PETROPHYSICAL STUDY OF THE LOWER SAN ANDRES FORMATION IN WESTERN YOAKUM COUNTY, TEXAS: USING CLASSICAL EXPLORATION TECHNIQUES FOR IDENTIFYING DEPRESSURING TARGETS IN THE UPPER RESIDUAL OIL ZONE (ROZ)

APPROVED BY SUPERVISORY COMMITTEE:

Dr. Robert Trentham, Ph.D.
Chair

Dr. Sumit Verma, Ph.D.

Dr. Joonghyeok Heo, Ph.D.

Dr. Shawn Watson, Ph.D.
Graduate Faculty Representative

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By

NORMAN E. WELLS, JR., B.A.

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ABSTRACT

The lower San Andres limestone that lies above the Yellowhouse dolomite is a deep open-marine highstand deposit. This limestone does not have an consistent isopachous slope, even though it is nearly 400 feet thick in the north of the study area and pinches out approximately five miles from the Yoakum-Gaines County border in the south. Two possible reasons for this are fractures in the isopachous thins could be a conduit for dolomitizing liquids from deeper formations prior to oil movement, or sabkha-reflux dolomitization from the Wasson Field structure. The limestone is not a vertical barrier to flow for the horizontal depressuring of the upper residual oil zone (DUROZ) wells, due to their landing zone and depth of the limestone. However, new terminology was developed based on observations of where most of the DUROZ wells are landing and producing. Also, there are "pressure shadow" concerns in the proximity of the conventional fields.

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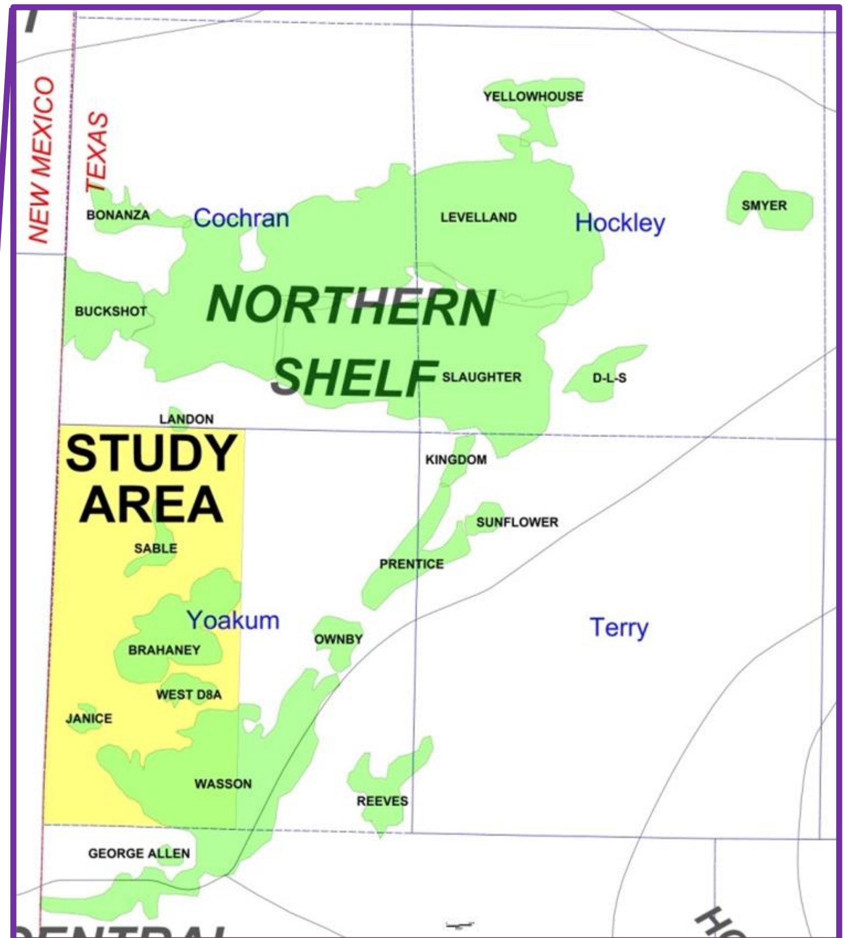
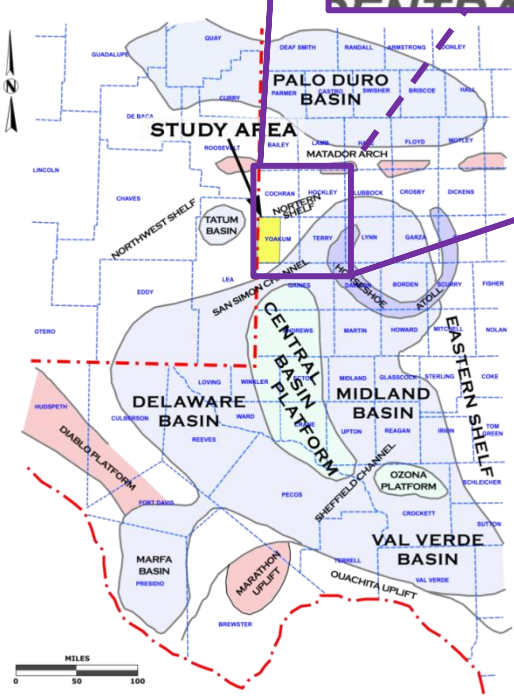
CHAPTER 1 - Introduction

With the renewed interest in the lower San Andres formation due to the residual oil zone (ROZ) horizontal play, western Yoakum County, Texas, has become an area of interest for new drilling activity. Although Yoakum County has been producing oil from the San Andres formation since the first well was drilled and completed in 1936 – Honolulu Oil Corporation and Davidson Drilling Company #1 L. P. Bennett, in what is now known as the Wasson Field (Smith, 2016) – the advent of production from the ROZ has shifted interest from the conventional "main pay zone" (MPZ) to a zone that previously had been considered primarily unproductive or non-commercial (Trentham and Melzer, 2011; Trentham 2011, 2017; Melzer, 2012, 2016; Trentham, Melzer, and Vance, 2012; West, 2014a & b; Melzer, Trentham, and Vance, 2016; Melzer and Trentham, 2016; Hall, 2016, 2017; Worrall and Hanagan, 2016; Taylor, 2017). However, geological challenges are still a main issue and concern for many operators, partly because a majority of the San Andres studies conducted have either been broad regional studies or centered upon local fields.

The San Andres on the Northern and Northwest Shelves (Figure 1), as described in Ramondetta (1982a) and Elliot and Warren (1989), is a series of cyclical regressive shallow marine carbonate ramp facies that grade to anhydrite to the north. It is because of this cyclic nature that the San Andres is such a prolific oil producing formation, because

FIGURE 1 – Map depicting the location of the Northern Shelf of west Texas and associated major conventional producing oil fields. Modified after Purves (1986) and "Permian Basin Stratigraphic Charts and Province Map" (Retrieved from http://rkingco.com/industry/permian-basin-geology/).





Modified after Purvis (1986) and "Permian Basin Stratigraphic Charts and Province Map" (Retrieved from http://rkingco.com/industry/permian-basin-geology/)

the formation of porosity, or its absence, is dependent on the environment of deposition and later facies specific diagenesis. Multiple overlapping (or stacked) porosity zones thus developed separated by non-porous anhydrite, or limestone, which can easily be observed on petrophysical logs and core; this in turn provides multiple zones of interest in a single well bore, as long as a suitable trapping mechanism can be determined.

Importance of the Study

There appears to be a highstand related basinal type limestone that is a few hundred feet (ft) thick near the Cochran-Yoakum County line, which pinches out to the south, just shelf-ward of Wasson Field a few miles north of the Gaines-Yoakum County boarder. This limestone (as observed on mud and sample/strip logs) appears to be a deeper marine mudstone to wackestone, which is interbedded with dolomite (as observed on petrophysical logs). The presence of this limestone could affect the overall production of the San Andres ROZ by thinning the overall potentially productive porosity interval, enabling greater oil production in the ROZ play by creating a barrier to the lower “big water” intervals, or it could be a stratigraphic trapping mechanism where porous, interbedded dolostones pinch out.

Study Objectives

There are three main objectives to this study; they are 1) to determine the overall thickness and extent of the lower San Andres limestone within the study area, 2) to determine a geologic explanation for why the limestone is present, and 3) to determine if the limestone has any effect on current San Andres horizontal ROZ production within western Yoakum County, TX. These objectives will be accomplished through petrophysical analysis, modeling (such as mapping and cross-sections), and analyzing production data from horizontal San Andres wells.

CHAPTER 2 – Regional Setting

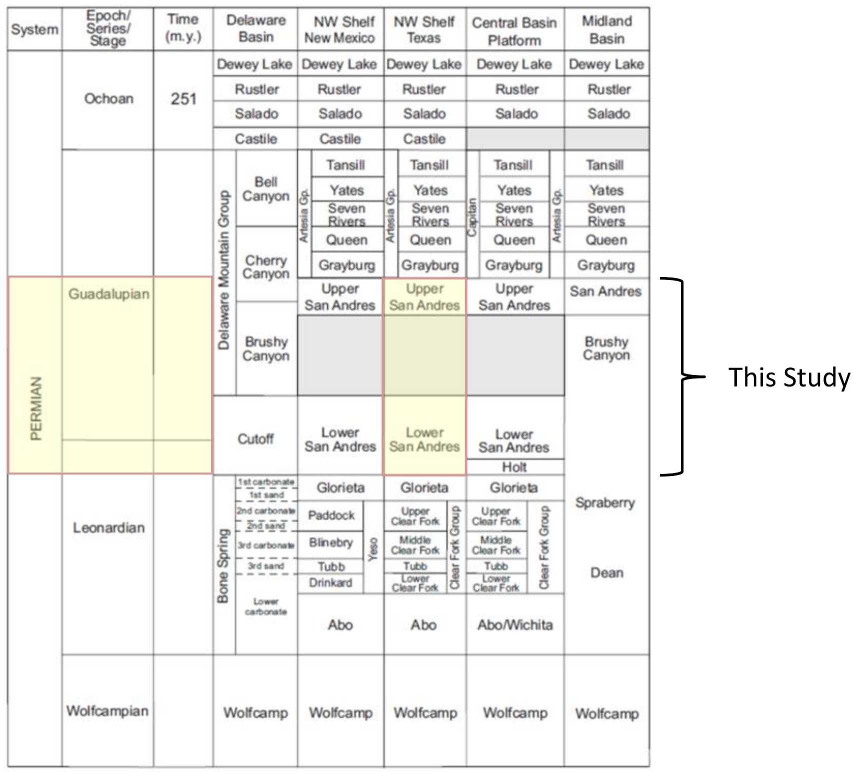
Permian Basin

The Permian Basin of west Texas and southeastern New Mexico covers approximately 115,000 square miles (mi^2) (300,000 square kilometers [km^2]) (Ward et. al., 1986), was originally shaped by the collision of the super continents Laurasia and Gondwanaland during the late Mississippian through Permian Periods (see Stratigraphic Charts, Figure 2) which resulted in the formation of the Ouachita-Marathon Fold Belt (southern boundary of the Permian Basin) (Elliot and Warren, 1989). The overall Permian Basin area is subdivided into multiple oil productive sub-structures and basins which include the Central Basin Platform, the Delaware Basin, the Eastern Shelf, the Midland Basin, the Northern/Northwest Shelves, and the Tatum Basin (Figure 1). It was during the late Pennsylvanian and Early Permian periods (Wolfcampian age) that subsidence reached a maximum in both the Delaware and Midland Basins, which allowed for the resultant structural uplifts to form carbonate platforms that separated the smaller basins (Beserra and Dorobek, 1994; Ramondetta, 1982b). The Permian Basin complex gets its name from these carbonate structural highs which ultimately rimmed the basin during the Permian period (Elliot and Warren, 1989) and are observed in areas to the east, west, and south.

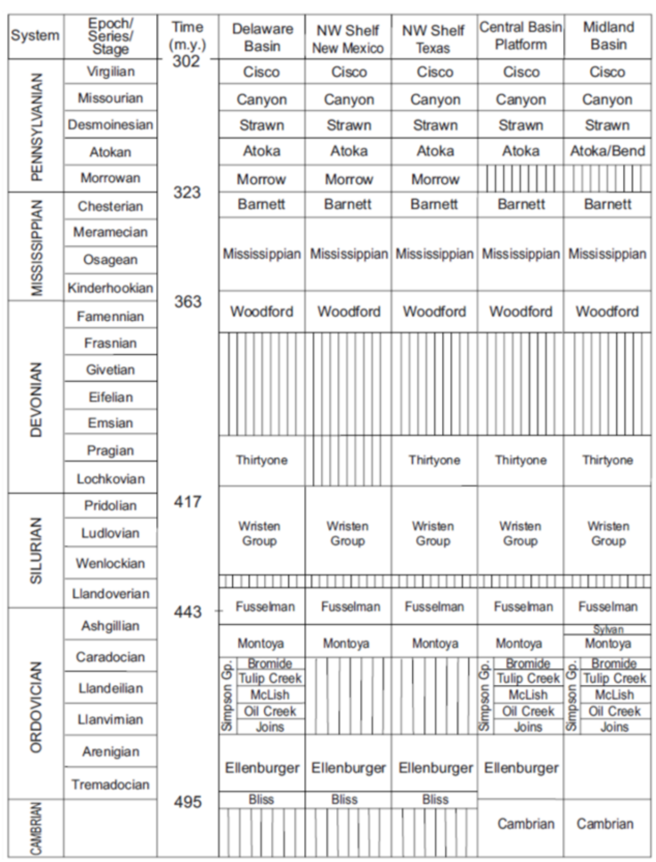
During the later Cretaceous period, the Laramide tectonics, centered in Colorado, uplifted the entire western region (West, 2014). During the early

FIGURE 2 – a. Permian Stratigraphic Section of the Permian Basin (Modified after Dutton et. al., 2004). b. Pre-Permian Stratigraphic Section of the Permian Basin (from Dutton et. al., 2004).

a)



b)



Modified after Dutton et. al. (2004)

FIGURE 3 – Stratigraphic Section of upper Leonardian through middle Guadalupian of the Permian Basin (Modified from Kerans, 2006).

