont.)

Well API #	Latitude	Longitude	Well Type	Refr. Elev. (ft)	Elev. Refr	Surface Elev. (ft)	Total Vert. Depth (ft)	Gph Log
25132517	32.51364	-97.39803	Gas	927	KB	905	7,240	NA
25130363	32.54659	-97.39768	Gas	898	KB	885	7,595	YesE
25130919	32.46132	-97.39478	Gas	922	KB	899	7,265	Inc1
25130241	32.42433	-97.39161	Abandoned	841	KB	831	7,700	YesE
25130433	32.22021	-97.38613	Abandoned	658	KB	646	7,313	YesE
43931540	32.55469	-97.38592	Abandoned	809	KB	809	7,109	NA
43933080	32.57145	-97.38562	Gas	849	KB	826	7,075	Inc2
25131558	32.39123	-97.38411	Gas	820	KB	807	7,291b	Inc2
25130299	32.32575	-97.38093	Injection	785	KB	768	10,952	YesC
25131266	32.30782	-97.38066	Injection	743	GR	743	10,128	NA
43931445	32.55538	-97.38016	Gas	836	KB	814	7,163	NA
25130356	32.25537	-97.38009	Gas	770	KB	752	7,260	Inc1
43931226	32.56085	-97.37996	Gas	808	KB	795	7,400	YesE
25130897	32.37945	-97.37574	Injection	791	GR	791	9,830	YesE
25130877	32.38913	-97.37495	Gas	814	KB	794	7,196	Inc1
25130306	32.25399	-97.37254	Abandoned	762	KB	761	7,595	YesE
25131430	32.52125	-97.37072	Gas	804	KB	791	7,208	Inc2
25130815	32.38455	-97.36858	Injection	780	GR	780	10,692	NA
25131282	32.21315	-97.36613	Gas	692	KB	667	7,602	YesE
25130327	32.42600	-97.36514	Gas	849	KB	826	7,700	YesE
43932604	32.55495	-97.36333	Gas	800	KB	775	7,196	Inc2
25131027	32.45158	-97.36287	Gas	914	KB	889	7,492	Inc1
25131105	32.36594	-97.36159	Abandoned	812	KB	784	7,596	NA
25131267	32.47668	-97.35639	Gas	841	KB	824	7,512	Yes
25132841	32.45609	-97.35616	Gas	900	KB	875	7,906	YesE
25130580	32.21234	-97.34828	Abandoned	707	KB	695	7,600	Yes
25130483	32.24389	-97.34773	Gas	707	KB	691	7,365	Inc1
25130988	32.30171	-97.34215	Gas	833	KB	810	7,815	YesE
25130755	32.36247	-97.34031	Gas	874	KB	853	7,486	Inc1
25131638	32.22376	-97.33961	Abandoned	735	KB	710	7,647	Inc1
25131525	32.50652	-97.33735	Gas	759	KB	734	7,354	Inc1
25130545	32.24484	-97.33655	Abandoned	712	GR	712	7,773	NA
43931911	32.56795	-97.33518	Gas	771	KB	749	7,176	Inc2

Table 3: List of all wells used to determine unit depth and layer thicknesses in Johnson County, Texas (cont.)

Well API #	Latitude	Longitude	Well Type	Refr. Elev. (ft)	Elev. Refr	Surface Elev. (ft)	Total Vert. Depth (ft)	Gph Log
25131081	32.46681	-97.33288	Gas	802	KB	782	7,507	NA
43931043	32.61978	-97.33005	Abandoned	748	KB	738	7,093	Inc2
25131261	32.47042	-97.32947	Abandoned	825	KB	807	7,729	Yes
43931061	32.58851	-97.32638	Gas	715	KB	701	7,615	YesE
25130838	32.51617	-97.32553	Gas	779	KB	758	7,397	Yes
43931637	32.55520	-97.32284	Gas	729	KB	710	7,309	Inc2
21730368	32.19339	-97.31859	Gas	724	KB	724	7,506	NA
25130586	32.28764	-97.31670	Gas	778	KB	753	7,757	NA
25130481	32.33687	-97.31476	Injection	855	KB	834	11,198	YesE
43932686	32.56660	-97.31469	Gas	719	KB	696	7,377	Yes
25131355	32.42179	-97.31406	Gas	809	KB	788	7,452	Inc2
25130530	32.48465	-97.31366	Gas	809	KB	794	8,020	YesE
25133149	32.51475	-97.31122	Gas	804	KB	788	7,386	NA
25132557	32.29643	-97.30912	Dry Hole	813	KB	795	8,180	Yes
25133237	32.50794	-97.30490	Gas	738	KB	731	7,476	Inc2
25132127	32.39356	-97.30392	Gas	792	KB	770	7,900	YesE
25133282	32.26400	-97.30212	Gas	839	KB	814	8,107	YesE
21730373	32.18800	-97.30129	Gas	793	KB	775	7,704	Inc1
25130497	32.22116	-97.29438	Gas	843	KB	830	7,629	NA
25131885	32.23859	-97.29366	Dry Hole	874	KB	842	8,140	YesE
25133137	32.54649	-97.29174	Gas	686	KB	661	7,356	NA
25131199	32.45503	-97.29005	Gas	889	KB	867	7,710	NA
43931075	32.60915	-97.28958	Gas	670	KB	657	7,235	Yes
25131223	32.46396	-97.28785	Gas	822	KB	804	7,968	YesE
43931335	32.57868	-97.28444	Gas	660	KB	638	7,464	Inc2
25132620	32.51979	-97.28424	Gas	721	KB	696	7,563	NA
25131023	32.37575	-97.28387	Gas	808	KB	785	7,663	Inc1
25130465	32.41974	-97.28155	Gas	810	KB	792	8,130	YesE
25130462	32.25045	-97.27844	Gas	851	KB	838	7,929	Inc2
25130292	32.34200	-97.27738	Gas	882	KB	866	8,085	YesE

Table 3: List of all wells used to determine unit depth and layer thicknesses in Johnson County, Texas (cont.)

Well API #	Latitude	Longitude	Well Type	Refr. Elev. (ft)	Elev. Refr	Surface Elev. (ft)	Total Vert. Depth (ft)	Gph Log
25132502	32.51003	-97.27737	Gas	757	KB	738	7,552	Inc2
43931283	32.58927	-97.27716	Gas	574	KB	564	7,402	Yes
25130160	32.36465	-97.26694	Gas	792	KB	771	7,756	Inc1
21730371	32.19796	-97.26684	Gas	746	KB	728	8,102	YesE
25130386	32.23022	-97.26661	Gas	822	KB	806	8,192	YesE
25131659	32.53155	-97.26454	Gas	762	KB	742	7,664	Yes
43931906	32.56288	-97.26354	Gas	740	KB	706	7,672	NA
21730331	32.15891	-97.26103	Injection	743	KB	727	10,080	YesE
21730386	32.19292	-97.25595	Gas	800	KB	782	7,904	Inc1
21730382	32.21313	-97.25456	Gas	804	KB	780	7,952	Inc1
25131020	32.44063	-97.25242	Injection	801	KB	781	11,250	YesC
25132327	32.44647	-97.25236	Injection	851	KB	831	11,428	Ellen
25131924	32.50301	-97.25036	Gas	838	KB	815	7,857	Yes
25130153	32.31552	-97.24675	Gas	770	KB	750	7,919	YesE
25130118	32.35110	-97.23842	Gas	799	KB	783	8,508	YesE
25133590	32.41034	-97.23829	Gas	762	KB	741	7,850	Yes
25130855	32.54017	-97.23694	Gas	717	KB	696	8,036	YesE
25132058	32.47860	-97.23256	Gas	748	GR	748	7,816	Inc2
21730444	32.16228	-97.23137	Gas	760	GR	760	8,294	NA
25132107	32.45009	-97.22778	Gas	808	KB	786	8,280	YesE
25130237	32.33998	-97.22765	Gas	790	KB	770	7,741	Inc1
25130869	32.51762	-97.22545	Gas	702	KB	687	7,783	Inc2
25131317	32.25506	-97.22517	Gas	767	KB	754	7,923	NA
21730383	32.21445	-97.22132	Gas	741	KB	728	8,465	YesE
21730367	32.16854	-97.21792	Gas	748	KB	729	8,770	YesE
43931210	32.58069	-97.21757	Gas	688	KB	678	8,067	YesE
21730392	32.23882	-97.21671	Gas	724	KB	711	8,152	Inc2
25130686	32.25032	-97.21099	Gas	745	KB	732	8,550	YesE
25131021	32.37717	-97.20817	Injection	694	GR	694	10,353	NA
25130383	32.44147	-97.20239	Gas	734	KB	711	8,181	YesE

Table 3: List of all wells used to determine unit depth and layer thicknesses in Johnson County, Texas (cont.)

Well API #	Latitude	Longitude	Well Type	Refr. Elev. (ft)	Elev. Refr	Surface Elev. (ft)	Total Vert. Depth (ft)	Gph Log
25130231	32.31955	-97.20174	Gas	720	KB	707	8,412	YesE
25130221	32.29720	-97.19905	Gas	685	KB	664	8,300	Yes
25130440	32.35128	-97.19748	Gas	706	GR	706	8,012	NA
25131502	32.36455	-97.19562	Gas	699	KB	674	8,435	YesE
21730427	32.15039	-97.19515	Abandoned	752	KB	734	8,989	YesE
21730377	32.21612	-97.19459	Gas	702	KB	689	8,760	YesE
25131263	32.49231	-97.19232	Gas	781	KB	761	8,563	YesE
25132774	32.25885	-97.19173	Gas	703	KB	676	8,341	NA
25131575	32.36492	-97.18769	Gas	698	KB	679	8,195	YesE
25130107	32.32493	-97.18173	Gas	728	KB	716	8,350	Gamma
25130798	32.54973	-97.18134	Gas	635	KB	614	7,918	YesE
25130641	32.38392	-97.18052	Gas	728	KB	703	8,111	Inc1
25130953	32.28617	-97.17882	Injection	730	GR	730	11,356	NA
25130528	32.42865	-97.17655	Gas	765	KB	746	8,015	Inc2
25134121	32.51250	-97.17497	INJ	746	KB	732	11,508	NA
25132198	32.35025	-97.17331	Gas	689	KB	687	8,545	YesE
25130637	32.30777	-97.16723	Gas	726	KB	702	8,361	NA
25130376	32.54858	-97.16685	Gas	690	KB	674	7,935	Yes
25130187	32.28852	-97.16325	Gas	610	GR	610	8,690	YesE
25131754	32.28364	-97.16113	Gas	654	KB	633	8,326	Inc2
21730671	32.22921	-97.15794	Gas	691	KB	666	8,415	NA
25130447	32.26485	-97.15748	Gas	638	GR	638	8,724.6	YesE
25100002	32.44602	-97.15296	Dry Hole	677	DF	677	8,809	Yes
21730464	32.24853	-97.15214	Gas	649	KB	626	8,560	YesE
25130742	32.47606	-97.15110	Gas	684	KB	666	8,550	YesE
25134160	32.41942	-97.14849	Gas	729	DF	704	8,133	NA
25130563	32.28114	-97.14664	Gas	623	KB	603	9,120	Inc2
25131122	32.50977	-97.14144	Gas	646	KB	628	8,269	Yes
25130188	32.29181	-97.14076	Abandoned	630	GR	630	8,750	YesE
25131259	32.40460	-97.13650	Gas	710	KB	692	8,259	Yes

Table 3: List of all wells used to determine unit depth and layer thicknesses in Johnson County, Texas (cont.)

Well API #	Latitude	Longitude	Well Type	Refr. Elev. (ft)	Elev. Refr	Surface Elev. (ft)	Total Vert. Depth (ft)	Gph Log
25130183	32.32236	-97.13531	Abandoned	632	KB	620	8,728	YesE
25130856	32.34877	-97.13448	Gas	674	GR	682	8,716	YesE
25130194	32.31415	-97.13332	Gas	612	KB	601	8,793	YesE
25130834	32.44971	-97.13110	Injection	691	KB	675	11,806	YesC
25132353	32.37347	-97.13029	Gas	677	KB	652	8,537	Yes
25130969	32.45733	-97.12831	Gas	683	KB	661	8,233	NA
25130318	32.53689	-97.12813	Gas	674	KB	658	8,100	Yes
25130336	32.37141	-97.12722	Abandoned	644	GR	644	8,373	NA
25130954	32.40820	-97.12308	Gas	658	KB	643	8,750	YesE
25131260	32.38029	-97.11057	Gas	674	GR	674	8,567	NA
25131219	32.48580	-97.11006	Gas	631	KB	613	8,270	Yes
25130830	32.38965	-97.10919	Gas	690	KB	665	8,317	NA
25131338	32.33772	-97.10905	Gas	641	GR	641	8,523	NA
25131305	32.51800	-97.10759	Injection	612	KB	595	13,090	YesC
21730364	32.25707	-97.10662	Abandoned	602	KB	585	8,936	YesE
25130752	32.47119	-97.10637	Gas	637	KB	619	8,849	YesE
25131797	32.36117	-97.10600	Gas	613	KB	588	8,554	NA
25130754	32.47132	-97.10580	Gas	633	KB	616	8,359	NA
25132402	32.51890	-97.10258	Injection	615	KB	593	12,823	YesC
43932421	32.56587	-97.10247	Abandoned	639	KB	616	8,376	Inc1
43932375	32.55562	-97.09873	Gas	584	GR	584	8,307	NA
25130443	32.47451	-97.09807	Gas	635	KB	617	8,372	Inc2
25131279	32.45314	-97.08963	Gas	637	KB	621	8,295	Yes
43931397	32.56750	-97.08472	Gas	607	KB	588	8,808	YesE
13930475	32.30552	-97.08206	Gas	557	GR	557	9,196	NA
13930493	32.50680	-97.08063	Gas	568	KB	551	8,656	Yes
13930465	32.41953	-97.07906	Abandoned	667	KB	653	8,650	YesE
21730529	32.20652	-97.07710	Abandoned	540	GR	540	9,235	NA
13930470	32.36239	-97.07683	Abandoned	598	KB	576	8,930	Yes
43932364	32.59894	-97.07558	Gas	578	KB	574	8,467	NA

Table 3: List of all wells used to determine unit depth and layer thicknesses in Johnson County, Texas (cont.)

Well API #	Latitude	Longitude	Well Type	Refr. Elev. (ft)	Elev. Refr	Surface Elev. (ft)	Total Vert. Depth (ft)	Gph Log
13930468	32.37602	-97.06192	Gas	631	KB	612	9,115	Yes
13930471	32.40190	-97.06102	Abandoned	659	GR	659	8,725	NA
21730553	32.18801	-97.05331	Gas	836	KB	819	10,215	YesE
13930573	32.51451	-97.05251	Gas	595	KB	579	8,483	Yes
13930486	32.53464	-97.03697	Gas	637	KB	612	9,076	YesE
13930520	32.31853	-97.03209	Abandoned	557	GR	557	9,56	East
13930498	32.48503	-97.02476	Gas	666	KB	644	8,872	YesE
13930500	32.51354	-97.02261	Gas	667	KB	642	8,737	Gamma

Key to Header Abbreviations	**Key for Geophysical Logs**
Elev.: Elevation	Yes: Log reaches from the bottom of the casing to the Barnett shale
Refr.: Reference Point for Elevation	YesE, Gamma-E: Log penetrates to the Ellenburger
Vert.: Vertical	YesC: Log penetrates to the Cambrian
Gph Log: Geophysical Log	Inc1: Log may or may not reach the Marble Falls limestone
	Inc2: Log reaches the Marble Falls but not the Barnett, or the log is only of the deeper part of hole, from the Marble Falls or Barnett to the Ellenburger
Key to Elev. Refr. Abbreviations	Gamma: Gamma ray only but useful for much of the hole
GR: Ground elevation	NA: Either the log is not available or the available log gives little or no useful information. Geologic data are based on reported depths in well reports
KB: Elevation at Kelly Bushing	East: Log is of a well east of the Ouachita Thrust Zone
DF: Elevation of the Derrick Floor	

The Gage well is listed as 8 miles west of Cleburne.

2.4 JOHNSON COUNTY GEOLOGIC UNIT DIVISIONS

Johnson County is in the eastern part of the basin, somewhat south of the heart of the Newark East gas field and south to southwest of the Dallas-Fort Worth metropolitan area. Though there is significant residential development, much of the county is agricultural. There are several geologic publications available that provide significant insight into the underlying geology. These include reports, maps, and cross-sections in Turner (1957), Lovick et al. (1982), and Flippen (1982).

A review of the literature, data reports, and geophysical logs were used as the basis for the following compilation of geologic units underlying Johnson County shown in Figure 3.

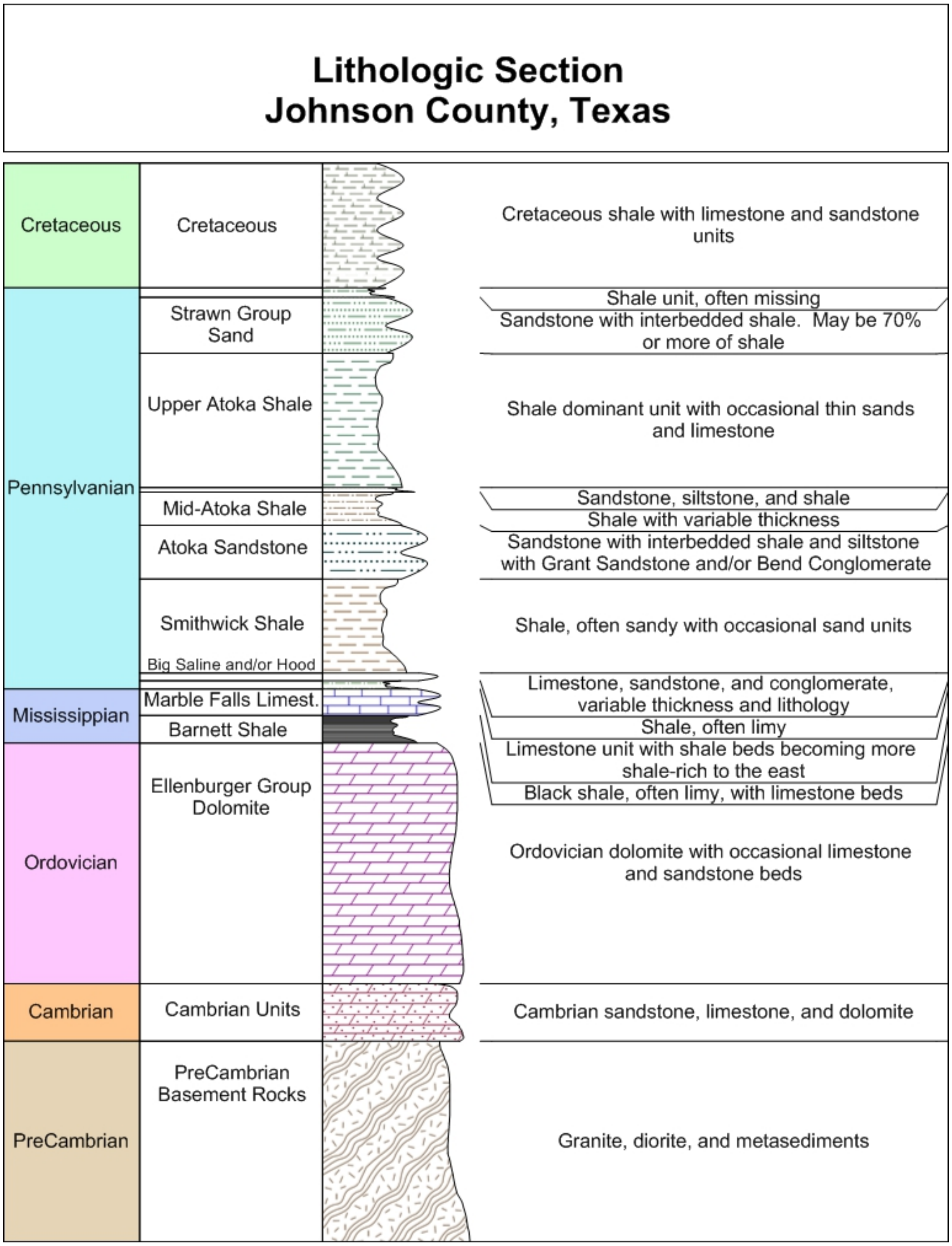

Figure 3: Stratigraphic Section of the Johnson County area, Texas.

Many of these geologic units were combined into unit groups (Table 2). This simplification of the geology enables the subsurface to be gridded in computational tractable models while combining the most relevant formation parameters for computations (Siriwardane and Vincent, 2015).

This list is based on an evaluation of geophysical logs, literature, and consideration of a lithologic rather than a time-constrained division. The Strawn is relegated to sandstone-shale sequences immediately below the Cretaceous unit, and the Atoka is divided into an upper (Atoka) shale, a sandstone-rich facies (Atoka sandstone), and a shale dominant unit (Smithwick). As indicated in Turner (1957), the Strawn Formation is absent or thin over the eastern part of Johnson County despite being indicated as much thicker in many data reports on the wells. For this report, the Strawn is restricted to a sandstone-shale sequence immediately below the Cretaceous sediments, though some Strawn-age shale probably occurs to the west.

2.5 CROSS-SECTIONS

Two regional stratigraphic cross-sections, A-A’ and B-B’, were prepared using subsurface data from geophysical logs and well data obtained from the Texas RRC (Table 3). The location of these sections is given in Figure 4. Vertical wells, mostly injection wells or dry holes, were chosen since accurate TVD and formation thicknesses could be determined. Wells with data on TVD were also used to complement or verify formation depths and thicknesses. The purpose of constructing the sections is to understand the subsurface stratigraphy in the study area, to identify and differentiate between different formations, show variations in formation thickness, and display indications of faulting. In particular, they aid in the identification of the wastewater injection zones within the Ellenburger carbonates.

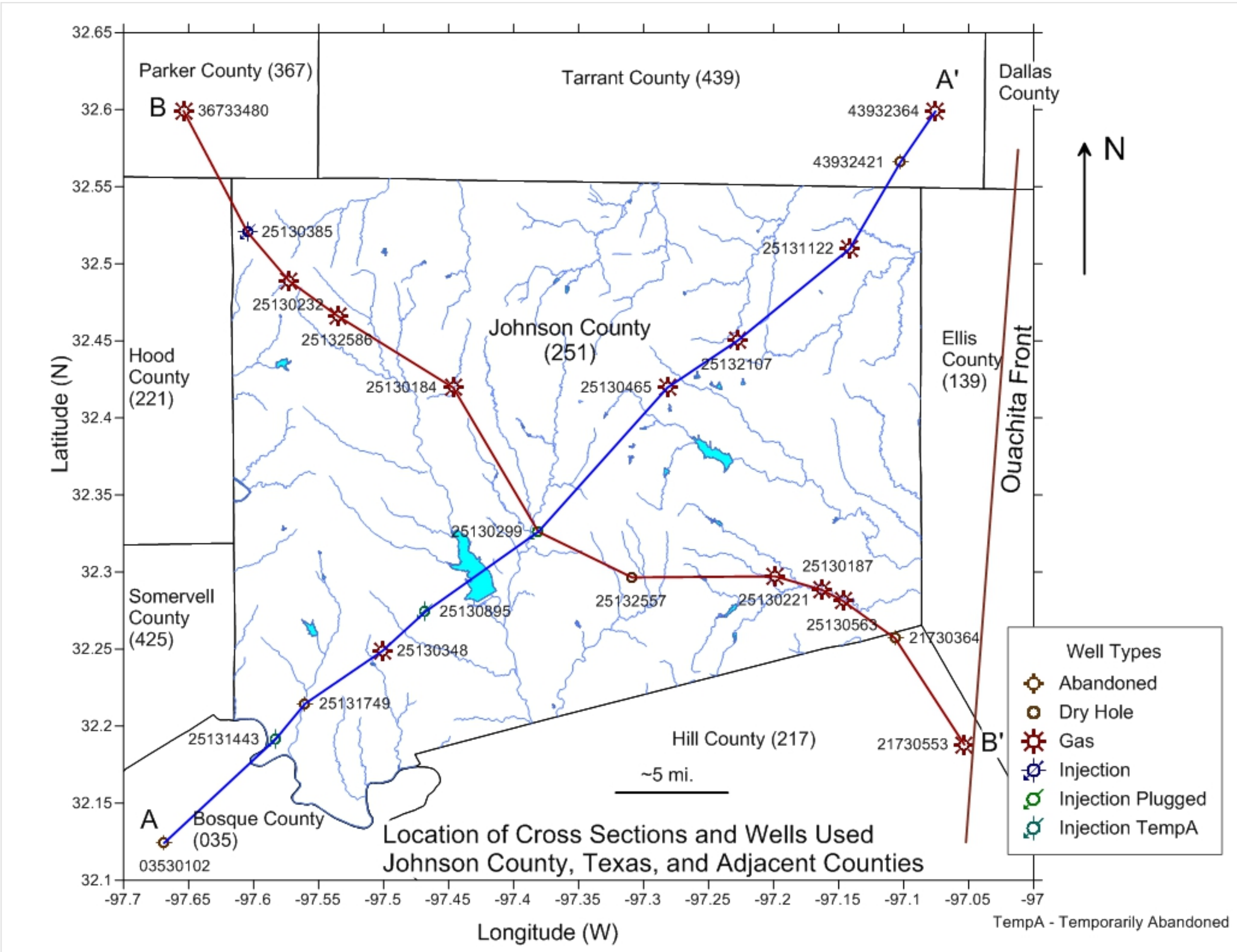

Figure 4: Cross-Sections A-A' and B-B' in Johnson County, Texas, showing the wells used for each section.

Cross-Section A-A' (Figure 5) is oriented northeast-southwest, and B-B' (Figure 6) is oriented northwest-southeast. These sections provide a cross-sectional view of the subsurface geology in two directions to better understand how the formations vary in depth, and thickness, both vertically and laterally. Mean sea level (msl, i.e. elevation of 0 ft) was used as a level datum from which the geophysical logs were positioned. The sections are "tied" together by well number 251-30299 in the south-central portion of the county. This tie-in assures consistency in correlating the same formations for each of the cross-sections. These cross-sections give an indication of the thickness variability of the units encountered and the lithologic changes in depth along the section. The well information data for these cross-sections are given in Table 4.

Table 4: Table of wells used in cross-sections across Johnson County, Texas, and overlapping adjacent counties

XC	Well (API No.) 42-	Latitude	Longitude	Well Type	Refr. Elev. (ft)	Elev. Refr	Surface Elev. (ft)	Total Vert. Depth (ft)
A	03530102	32.12425	-97.66884	Abandoned	831	KB	817	5,985
A	25131443	32.19119	-97.58295	Injection	636	GR	636	9,260
A	25130348	32.24890	-97.50075	Gas	823	KB	795	6,864
A	25130895	32.27424	-97.46788	Injection	860	KB	844	9,810
A,B	25130299	32.32575	-97.38093	Injection	785	KB	768	10,952
A	25130465	32.41974	-97.28155	Gas	810	KB	792	8,130
A	25132107	32.45009	-97.22778	Gas	808	KB	789	7,898
A	25131122	32.50977	-97.14144	Gas	646	KB	628	8,269
A	43932421	32.56587	-97.10247	Abandoned	639	KB	616	8,376
A	43932364	32.59894	-97.07558	Gas	578	KB	565	8,467
B	36733480	32.59837	-97.65410	Gas	989	KB	975	6,908
B	25130385	32.52066	-97.60451	Injection	1,012	GR	1,012	11,000
B	25130232	32.48898	-97.57282	Gas	1,040	KB	1,025	7,055
B	25132586	32.46599	-97.53515	Gas	1,002	KB	989	6,600
B	25130184	32.41966	-97.44653	Gas	881	KB	865	7,360
B	25132557	32.29648	-97.30889	Dry hole	813	KB	795	8,180
B	25130221	32.29720	-97.19905	Gas	685	KB	664	8,300
B	25130187	32.28852	-97.16325	Gas	611	GR	610	8,690
B	25130563	32.28114	-97.14664	Gas	623	KB	603	9,120
B	21730364	32.25707	-97.10662	Abandoned	602	KB	585	8,936
B	21730553	32.18801	-97.05331	Gas	836	KB	819	10,130

XC – Cross-section. All other abbreviations are defined at the end of Table 3.

For wells that do not have a geophysical log available, nearby wells with geophysical logs were used to fill in geologic data not presented in the well data reports and to verify depth data in those reports.

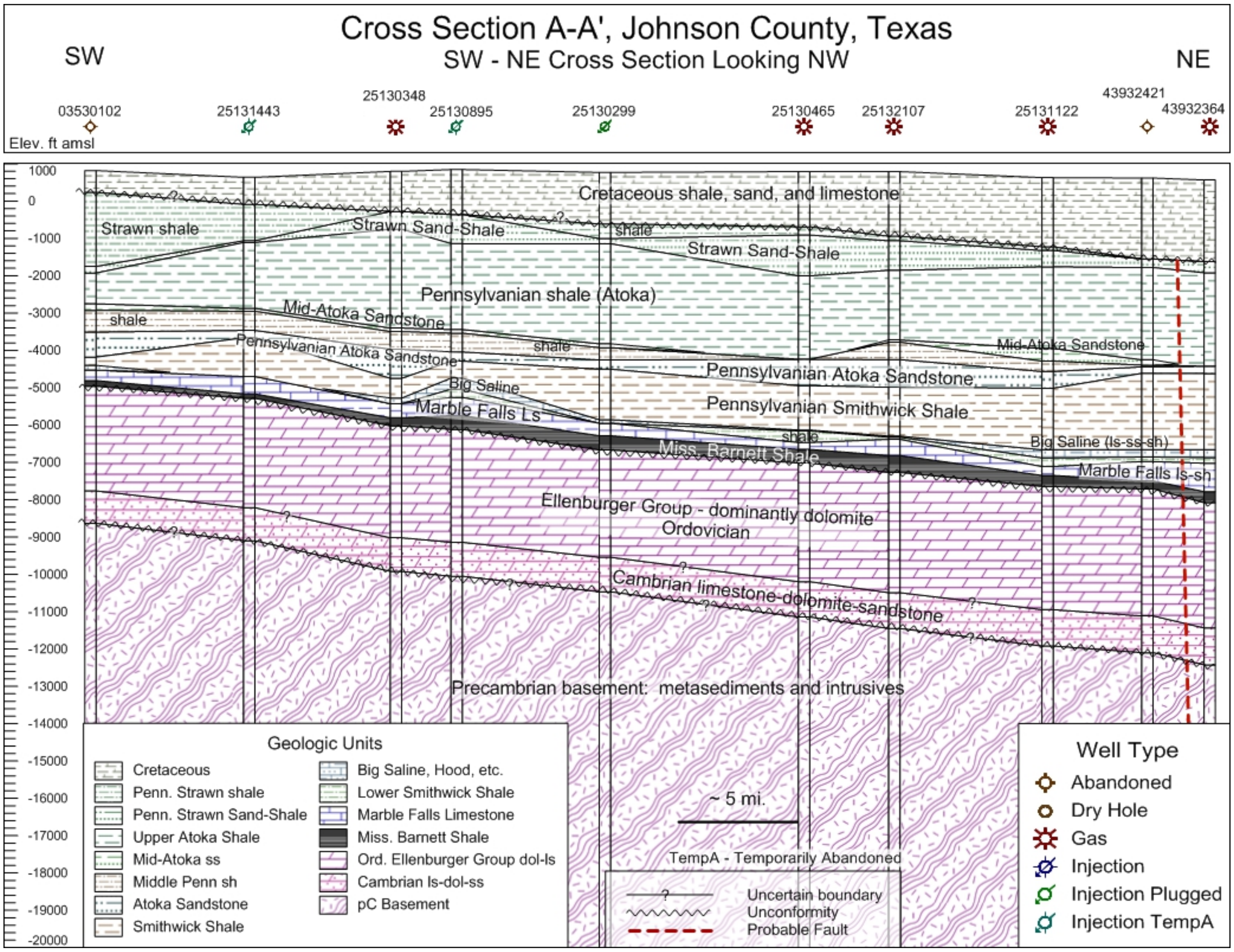

Figure 5: Cross-Section A-A'.