This Study

	Guad Mts.	Downdip Northwest Shelf NM	Updip Northwest Shelf NM	Delaware Basin	Updip Northern Shelf TX	Downdip Northern Shelf TX	Downdip Northern Shelf Local	Central Basin Platform	Eastern Shelf, NE Midland Basin
	Guad. 10	Grayburg 1 Premier Sand	Evaporites	U. Cherry Cnyn	Evaporites	Grayburg		L. Grayburg	L. Grayburg
Upper San Andres Composite Seq. CS10	Guad. 9	Upper S.A. Lovington Sand	Evaporites	L. Cherry Cnyn	Evaporites	Upper S. A.		Upper S.A. Lovington Sand	
	Guad. 8	Upper S.A.	P1 - 3		Slaughter 1-3	Upper S. A. Pi Marker		Upper S.A.	Upper S.A. Cedar Lake, Welch
	Guad. 7								
	Guad. 6			Brushy Canyon					
	Guad. 5								
Lower San Andres Composite Seq. CS9	Guad. 4	Upper S.A. 2	P4		Slaughter 4	P0 - 1	P0 - Chamblis	San Andres	
	Guad. 3	Upper S.A. 1	P5		Slaughter 5	P2 - 3	Brahaney "B" - "C"	San Andres	San Andres
	Guad. 2	Middle S.A. 2	P6	U. Bone Spring or Cut Off		P4	Brahaney "D"	McKnight Shale	
	Guad. 1	Middle S.A. 1	P7			P5	Brahaney "E"		
	Leon. 8	Lower S.A. 2	P8			P6	Yellowhouse	Holt	Lower S.A.
	Leon. 7	Lower S.A. 1	P8	Pipeline Shale		P7	P7		Howard, Glasscock, Iatan, Diamond M
	Leon. 6	Glorieta	Yeso	Bone Spring	Glorieta	Glorieta		Glorieta	San Angelo

Modified after Kerans (2006)

= Zones Discussed

Oligocene period the Trans-Pecos Magmatic Province began, which includes intrusives and volcanics along the south-western Permian Basin margin (Trentham, 2018). After the cessation of the volcanics, while still in the Oligocene, there is a transition to Basin and Range tectonics which continued through the Early Miocene, ultimately creating the mountain ranges (Guadalupe, Apache, San Andres, etc.) and tilting the Permian Basin eastward (West, 2014; Trentham, 2018). The San Andres formation in this area became uplifted over 7000ft by these processes, with a gradient across the Delaware Basin of over 80 miles (mi), with the Guadalupe Mountains at 6000 ft above sea level and the CBP of 1000 ft below sea level (Trentham, 2018).

The first commercial oil well drilled in the Permian Basin was located on the Eastern Shelf and completed in 1921 within the Westbrook Field of Mitchel County, Texas. The well was drilled to a depth of 2,500 feet (ft) total depth (TD) and produced from the lower San Andres Formation (Figure 3) at 10 barrels of oil per day (BOPD) (Trentham, 2016; Vertrees, 2019; Ward et. al., 1986.) Since then a number of world class, and quite a few more marginal, oil fields have been discovered and produced within the Permian Basin, most notably the Yates Field located in Pecos County, Texas (1.18 billion barrels [Bbbl] of oil by 1989) and the Wasson Field, the largest-volume producing field in West Texas, located in Gaines and Yoakum Counties, Texas (1.82 Bbbl oil by 1992) both producing primarily out of the San Andres formation (Smith, 2010; Smith, 2016). Overall, through the year 2000 the Permian Basin has produced over 30 billion barrels out of its multiple productive zones (Dutton et. al., 2004).

San Andres Formation

The San Andres Formation extends west to east from Arizona and Utah to central Texas, and from southern Texas in the South up to the Texas Panhandle, Oklahoma, and Kansas in the north. The San Andres constitutes a primary low angle carbonate ramp environment in the south and grades northward to anhydrite, salt, and ultimately red beds (Ramondetta, 1982a&b). The San Andres formed during the middle Permian Period (upper Leonardian to lower Guadalupian; see Stratigraphic Charts, Figures 2 and 3) formed under arid conditions near the equator in a warm shallow sea (Garcia-Fresca et. al., 2012; Pitt and Scott, 1981). Within the Permian Basin, the San Andres is a series of interbedded prograding cyclic depositional carbonate to evaporite deposits, interbedded occasionally with siliclastics that represent environments ranging from the subtidal deep marine through supratidal aerially exposed (Elliot and Warren, 1989; Pitt and Scott, 1981). Stratigraphically the San Andres formation is bounded by the late Leonardian Glorieta Formation in Texas (upper Yeso Formation in New Mexico), which is carbonates and siliciclastics (Beserra and Dorobek, 1994; Hinrichs et. al., 1986). The San Andres is overlain by the middle Guadalupian Grayburg Formation which consists of carbonates and siliciclastics (Ramondetta, 1982a).

Regionally, the San Andres Formation has been studied in great detail by numerous scientists since the early 1900's: Lee and Girty in 1909, followed by N. H. Darton, R. I. Dickey, F. E. Lewis, P. B. King, J. E. Galley, and P.T. Hayes, from 1922 through 1964, who hypothesized whether the age of the San Andres was Leonardian or Guadalupian (Ramondetta, 1982). However, it wasn't until the mid- to late-1980s that it was determined that the lowest portion of the San Andres was in fact late Leonardian (L7-L8), by Kerans, and then extended into the early Guadalupian (G1-G4 and G8-G9) (Kerans, 2006) in which biostratigraphy and stratigraphy were utilized to determine the ages (Wilkinson et. al., 1991). There have been numerous studies on the San Andres exposed in outcrops of the Guadalupe and Sacramento mountains (Ward et. al., 1986), while other workers have extended our knowledge of the outcrops through to the sub-surface to better understand productive fields (Pitt and Scott, 1981; Hinrichs et. al., 1986; Wilkinson et. al., 1991; Beserra and Dorobek, 1994; Kerans and Ruppel, 1994; Garcia-Fresca et. al., 2012; Kerans et. al., 2017; and others).

The facies tracts observed within the San Andres can best be described as shallowing upward sequences formed during subsequent regression of multiple overlapping high stands (Hinrichs et. al., 1986; Ramondetta, 1982a). Beserra and Dorobek (1994) note that the San Andres has been considered as only having a single shallowing upward interval (most notably by L.A. Elliot, P.D. Hinrichs, and J.K. Warren); as having two third-order sequences (by J.F. Sarg and P.J. Lehmann), and as having three "major" depositional phases (by W.M. Fitchen). Kerans and Ruppel (1994) have subdivided the San Andres into two low composite sequences (upper and lower), with fifteen (15) high frequency sequences (HFS), aged from Leonardian-4 (L4) through Guadalupian-13 (G13). However, Kerans in 2006 revised his stratigraphic correlations (Figure 3) with the lower San Andres composite sequence containing L7, L8, G1, G2, G3, and G4, with the upper San Andres composite sequence containing G5 though G9 (or eleven [11] HFSs). It is interesting to note that G5 though G7 lowstand deposition is nearly non-existent across the Permian Basin, except for the Delaware Basin's Brushy Canyon Formation (Kerans, 2006).

The Basin and Range tectonics that not only tilted the Permian Basin, but created the mountain ranges along its northwestern edge, exposed the San Andres Formation at the surface which also allowed for meteoric waters to enter and recharge the formation, facilitating the eventual creation of the ROZ (Lindsay, 1998 & 2018; West, 2014a&b; Trentham et. al., 2012). The meteoric waters moved through the oil wet San Andres and flushed a large volume of the oil out of the Permian Basin – some oil being converted by anaerobic bacteria resulting in the sulfur deposits in Pecos County Texas at the southern end of the CBP, through aerial exposure and bacterial interaction (Trentham et al, 2011) – and thus creating the ROZ, while also being the catalyst for massive diagenetic changes (Lindsay, 1998 & 2018; West, 2014; Trentham et. al., 2012). These diagenetic changes include, but are not limited to, fabric and textural changes (i.e. recrystallization and dolomitization) as well as porosity loss or alteration and development (i.e. cementation, evaporite growth, and allochem dissolution). The meteoric influx, that is still occurring today, generates a tilted OWC that can be seen in a majority of the fields in the Northern/Northwest Shelves and CBP (Brown, 2002; Lindsay, 1998; Trentham, 2011, 2017, & 2018; Trentham and Melzer, 2011).

The San Andres Formation of the Permian Basin is one of the most prolific oil producing intervals and has been a primary objective for producers for multiple years (Pitt and Scott, 1981). The San Andres has produced 3.97 Bbbl oil from the Northern Shelf and 2.15 Bbbl oil from Platform Carbonates (6.12 Bbbl oil cumulative), or approximately 25%

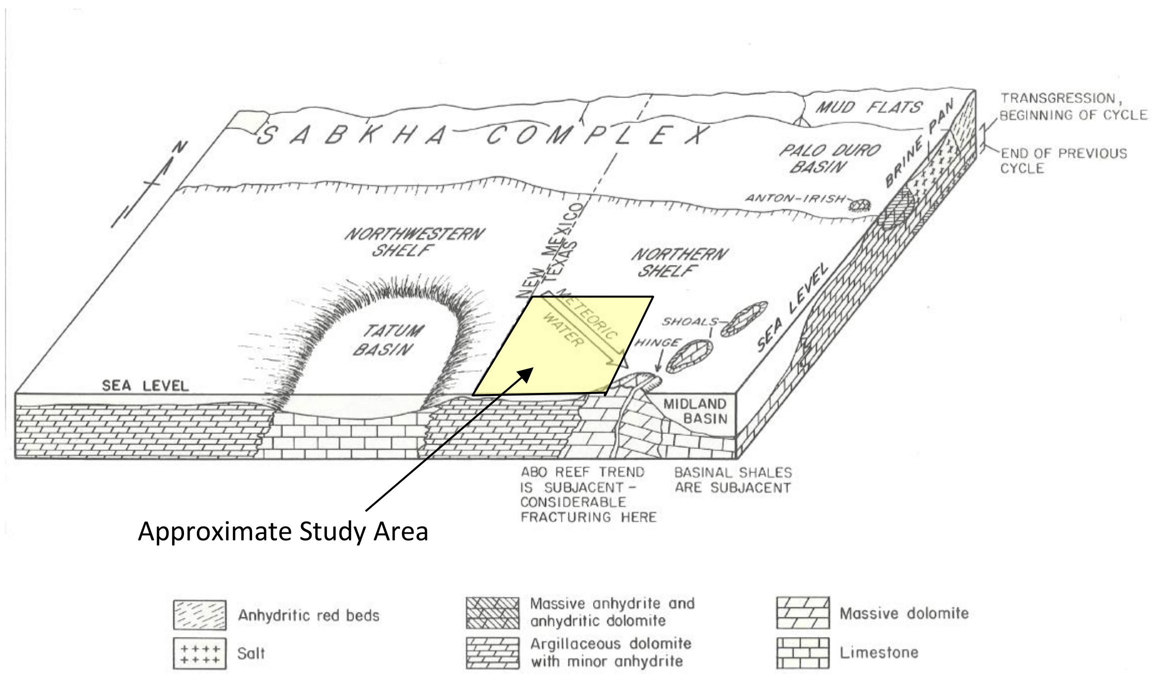
of the overall oil recovered from the Permian Basin (Dutton et. al., 2004; Kerans et. al., 2017). Due to this fact, the importance of understanding the San Andres Formation cannot be overstated. However, with the advent of the San Andres ROZ plays located on the Central Basin Platform (CBP) and Northern/Northwest Shelf, the importance of the San Andres has become even greater as the technology and understanding of this reservoir evolve.

Northern/Northwest Shelves

This author will use the delineation of the Northern and Northwest shelves as described by Ramondetta (1982a), in which the New Mexico-Texas state line is arbitrarily used as follows: the Northern Shelf is located in Texas, and the Northwest Shelf is located in New Mexico. The San Andres Formation on the Northern and Northwest Shelves is a series of cyclical and progradational carbonate ramp deposits that developed southward (seaward) over time (Ramondetta, 1982a; Silver and Todd, 1969). The Northern and Northwest shelves of the Permian Basin are separated from the Midland and Delaware Basins by the structural ridge created by the deeper Leonardian Abo Reef Trend, and ultimately the lower Wolfcampian shelf margin (Ramondetta, 1982a; Silver and Todd, 1969). The San Andres deposition along the Abo Reef Trend paleo-structure was primarily shelf-margin shoal and bank deposits, which extends west to east from Eddy County in eastern New Mexico to Hockley County in western Texas (Ramondetta, 1982a), and along with the Eastern Shelf forms a broad horse-shoe shaped feature around the northern Midland Basin (Elliot and Warren, 1989). The San Andres on the Northern and Northwest Shelves consists primarily of carbonate shelf-margin deposits that range from subaqueous basinal carbonates to supratidal sabkha evaporite deposits, which reflect a clear relationship with the deeper structure (Pitt and Scott, 1981; Ramondetta, 1982a). The carbonate facies of the Northern and Northwest Shelves were deposited in a broad shallow marine environment, extend south onto the Central Basin Platform and west into New Mexico (north of the Delaware Basin), while grading into a more sabkha like environment to the north in the Palo Duro Basin (Figure 4) (Ramondetta, 1982a&b).

Located in Lea County, New Mexico, almost along the border of Texas, the smaller Tatum Basin (Figures 1 and 4) became filled; by the time of the San Andres, the carbonate shelf deposits of the Northwest Shelf having already prograded south over much of this basin (Ramondetta, 1982b; Grover, 1993b). Unlike the rest of the Northern Shelf, the porous dolostones (rock made primarily of dolomite) grade into tight limestone instead of evaporites towards the Tatum Basin, unlike towards the north where the dolostones grade into anhydrites (Ramondetta, 1982a).

FIGURE 4 – Block diagram of depositional environments during early San Andres along Northwest and Northern Shelves (Modified from Ramondetta, 1982a).



Modified after Ramondetta (1982a)

CHAPTER 3 – Sub-Regional Setting

It is interesting to note that throughout the research that this author has conducted no broad sub-regional or county wide geological studies have been found on the San Andres Formation of the Northern Shelf. Instead, the majority of the works appear to concentrate on the productive fields only, which, in retrospect, makes sense since that is where companies have made their money. However, with the advent of the ROZ play, brownfields (or where there is already production from overlying MPZ) are not the only areas with the potential to produce from the San Andres. Instead, greenfields (areas with no conventional MPZ, or considered non-productive or uneconomic) have now been shown to be productive from the San Andres ROZ; for instance, the Tall Cotton (San Andres) Field located in Gaines County, Texas, has produced nearly 2 million barrels (MMbbl) oil and over 2 billion cubic feet (bcf) in a vertical CO_2 flood (IHS Enerdeq) from July 2014 through October 2018 from 30 wells (Kinder Morgan, 2018; Melzer, 2017). This suggests a need for more broad ranged sub-regional geological studies, especially in areas and formations with a ROZ potential.