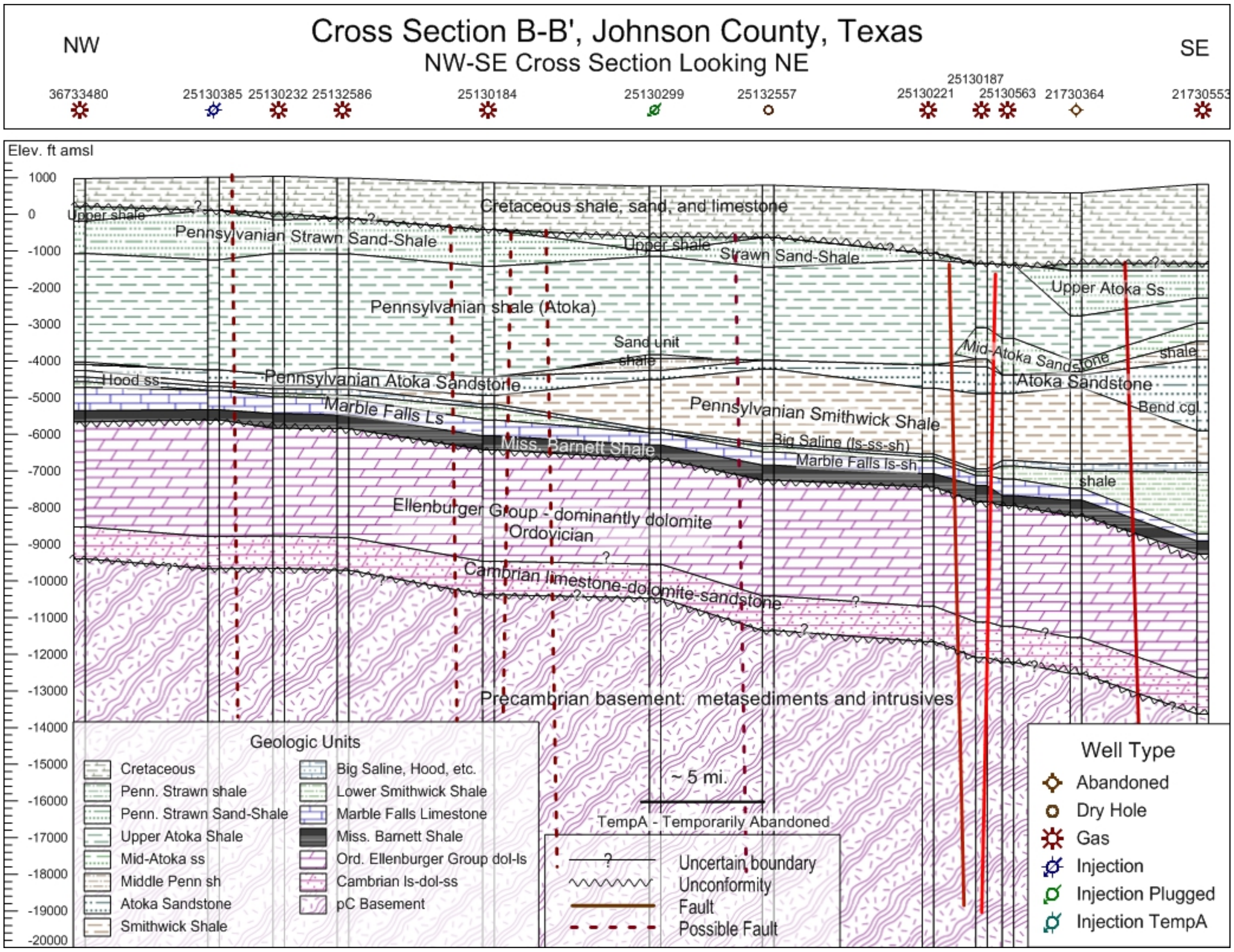

Figure 6: Cross-Section B-B'.

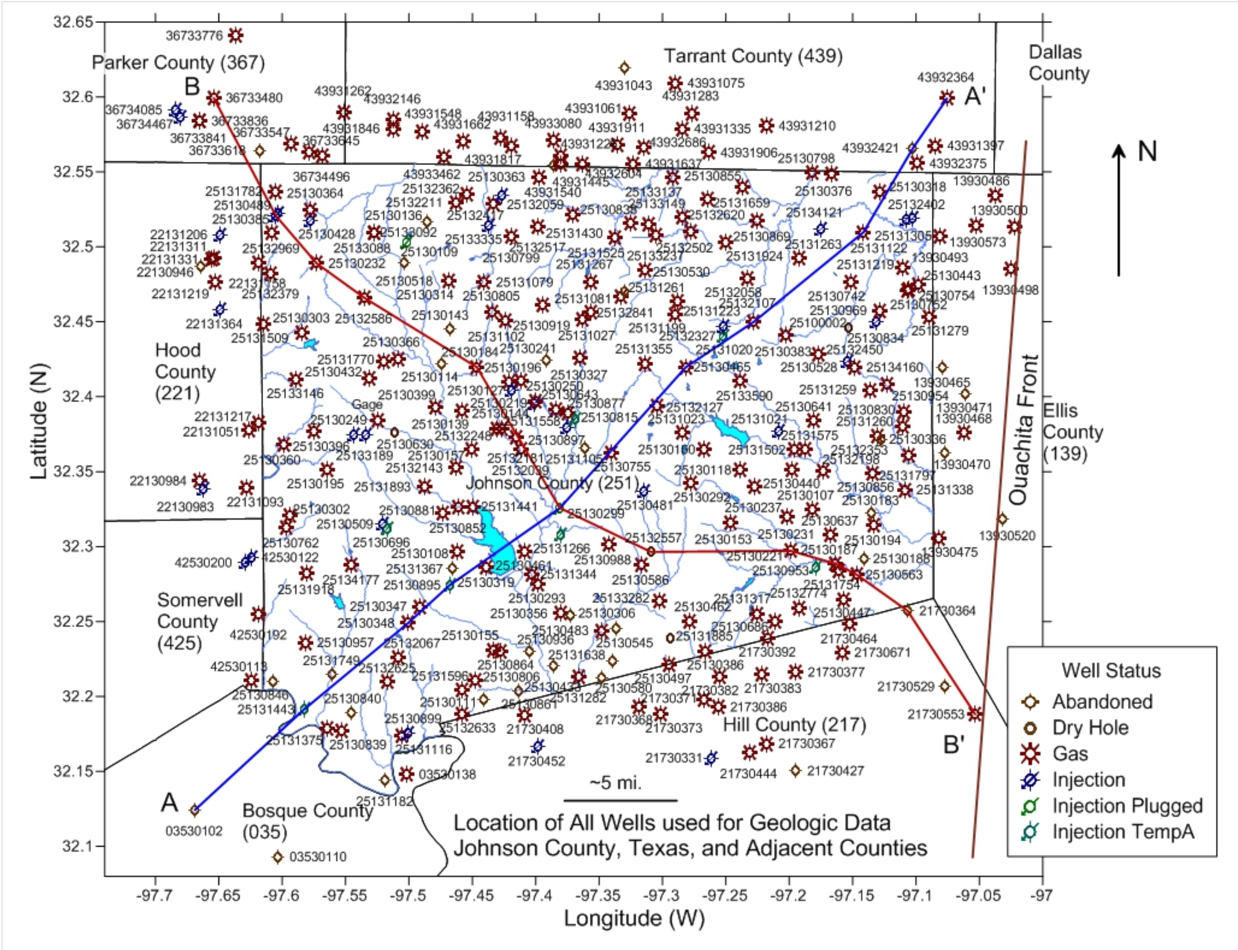

Figure 7: Map of Johnson County showing all wells that were evaluated for formation depths. The cross-sections are shown for reference.

Vertical wells having well records were initially identified because they often list the TVD to the geologic units, as opposed to measured depths from wells that can have a significant horizontal component. Four injection wells were chosen because they penetrate deep into the injection layer, usually to and a little below the bottom of the Ellenburger Group carbonates. The geophysical logs provide accurate formation data that include formation top and thickness, lithology, porosity, and oil, gas, and water saturations. Since this area has been extensively drilled using horizontal wells for Barnett shale production, not all of the well data reports provided vertical depths. Of the 20 wells used in the cross-sections, 15 had useful geophysical logs. Where geophysical logs were not available, nearby logs were used to estimate unit depths not identified in the well data reports. The presence or absence of geophysical logs is given in the tables at the end of this document. Data from injection wells are often sparse so some data were estimated, usually based on nearby Barnett shale gas wells. For Barnett gas wells in the cross-sections, either the data reports gave vertical depths to the formations, or these vertical depths were calculated from well surveys provided in those reports. Depths not given in the reports were based on geophysical logs of these wells.

Using the data reports and available geophysical logs, 3D maps showing the surface of the top of the Barnett shale (Figure 8) and Ordovician carbonates (Figure 9) were created. The tops of other units were inconsistent and surface maps must wait on further evaluation of these unit depths. Insufficient data are available to map the base of the Ellenburger.

Where only well data reports were available, the top of the Barnett shale was selected because it was the targeted reservoir for oil and gas production. Occasionally, other shallower formation tops were listed in the data reports, but these occurred erratically and were often inconsistent with other wells. As such, most depths of units above the Barnett are based on geophysical logs.

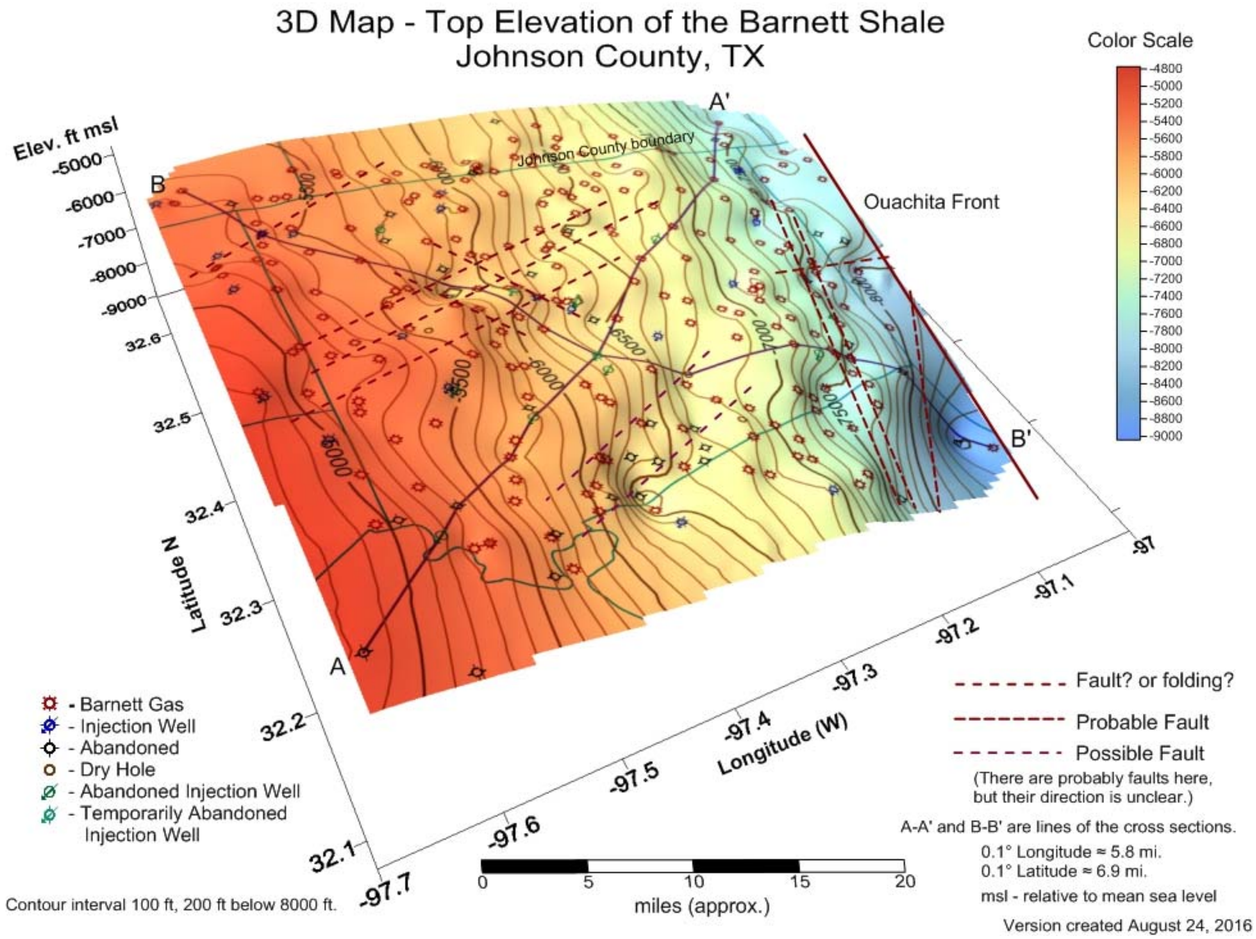

Figure 8: 3D map of the surface of the Barnett shale, Johnson County, Texas, showing discontinuities (lineaments) that could represent faults. This surface is based on data from 278 wells.

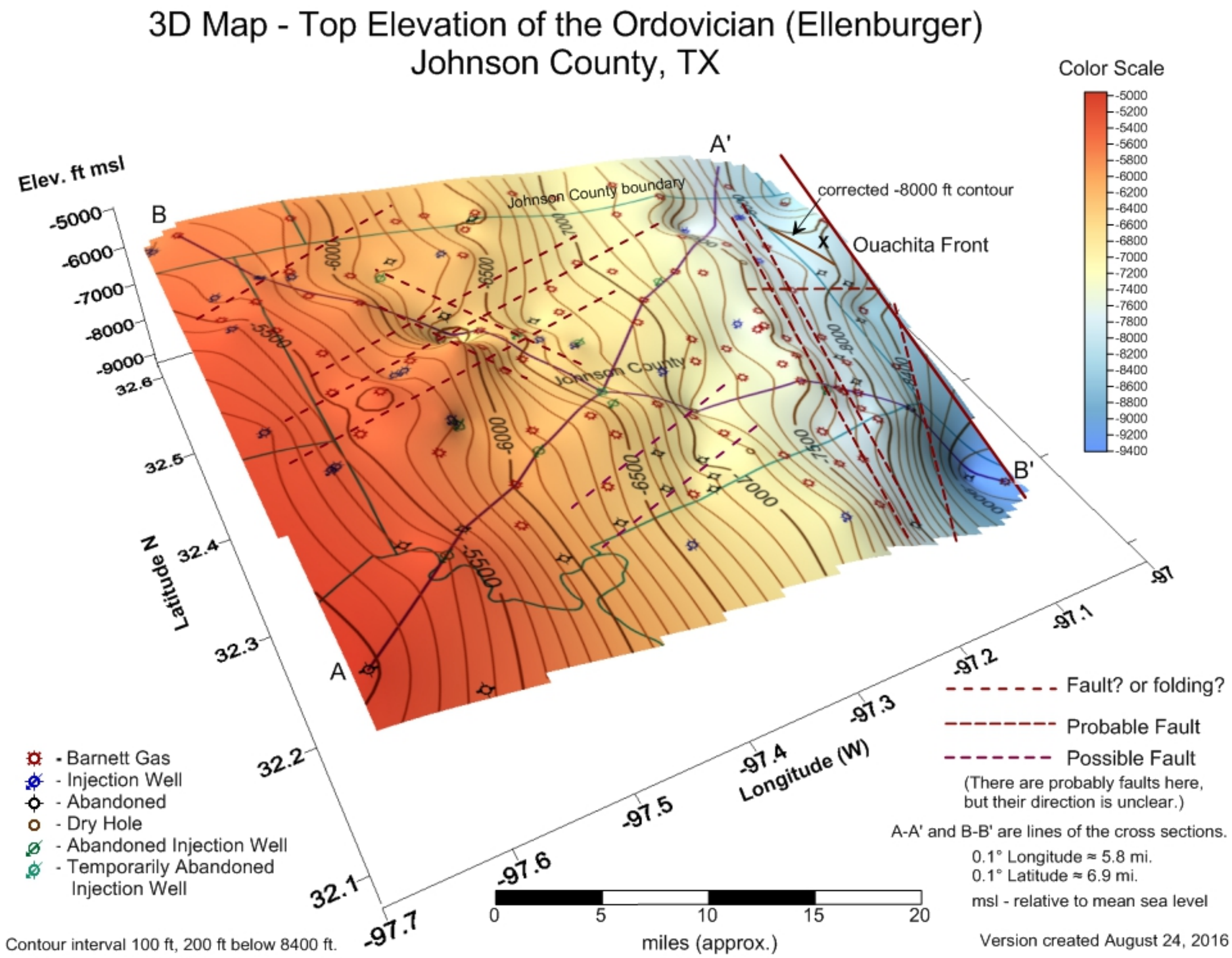

Figure 9: 3D map of the surface of the Ordovician top (base of the Barnett), Johnson County, Texas, showing discontinuities (lineaments) that could represent faults. This surface is based on data from 144 wells.