The next two sections will describe the field studies that have been conducted on the San Andres fields in both the sub-regional area of the Northern Shelf, and then describe the smaller study area (western Yoakum County) and the fields within.

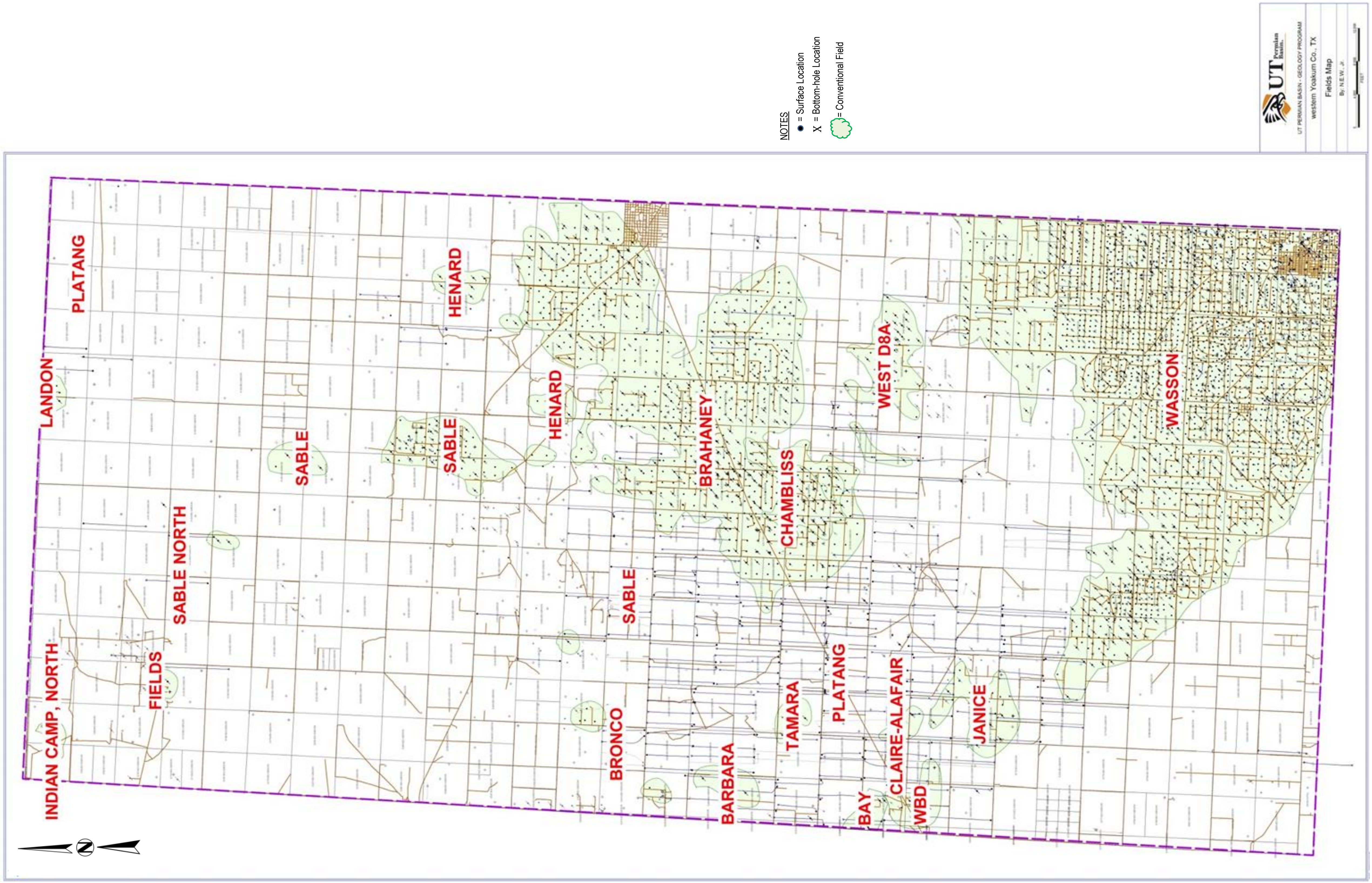
Northern Shelf Oil Field Studies

The Northern Shelf of the Permian Basin consists primarily of Cochran, Hockley, and Yoakum Counties, along with portions of Gaines and Terry Counties, located in western Texas (Figure 1). There are multiple producing San Andres fields (Figure 1) on the Northwest Shelf, most notable are the Wasson (2.21 billion barrels oil cumulative), Slaughter (1.39 billion barrels oil cumulative), and Levelland (777.5 million barrels oil cumulative) (cumulative production is from inception through October 2018; contains production for fields with prefixes or suffixes such as "East", "West", etc.; data retrieved from IHS Enerdeq). A majority of the studies published on the Northern Shelf consists of specific field studies (i.e. Brown, 2002; Cowan and Harris, 1999; Danielli, 1995; Hagar and Heathcote, 1986; Henderson et al, 1995; Masterson, 1985; Mathis, 1986; Smith, 2010; Winfree, 1995), usually on the largest productive fields (such as those mentioned above), even though there are a multitude of smaller producing fields in the study area. These studies describe the Northern Shelf depositional environment using the same terminology discussed in the Regional Study section of this study. These studies concentrate specifically on the depositional series and rock types that make up the large fields, such as 1) Wasson field: Mathis (1986), Brown (2002), Winfree (1995); 2) Reeves field: Henderson et. al. (1995), Chuber and Pusey (1972), Danielli (1995); and, 3) Slaughter and Levelland fields: Cowan and Harris (1999), Masterson (1985), Watson (2005). More recently, talks have been given on a general area of the Northern Shelf outlining the challenges associated with ROZ/DUROZ potential and production (Hall, 2016, 2017, 2018; Melzer et. al., 2016; Rodriquez and Changrui, 2017; Taylor, 2017; Trentham, 2017; Worral and Hanagan, 2016). Although these presentations give a general overview of each operator's or consultant's area of interest, along with completion methods and production statistics, they lack specifics and geological research beyond the formations, and/or depths, and areas where they are producing, or concepts they are trying to convey (i.e. ROZ or DUROZ).

Study Area

The study area is restricted to western Yoakum County, Texas (Figure 1), west to east from the Texas-New Mexico border to Texas State Highway-214 (TX-214) and north to south from the Cochran County to Gaines County, Texas, county lines. Within this area there are multiple San Andres fields, including Barbara, Bay, Brahaney, Flaire-Alafair, Broncho, Fields, Henard, Janice, Landon, McFall, North Indian Camp, Platang, Sable, Tamara, Wasson, WBD, and West District 8A (Figure 5). There is, or have been, approximately 4,586 productive wells (255 horizontal and 4331 vertical or directional) within the study area, that have produced 720.2 million barrels oil and 956.5 billion cubic feet gas (as of December 2018; IHS Enerdeq). Most of the production has come out of the Permian Basin's largest producing field, the Wasson Field, which has produced 84% of the oil and 91% of gas recovered within the study area (recovered from IHS Enerdeq). The Wasson field consists of multiple units, where smaller individual leases were consolidated and formed into a larger unit under a single lease agreement, usually under a single operator. The Wasson Field units that are within the study are: Cornell Unit, Denver Unit, Roberts Unit, and the Willard Unit (Figure 6). These units are important

FIGURE 5 – Map depicting the Study Area with productive fields named. Highlighted in green are the conventionally drilled and produced oil fields.



NOTES
● = Surface Location
X = Bottom-hole Location
= Conventional Field
UT Permian Basin
UT PERMIAN BASIN - GEOLOGY PROGRAM
western Yoakum Co., TX
Fields Map
By: N.E.W., Jr.
PLATANG
LANDON
INDIAN CAMP, NORTH
FIELDS
SABLE NORTH
SABLE
SABLE
HENARD
HENARD
SABLE
BRONCO
BARBARA
BRAHANEY
CHAMBLISS
TAMARA
PLATANG
BAY
CLAIRE-ALAFAIR
WBD
WEST D8A
JANICE
WASSON

FIGURE 6 – Map depicting the Wasson Field's unitized leases.

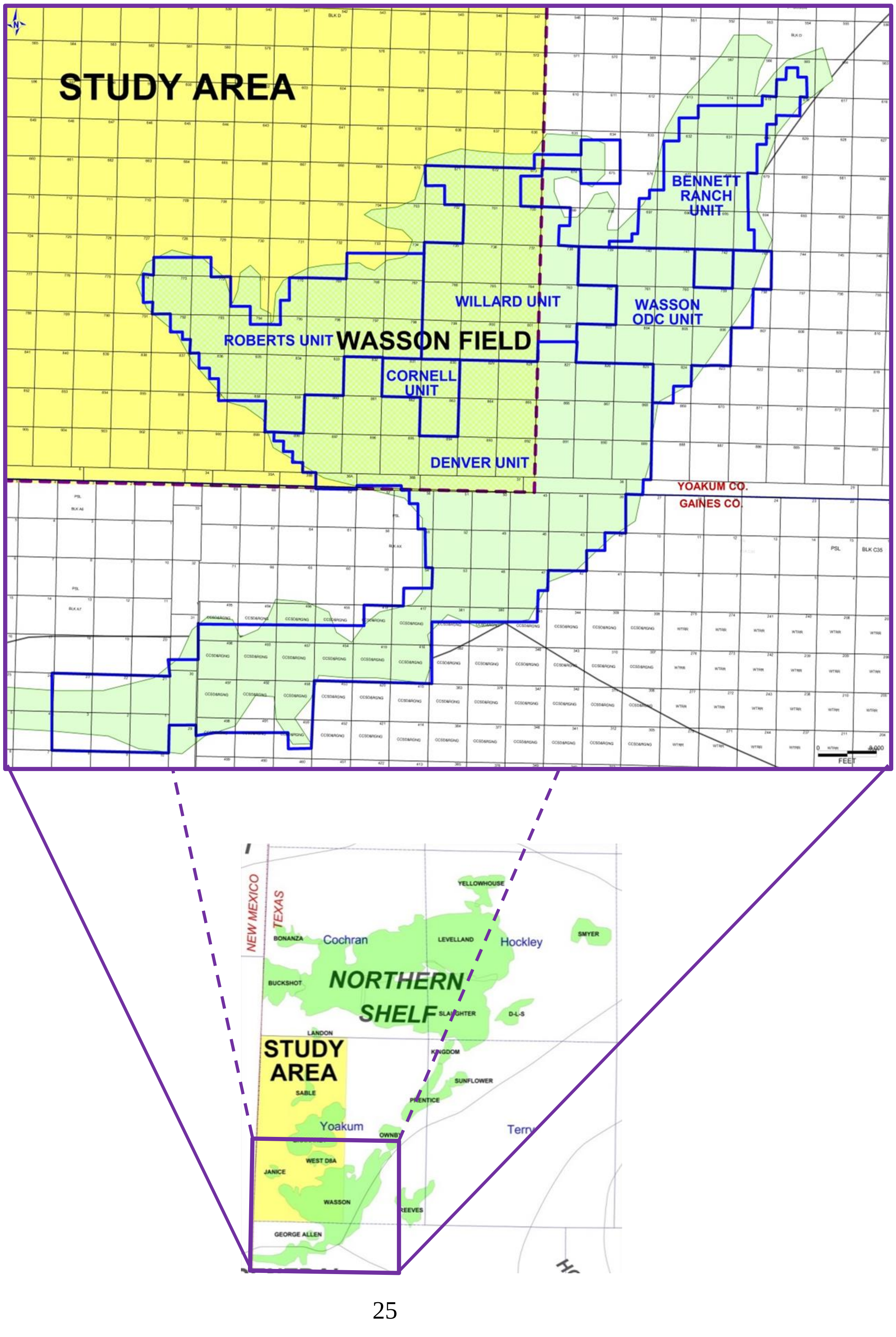
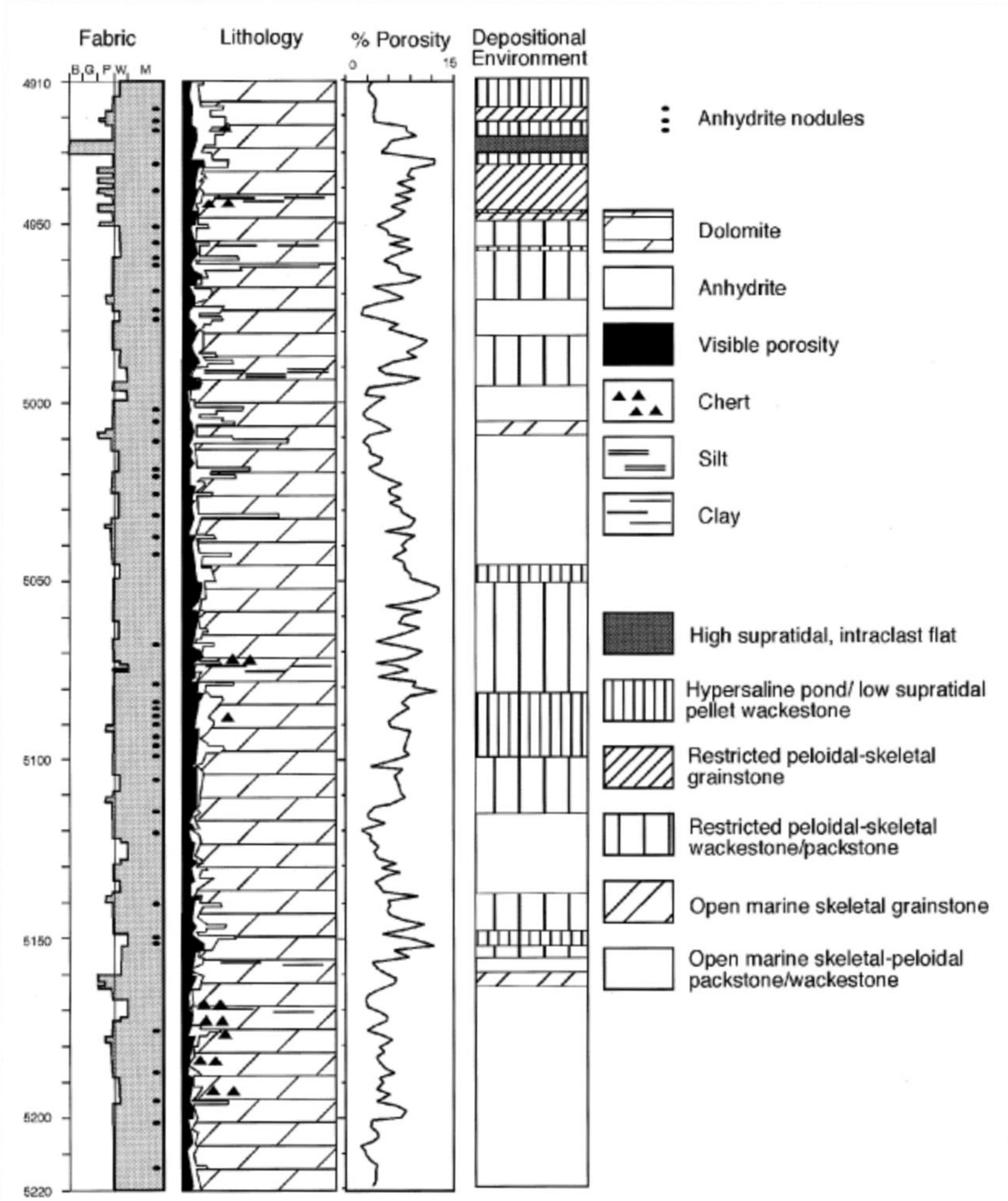