2.6 JOHNSON COUNTY GEOLOGY

Johnson County is underlain by a succession of sediments from Cambrian to Cretaceous in age atop a basement of metamorphic and igneous rocks. The older sediments were deposited prior to the formation of the FWB and include a series of carbonates and sandstones from Cambrian to Ordovician age. These units range from about 3,500 to 4,500 ft in thickness and include the Ellenburger Group, primarily dolomite, which is the primary unit for fluid injection. The FWB formed during early Mississippian through Pennsylvanian time, bounded on the east and north by major structures. The Ouachita Thrust Zone is the primary structure on the east side of Johnson County with up to 12,000 ft of vertical offset (Montgomery et al., 2005; Turner, 1957). Initially the Barnett shale was deposited along with limestones and shales at the beginning of the orogeny. This period was followed by the deposition of a significant thickness of shales and sandstones throughout much of the Pennsylvanian Period. The Cretaceous sediments were deposited following additional structural deformation of the Pennsylvanian and earlier rocks and represent the topmost unit in the area of Johnson County (Turner, 1957).

The surface geology of Johnson County consists almost entirely of Cretaceous-age sediments with Quaternary alluvial deposits along streams. These Cretaceous rocks contain groundwater aquifers that are used as a drinking water supply and for irrigation. The lithology is predominantly of limestones, shales, and sandstones (Winton and Scott, 1922). The sediments have a slight eastward dip and range in thickness from a few hundred feet on the west edge of the county to at least 2,000-ft thick to the east (Winton and Scott, 1922; Turner, 1957; geology from well data reports and geophysical logs). Electric and gamma-ray logs of wells where the Cretaceous had been penetrated usually show interbedded resistive and conductive units with indications of sandstone, shale, and limestone. However, most of the Barnett wells drilled in Johnson County are cased through the Cretaceous sediments as required by the RRC to protect groundwater supplies. Older oil and gas test wells occasionally have geophysical logs through a portion of the Cretaceous (cross-sections in Turner, 1957, e.g. Figure 2), and some geophysical logs show the gamma-ray response through that interval.

Beneath the Cretaceous of Johnson County the Pennsylvanian formations show considerable variation in thickness due to lateral facies changes across the county and structural deformation in later Pennsylvanian time. There is a definite thickening northeastward of these sediments due to orogenic movement along the Ouachita Front. Subsequent uplift of the basin during the late Paleozoic and early Mesozoic eras has resulted in tilting and erosion of these units prior to deposition of the Cretaceous sediments. In Johnson County, these sediments include the Strawn and Bend Groups, composed primarily of sandstone and shale with occasional thin limestone beds (Turner, 1957; Lovick et al., 1982; Flippen, 1982; Montgomery et al., 2005).

The Strawn Group consists of sandstones and shales and thickens eastward toward the Ouachita Front. However, folding and post-depositional erosion has reduced its extent significantly within the county. As such, the Strawn is considered to be absent or limited in eastern Johnson County, though it may be up to 4,000-ft thick to the west (Turner, 1957). The data reports contained insufficient evidence that much of the reported Strawn units are actually from the Strawn Group. Based on geophysical logs and correlation with logs in Turner (1957), much of the “Strawn” in eastern Johnson County is actually Atokan in age. In the cross-sections, the Strawn is represented as a sequence of interbedded sandstones and shales near the top of the Pennsylvanian section.

The Bend Group consists of sandstones and shales below the Strawn and also thickens eastward to over 4,000-ft (Turner, 1957). This unit also had post-depositional erosion where the Strawn was completely removed. In this report, the Bend Group is divided into an upper Atoka unit and a lower unit that includes sandstones and shales below a consistent Atokan sandstone. This division is consistent with well data reports that list the Atoka and Bend as separate clastic units. For this report, the Atoka was divided into sandstone and shale units in the cross-sections, including an upper shale-dominant unit, an upper sandstone unit that is often thin or absent, and a more consistent sandstone, the Atoka sandstone, above a variably thick shale dominant unit called the Smithwick shale (Turner, 1957; Lovick et al., 1982). Deeper sandstone, conglomerate, and limestone units occur below the Atoka sandstone, particularly the Grant sandstone, the Bend conglomerate, the Big Saline (limestone-sandstone with interbedded shale), the Hood sandstone (western Johnson County), and other minor units (reference Table 1 and Figure 3). Some of these units are subdivided in the cross-sections, though they are often discontinuous and relatively thin. Near the Ouachita Front, the Pennsylvanian sandstones thicken at the expense of the shales, probably since this area is nearer to the sediment source, previously a highland to the east (Turner, 1957; Lovick et al., 1982).

Below the preceding sequence of clastics and shales is the Mississippian to Pennsylvanian Marble Falls Formation, often called Marble Falls limestone. The limestones within this unit are quite variable in thickness from 100 ft to 700 ft thick in the well logs, though, the thicker values probably include limestone of the Big Saline unit. In central and eastern Johnson County, limestone occurs near the top of the unit with a thickness of shale below it, often with a sequence of thin limestone beds (Comyn limestone) just above the Barnett shale. The proportion of shale increases eastward, and in eastern Johnson County, the Marble Falls may be as much as 80% shale. Some authors (e.g. Montgomery et al., 2005) consider the Marble Falls to be absent in the area of high shale content. However, well data reports continue to pick the top of the Marble Falls in eastern Johnson County, so for the maps generated, it is continued throughout as a stratigraphic horizon.

The Mississippian Barnett shale underlies the Marble Falls and comprises black shale with thin limestone beds and sandy units. A thicker limestone bed is often present within the Barnett, the Forestburg limestone, which is often called out in the well data reports. The presence of limestone and gas is indicated by higher porosity and resistivity on the geophysical logs. These higher values are due to the high gas content of the shale and the high resistivity of the limy units. Shale above the Barnett is attributed to the Marble Falls, though it is also a very dark gray to black shale with lower gamma values. The thickness of the Barnett varies from 180 to 500 ft, generally about 250 to 400 ft thick. The thickness may be reduced by thinner zones of high gamma-ray material and sections of low gamma Barnett relegated to the Marble Falls unit in the well data reports.

In eastern Johnson County, the Ordovician Viola and Simpson Formations underlie a portion of the Barnett (Montgomery et al., 2005). These units are of limestone and sandstone that are limited in extent, primarily due to erosion between the Ordovician and Mississippian periods (Turner, 1957). Because of their limited extent, they are included within the Ordovician Ellenburger Group for the cross-sections. The Ellenburger Group consists principally of dolomite and occasional limestone and sandstone and varies in thickness from about 2,800 to 3,400 ft in Johnson County, generally increasing eastward. An erosional surface formed on the Ellenburger and a karst topography developed (Montgomery et al., 2005; Elebiju et al., 2010) that may have influenced the thickness and productivity of the Barnett. Despite low porosity, the Ellenburger is relatively permeable (Manger, 1963) and is the principal unit into which injection wells were completed.

Below the Ellenburger is a group of Cambrian units including sandstone and limestone about 800 to 1,000 ft thick. Very few wells are completed through this unit, though several injection wells penetrate the top of it. For the cross-sections in this report, the Cambrian top is based on the wells that penetrate the top of it and a general trend of increasing thickness of the Ellenburger eastward across Johnson County. The total thickness of the Ellenburger and Cambrian units is based on a seismic study and four wells that were drilled into the basement. The seismic study (Elebiju et al., 2010) coupled with velocity data from the Trigg well (Frohlich et al., 2011) suggests a total thickness of these units between 4,000 to 4,400 ft (Figure 10 and Figure 11). Geophysical logs that do penetrate the Cambrian unit appear to confirm this thickness.

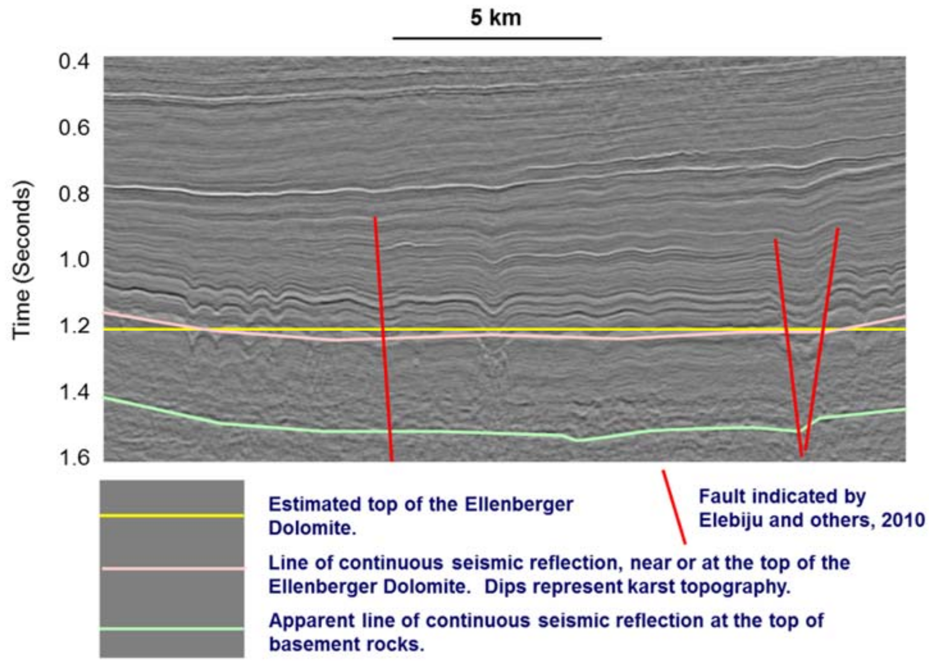

Figure 10: Seismic profile from Elebiju et al. (2010), showing time interval between the top of the Ellenburger and the basement rocks, about 0.24 to 0.28 seconds.

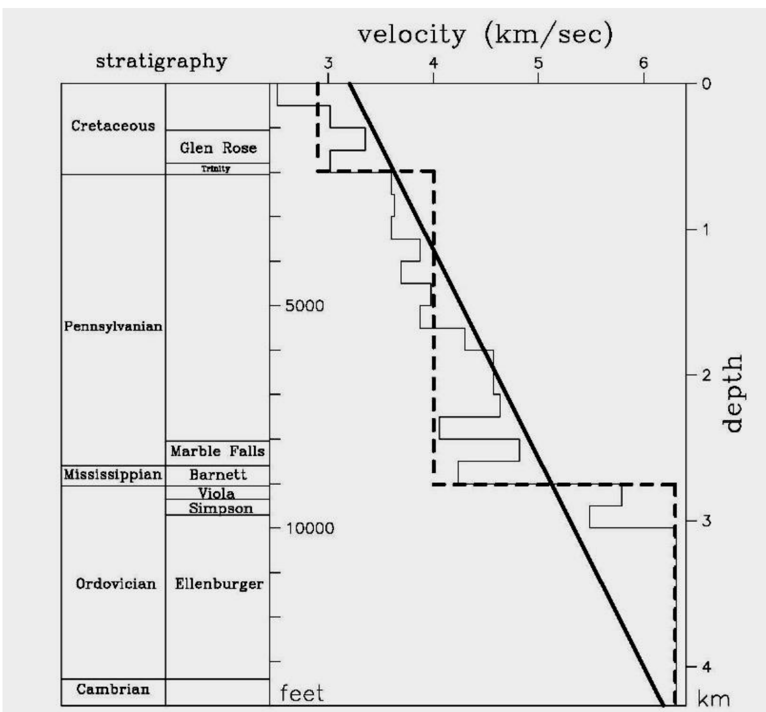

Figure 11: Velocity profile for the Trigg Well, NW Dallas County, Texas. (Frohlich et al., 2011; Geotechnical Corporation, 1964.)

Basement rocks underlie the Cambrian and consist of granitic and metamorphic rocks (Turner, 1957; Flippen, 1982; Montgomery et al., 2005; Pollastro et al., 2007; Khatiwadi et al., 2013). These rocks are assumed to continue to very deep depths, and the cross-sections stop at a depth of about 20,000 ft (6,100 m) below sea level. Outcrops of the Precambrian basement units are present to the west from which the rock types have been defined, and a seismic study identified a granitic body within the metamorphic rocks of the basement material (Khatiwadi et al., 2013).

3. FAULTING

3.1 FORT WORTH BASIN

Seismic activity in the Fort Worth Basin appears to be related to pre-existing fractures and faults as evidenced by an apparent disconnect between the seismic activity and some of wastewater injection wells where wells with high volumes of injected fluids were in areas of little, if any, seismic activity (Frohlich, 2012). Faults susceptible to earthquakes may not exist near these wells, or the wells may be noticeably offset from the earthquake activity. In addition, much of the seismic activity appears to be within the basement rocks, below the depth of fluid injection (Frohlich, 2012; Justinic et al., 2013). In many areas outside of Johnson County, where injection wells are being used, seismic activity is relatively low compared to that in Johnson County (Frohlich, 2012; Justinic et al., 2013). Commonly the seismic activity is along a north-south to northeast-southwest trend, which corresponds to some of the fault directions within the area (Figure 12).

Faulting within the Fort Worth Basin sediments and basement rocks has been studied within the Newark East field and to the northwest and west of Johnson County, Texas (Montgomery et al., 2005; Elebiju et al., 2008; Baruch et al., 2009; Perez et al., 2009; Elebiju et al., 2010; Khatiwadi et al., 2013; Geophysics International, 2014). These studies indicate faulting in a north-south to northeast direction related to the Ouachita Thrust Zone, the Mineral Wells Fault, the Muenster Arch, the Lampasas Arch, and related folding within the basin (Figure 1). Seismic studies have been particularly effective at showing fault trends (Elebiju et al., 2008; Baruch et al., 2009; Elebiju et al., 2010) and these studies tend to show northeast to east-west and northwest trending faults (Figure 1, Figure 12). These studies were performed near the Mineral Wells Fault and nearby areas. The Mineral Wells fault trends east-northeast and the nearby Muenster Arch trends northwest, both of which may have influenced the fault trends in that area.

3.2 JOHNSON COUNTY

Faulting within Johnson County is noted in Frohlich (2012) and Justinic et al. (2013), and is generally in a northeast direction, roughly parallel to the Ouachita Thrust Zone, which trends northeast passing just east of the southeast corner of the county. Northeast-trending faults west and southwest of Johnson County are noted on maps in Turner (1957) and Montgomery et al. (2005), some of which trend toward the county. Known faults within the county are shown on Figure 12 and trend northeastward (Ewing, 1990).

An attempt was made to delineate possible additional fault zones within Johnson County on which seismic activity could occur as a result of the injection of waste fluids from hydrofracturing. Based on a surface maps of the Barnett shale and Ordovician units (Figure 8 and Figure 9), there are discontinuities in the contours of the unit that may indicate fracture zones or faults within the unit that could be reactivated by wastewater injection pumping. These discontinuities are generally east-northeast to northeast trending and there appear to be some northwest-trending cross faults. North-northeast-trending structures appear to be represented by variations in the dip of the Barnett surface near the eastern edge of the county. The northeast trend of the fault zones appears to be subparallel to the roughly northeast-trending zone of earthquake epicenters noted in Justinic et al. (2013), reproduced here as Figure 12.