STUDY AREA
WASSON FIELD
WILLARD UNIT
ROBERTS UNIT
CORNELL UNIT
DENVER UNIT
BENNETT RANCH UNIT
WASSON ODC UNIT
YOAKUM CO.
GAINES CO.
NEW MEXICO
TEXAS
YELLOWHOUSE
BONANZA
Cochran
LEVELLAND
Hockley
SMYER
BUCKSHOT
NORTHERN SHELF
SLAUGHTER
D-L-S
LANDON
STUDY AREA
KINGDOM
SUNFLOWER
SABLE
PRENTICE
Yoakum
OWNBY
Terry
WEST DBA
JANICE
WASSON
REEVES
GEORGE ALLEN

FIGURE 7 – Generalized core description from within the Wasson Field, depicting carbonate depositional facies. (Retrieved from Brown, 2002)

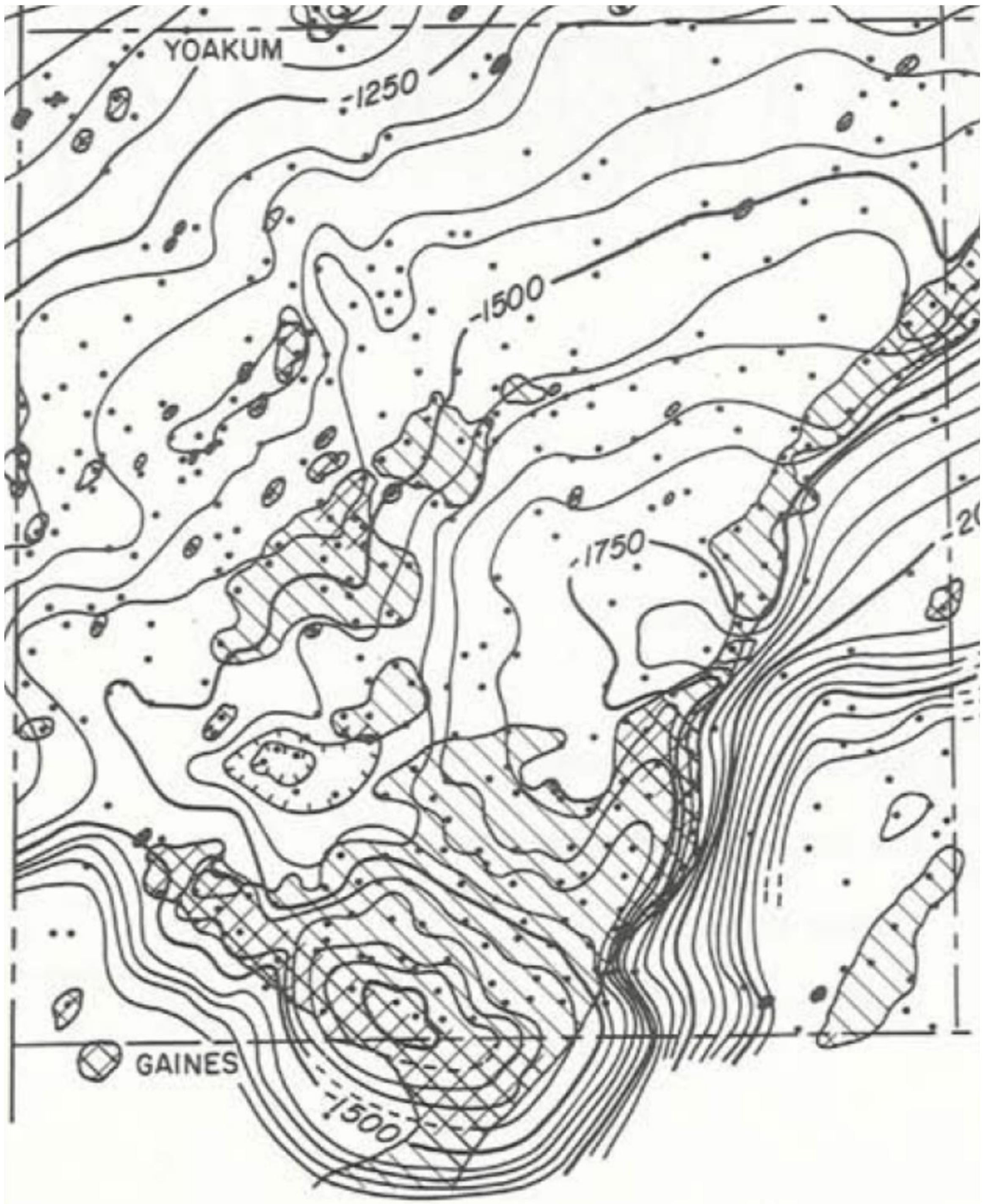


Retrieved from Brown (2002)

because most studies concentrate on a single unitized portion of the Wasson Field, not the field as a whole.

Mathis (1986) described the Denver Unit, while Brown (2002) described the Willard Unit of the Wasson Field. Both have determined that the lower San Andres interval contains primary reservoir rock in which the primary depositional environment was a shelf-margin bank deposit, while the upper San Andres depositional environment consisted mostly of intertidal lagoonal to supratidal sabkha environments (Figure 7). This corresponds to the interpretation from the larger regional studies conducted by Ramondetta (1982a&b) and Silver and Todd (1969). There also appears to be a stacking pattern to the depositional environments of the San Andres, which can be explained by the Wasson field overlying the deeper Abo Reef trend (Ramondetta, 1982b; Brown, 2002). The Wasson structure (Figure 8) is bounded on the southeast and southwest by step flanks of up to 400 feet per mile, while on the north flank the dip is usually less than 100 feet per mile (Brown, 2002). The primary reservoir rocks of the lower San Andre have been described as dolomitized open-marine shoaling upward sequences that are comprised of skeletal dolo-wackestone and dolo-packstones at the base and grade to thinly laminated supratidal and hypersaline strata forming the seal (Mathis, 1986; Brown, 2002). However, the upper San Andres of the Wasson Unit is comprised of sequences of supratidal and hypersaline mud-flat or pond deposits that are representative of the sabkha environment (Brown, 2002).

FIGURE 8 – Map showing the top of the Pi Marker Structure. Notice the steep gradient to the south and southwest of the Wasson Field. (Retrieved from Ramondetta, 1982a)



Retrieved from Ramondetta (1982a)

It is unfortunate that no other field studies outside the Wasson Field have been found within the study area. This is likely due to the prolific production and importance of the Wasson Field. However, a few brief field descriptions of the Brahaney, Henard, and Wasson fields were made by Herald (1957). Brahaney Field and Henard Field reservoirs, due to their relative proximity and relationship, have been described as being upwards of 225 ft thick (30 ft effective net pay), produce from the sufficiently porous upper zone, and are primarily light gray to brown finely crystaline dolomite with scattered chert nodules and streaks of dark gray shale (Herald, 1957). The Brahaney/Henard is anticlinal with a southward plunging nose (Herald, 1957).

CHAPTER 4 - Methods

The thesis study was completed by using a premier petroleum software with capabilities that include geographic information system (GIS) qualities, petrophysical well log handling, database utilization, various map and cross-section creation. The author's familiarity with the program sped the project to completion. TX-214 was chosen as the eastern border of the project as it is a physical landmark that extends from north to south in approximately the center of Yoakum Co. The coordinate grid used for the Petra map is North American Datum 83 (NAD83), State Plane Texas North Central, United States feet (ftUS). Free-use shapefiles were obtained from government and corporate websites (i.e., Texas Department of Transportation [http://gis-txdot.opendata.arcgis.com], Texas General Land Office [http://www.glo.texas.gov], Texas Natural Resources Information System [https://tnris.org], OGI [http://www.oginfo.com]), then imported into individual map layers. Well locations and data were downloaded directly, which automatically populated the map and database. The last update performed on the database to capture new wells and data changes was February 16, 2019. However, the reader needs to be aware that new wells are constantly being drilled, and older wells are being re-permitted or abandoned, and this is not a complete dataset beyond this date.

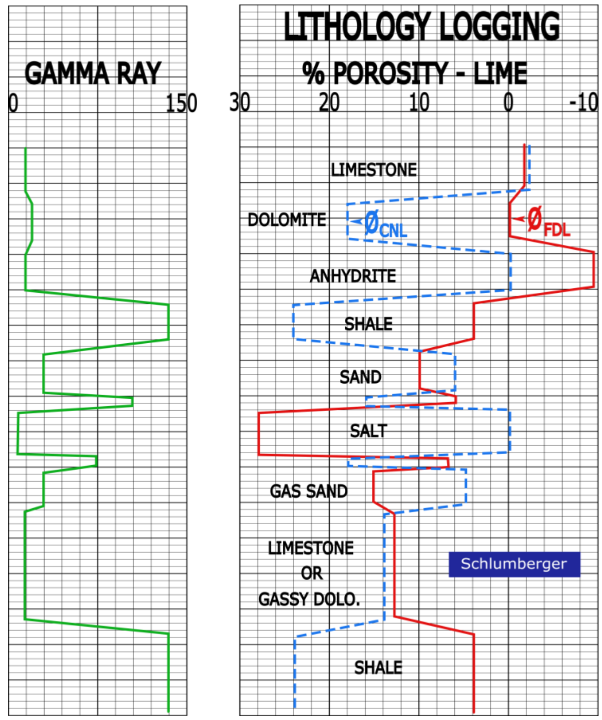
The petrographic study of western Yoakum County, Texas, requires the use of open-hole or cased-hole well logs. However, since the understanding of the limestone in the lower San Andres is the primary goal, this requires the use of Neutron/Density logs, preferably with a photo-electric (PE) curve, to a depth that is adequate to determine both the top and base of the limestone. The majority of open-hole logs are run on limestone matrices where the neutron and density curves should “stack”, or be nearly overlapping, each other when run through a limestone section and separate when registering another formation type (Figure 9) (Mercier, 1951; Asquith and Krygowski, 1982 & 2004). If the PE curve, which measures the formation’s density (Limestone’s density is approximately 5.0 as observed in Table 1 [Asquith and Krygowski, 2004]), is available, then it is used in conjunction with the neutron/density curves to confirm the lithology. Other logs such as Neutron, Sonic, and Resistivity in conjunction with a Gamma-Ray log would be useful for picking the top and base of the San Andres. The Top of the Yellowhouse Formation, a regionally correlative marker, could be picked if neutron logs of quality are available and cross the lithologic boundary of the limestone. Mud logs and sample logs were also collected within the study area and utilized if the log could be depth corrected to an aforementioned petrographic log.

Petrographic, mud, and sample logs were obtained from multiple sources (i.e.: Midland Energy Library [MEL], Subsurface Library [SSL], Drilling Info [DI], and the Texas Railroad Commission [TRRC]). Physical logs from MEL and SSL were gathered and digitized into a raster file using a log scanner, while digital raster logs were downloaded from DI and TRRC websites. After a sub-set of logs was obtained and reviewed, it was determined that the top of the San Andres Formation within the study area is approximately 4,500 feet (ft) Measured Depth (MD) [the length of the wellbore

FIGURE 9 – a. Generalized lithology logging with older combination Gamma Ray, Neutron, and Density logs. This figure depicts the log responses and rock types. (Modified from Asquith and Krygowski, 1982)

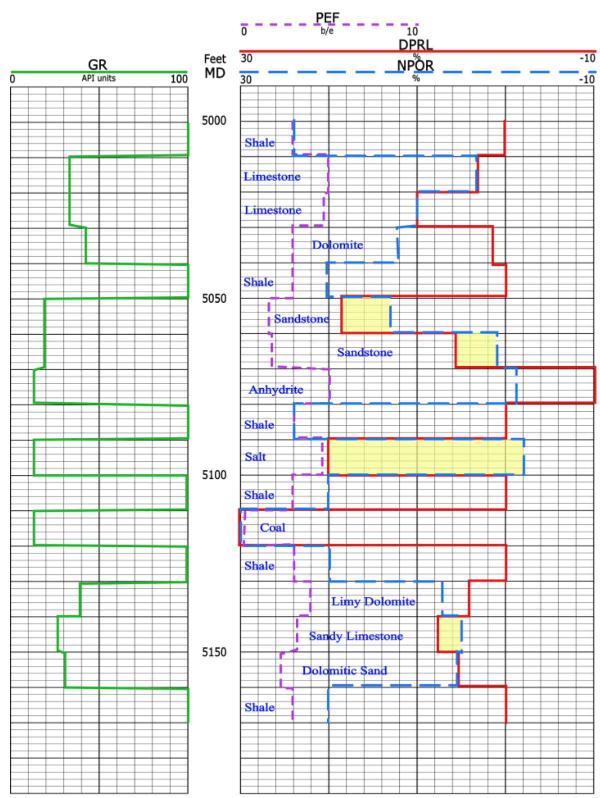
b. Generalized lithology logging with modern combination Gamma Ray, Neutron, Density, and Photo-Electric (PE) logs. This figure depicts the log responses and rock types. (Modified from Asquith and Krygowski, 2004).

a)



Modified after Asquith and Krygowski (1982)

b)



Modified after Asquith and Krygowski (2004)

TABLE 1 – Common lithologies, their matrix densities and photoelectric-effect (Pe) values (from Asquith and Krygowski, 2004).