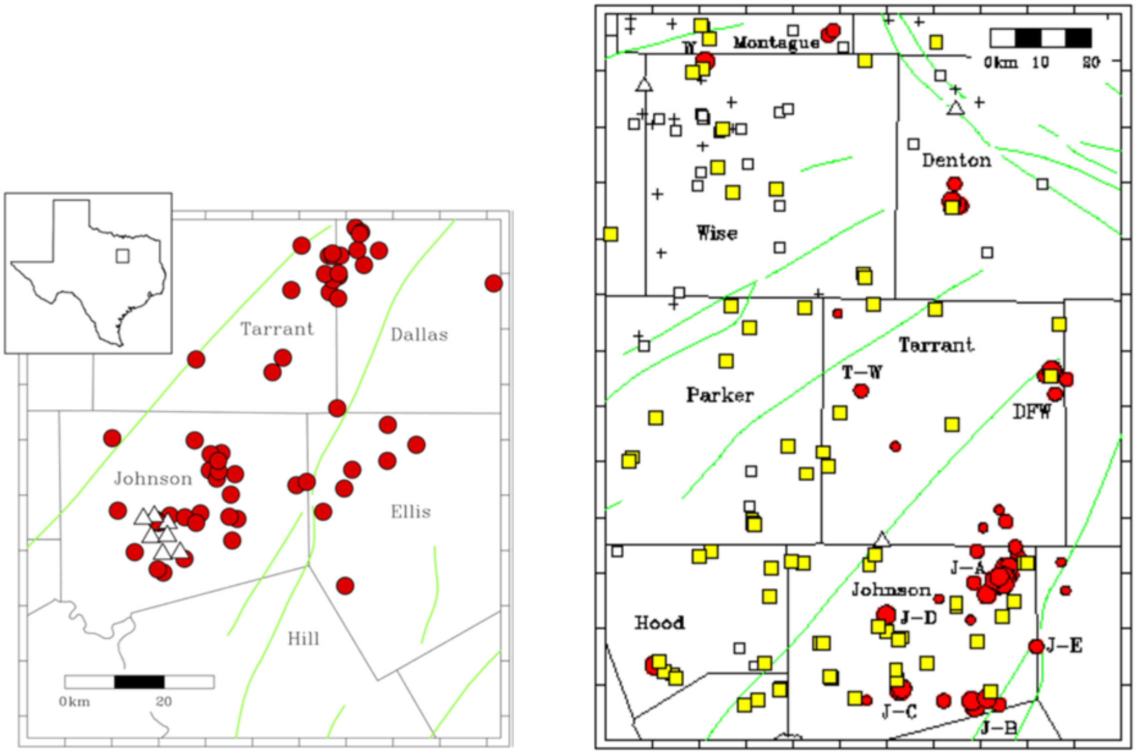

Figure 12: Left: Earthquake epicenters (red circles) in Johnson and neighboring counties, Texas, June 2009 to June 2010. Triangles are temporary seismic stations (Figure 1 in Justinic et al., 2013). Right: Earthquake epicenters (red circles) in the Fort Worth Basin, including Johnson County between November 2009 and September 2011 (Figure 2.2 in Frohlich et al., 2015). Green lines in both figures are mapped faults (Ewing, 1990).

Also, some of the earthquake clusters (red circles) in Johnson County on the left figure appear to be oriented north-south to north-northwest. These are subparallel to possible cross faults noted in the Barnett and Ellenburger contours (Figure 8 and Figure 9). The northeast-trending earthquake epicenters are evident in both figures. Triangles (left figure) are temporary seismic stations. Squares (right figure) are injection wells, with yellow squares being larger volume wells.

A surface map of the Ellenburger in Turner (1957) suggests an even closer relationship between mapped faults and the potential faults noted on the surface maps of the Barnett and Ellenburger presented here (Figure 13). Even the trend of the Ouachita Structural Belt in Turner (1957) follows the probable north-northeast-trending fault zones noted on the contour map of the Ellenburger. Two of the wells directly adjacent to the Ouachita Thrust Zone appear to penetrate through the thrust and into the Barnett and Ellenburger beneath.

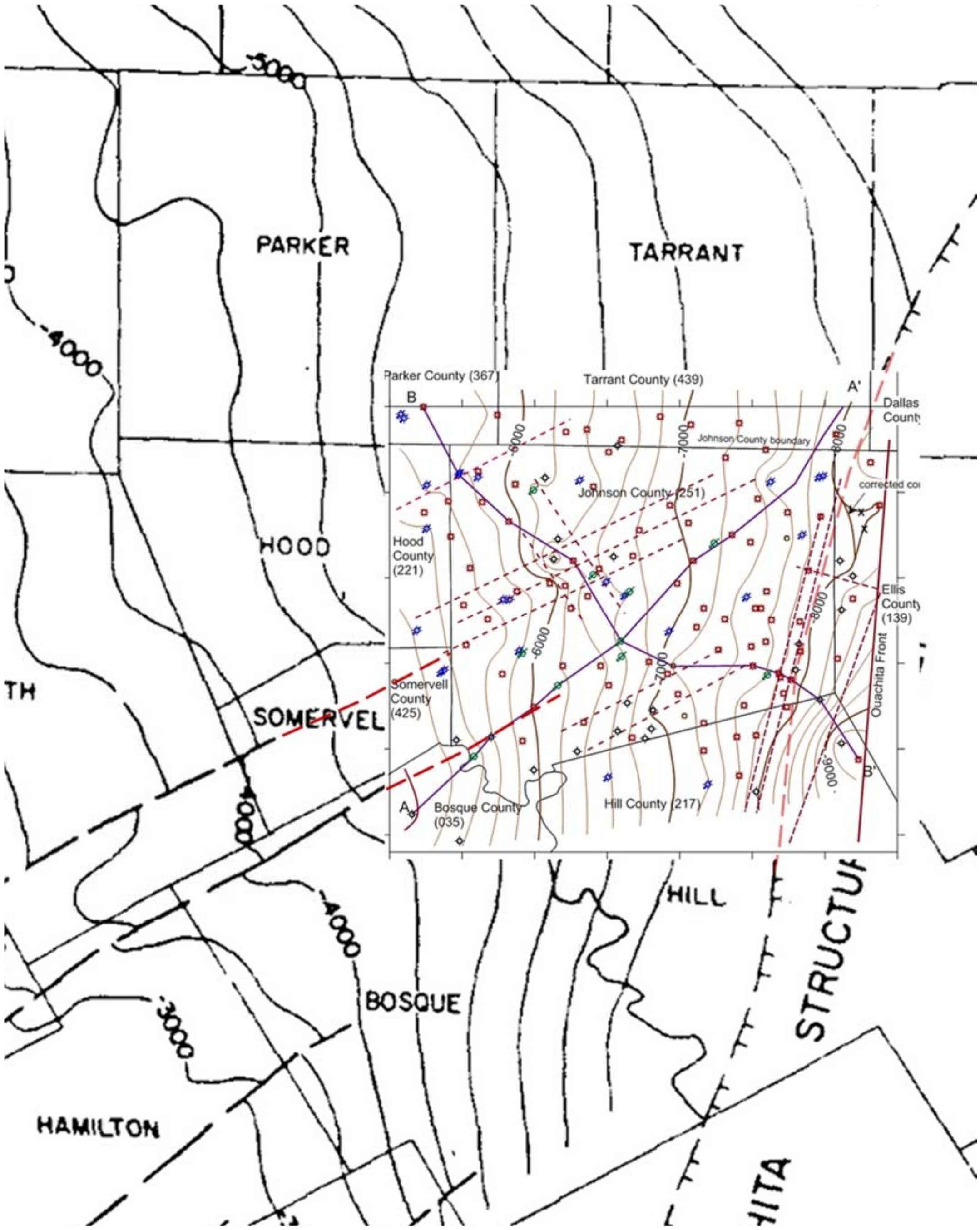

Figure 13: Structure map of the Ellenburger surface from Turner (1957) in comparison with potential faults based on contours of the Ellenburger surface of this report (overlain on the Turner structural map).

Note that the faults presented in Justinic et al. (2013) have a more northerly orientation, so the coincidence of actual faulting in the Johnson County area with faults suggested by the contour maps is still not certain. Evaluation of additional well data with validated depths to the Barnett and Ellenburger units could improve the fault interpretation, however there is not much additional publicly available data to use for this purpose.

Despite the multitude of data, the offset on these proposed faults and fractures is rarely over 100 ft. As such, variations on the structure contour maps are subtle and could be the result of folding rather than faulting. A review of additional wells in the area could further help to identify potential faults in and adjacent to Johnson County.

4. DISCUSSION OF INJECTION

4.1 INJECTION VS. PRODUCTION

Much of the research performed on wastewater injection related to induced seismicity focuses on the injection of wastewater into the Ellenburger carbonates (dolomite with limestone). This research shows that huge volumes of water have been injected (e.g. Ficker, 2012), exceeding a billion barrels since inception. This is enough water to cover 1,500 square miles (about twice the area of Johnson County) to a depth of 1 ft. Porosity within the Ellenburger is already saturated with water, and this porosity is generally less than 10% (Manger, 1963). The assumption is that all of this injected water will increase the hydrostatic pressure within the Ellenburger resulting in seismic activity due to the release of that pressure along existing faults and fractures. This water will also tend to move up or down along faults and fractures at sufficient pressure to induce seismic activity (Justinic et al., 2013; Frohlich, 2012; Skoumal et al., 2015).

The source of this water is produced water from the hydraulic fracturing of Barnett shale wells. The produced water is a combination of saline water from within the Barnett shale and water injected for the fracking process. As the water is injected into the Ellenburger, there must be displacement of natural formation water. This formation water must go somewhere as the compressibility of water is very small. Some of the water may move upward into the Barnett to replace the water produced from hydrofracturing, some may force the expansion of pores within the Ellenburger, and some may force its way into deeper horizons such as the basement rocks. The forced expansion of pores in the Ellenburger or in deeper horizons creates tremendous stress, resulting in the likelihood of seismic activity along pre-existing faults. Only movement into the Barnett where available pore space has been created through oil and gas production will stress be relieved, and that depends on the injection being near producing wells and the permeability of shales between the Barnett production and the Ellenburger.

There is a probability that much of the water moves upward into the Barnett; however, the injection wells are not necessarily in the same location as the Barnett gas wells being fracked (Frohlich, 2011, reproduced here as Figure 14). As such, there is a disconnect between areas of injection into the Ellenburger and areas of Barnett production where the movement of water upward into the Barnett may be facilitated by the removal of water from the Barnett. Where injection wells are injecting more than is being produced from the Barnett, hydrostatic pressure within the Ellenburger will be high and the release of that pressure will cause seismic activity. The purpose of the geologic characterization of the subsurface in this report is to assist in the modeling of these pressure changes

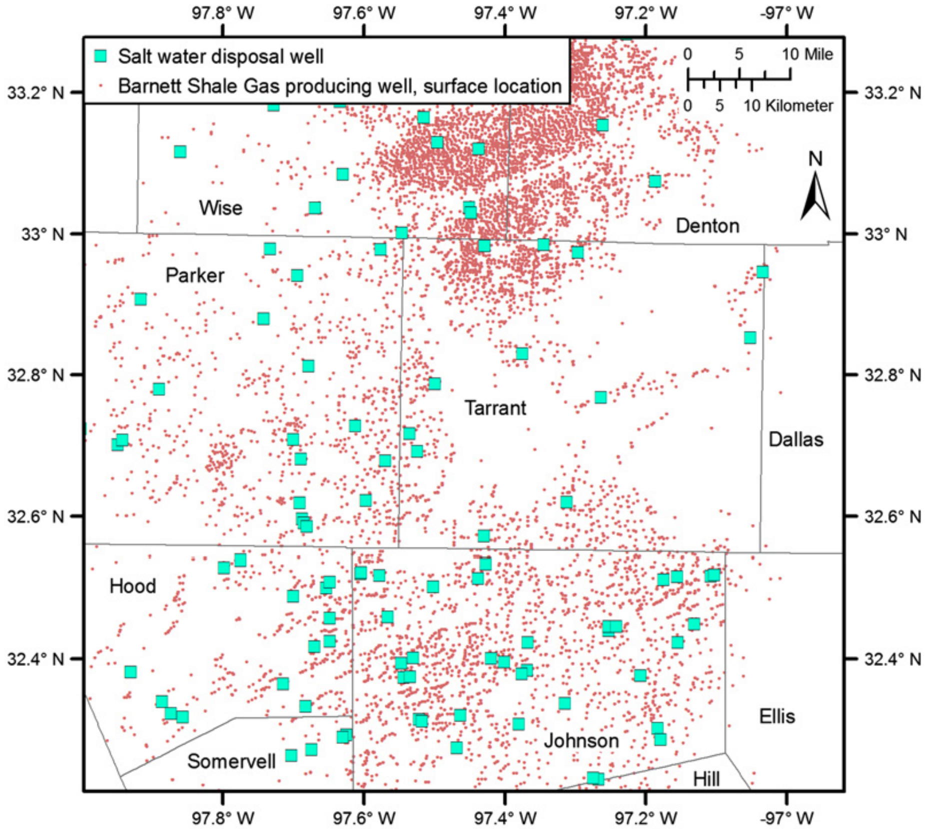

Figure 14: Map of producing gas wells (red dots) and fluid injection (SWD) wells (light blue squares) over a large portion of the Fort Worth Basin (Frohlich et al., 2011).

4.2 GROUNDWATER MODEL RECOMMENDATION

It would be useful to have a groundwater model showing the movement of this water within the geologic units, upward into the Barnett shale, and downward into the basement rocks. This model can assume production of water from the Barnett based on the distribution of wells versus the location of the injection wells. It is not possible to obtain information on the production of water from the Barnett (over 13,000 wells in the FWB by December 2010 (Justinic et al., 2013) and at least that many since (over 30,000 wells total, personal communication at the National Seismic Hazard Workshop on Induced Seismicity, 2014)). It must be assumed that the water produced was equivalent to the volume of injection. A second assumption is that the distribution of water production would be similar to the distribution of producing wells.

Using the injection data, a groundwater model could show the movement of water into the Ellenburger and though fracture zones into overlying formations to replace the produced water from the Barnett. This model, along with other seismic models, could help to understand the variation of seismic activity where only some areas are seismically active and others are not (Frohlich, 2012). It may also provide gas well operators with information to help them understand the replacement of produced water within the Barnett. More careful management of injection could help operators that must deal with formation water, which can affect the ultimate gas production from their wells. Models and water management can also help to determine if existing, or proposed, injection wells may create induced activity events that may cause adverse environmental impacts harmful to groundwater or surface structures.

4.3 GEOLOGIC DATA AVAILABLE FROM THIS STUDY

Evaluation of the geophysical logs and well data reports have uncovered considerable additional geologic information on the units penetrated by the wells of Johnson County, Texas. Some of this data are presented in the Appendix at the end of this report and can be accessed from NETL's Energy Data eXchange (EDX) online system (https://edx.netl.doe.gov) using the following link: https://edx.netl.doe.gov/dataset/supplementary-data-for-trs-geologic-characterization-of-johnson-county-texas. Additional data are available in the spreadsheets generated during this study on the page “gphlogs” and to a less extent on the “condensed depth” page. The understanding of the geologic units as represented in the geophysical logs evolved during the course of this study, so some of the earlier studied logs are not as complete as logs evaluated later and may contain inconsistencies for some of the units. However, the geophysical logs used are still available for other researchers interested in the more complete evaluation of the geologic materials encountered by these logs.

5. REFERENCES

Baruch, E.; Elebiju, O. O.; Perez, R. Geophysical evidence of basement controlled faulting in the Ellenburger Group and Viola Limestone, Fort Worth Basin, Texas. SEG Houston 2009 International Exposition and Annual Meeting, Houston, TX, 2009; p 995–999.

Brown, L. F. Pennsylvanian rocks of north-central Texas: An introduction. In *Pennsylvanian Depositional Systems in North- Central Texas: Guidebook 14*; Texas Bureau of Economic Geology, University of Texas: Austin, TX, 1973; p 1–9.

Bruner, K. R.; Smosna, R. *A comparative study of the Mississippian Barnett Shale, Fort Worth Basin, and Devonian Marcellus Shale, Appalachian Basin*; DOE/NETL-2011/1478; U.S. Department of Energy, 2011.

Elebiju, O. O.; Keller, G. R.; Marfurt, K. J. New structural mapping of basement features in Fort Worth basin, Texas, using high-resolution aeromagnetic derivatives and Euler depth estimates. 78thAnnual International Meeting, SEG, Expanded Abstracts 2008; p 844–848.

Elebiju, O. O.; Keller, G. R.; Marfurt, K. J., Investigation of links between Precambrian basement structure and Paleozoic strata in the Fort Worth basin, Texas, U.S.A., using high-resolution aeromagnetic (HRAM) data and seismic attributes. *Geophysics* **2010,** *75–4*, B157–B168.

Ewing, T. Tectonic Map of Texas. Univ. Texas Bureau of Economic Geology: Austin, TX, 1990.

Ficker, E. Five years of deep fluid disposal into the Ellenburger of the Fort Worth basin. AAPG SW Section meeting, abstract and poster presentation, 2012.

Flippen, J. W. The stratigraphy, structure, and economic aspects of the Paleozoic strata in Erath County, north-central Texas. In *Petroleum Geology of the Fort Worth Basin and Bend Arch Area*; Martin, C. A., Ed.; Dallas Geological Society, 1982.

Frohlich, C. Two-year survey comparing earthquake activity and injection-well locations in the Barnett Shale, Texas. *PNAS* **2012,** *109*, 13934–13938.

Frohlich, C.; Ellsworth, W.; Brown, W. A.; Brunt, M.; Luetgert, J.; MacDonald, T.; Walter, S. The 17 May 2012 M4.8 earthquake near Timpson, East Texas: An event possibly triggered by fluid injection. *J. Geophys. Res. Solid Earth* **2014,** *119*. DOI: 10.1002/2013JB010755.

Frohlich, C.; Gale, J.; Eichhubl, P. *Relationships between Induced Seismicity and Fluid Injection: Development of Strategies to Manage Fluid Disposal in Shale Hydrocarbon Plays – Draft Final Report*; RPSEA Project No. 11122-27; 2015.

Frohlich, C.; Hayward, C.; Stump, B.; Potter, E. The Dallas-Fort Worth earthquake sequence: October 2008 through May 2009. *Bull. Seismological Soc. of America* **2011,** *101*, 327–340.

Geophysics International. *Case history – Barnett shale fault detection*; Company test report obtained in June 2014; undated.

Geotechnical Corporation. *Geotechnical Corporation Deep-Hole Site Report, Trigg No. 1, Dallas County, Texas*; Geotechnical Corporation Tech. Report 64-100; 1964.

IHS Enerdeq® Browser, 2015, IHS Energy https://my.ihsenergy.com/

Justinic, A. H.; Stump, B.; Hayward, C.; Frohlich, C. Analysis of the Cleburne, Texas, Earthquake Sequence from June 2009 to June 2010: *Bull. Seismological Soc. of America* **2013,** *103*, 3083–3093.

Khatiwada, M.; Keller, G. R.; Marfurt, K. J. A window into the Proterozoic: Integrating 3D seismic, gravity, and magnetic data to image subbasement structures in the southeast Fort Worth basin. *Interpretation* **2013,** *1*, T125–T141.

Lahti, V. R.; Huber, W. F. The Atoka group (Pennsylvanian) of the Boonsville Field Area, north-central Texas. In *Petroleum Geology of the Fort Worth Basin and Bend Arch Area*; Martin, C. A., Ed.; Dallas Geological Society, 1982.

Lovick, G. P.; Mazzine, C. G.; Kotila, D. A. Atokan clastics – depositional environments in a foreland basin. In *Petroleum Geology of the Fort Worth Basin and Bend Arch Area*; Martin, C. A., Ed.; Dallas Geological Society, 1982.

Manger, G. E. *Porosity and bulk density of sedimentary rocks: Contributions to Geochemistry*, USGS Bull 1144-E; 1963; pp 60.

Martin, C. A., Ed. *Petroleum geology of the Fort Worth Basin and the Bend Arch area: Dallas Geologic Society*; Series of articles on the basin geology, 1982.

Montgomery, S. L.; Jarvie, D. M.; Bowker, K. A.; Pollastro, R. M. Mississippian Barnett Shale, Fort Worth basin, north-central Texas: Gas-shale play with multi-million cubic foot potential. *American Association Petroleum Geologists Bulletin* **2005,** *89*, 155–175.

Mosher, S. Tectonic evolution of the southern Laurentian Grenville orogenic belt. *Geological Society of America Bulletin* **1998,** *110*, 1357–1375.

National Seismic Hazard Workshop on Induced Seismicity, Midwest City, OK, Nov 17–18, 2014.

Nicholson, C.; Wesson, R. L. Earthquake hazard associated with deep well injection – A report to the U.S. Environmental Protection Agency. *U.S. Geological Survey Bull.* **1990**.

Perez, R.; Elebiju, O. O.; Baruch E. Geophysical evidence of basement controlled faulting in the Ellenburger Group and Viola Limestone, Fort Worth basin, Texas. 79th Annual International Meeting, SEG, Expanded Abstracts, 2009; p 995–999.

Pollastro, R. M.; Jarview, D. M.; Hill, R. J.; Adams, C. W. Geologic framework of the Mississippian Barnett shale, Barnett-Paleozoic total petroleum system, Bend arch–Fort Worth Basin, Texas. *American Association Petroleum Geologists Bulletin* **2007,** *91*, 405–436.

Siriwardane, H. West Virginia University. Personal communication, Induced Seismicity project meetings in 2014 and on February 20, 2015.

Skoumal, R. J.; Brudzinski, M. R.; and Currie, B. S. Earthquakes induced by hydraulic fracturing in Poland Township, Ohio. *Bull. Seismological Soc. of America* **2015,** *05*. DOI: 10.1785/0120140168.

Texas Bureau of Economic Geology. Gage well log, Johnson County, Texas; University of Texas at Austin, 2014.

Texas Railroad Commission (RRC), 2015, www.rrc.state.tx.us. RRC Oil and Gas Well Records, 2015. http://www.rrc.state.tx.us/about-us/resource-center/research/ and Public GIS Viewer http://wwwgisp.rrc.state.tx.us/GISViewer2/

Turner, G. I. Paleozoic stratigraphy of the Fort Worth Basin. In *Abilene and Fort Worth Geological Societies Joint Field Trip Guidebook;* Bell, W. C., Ed.; 1957; p 57–77.

Vincent, P. Oregon State University. Personal communication, Induced Seismicity project meetings in 2014 and on February 20, 2015.

Wickipedia, https://en.wikipedia.org/wiki/North_American_Datum#North_American_Datum_of_1983, August 26, 2016.

Winton, W. M.; Scott, G. *The Geology of Johnson County*; University of Texas Bull. no. 2229; UT Austin, 1922.

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APPENDIX

Table A1: Geologic unit depths used in Cross-Sections A-A' and B-B', Johnson County and adjacent counties, Texas

XC	Well (API No.) 42-	Refr. Elev. (ft)	Elev. Refr	Base Creta-ceous	Strawn ss-sh	Upper Penn. Shale	Atoka ss-sh	Smithwick shale	Big Saline & others	Lower Smithwick	Marble Falls	Barnett Shale	Viola-Ellenburger	Cambrian ss-ls	pC Basement
A	03530102	831	KB	600e	2580gp	2760gp	4340gp	4980gp	5232gp		5360gp	5640gp	5794gp	8594e	9465e
A	25131443	636	GR	725e		725e	4100e	4300e	4800e	5080e	5337	5801	5923	8805e	9693e
A	25131749	627	KB	710dr	1430gp	1467gp	4850gp	5138gp	5554gp	5625gp	5728gp	5950gp	6212gp	9114e	10007e
A	25130348	823	KB	1100e	1535gp	1570gp	4792gp	5573gp	6100gp		6252v	6628	6848	9804e	10710e
A	25130895	860	KB	1220e	1220e	1700e	4900e	5250e	5600	5900e	6120e	6605	6980	10000e	10912e
A,B	25130299	785	KB	1400e	1787gp	1928gp	5041gp	5290gp	6640gp		6740gp	7070gp	7454gp	10295gp	11225e
A	25130465	810	KB	1500egp	1718gp	2815gp	5045gp	5755gp	6943vg	6968vg	7280vg	7462vg	7830vg	10984e	11934e
A	25132107	808	KB	1750e	1880e	2658gp	5053gp	5800gp	7105gp	7212gp	7330gp	7695gp	8080gp	11283e	12243e
A	25131122	646	KB	1870e	1970gp	2410gp	5210gp	5660gp	7308gp	7530gp	7760gp	7995gp	8300e	11590e	12568e
A	43932421	639	KB	2100e	2191gp	2420gp	5080vg	5254vg	7301vg	7497vg	7640vg	8134v	8430e	11752e	12738e
A	43932364	578	KB	2200e	2200e	2500e	5000e	5200e	7240e	7450e	7602egp	8361egp	8669e	12008e	12999e
B	36733480	989	KB	775egp	1173gp	2057gp	5084gp	5250gp	5420gp	5553gp	5709gp	6338gp	6649gp	9463e	10336e
B	25130385	1,012	GR	900e	900e	2250e	5250	5600e	5700e		5815	6338	6620	9800e	10680e
B	25130232	1,040	KB	1017gp	1180gp	2110gp	5415gp	5712gp	5797gp	5923gp	6020gp	6469vg	6878vg	9766e	10656e
B	25132586	1,002	KB	1112	1112	2078gp	5196gp	5670gp	5761gp	5935gp	6032gp	6472v	6850e	9773e	10671e
B	25130184	881	KB	1300e	1300gp	2300gp	5308gp	5821gp	6053gp	6153gp	6488gp	6920gp	7304	10308e	11224e
B	25132557	813	KB	1442	1442	2252gp	4788gp	5032gp	7063gp	7142gp	7295gp	7650gp	8066	11197e	12141e
B	25130221	685	KB	1736gp	1736gp	1939gp	4790gp	5422gp	7218gp	7305gp	7411gp	7755gp	8122	11353e	12320e
B	25130187	611	GR	1950e	1950e	1950e	4768gp	5500gp	7552gp	7630gp	7734gp	8008gp	8450gp	11714e	12688e
B	25130563	623	KB	2000e	2000e	2000e	4950e	5505e	7335dr		7844vg	8295v	8570vg	11849e	12827e
B	21730364	602	KB	1950e	2132gp	3370gp	4980gp	5330gp	7410gp	7600gp	8070gp	8390gp	8818gp	12134e	13120e
B	21730553	836	KB	2300e	2768gp	3120vg	4788vg	5402vg	7608vg	7872vg	9544vg	9747vg	10105vg	13470e	14468e

Additional formation data, including elevations and thicknesses, are available in separate spreadsheet files (https://edx.netl.doe.gov/dataset/supplementary-data-for-trs-geologic-characterization-of-johnson-county-texas).

Depths are based on well reports and geophysical logs from Texas RRC (2014, 2015) and IHS Enerdeq (2015). All depths are in feet.

Depth notations:
- e – estimated from depth data in other nearby wells, geophysical logs (egp), and the literature.
- Some estimates, particularly for the Cambrian and Precambrian, are estimated for the cross-sections.
- v – vertical depth calculated from measured depth and well survey given in the well data report.
- gp – from geophysical log. vg – geophysical log depth corrected to vertical depth.
- Base of the Cretaceous is often based on estimates given for casing depth requirements from the RRC.
- Atoka sandstone and shale often includes the Grant sandstone and Bend conglomerate and may be up to 65% shale.
- Big saline and others include the Hood sandstone and other units. The Big saline is of sandstone, conglomerate, and limestone.
- The Marble Falls is of limestone and shale, and it increases in shale content eastward where it may be up to 80% shale.

Geologic Notations:
- Penn. - Pennsylvanian
- ss - sandstone
- sh - shale
- ls - limestone
- pC - Precambrian

All wells are included, arranged by ascending longitude (-97.68 to -97.02), to more easily compare wells with similar locations. Well coordinates are listed in Table 3. Explanation of depth and geologic notations are given at the end of Table A1 and at the end of this table.

Table A2: Geologic unit depths from wells used to estimate unit elevations and layer thicknesses for Johnson County, Texas

Well (API No.) 42-	Refr. Elev. (ft)	Elev. Refr	Base Creta-ceous	Strawn ss-sh	Upper Penn. Shale	Atoka ss-sh	Smithwick shale	Big Saline & others	Lower Smithwick	Marble Falls	Barnett Shale	Ellenburger-Viola	Cambrian ss-ls	pC Basement
36734085	1084	KB	918egp	1254gp	2415gp	5314gp	5432gp	5876gp	5923gp	5962gp	6438gp	6816gp	9200gp	
36734467	1144	KB								6020	6315	6800		
03530102	831	KB	600e	2580gp	2760gp	4340gp	4881gp	5232gp	5325gp	5360gp	5640gp	5794gp		
36733841	1084	KB	820egp		2052gp	5152gp	5300gp	5786vg	5824vg	5871vg	6379dr			
36733836	1084	KB	820e		2122gp	5164gp	5300gp	5790gp	5830gp	5866gp	6406vg			
22130984	670	KB			1658gp	4595gp	4767gp	4860gp	4890gp	4993gp	5488gp			
22130946	930	KB	780egp	1010gp	2535gp	5080gp	5325gp	5487gp						
22130983	687	GR			1640gp	4475gp	4740gp	4836gp	4870gp	4969gp	5469gp	5752gp	8612vg	9485egp
22131331	957	GR	830egp	1115gp	2310gp	5191vg	5381vg	5541vg		5729vg	6209v			
36733480	989	KB	775egp	1173gp	2057gp	5112gp	5250gp	5709gp	5742gp	5800gp	6338gp	6649gp		
22131311	1020	KB				5199vg	5447vg	5613vg		5733v	6200v			
22131219	965	KB	777egp	1158gp	2193gp	5060gp	5300gp	5400vg	5486vg	5604vg	6040vg	6495vg		
22131206	990	KB				5309gp	5484gp	5640gp	5996gp	6125gp	6274gp	6612gp		
22131364	850	GR						5290dr		5433dr	5892dr	6222dr	9295e	
36733776	987	KB	778egp	1090gp	2242gp	4878gp	5065gp	5770gp			6443v			
42530200	788	KB	750e	2000gp	2054gp	4450gp	4577gp	5440gp		5502gp	5760gp	6080gp		
22131093	971	KB		1142gp	1272gp	4866gp	5276gp	5410gp	5470gp	5620gp	6119vg			
22131051	785	KB		991gp	1357gp	4776gp	5073gp	5187gp	5268gp	5367gp	5805vg			
42530113	650	KB			1943gp	3977gp	4242gp	5225gp	5285gp	5370gp	5602gp			
42530122	770	GR										6110		
22131158	979	KB	1000e		2210gp	5205gp	5492gp	5618gp	5720gp	5783gp	6200gp	6580gp		
22131217	802	KB				4810gp	5140gp	5244gp		5423gp	5898v			
42530192	816	KB				4423gp	4707gp	5560gp		5600gp	5894v			

Table A2: Geologic unit depths from wells used to estimate unit elevations and layer thicknesses for Johnson County, Texas (cont.)

Well (API No.) 42-	Refr. Elev. (ft)	Elev. Refr	Base Creta-ceous	Strawn ss-sh	Upper Penn. Shale	Atoka ss-sh	Smithwick shale	Big Saline & others	Lower Smithwick	Marble Falls	Barnett Shale	Ellenburger-Viola	Cambrian ss-ls	pC Basement
36733618	980	KB	828egp	1007gp	2467gp	5345vg	5523vg	5666vg	5733vg	5800vg	6260vg			
25131509	864	KB		1426gp	1992vg	5049vg	5260vg	5387vg	5484vg	5602vg	5991vg	6395vg		
25132379	966	KB		1142gp	2138gp	5116vg	5450vg	5590vg	5690vg	5734vgd	6222vd			
25132969	1,032	KB			2258vg	5335vg	5633vg	5757vg		5904vg	6410v			
25130846	728	KB	1005e	1787gp	1848gp	4868gp	5080gp	5381gp	5432gp	5553gp	5780vd	6050gp		
25131782	1,055	KB	932		2242gp	5403gp	5780gp	5832vg		5990vg	6445			
25130385	1,012	GR	900e	1100e	2250e	5250	5600	5700e		5815e	6338dr	6620dr	9800e	10680e
25130489	1,030	KB								5928d	6350d		9770e	
03530110	846	KB		2142gp	2326gp	4540gp	4980gp	5100vg	5232vg	5652vg	6030vg	6215vg		
25130360	759	KB	868egp	1128gp	1240gp	4749.3gp	5192gp	5327gp	5404gp	5566gp	5931gp	6318gp		
25130762	839	KB	850		1196gp	4732gp	5207gp			5671dr	6103dr			
25130302	955	KB	972egp	1029gp	1152gp	4826gp	5310gp	5742gp		5791gp	6174gp	6513gp		
36733547	966	KB			2352gp	5457gp	5660gp	5797gp	5852	5954gp	6413			
25133146	952	KB		1354gp	1777gp	5107vg	5332vg	5527vg	5680	5730vg	6224vg	6524vg		
25130303	933	KB		1205	2366gp	5009gp	5520gp	5628gp	5742gp	5843gp	6332gp			
25131443	636	GR	725e		725e	4100e	4300e			5337dr	5801dr	5923dr		
25130957	751	KB	825e	1072gp	1397gp	4664gp	5300gp	5620vg		5811vg	6022vg			
25131918	943	KB	875e	1084gp	1234gp	5042gp	5226gp	5817vg	5898	5914vg	6282vd			
36733645	982	KB	1105	1105	2280gp	5390gp	5612gp	5754gp	5810gp	5930gp	6453v			
25130428	968	GR				5200e				5980dr	6473dr	6822dr		
25130364	982	KB			2085gp	5322gp	5648gp	5770gp		5975gp	6457gp	6790		
25130396	942	KB		1310gp	1530gp	4917gp	5720vg	5805vg	6015vg	6054vg	6220vg			
25130232	1,040	KB	1017gp	1180gp	2110gp	5415gp	5712gp	5797gp	5923gp	6020gp	6469vg	6878vg		
36734496	966	KB	1085	1085		5392v		5738v		5912v	6409v			
25131375	689	KB	850e		850e	4780gp	5200gp	5602gp		5757gp	6080evg			
25130195	942	KB			1535gp	4625gp	5165gp	5505gp	5551gp	5670gp	6108gp	6372gp		

Table A2: Geologic unit depths from wells used to estimate unit elevations and layer thicknesses for Johnson County, Texas (cont.)