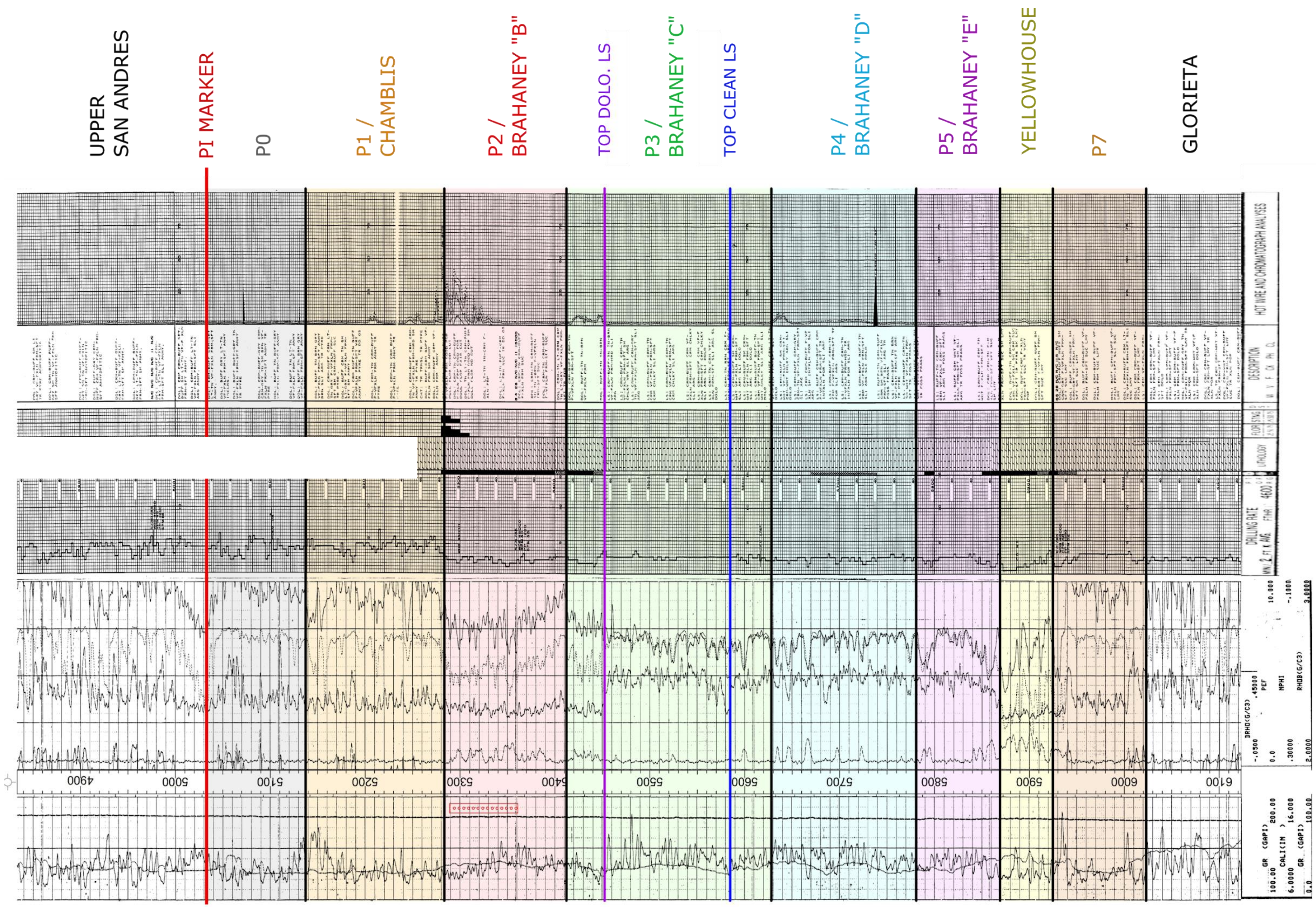
Lithology/ Fluid	ρ_{ma} or ρ_{fl} g/cm^3 [Kg/m^3]	P_e (b/e)
Sandstone	2.644 [2644]	1.81
Limestone	2.710 [2710]	5.08
Dolomite	2.877 [2877]	3.14
Anhydrite	2.960 [2960]	5.05
Salt	2.040 [2040]	4.65
Fresh Water	1.0 [1000]	
Salt Water	1.15 [1150]	
Barite (mud additive)		2.67

Retrieved from Asquith and Krygowski (2004)

(Schlumberger, 2018)] while the base is at approximately 6,000ft MD (see Type Log: Figure 10). Once the Zone of Interest (ZoI) was identified, it was decided that logs greater than 6,000ft MD should be collected and calibrated. Logs were calibrated from 3,500ft MD to 7,000ft MD (where applicable) in order to provide sufficient depth above and below the San Andres Formation to allow for any variances in depth. All logs are calibrated to a specific datum, usually the Kelly Bushing (KB) or Drill Floor (DF) which is some distance above ground level (GL), from which all electric logs are referenced. KB's were populated based on values found on the logs (that were either different or non-existent in the database download), or if the datum was not noted then scout tickets were obtained and values populated from the datum listed on the ticket. If the logs were measured from the DF or GL then the KB value was populated as such and a remark was made stating where the datum came from: this was done for consistency purposes. Appendix A is a table that depicts the unique well identifier or API (American Petroleum Institute) Number value, KB, TD, spud date, and location for wells utilized in this study.

Within the study area there are 1,010 wells deeper than 6,000ft MD, of which 237 are horizontal wells likely drilled to a true vertical depth (TVD) [vertical distance from a point in the well to the surface datum (Schlumberger, 2018)] shallower than 6,000ft in order to produce from the San Andres Residual Oil Zone (ROZ), though a small percentage may have had a pilot hole drilled through the San Andres Formation to explore a landing zone (Worrall, 2016). The earliest Neutron/Density log run on a well within the study area was the Oklahoma Oil Company #1 Prewit, which was conducted

FIGURE 10 – Type Log. Log depicting zones of interest, used to aid in correlating zones on other logs.

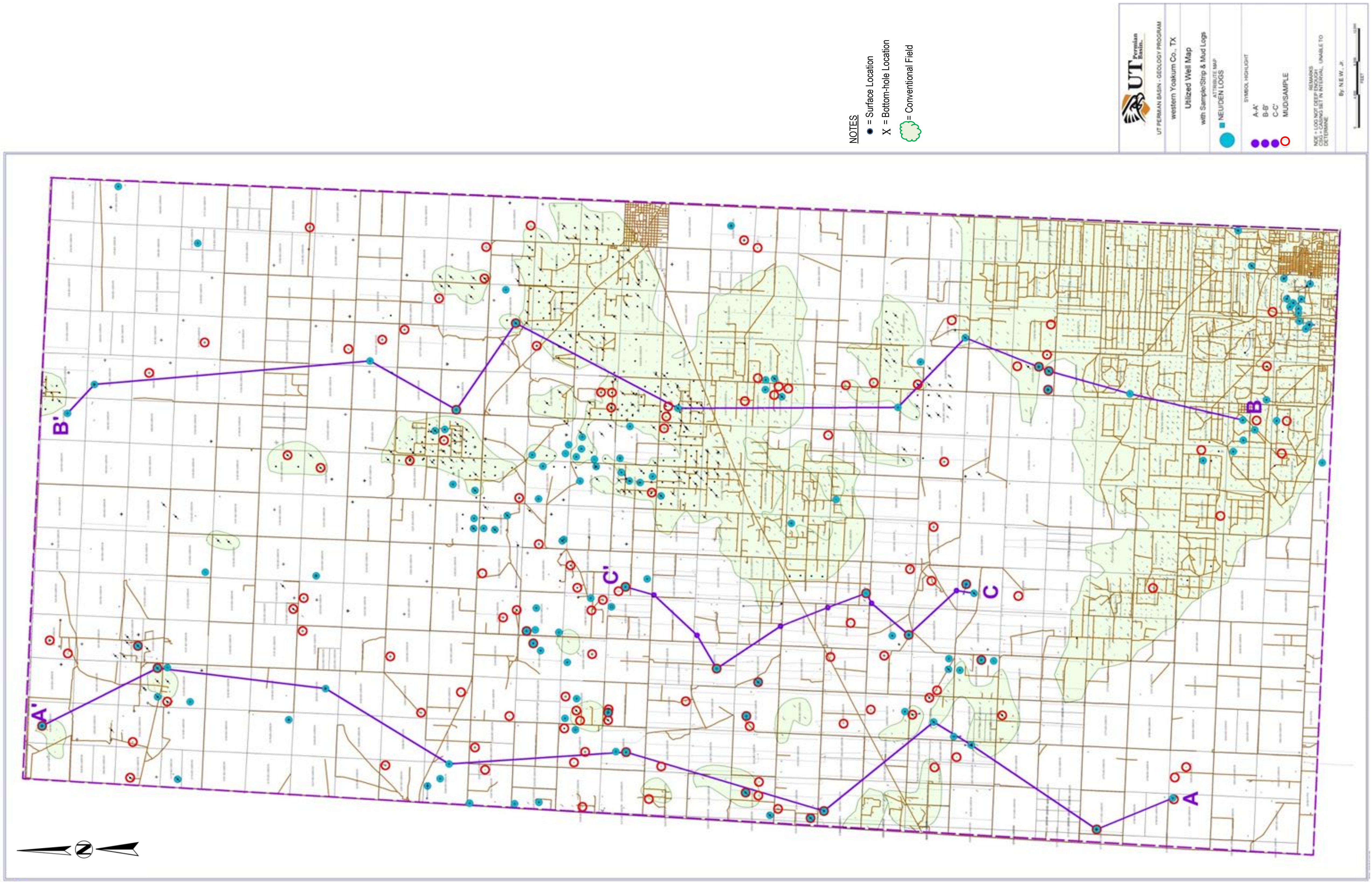


UPPER SAN ANDRES
PI MARKER
P0
P1 / CHAMBLIS
P2 / BRAHANEY "B"
TOP DOLO. LS
P3 / BRAHANEY "C"
TOP CLEAN LS
P4 / BRAHANEY "D"
P5 / BRAHANEY "E"
YELLOWHOUSE
P7
GLORIETA
4900
5000
5100
5200
5300
5400
5500
5600
5700
5800
5900
6000
6100
HOT WIRE AND CHROMATOGRAPH ANALYSES
DESCRIPTION
LITHOLOGY
DRILLING RATE

on November 29, 1976; since then there have been approximately 623 wells drilled or deepened past 6,000ft MD. It is also important to note that there have been 128 horizontal and 20 vertical wells (148 well total) drilled within the past 3 year period (at the time of last database update) allotted by the Texas Administrative Code 9Title 16, Part 1 Chapter 3, Rule 3.16, Part d [Texas Railroad Commission, 2018]) to withhold confidential well information, including well logs. Out of the 623 potential wells, this leaves 475 wells with possible neutron/density logs, yet not all of the wells had these tools run.

Over 348 wells were collected with at least one petrographic log that reached a depth of 6000ft MD or greater (including those older than November 1976) were collected and calibrated into Petra, and out of these 128 contained a neutron/density log. This equates to 34.7% of potential neutron/density logs to have been collected for use in this study, and the overall spatial distribution covers the full study area (see Figure 11). A type log was developed (Figure 10) for correlation purposes that shows the top of the San Andres, Pi Marker, Limestone, Yellowhouse, and Glorieta, as well as the top and base of the Dolomitic Limestone (limestone that has only partly been diagenetically converted to dolomite) segments that are above the top of "clean" limestone. It should be noted that not all of the tops (especially the limestones) were present in all of the logs. Tops were picked based on the method that Mercier (1951) described, and each of the 128 neutron/density logs were correlated as such. Mud logs and sample logs were used primarily to confirm the observations of the petrographic logs. Structural and isopach

Figure 11 – Map depicting all wells utilized for study. Black symbols indicate wells with raster logs, Blue dos indicate wells with Gamma Ray-Neutron-Density logs, while Red Circles indicate wells with Sample/Strip or Mud Logs. All cross-sections referenced in study depicted and labeled.


NOTES
= Surface Location
X = Bottom-hole Location
= Conventional Field
UT PERMIAN BASIN - GEOLOGY PROGRAM
western Yoakum Co., TX
Utilized Well Map
with Sample/Strip & Mud Logs
NEU/DEN LOGS
A-A'
B-B'
C-C'
MUD/SAMPLE
A
A'
B
B'
C
C'

maps, along with structural and stratigraphic cross-sections were then generated by the author (these will be discussed in greater detail later).

Production for the horizontal San Andres wells were also analyzed on a per year basis. This is because as technology and techniques advance throughout time it becomes more difficult to analyze production in wells completed over a one year time span. Both well stimulation (fracking fluid and proppant used) as well as first year production were utilized to compare wells within these single year periods. Generating a proppant ratio (total proppant in pounds [Lbs.] vs total fluid in gallons [gal]) makes it possible to determine which component of a frack is being utilized more, and thus makes it possible to observe the general differences between stimulations. A similar, yet different, technique was utilized to make observations on the overall production. Oil and water cuts, or the fraction of total fluid produced from a well (Schlumberger, 2018), were calculated using the following equations (from Fekete Associates Inc., http://www.fekete.com/san/webhelp/feketeharmony/harmony_webhelp/content/html_files/reference_material/analysis_method_theory/WOR_Forecasting_Theory.htm):

1) $WOR = q_w / q_o$

2) $WOR+1 = (q_w + q_o) / q_o$

3) Water Cut (%) = (WOR / WOR+1) * 100

4) Oil Cut (%) = 100 – Water Cut (%)

Where: WOR = Water-Oil Ratio

q_w = quantity of produced water (gal, L, bbl)

q_w = quantity of produced oil (gal, L, bbl)