Well (API No.) 42-	Refr. Elev. (ft)	Elev. Refr	Base Creta-ceous	Strawn ss-sh	Upper Penn. Shale	Atoka ss-sh	Smithwick shale	Big Saline & others	Lower Smithwick	Marble Falls	Barnett Shale	Ellenburger-Viola	Cambrian ss-ls	pC Basement
25131749	627	KB	710dr	1430gp	1467gp	4850gp	5138gp	5554gp	5625gp	5728gp	5950gp	6212gp		
25130839	685	KB		2662gp	3285gp	4747gp	5168gp	5647vg		5774vg	5964v			
43931262	809	KB		1170gp	1906gp	5255gp	5470gp	5594gp	5662gp	5755gp	6200gp	6624gp		
25130840	744	KB	850e			4826vg	5232vg	5662vg	5747vg	5842vg				
25134177	903	KB	900e	1870gp	1940gp	4993gp	5183gp	5917gp	5970gp	6103gp	6350gp	6617gp		
25130249	950	GR										6750		
25132586	1,002	KB	1112	1112	2078gp	5196gp	5670gp	5761gp	5935gp	6032gp	6472v	6850e		
25133189	967	KB	1150e	1352gp	1700gp	5094gp	5438gp	5952gp		6010gp	6385gp	6690gp		
25130432	1,015	KB		1340gp	1600gp	5295gp	5570gp	5690gp		6137gp	6546v			
25133088	984	KB			2275gp	5399gp	5785gp	5890gp	6031gp	6101gp	6572gp	7070gp		
25133092	984	KB		1224gp	2280gp	5398vg	5804vg	5880vg	6035vg	6100vg	6610vg	7070		
Gage	872	GR	1020		1420	4662				6000	6454	6640	9546	
25130509	934	KB	1125e		1440gp	4835gp	5228gp	5950gp	6005gp	6076gp	6382gp	6625gp	9630egp	
25131770	957	KB	1157							6046v	6432v			
25131182	602	KB	1066		1066	4590gp	5068gp	5626gp	5697gp	5920vgd	6215dr			
25130696	893	KB				4975gp	5104gp	5955gp	5988gp	6275gp	6370gp	6600gp	9527vg	
25132625	832	KB	1000dr	2332vg	2540vg	5072vg	5270vg	6013vg	6057vg	6190vg	6505vg	6692vg		
43932146	876	KB								6200e	6546v			
43931846	889	KB				5424gp	5690gp	5758gp		6005gp	6563v			
25130630	853	KB	950egp		1376gp	4730gp	5397gp				6403dr			
25130366	903	KB			1872gp	5050vg	5570gp	5703vg	6000vg	6080vg	6457v			
25132067	781	KB	970egp		1346gp	4622vg	5331vg			6008v	6425v			
25131116	702	KB	910		910gp	4756gp	5203gp	5958gp	6034vg	6060vg	6375v			
25130518	994	KB		1347gp	2510gp	5268vg	5784.5vg	5885vg	6044vg	6203vg	6738vd			
25130109	937	KB	1100dr	1100dr	2042gp	5320gp	5810gp	5920gp	6044gp	6133gp	6642gp	7178gp		
03530138	644	KB		2466gp	2558gp	4703gp	5176gp	6050gp	6160gp	6190gp	6418vg			

Table A2: Geologic unit depths from wells used to estimate unit elevations and layer thicknesses for Johnson County, Texas (cont.)

Well (API No.) 42-	Refr. Elev. (ft)	Elev. Refr	Base Creta-ceous	Strawn ss-sh	Upper Penn. Shale	Atoka ss-sh	Smithwick shale	Big Saline & others	Lower Smithwick	Marble Falls	Barnett Shale	Ellenburger-Viola	Cambrian ss-ls	pC Basement
25130899	795	KB	1040egp	2324gp	2452gp	4870gp	5320gp	6087gp	6152gp	6190gp	6504gp	6750gp		
25130348	823	KB	1100e	1535gp	1570gp	4792gp	5573gp	6100gp		6252v	6628	6848		
25130347	874	KB	1155egp		1610gp	4910gp	5657gp	6205gp		6382v	6626v			
43931548	758	KB						5970v			6504v			
25131893	866	KB		1580gp	1998gp	4822gp	5210gp	5497vg	5634vg	5993vg	6387vd			
25130136	934	KB	1103egp	1874gp	2121gp	5287vg	5758vg	5870vg	6105vg	6148vg	6633vg	7088vg		
25130399	830	KB	1250e	1427gp	1965gp	4937gp	5350gp	5520gp	5790gp	5990gp	6353vd	6655vd		
25130114	884	KB			1550gp	5380vg	5835vg	6012vg	6274vg	6520vg	6963vg	7662vg		
25130881	828	KB	1310egp	1378gp	2280gp	4733gp	5100gp	5554gp	5765gp	5985vg				
43933462	853	KB	1096egp	1194gp	2767vg	5330vg	5793.9vg	5886vg	5962vg	6062vg	6584vd			
25130314	986	KB		1414gp	2332gp	5490gp	5842gp	5958gp	6176gp	6305vg	6752v			
25130895	860	KB	1220e	1220e	1700e	4900e	5250	5600	5900e	6120e	6605	6980		
25130143	915	KB			1514gp	5386gp	5814gp	5915vg	6133vg	6362vg	6760vg	7250vg		
25131367	860	KB		1260gp	1415gp	4686gp	5114gp	5570gp	5703gp	6190vg	6684vg			
25132211	919	KB						6243			6767.7			
25132143	793	KB						6185			6642			
25130108	818	KB		1309gp	1642gp	4642vg	5098vg	5578vg	5750vg	6180vg	6700vg	7038vg	9945evg	
25130852	768	GR				4988gp	5082gp	6120gp	6160vg	6305vg	6582vg			
25131596	832	KB	1200	1420gp	1523gp	5147vg	5586vg	6230vg	6269vg	6378vg	6826vd			
25130139	904	KB		1435gp	1758gp	5100vg	5518vg	5732vg	6120vg	6278vg	6700vg	7043vg		
25132633	751	KB	1100								6763			
43931662	804	GR			2690gp	5354gp	6044gp	6190gp		6402gp	6686gp	7080gp		
25132362	874	KB	1242egp	1340gp	2388gp	5330vg	5793vg	5895vg	6061vg	6166vd	6678vd			
25130157	845	KB		1411gp	2080gp	5038gp	5129gp	5781gp	6182gp	6343gp	6726gp	7158gp		
25131441	776	KB	1145egp	1313gp	1536gp	5000vg	5200vg	5598vg	5834.5vg	6404v	6704v			
25130806	803	KB			1728gp	4608gp	5555gp	6100gp			6927			

Table A2: Geologic unit depths from wells used to estimate unit elevations and layer thicknesses for Johnson County, Texas (cont.)

Well (API No.) 42-	Refr. Elev. (ft)	Elev. Refr	Base Creta-ceous	Strawn ss-sh	Upper Penn. Shale	Atoka ss-sh	Smithwick shale	Big Saline & others	Lower Smithwick	Marble Falls	Barnett Shale	Ellenburger-Viola	Cambrian ss-ls	pC Basement
25130184	881	KB	1300e	1300e	2300gp	5308gp	5821gp	6053gp	6153gp	6488gp	6920gp	7304		
25130111	801	KB	1150e	1494gp	1720gp	4522gp	4762gp	6118gp	6162gp	6362gp	6873gp	7150gp		
25131079	894	KB		1500gp	1628gp	5470gp	5930gp	6219gp	6315gp	6532gp	6840gp			
25130319	755	KB		1872gp	2152gp	4818gp	5052gp							
25133335	850	GR	1125e								6766	7140		
25130805	944	KB		1720gp	2510gp	5420gp	5938gp	6100gp	6315gp	6502gp	6946vd			
25132417	856	KB	1123dr	1123dr	1835gp	4217vg	5367vg	6084vg	6103vg	6235vg	6672vg			
25130155	747	KB	1123dr	1123dr	1469gp	5155gp	5326gp	6305gp	6368gp	6503gp	6813gp	7090gp		
25132248	865	KB		1800gp	2142gp	5431vg	5655vg	6570vg	6613vg					
25130864	751	KB		1338gp	1560gp	4596vg	4832vg	5146vg	5365vg	6312vd	6922vd			
43931158	800	KB		1200gp	1670gp	5348gp	5970gp	6277gp	6414gp	6440gp	6725gp	7205gp		
25130144	863	KB		1430gp	1902gp	5395gp	5640gp	6548gp	6588gp	6728gp	6918gp	7395gp		
25132059	844	GR							6287		6823			
25131102	915	KB		1630gp	2380gp	5420gp	5982gp	6207gp	6372gp	6562gp	6930gp			
25130196	871	KB			2220gp	5232gp	5675gp	6178gp		6531dr	6900v			
43931817	846	KB	1130e		2643gp	5364gp	6037gp	6245gp	6385gp	6466	6810			
25130127	864	KB	1305egp	1592gp	2150gp	5323gp	5657gp	6059gp	6212gp	6435gp	6780gp	7270gp		
25130799	872	KB		1400gp	2522gp	5460gp	5860gp	6332gp	6490gp	6542gp	6752gp	7190gp		
25132181	847	KB	1250e	1380gp	1773gp	5277vg	5568vg	6518vg	6590vg					
25130861	700	KB						6641vg	6704vg	6896vg	7359vd			
25130250	858	KB	1570		2110gp	5140gp	5950gp	6520gp		6700gp	6955gp	7445gp		
25132039	840	KB		1551gp	1941gp	5252gp	5536gp	6535vd		6915vd	7061vd			
21730408	722	KB			1322gp	4521vg	4767vg	6605vg	6744vg	7075vg	7320vg			
25130461	763	KB		1572gp	1608gp	4793gp	5030gp	6253gp	6355gp	6724gp	6849gp	7099gp		
25130936	690	KB			1382gp	4585gp	4860gp	6454vg			7052			
25131344	705	KB	1110egp	1362gp	1510gp	4685gp	4925gp	6288gp	6317gp	6711dr	6847.4dr			

Table A2: Geologic unit depths from wells used to estimate unit elevations and layer thicknesses for Johnson County, Texas (cont.)

Well (API No.) 42-	Refr. Elev. (ft)	Elev. Refr	Base Creta-ceous	Strawn ss-sh	Upper Penn. Shale	Atoka ss-sh	Smithwick shale	Big Saline & others	Lower Smithwick	Marble Falls	Barnett Shale	Ellenburger-Viola	Cambrian ss-ls	pC Basement
25130219	852	KB			2153gp	5348gp	5683gp	6342gp		6592gp	6946gp	7418gp		
25130643	818	GR	1430		1974gp	5290gp	5626gp			6615	7006v			
21730452	727	GR				4776egp	5080egp	6645egp		6736egp	7106dr	7302gp		
25130293	772	KB		1353gp	1818gp	4702gp	4970gp	6435gp	6468gp	6660gp	6917gp	7206gp	10260egp	
25132517	927	KB	1300e	1300e				6514vd						
25130363	898	KB		1540gp	2256gp	5282gp	5520gp	6530gp	6678gp	6718gp	6955gp	7458gp		
25130919	922	KB			2450sh	5410gp	6076gp	6658v		6942v	7132v			
25130241	841	KB		1577gp	1968gp	5433gp	5782gp	6610gp	6740gp	6840gp	7084gp	7623gp		
25130433	658	KB	1115egp	1690gp	2027gp	4655gp	4787gp	6493gp	6550gp	6764gp	7042gp	7302gp		
43931540	809	KB								6723vd	6925vd	7268vd		
43933080	849	KB		2174gp	2580gp	5412gp	5796gp	5884gp	6341gp	6708gp	7016vd			
25131558	820	KB	1410		1925gp	5217vg	5583vg	6587vg		6769vg	7088dr			
25130299	785	KB	1400e	1787gp	1928gp	5041gp	5290gp	6640gp		6740gp	7070gp	7454	10325egp	
25131266	743	GR									6980	7298	10200e	
43931445	836	KB						6449			6990			
25130356	770	KB			2003gp	4649gp	4940gp				7169v			
43931226	808	KB	1224egp	1740gp	2665gp	5114gp	5940gp	6347gp	6450gp	6520gp	6780gp	7230gp		
25130897	791	GR	1280		1826gp	5276gp	5608gp	6730gp	6808gp	6912gp	7120gp	7380gp		
25130877	814	KB			1850gp	5190gp	5540gp	6600gp		6843v	7206v			
25130306	762	KB		1353gp	2292gp	4600gp	4956gp	6618gp	6685gp	6852gp	7220gp	7460gp		
25131430	804	KB	1299	1299	2858gp	5479vg	6183vg	6634vg		6717vg	6963v			
25130815	780	GR				5190dr					7010	7510	10500e	
25131282	692	KB		2220gp	2292gp	4458gp	4958gp	6630gp	6792gp	6839gp	7306gp	7537vg		
25130327	849	KB	1360e	1360e	2144gp	5326gp	5746gp	6633gp	6745gp	6880gp	7110gp	7618gp		
43932604	800	KB	1467egp		2185gp	5640vg	6097vg	6493vg		6635vg	7054vd			
25131027	914	KB			2461gp	5220gp	5391gp			6762	7330vd			

Table A2: Geologic unit depths from wells used to estimate unit elevations and layer thicknesses for Johnson County, Texas (cont.)

Well (API No.) 42-	Refr. Elev. (ft)	Elev. Refr	Base Creta-ceous	Strawn ss-sh	Upper Penn. Shale	Atoka ss-sh	Smithwick shale	Big Saline & others	Lower Smithwick	Marble Falls	Barnett Shale	Ellenburger-Viola	Cambrian ss-ls	pC Basement
25131105	812	KB								6772v	7294v			
25131267	841	KB	1435dr	1585gp	2255gp	5250vg	5983vg			6732vg	7223evg			
25132841	900	KB	1430egp	1600gp	2469gp	5320gp	5450gp	6780vg		6853vg	7275vg	7715vg		
25130580	707	KB	1255egp	1388gp	1880gp	4552gp	4995gp	6643gp	6925gp	6950gp	7332gp	7590vd		
25130483	707	KB			2023gp	5140gp	5503gp	6650gp			7246v			
25130988	833	KB	1490egp	1653gp	2447gp	4798gp	4960gp	6733vg	6855vg	6981vg	7285vg	7622vg		
25130755	874	KB	1516gp		2148gp	5187gp	5528gp	6844dr			7404v			
25131638	735	KB		1750	2055gp	4332gp	4780gp	6688vd			7390vd	7635vd		
25131525	759	KB		1595	2683gp	5325gp	6033gp			6904vd	7204vd			
25130545	712	GR						6728dr			7478v	7771v		
43931911	771	KB			2238gp	5399gp	6046gp	6504gp	6616gp	6646gp	7078v			
25131081	802	KB	1606			5222		6701v		6796v	7325v			
43931043	748	KB			2312gp	5313vg	6084vg	6402vg	6649vg	6707vg	7015vd			
25131261	825	KB	1640egp	1890gp	2330gp	5148gp	5940gp	6830vg		6884vg	7364vg			
43931061	715	KB	1245egp	1430gp	2030gp	5537gp	6114gp	6527vg	6672vg	6747vg	6947vg	7504vg		
25130838	779	KB		1486gp	2352gp	5564gp	5960gp	6683vg	6873vg	6905vg	7156vg			
43931637	729	KB				5342vg	5798vg	6575v	6690vg	6892vg	7118v			
21730368	724	KB						6229		6814v	7390v			
25130586	778	KB						6953v		7447v	7622v	7840sv		
25130481	855	KB	1584		2448gp	4950gp	5108gp	6964gp		7353gp	7520gp	7837gp	10860gp	
43932686	719	KB	1407egp	1462gp	1887gp	5379vg	6126vg	6629vg	6729vg	6756vg	7130vg			
25131355	809	KB	1606egp	1935gp	2542gp	5165gp	5365gp	6807gp	6830gp					
25130530	809	KB	1374egp	1770gp	2257gp	5495vg	5683vg	6772vg	6799vg	6816vg	7224vg	7794vg		
25133149	804	KB								6688vd	7229vd			
25132557	813	KB	1442	1442	2252gp	4788gp	5032gp	7063gp	7142gp	7295gp	7650gp	8066		
25133237	738	KB	1565egp	1846vg	2438vg	5435vg	5938vg	6730vg	6820vg	6848vg	7290vd			

Table A2: Geologic unit depths from wells used to estimate unit elevations and layer thicknesses for Johnson County, Texas (cont.)