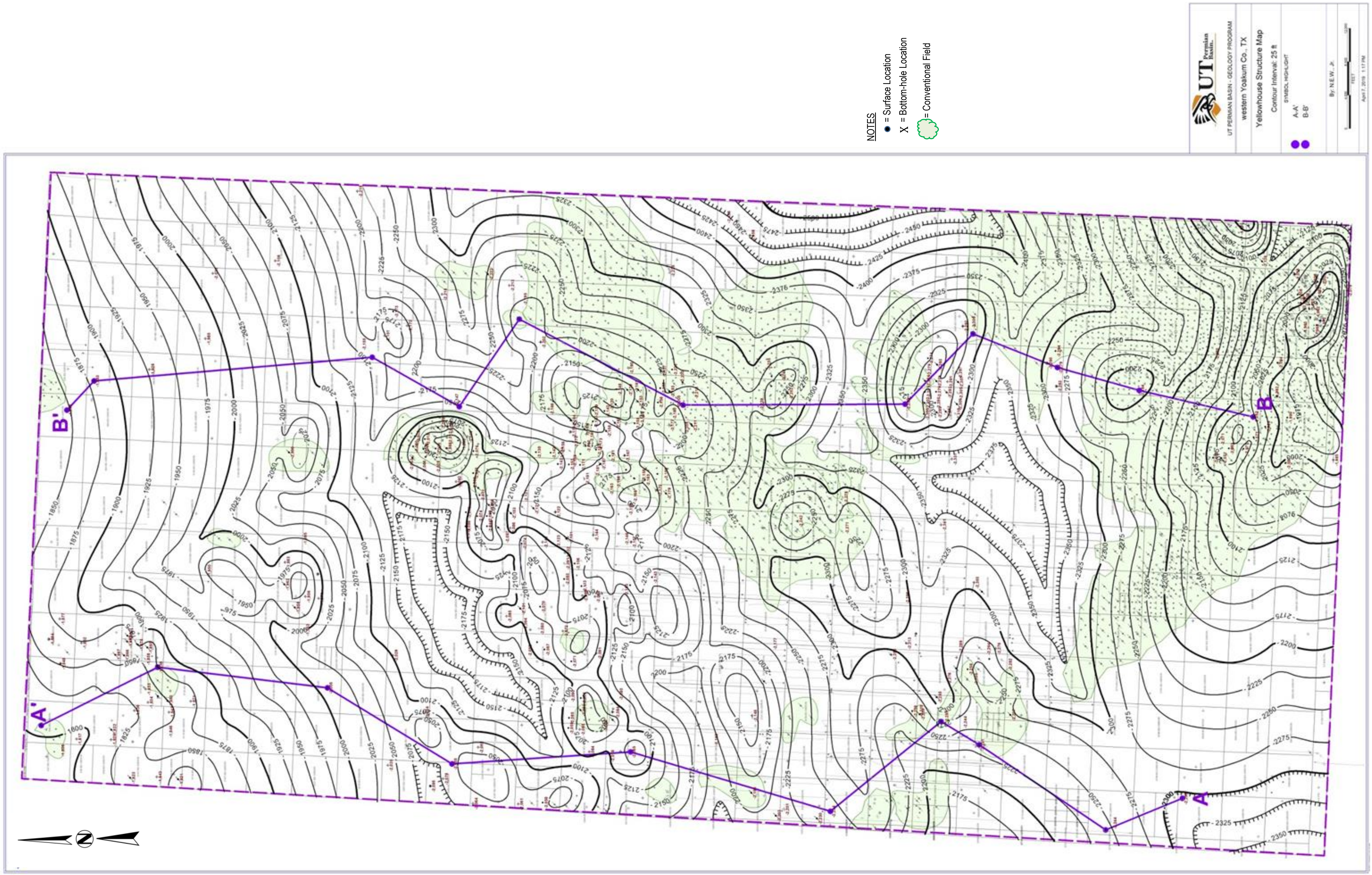
By normalizing the production into cuts, one can more easily observe the general production patterns, rather than trying to distinguish trends in a per well total production number for any specific time period. By calculating the oil cuts for the wells that have first year (first 12 months) production, and plotting the wells that started producing within a one year time period, a trend, if there is one, should be observable. Comparing the first year production cut to total production cut should show if a well is dewatering (producing less water), staying the same, or producing more water than oil (Appendix B).

CHAPTER 5 - Observations

Yellowhouse Dolomite

The Lowest intervals of the San Andres Formation are the P7 (L7) and Yellowhouse dolomite (Yellowhouse) (P6 or L8) respectively. The Yellowhouse is a productive interval in the lower San Andres Formation to the north in Hockley County, Texas; however, due to progradation the Yellowhouse producing zone is deeper than the rest of the productive San Andres which lies above the max flood (G1) within Yoakum County (Ramondetta, 1982a). The Yellowhouse is a fairly easy unit to correlate as it can be picked primarily by the increased porosity at the base of a high gamma-ray spike (see Type Log, Figure 10), is generally below a thick limestone interval (max flood), and has some of the highest porosity in the lowest portion of the San Andres. It is within approximately 100ft to 200ft above the top of the Glorieta Formation across the area. However, the Yellowhouse becomes more difficult to pick within the Wasson Field, in particular due to the dominance of dolomite throughout the entire lower San Andres interval. A structure map on the top of the Yellowhouse (Figure 12) was created using 286 well logs that consisted of Gamma-Ray and a porosity curve (i.e. Neutron, Neutron-Density, Density, and/or Sonic curves).

FIGURE 12 – Yellowhouse Structure Map. Only Cross-sections that transect the Yellowhouse are depicted (A-A' and B-B').



NOTES
= Surface Location
X = Bottom-hole Location
= Conventional Field
UT Permian Basin
UT PERMIAN BASIN - GEOLOGY PROGRAM
western Yoakum Co., TX
Yellowhouse Structure Map
Contour Interval: 25 ft
A-A'
B-B'
By: N.E.W., Jr.
A
A'
B
B'

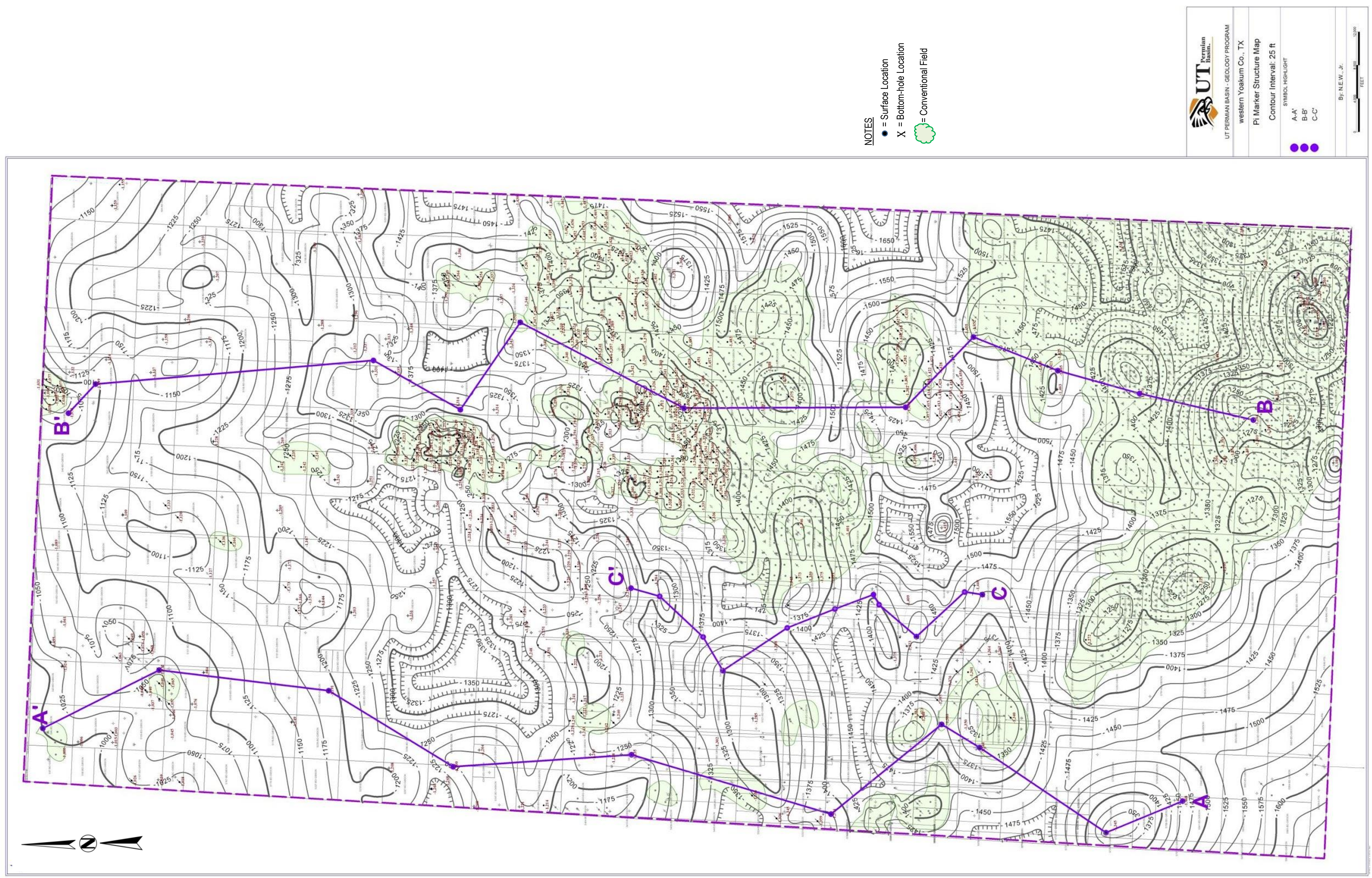
The highest picked point on the Yellowhouse structure (Figure 12) is in the northwest corner of the county at an elevation of -1,806 feet sub-sea, while the lowest picked point is at an elevation of -2,458 feet sub-sea in the southeastern part of the study area, creating a 652 foot change in elevation. The Regional dip of the structure appears to be from north-northwest to south-southeast across the county. The Wasson Field is an anticlinal structure that is located along the shelf margin at the southern edge of the mapped area that causes an increase in the elevation of the Yellowhouse along the southern edge of the mapped area. Many of the smaller structural controlled highs tend to form a "string-of-pearls" or row of structures that generally trend from southwest to northeast paralleling the shelf edge (Figure 12). Smaller structural lows, or basins, can also be observed mimicking the same trend.

Pi Marker

The Pi (Π) Marker is a regionally correlative (Figure 13), relatively thin (usually under 10ft thick) siltstone that is used as the marker separating the upper and lower San Andres (Cowan and Harris, 1986; Elliot and Warren, 1989; Pitt and Scott, 1981; Ramondetta, 1982a). As a lowstand deposit, the Pi Marker is deposited on an eroded surface and thus correlations and thicknesses are not always consistent. Within the study area the Pi Marker occurs between 517 to 638 feet below the top of the San Andres Formation, or approximately 800 feet to 1,050 feet above the top of the Glorieta. The resultant total San Andres thickness ranges from 1,376 feet to 1,626 feet across the study area. There are two major and a number of minor erosional surfaces, along with shifting paleotopography, which resulted in local thickening and thickening of the entire San Andres interval. These numbers correlate to the Cowan and Harris (1986) study of the San Andres in Cochran and Hockley Counties, as a shelf deepening towards the south culminating at the shelf margin within Yoakum County. A structure map on the top of the Pi Marker (Figure 13) was created from 572 wells that had Gamma Ray and a porosity log (see Yellowhouse section for list of logs).

The shallowest Pi Marker pick was at -1,152ft sub-sea, while the deepest is at -1,578 sub-sea, giving 426 feet of relief. This is nearly two-thirds the relief observed within the Yellowhouse section. Once again the overall regional dip is similar to that of the Yellowhouse structure, which dips from north-northwest to south-southeast. The Wasson Field, in the southern study area, is an anticlinal feature, and thus creates an isolated structural high. Smaller structural highs can be observed throughout the study area; however, unlike the Yellowhouse, there is no “string-of-pearls” pattern or trends. Similarly, the structural lows tend to be more meandering rather than falling along a trend. It is important to note that the majority of the productive oil fields tends to coincide with structural highs or noses of the Pi Marker structure. The relationship with deep lower to middle Paleozoic structures, such as the Wasson Field structure, cannot be stressed enough, and is the likely reason for where the productive fields are located.

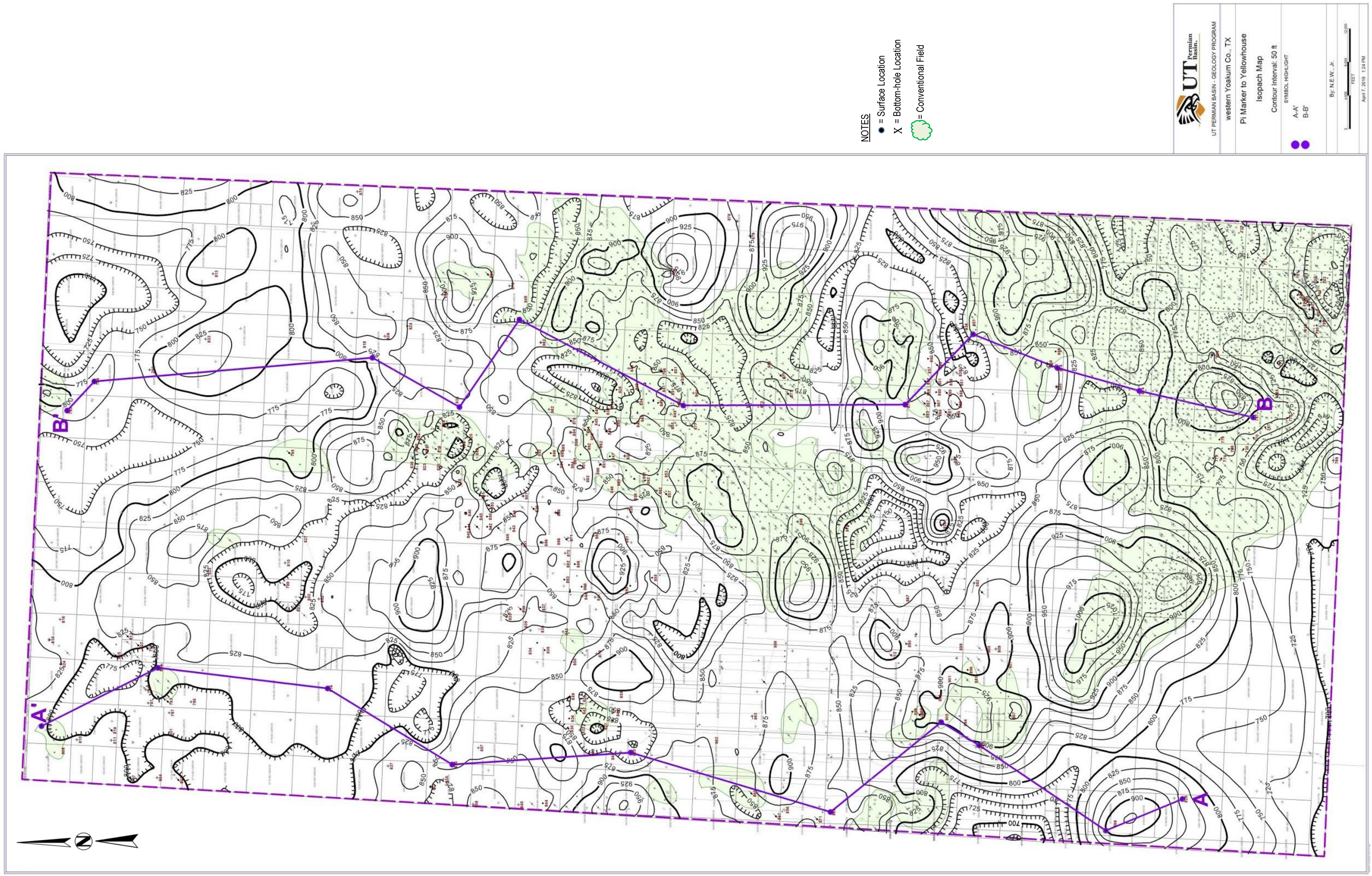
FIGURE 13 – Pi (Π) Marker Structure Map. Only cross-sections that transect the Pi Marker are depicted (A-A', B-B', and C-C').


NOTES
• = Surface Location
X = Bottom-hole Location
= Conventional Field
UT Permian Basin
UT PERMIAN BASIN - GEOLOGY PROGRAM
western Yoakum Co., TX
Pi Marker Structure Map
Contour Interval: 25 ft
SYMBOL HIGHLIGHT
A-A'
B-B'
C-C'
By: N.E.W., Jr.
A
A'
B
B'
C
C'

Pi Marker to Yellowhouse

The Pi Marker to Yellowhouse, or Pi Marker to Glorieta (Yeso Formation in New Mexico), interval has been considered by some (Ramondetta, 1982a) as an important test of proper correlation, as well as a test of the depositional environment. A relatively consistent thickness between these two tops would indicate that there are no major paleotopographic elements and/or changes to the overall environment of deposition. Figure 14 is the gross isopach map between the Pi Marker and the Yellowhouse, generated by subtracting the grids of each mapped unit. Overall the thickness ranges from 718 feet to 926 feet with an average thickness of 850 feet across the study area. The Pi Marker to Yellowhouse primarily thickens south towards the Wasson Field (and edge of the clean limestone interval as will be discussed in a later section); while over the Wasson Field it becomes thinner (It has been shown that there was periodic uplift during the San Andres in the Wasson Field and hence the change in thickness [Trentham, R., personal communication from K. Winfree]). It is interesting to note that a majority of the horizontal depressuring of the upper residual oil zone (DUROZ) wells tend to be within the interval of 800 feet to 900 feet of total thickness.

FIGURE 14 – Pi Marker to Yellowhouse Isopach Map. Only cross-sections that transect both the Pi Marker and Yellowhouse are depicted (A-A' and B-B').


NOTES
= Surface Location
X = Bottom-hole Location
= Conventional Field
UT Permian Basin
UT PERMIAN BASIN - GEOLOGY PROGRAM
western Yoakum Co., TX
Pi Marker to Yellowhouse
Isopach Map
Contour Interval: 50 ft
A-A'
B-B'
A
A'
B
B'

Limestone

Above the Yellowhouse within much of the study area a clean limestone and dolomitic limestone (see Type Log; Figure 10) can be observed through use of Gamma Ray-Neutron-Density Logs, in coordination with the many mud and sample/strip logs from wells that were drilled deep enough through the interval to make such observations. From many of the sample/strip logs, as well as mud logs, the limestone appears to be a white to gray to brown in color, dense to medium crystaline, argillaceous in part, and contains chert and fossils, including sponge spicules, foraminifera, bryozoans, crinoids, and fusulinids. However, the picked top of clean limestone and dolomitic limestones are the upper limits of where each are observed, as there are multiple dolomitic zones within each interval which vary in both thickness and number of zones vary depending on the well. Clean limestone and total limestone (clean limestone along with overlying dolomitic limestone, where applicable) isopach maps (Figures 15 and 16 respectively) were developed using 94 wells that had sufficient Gamma Ray-Neutron-Density logs in order to make the necessary observations (see Methods Section). On both maps, the limestone disappears approximately five (5) miles north of the southern boundary of the study area (Gaines-Yoakum County boarder), and at the approximate northern margin of the Wasson Field. Although the dolomitic limestone pinches out further to the north, the total limestone border is the same as the clean limestone edge (see Cross-Sections A-A' and B-B', Figures 17 and 18 respectively).

FIGURE 15 – Clean Limestone Isopach Map. Only cross-sections that transect the limestone interval are depicted (A-A’ and B-B’).

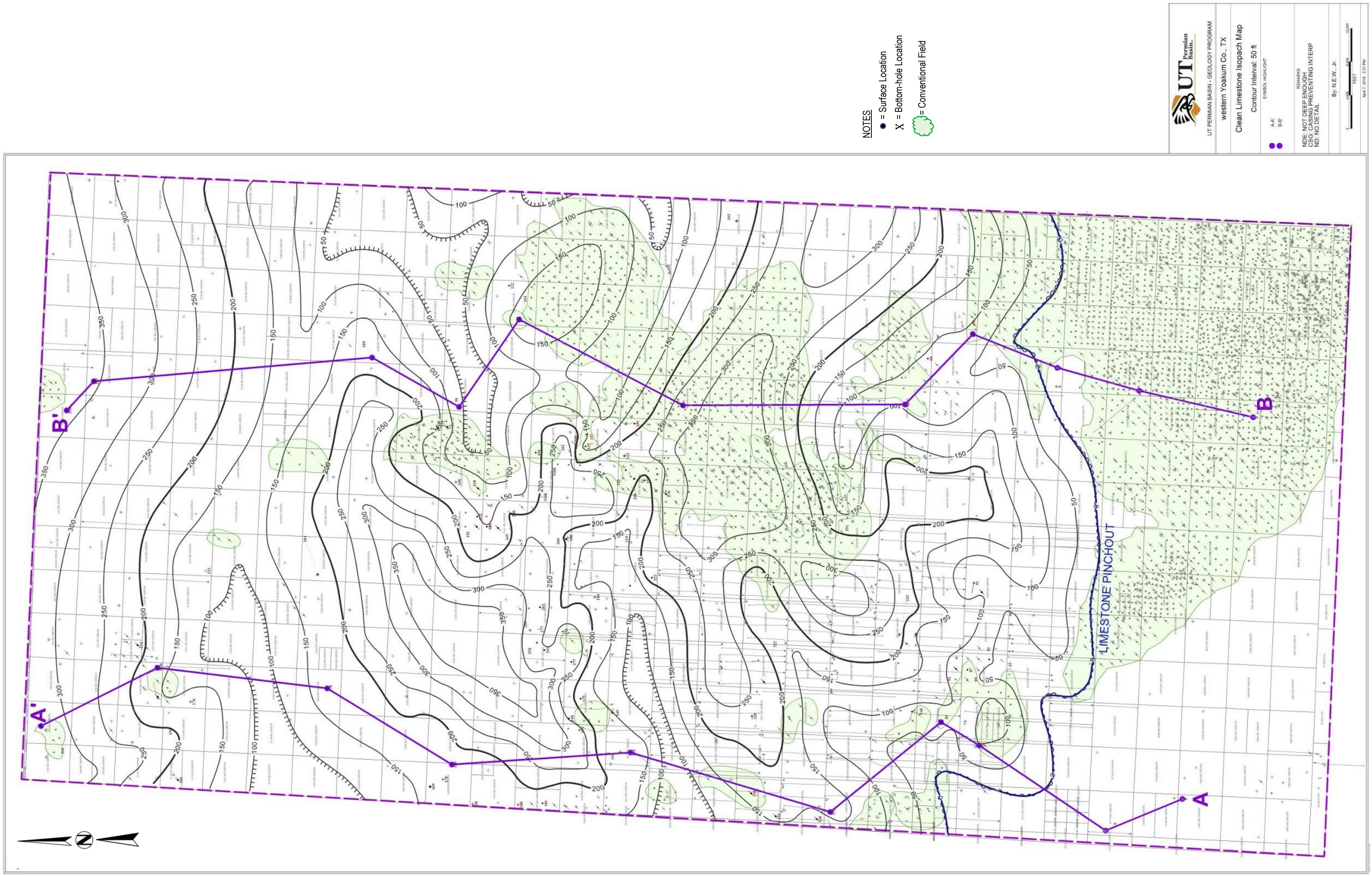

NOTES
● = Surface Location
X = Bottom-hole Location
= Conventional Field
UT Permian Basin
UT PERMIAN BASIN - GEOLOGY PROGRAM
western Yoakum Co., TX
Clean Limestone Isopach Map
Contour Interval: 50 ft
REMARKS
NDE: NOT DEEP ENOUGH
CSG: CASING PREVENTING INTERP
ND: NO DETAIL
By: N.E.W., Jr.
LIMESTONE PINCHOUT
A
A'
B
B'

FIGURE 16 – Total Limestone Isopach Map. Only cross-sections that transect the limestone intervals are depicted (A-A' and B-B').

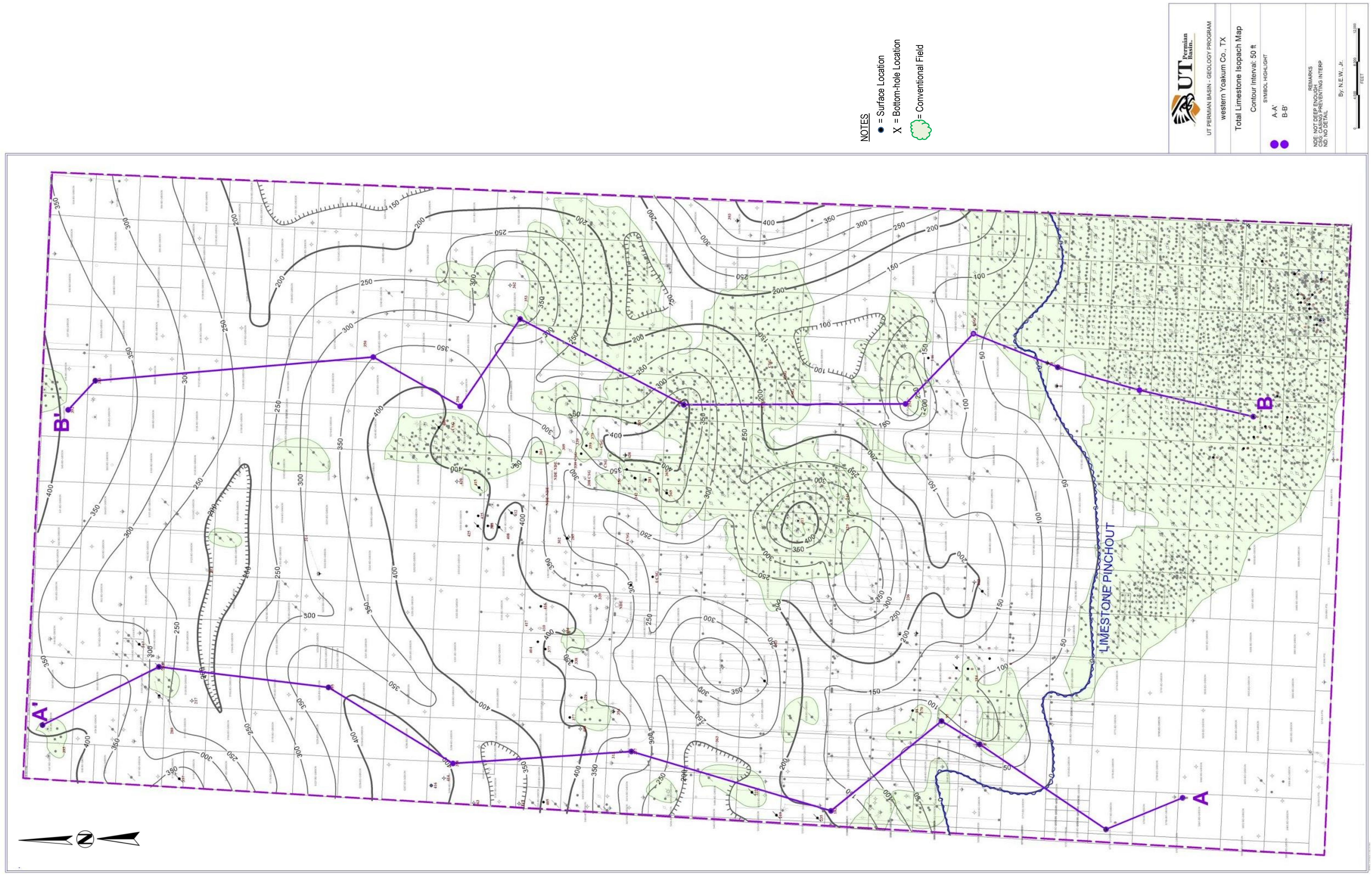

UT Permian Basin.
UT PERMIAN BASIN - GEOLOGY PROGRAM
western Yoakum Co., TX
Total Limestone Isopach Map
Contour Interval: 50 ft
SYMBOL HIGHLIGHT
A-A'
B-B'
REMARKS
NDE: NOT DEEP ENOUGH
CSG: CASING PREVENTING INTERP
ND: NO DETAIL
By: N.E.W., Jr.
FEET
NOTES
= Surface Location
X = Bottom-hole Location
= Conventional Field
LIMESTONE PINCHOUT
A
A'
B
B'

FIGURE 17 – South to North Stratigraphic Cross-Section A-A’, flattened on the top of the Yellowhouse dolomite. Depicts complete San Andres interval, with particular attention paid to lower San Andres interval. Color scheme is same represented on Type Log (Figure 10).