Well (API No.) 42-	Refr. Elev. (ft)	Elev. Refr	Base Creta-ceous	Strawn ss-sh	Upper Penn. Shale	Atoka ss-sh	Smithwick shale	Big Saline & others	Lower Smithwick	Marble Falls	Barnett Shale	Ellenburger-Viola	Cambrian ss-ls	pC Basement
25132127	792	KB	1475e	1726gp	2678vg	5122vg	5224vg			6968vg	7293vg	7706vg		
25133282	839	KB	1680egp		1987gp	4945gp	5050gp	7005vg	7108vg	7213vg	7632vg	7955vg		
21730373	793	KB	1700e		1700e	5099gp	5420gp	6970gp	7080gp		7683v			
25130497	843	KB						6885dr			7629v			
25131885	874	KB		1592gp	1847gp	4538gp	4866vg	7003vg	7118vg	7234vg	7630vg	7955vg		
25133137	686	KB									7201vd			
25131199	889	KB	1626							7177v	7506v			
43931075	670	KB		1393gp	1959gp	5224gp	5375gp	6572gp	6760gp	6785gp	7168vg			
25131223	822	KB	1605egp	2340gp	3090gp	5302gp	5815gp	6940gp	7013gp	7287gp	7548gp	7859gp		
43931335	660	KB		1570gp	2327gp	5320gp	6033gp	6710gp	6800gp	6917vg	7291v	7725dr		
25132620	721	KB						6720		7047dr	7248			
25131023	808	KB			2414gp	4920gp	5458gp	6974v		7370v	7540v			
25130465	810	KB	1500egp	1718gp	2815gp	5045gp	5755gp	6943vg	6968vg	7280vg	7462vg	7830vg		
25130462	851	KB		1654gp	2800gp	4517gp	4966gp	7078vg	7215vg	7316vg	7797v			
25130292	882	KB		1732gp	2217gp	5078gp	5115gp			7328gp	7667gp	8040gp		
25132502	757	KB			2580	5307vg	6057vg	6800vd		6852vg	7305vd			
43931283	574	KB	1500egp		2530gp	5243vg	6061vg	6710vg	6840vg	6890vg	7144dr			
25130160	792	KB			2300gp	5215gp	5575gp	7050dr			7542v	7892v		
21730371	746	KB		2313gp	2513gp	4193gp	4615gp	7064gp	7262vg	7395vg	7766vg	7984vg		
25130386	822	KB	1580egp	1745gp	2167gp	4330gp	4708gp	7193gp	7252gp	7400vg	7840vg	8109vg		
25131659	762	KB	1630egp	1894gp	2406gp	5440vg	6002vd	6919vg	6956vg	6982vg	7416vg			
43931906	740	KB						6766dr		7166dr	7384			
21730331	743	KB			2345gp	4730gp	5005gp	6928vg	6983vg	7124vg	7643vg	7922vg		
21730386	800	KB		1840gp	2280gp	4215gp	4400gp	7218gp	7340gp		7902vd			
21730382	804	KB			2200gp	4850gp	5270	7228gp	7355gp		7888v			
25131020	801	KB		1846gp	2759gp	5074gp	5845gp	7050gp	7110gp	7212gp	7588gp	7954gp	11200gp	

Table A2: Geologic unit depths from wells used to estimate unit elevations and layer thicknesses for Johnson County, Texas (cont.)

Well (API No.) 42-	Refr. Elev. (ft)	Elev. Refr	Base Creta-ceous	Strawn ss-sh	Upper Penn. Shale	Atoka ss-sh	Smithwick shale	Big Saline & others	Lower Smithwick	Marble Falls	Barnett Shale	Ellenburger-Viola	Cambrian ss-ls	pC Basement
25132327	851	KB								7180dr	7580dr	8030gp	11272gp	
25131924	838	KB	1697egp	1770gp	1872gp	5250vg	5823vg	7030vg	7100vg	7378vg	7512vg			
25130153	770	KB	1718egp	1780gp	2500gp		4663gp	7080egp	7222egp	7315gp	7620gp	8083gp		
25130118	799	KB			2264gp	5130vg	5170vg	7085vg	7200vg	7350vg	7780vg	8174vg		
25133590	762	KB			2290vg	5192vg	5635vg	6801vg	6908vg	7407vg	7556vg			
25130855	717	KB	1730egp	2030gp	2220gp	5330gp	5976gp	6982gp	7210gp	7315gp	7518gp	7927gp		
25132058	748	GR	1756e	1996gp	2855gp	5220gp	5846gp	7145vg	7168vg	7441vg	7530vg			
21730444	760	GR								7800	8022			
25132107	808	KB	1750e	1870gp	2662gp	5054gp	5797gp	7104gp	7137gp	7192gp	7625gp	8080gp		
25130237	790	KB			2500gp	5370gp	5595gp			7471v	7698v			
25130869	702	KB	1816egp	2647gp	2972gp	5103gp	5840gp			6998gp	7332dr			
25131317	767	KB	1675							7443dr	7810dr			
21730383	741	KB			1850gp	4557gp	4644gp	7478gp	7610gp	7710gp	8082gp	8348gp		
21730367	748	KB		1782gp	1862gp	4226gp	4808gp	7610gp	7695gp	7728gp	7966gp	8338gp		
43931210	688	KB	1750egp	2150gp	2596gp	5216gp	5983gp	6976gp	7080gp	7270gp	7494gp	7890gp		
21730392	724	KB		1837gp	2272gp	4662gp	4858gp	7425gp	7538gp	7660vg	8087v			
25130686	745	KB	1765e	1776gp	1987gp	4752gp	4880gp	7452gp	7540gp	7690gp	8100gp	8437gp		
25131021	694	GR			2585gp					7335gp	7802	8173gp		
25130383	734	KB	1675e	1720gp	2250gp	5292gp	5666gp	7118gp	7140gp	7530gp	7796gp	8078gp		
25130231	720	KB				5232gp	5490gp	7225vg	7325vg	7416vg	7818vg	8177vg		
25130221	685	KB	1736gp	1736gp	1939gp	4790gp	5422gp	7218gp	7305gp	7411gp	7755gp	8122		
25130440	706	GR								7658dr	7791			
25131502	699	KB			2445gp	5298gp	5665gp	7264gp	7503gp	7686gp	7835gp	8200gp		
21730427	752	KB	1740egp		1740gp	4070gp	4810gp	7950gp	8000gp	8082gp	8512gp	8727gp		
21730377	702	KB	1720e			4808gp	4957gp	7702vg	7759vg	7857vg	8221vg	8502vg		
25131263	781	KB		2443gp	2683gp	4890gp	5844gp	6997gp	7082gp	7208vg	7687v	8080vg		

Table A2: Geologic unit depths from wells used to estimate unit elevations and layer thicknesses for Johnson County, Texas (cont.)

Well (API No.) 42-	Refr. Elev. (ft)	Elev. Refr	Base Creta-ceous	Strawn ss-sh	Upper Penn. Shale	Atoka ss-sh	Smithwick shale	Big Saline & others	Lower Smithwick	Marble Falls	Barnett Shale	Ellenburger-Viola	Cambrian ss-ls	pC Basement
25132774	703	KB						7478dr			8230sv			
25131575	698	KB	1675	1873gp	2510gp	5200gp	5580gp	7175gp	7410gp	7590gp	7730gp	8100gp		
25130107	728	KB	1712egp	1712egp	2032gp	5078vg	5300vg	7284vg	7366vg	7542vg	7846vg	8209vg		
25130798	635	KB	1695egp	2058gp	2690gp	5100gp	5822gp	7088gp	7115gp	7340gp	7504gp	7860gp		
25130641	728	KB			2515gp	5420gp	5686gp	7280dr		7662sv	7862sv	8203sv		
25130953	730	GR									7990dr	8348dr	11400e	
25130528	765	KB		2070gp	2162gp	5186gp	5604gp	7416vg	7466vg	7798evg	7978vd			
25134121	746	KB										8470IHS		
25132198	689	KB	1675e		2020gp	5158gp	5705gp	7405vg	7500vg	7850evg	7980evg	8340evg		
25130637	726	KB				5490egp	5766egp	7150egp	7295egp	7551	8097v			
25130376	690	KB			2430gp	5212gp	5910gp	7300gp	7362gp	7592gp	7807gp			
25130187	610	GR	1950e	1950e	1950e	4768gp	5500gp	7552gp	7630gp	7734gp	8008gp	8450gp		
25131754	654	KB	1738gp		2168gp	4528vg	4888vg	7502vg	7574vg	7627vg	8000sv	8420sv		
21730671	691	KB					6543dr				8235			
25130447	638	GR	1740e		1880gp	5133gp	5232gp	7640gp	7678gp	7837gp	8210gp	8570gp		
25100002	677	DF	1750		2590	4995	5730	7355		7702		8190		
21730464	649	KB	1750egp		1750	4940gp	5390gp	7230gp	7364gp	7620gp	8140gp	8494gp		
25130742	684	KB			2308gp	4924vg	5705vg	7308vg	7360vg	7495vg	7845vg	8254vg		
25134160	729	DF						7366vg	7467vg	7578vg	8071vg			
25130563	623	KB	2000e	2000e	2000e	4950e	5505e	7335dr		7844vg	8295v	8570vg		
25131122	646	KB	1870e	1970gp	2410gp	5210gp	5660gp	7308gp	7530gp	7760gp	7995gp			
25130188	630	GR	1914gp		1914gp	5094gp	5538gp	7500gp		7730gp	8150gp	8518gp		
25131259	710	KB	1855egp	2160gp	2495gp	4830gp	5405gp	7617vg	7757vg	7815vg	8105v			
25130183	632	KB	1913egp		1913gp	4431gp	5637gp	5860gp	6055gp	7680gp	8130gp	8560gp		
25130856	674	GR		3140gp	3960gp	4845gp	5270gp	7535gp		7707gp	8105gp	8580gp		
25130194	612	KB	1914egp	2113gp	2896gp	4450gp	5415gp	7549gp	7562gp	7615gp	8140gp	8520gp		

Table A2: Geologic unit depths from wells used to estimate unit elevations and layer thicknesses for Johnson County, Texas (cont.)

Well (API No.) 42-	Refr. Elev. (ft)	Elev. Refr	Base Creta-ceous	Strawn ss-sh	Upper Penn. Shale	Atoka ss-sh	Smithwick shale	Big Saline & others	Lower Smithwick	Marble Falls	Barnett Shale	Ellenburger-Viola	Cambrian ss-ls	pC Basement
25130834	691	KB			2673gp	4860gp	5040gp	7498gp		7701gp	8080gp	8424gp	11740egp	
25132353	677	KB	1846egp		1846gp	4540gp	5010gp	7610gp	7703gp	7774gp	8130gp			
25130969	683	KB	1848			4863				7652	8020			
25130318	674	KB			2350gp	4858gp	5162gp	7457v		7515v	8039v			
25130336	644	GR								7680	8320			
25130954	658	KB	1850e		1850e	4565gp	4905gp	7216gp	7267gp	7634gp	8036gp	8515gp		
25131260	674	GR	1925		1925					8159	8389			
25131219	631	KB	1820gp	1915gp	2560gp	5002gp	5280gp			7715vg	8064v			
25130830	690	KB						7739v		8123v	8271v			
25131338	641	GR	1847							8322	8464			
25131305	612	KB	1814gp	2470gp	2703gp	4850gp	5082gp			7730gp	8068gp	8472gp	11845gp	12880gp
21730364	602	KB	1950e	2132gp	3370gp	4567gp	5330gp	7410gp	7600gp	8070gp	8390gp	8818gp		
25130752	637	KB	1917gp	2110gp	2645gp	4978gp	5112gp	7647vg	7670vg	7796vg	8120vg	8554vg		
25131797	613	KB	1825		1825					8187	8293			
25130754	633	KB	1979		1979	4988dr		7639dr		7810dr	8189dr			
25132402	615	KB	1925dr	1996gp	2783gp	4840gp	5060gp			7707gp	8252gp	8558gp	11805gp	12768gp
43932421	639	KB	2100e	2191gp	2420gp	4889vg	5254vg	7301vg	7497vg	7640vg	8134vd			
43932375	584	GR								7582vd	8062vd			
25130443	635	KB		2270gp	2665gp	5110gp	5365vg			7917vg	8371v			
25131279	637	KB	1922gp			4928vg	5143vg	7602vg	7650vg	7776vg	8145vg			
43931397	607	KB	1896gp	2020gp	3062gp	5170gp	5362gp	7370gp	7520gp	7698gp	8078gp	8582gp		
13930475	557	GR	1903	2536				7187dr			8468v	8868v		
13930493	568	KB	1890egp	1932gp	2112gp	4982gp	5038vg	7976vg	8036vg	8085vg	8356vg			
13930465	667	KB	2004egp	2414gp	3120gp	4560gp	4788vg			8164vg	8352vg	8586vg		
21730529	540	GR			2270					9340dr	9600dr	9950dr		
13930470	598	KB				3662gp	4200gp			8372vg	8481vg	8800vd		

Table A2: Geologic unit depths from wells used to estimate unit elevations and layer thicknesses for Johnson County, Texas (cont.)

Well (API No.) 42-	Refr. Elev. (ft)	Elev. Refr	Base Creta-ceous	Strawn ss-sh	Upper Penn. Shale	Atoka ss-sh	Smithwick shale	Big Saline & others	Lower Smithwick	Marble Falls	Barnett Shale	Ellenburger-Viola	Cambrian ss-ls	pC Basement
43932364	578	KB	2200e	2200e	2500e	5000e	5200e	7240e	7450e	7602egp	8361egp			
13930468	631	KB		2517gp	3175gp	4742gp	5990gp			8317vg	8693vg	8993vg		
13930471	659	GR	2010	2420							8270vd	8700vd		
21730553	836	KB	2300e	2768gp	3120vg	4788vg	5402vg	7608vg	7872vg	9544vg	9747vg	10105vg		
13930573	595	KB	1976vg	3008vg	3372vg	5980vg	6216vg			8018vg	8240vg			
13930486	637	KB		2498gp	3034gp	5998gp	6326gp	7650gp	7880gp	8220gp	8457vg	8955vg		
13930520	557	GR												944
13930498	666	KB		2312gp	2985gp	5569vg	6078vg	6856vg	6935vg	8292vg	8437vg	8649vg		
13930500	667	KB	2418gp	2540gp	3155gp	4960gp	5935gp				8382vg			

Additional formation data, including elevations and thicknesses, are available in separate spreadsheet files (https://edx.netl.doe.gov/dataset/supplementary-data-for-trs-geologic-characterization-of-johnson-county-texas).

Depths are based on well reports and geophysical logs from the Texas RRC (2014, 2015) and IHS Enerdeq (2015). All depths are in feet.
Depth and geologic notations are given at the end of Table A1.

Additional depth notations:
d, dr – depth from the well data report; vd – vertical depth from the well data report
egp – estimated from geophysical log, but with some uncertainty, evg = estimated vertical depth from the geophysical log, corrected to vertical depth.

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