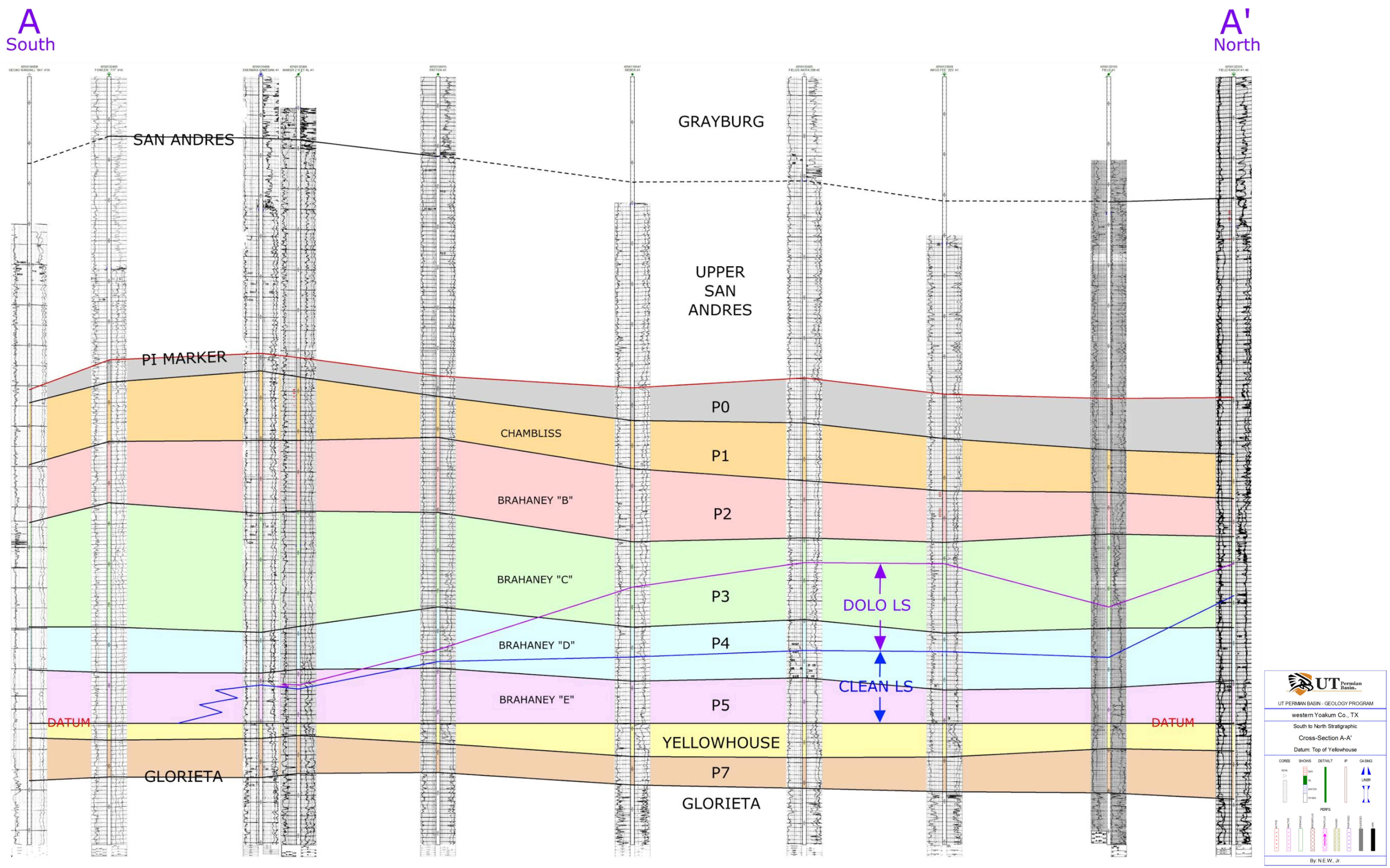
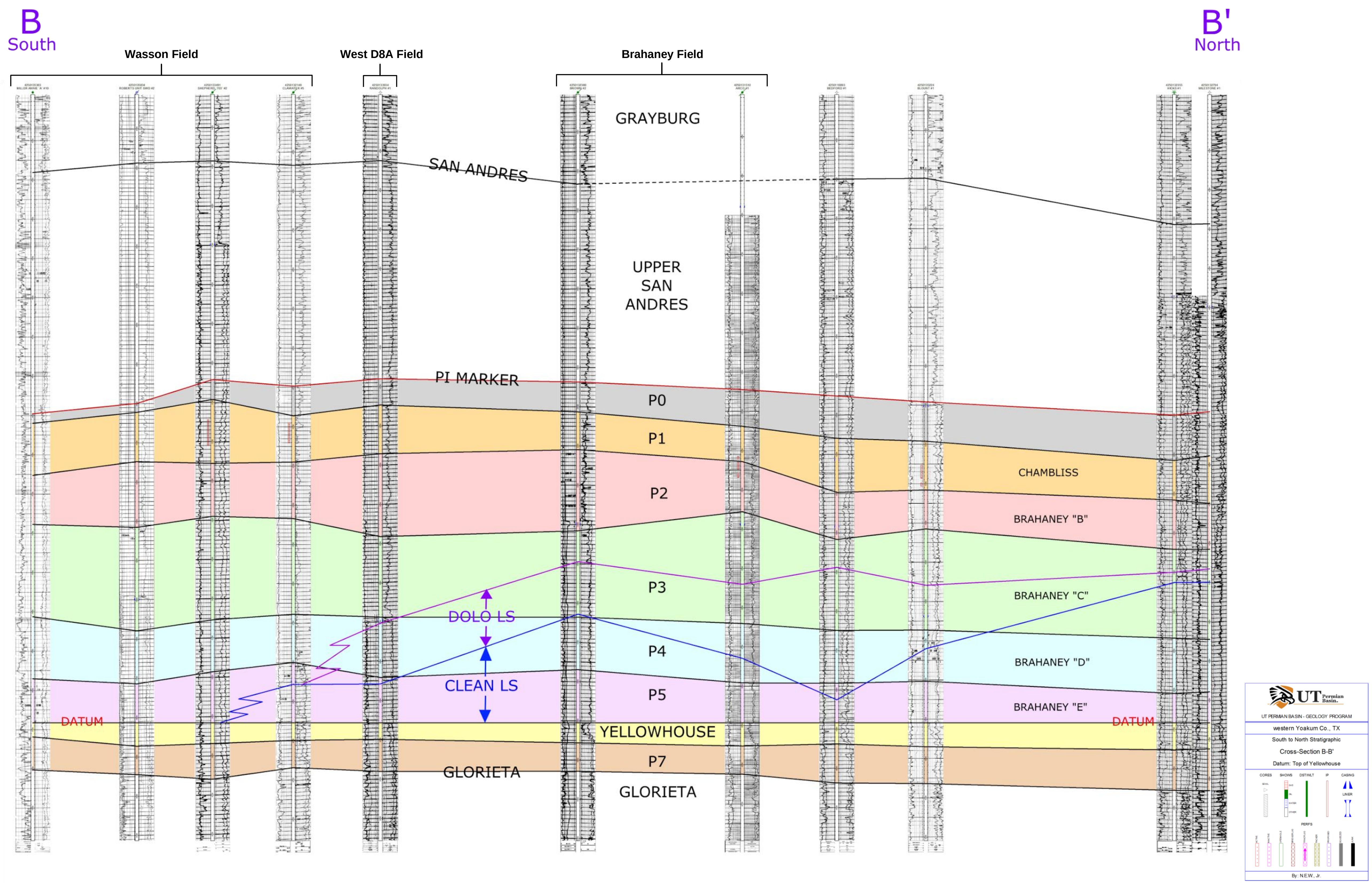

A
South
A'
North
GRAYBURG
SAN ANDRES
UPPER
SAN
ANDRES
PI MARKER
P0
CHAMBLISS
P1
BRAHANEY "B"
P2
BRAHANEY "C"
P3
DOLO LS
BRAHANEY "D"
P4
CLEAN LS
BRAHANEY "E"
P5
DATUM
DATUM
YELLOWHOUSE
P7
GLORIETA
GLORIETA
UT PERMIAN BASIN - GEOLOGY PROGRAM
western Yoakum Co., TX
South to North Stratigraphic
Cross-Section A-A'
Datum: Top of Yellowhouse
By: N.E.W., Jr.

FIGURE 18 – South to North Stratigraphic Cross-Section B-B', flattened on the top of the Yellowhouse dolomite. Depicts complete San Andres interval, with particular attention paid to lower San Andres interval. Color scheme is same represented on Type Log (Figure 10).

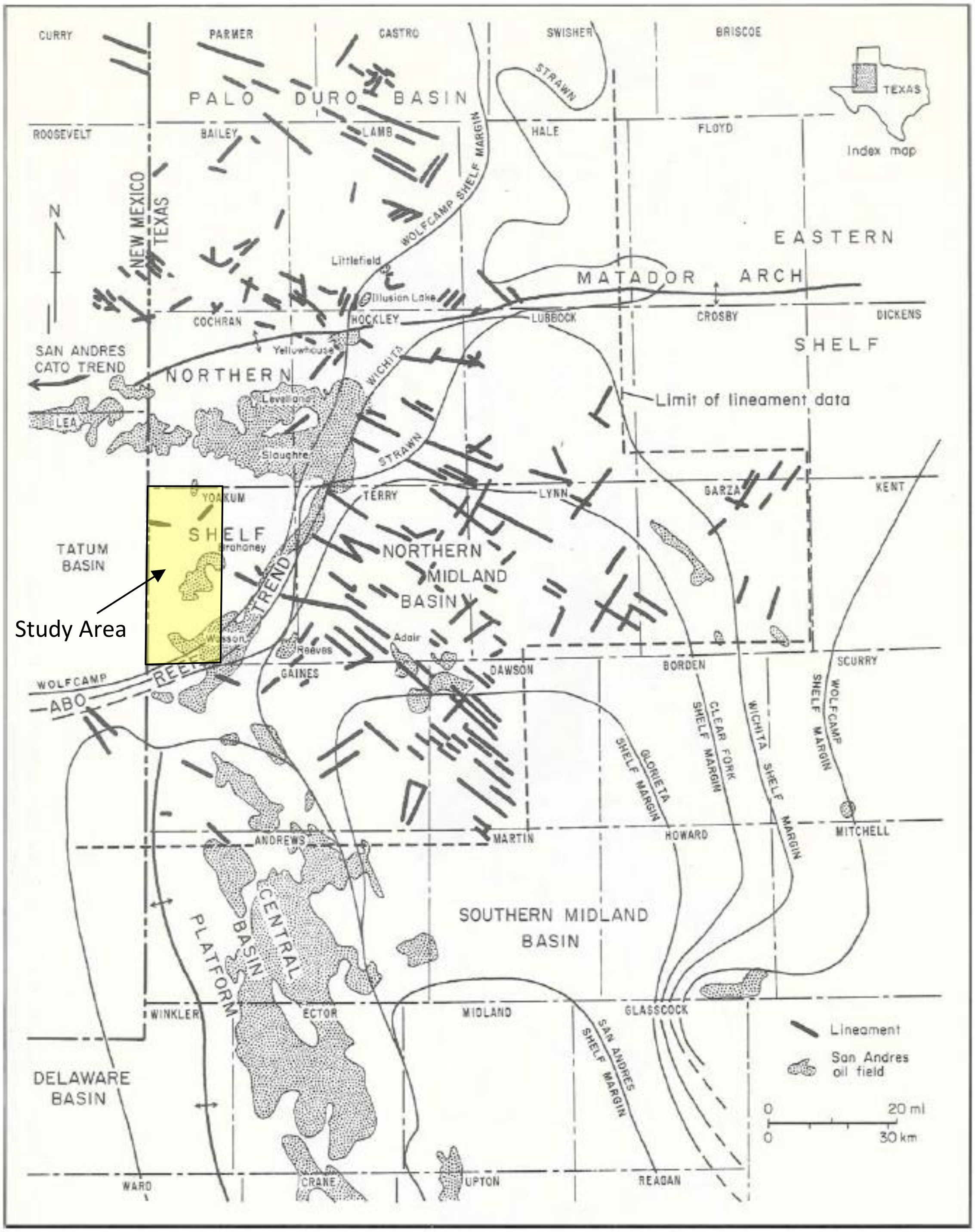

B
South
B'
North
Wasson Field
West D8A Field
Brahaney Field
GRAYBURG
SAN ANDRES
UPPER
SAN
ANDRES
PI MARKER
P0
P1
P2
P3
P4
P5
DOLO LS
CLEAN LS
DATUM
YELLOWHOUSE
P7
GLORIETA
GLORIETA
CHAMBLISS
BRAHANEY "B"
BRAHANEY "C"
BRAHANEY "D"
BRAHANEY "E"
DATUM
UT Permian Basin.
UT PERMIAN BASIN - GEOLOGY PROGRAM
western Yoakum Co., TX
South to North Stratigraphic
Cross-Section B-B'
Datum: Top of Yellowhouse
CORES
SHOWS
DST/WLT
IP
CASING
GAS
OIL
WATER
OTHER
LINER
PERFS
By: N.E.W., Jr.

As can be observed on the clean limestone isopach map (Figure 15), the thickest limestone interval tends to be in the north with a maximum of 358 feet, and thins southward, ultimately to zero feet. However, localized thicks and thins interrupt the overall trend. These thick clean limestone intervals also tend to correlate with the Yellowhouse structural lows. It is interesting to note that the majority of the productive fields (outside of Wasson) lie along isopachous slopes, not necessarily over a thick or a thin, but occasionally crossing these features.

Within the Total Limestone isopach map (Figure 16), there is a similar regional trend as observed in the clean limestone, with the thickest (395 feet) to the north, and thinning to the south until the approximate northern boundary of the Wasson Field. However, it appears that the thickest intervals tend to have a more southwest to northeast trend, much like the structural highs of the Yellowhouse structure. Unlike on the clean limestone isopach map, more of the productive fields (outside of Wasson) tend to be located along the thickest intervals, such as Brahaney, West, and Sable Fields.

Another observation was made concerning the thin isopaches within the clean limestone isopach map, and the surface lineament map from Ramondetta (1982a) (Figure 19). It appears that even though not all of the surface lineaments extend into the study area, there seems to be a slight correlation between the orientation and location of most of the surface lineaments and the thinnest intervals in the limestone.

FIGURE 19 – Map depicting the features of the Permian Basin, San Andres productive fields, and Surface lineaments. (Retrieved from Ramondetta, 1982a)



Modified after Ramondetta (1982a)

Lower San Andres

Two primary stratigraphic cross-sections were created, from south to north, with A-A' along the western edge and B-B' in the eastern portion of the study area (Figures 17 and 18 respectively), in order to show the relationships of the stratigraphic sections (as described in Pitt and Scott, 1981) and to show the correlations of both the clean limestone and dolomitic limestones within the study area. By flattening these cross-sections on the top of the Yellowhouse Dolomite, the relative thicknesses in relation to each section becomes clearer and interpretation becomes easier to make; while allowing, especially in the dolomite, to see the relative position and thickness of the limestone across the section.

In both cross-sections (A-A' and B-B') it is observed that the Yellowhouse, as well as the P0, tend to be thicker in the north while generally thinning in the south. The P4 and P5 intervals (Brahaney "D" and "E" respectively; see Type Log, Figure 10), along with the P2 (Brahaney "B"), stay relatively uniform in thickness across both cross-sections. The P1 and P3 (Chambliss and Brahaney "C" respectively) can be observed as thickening from north to south. The Upper San Andres interval tends to retain relatively consistent thickness in both cross-sections. It is also important to note that the two productive main pay zones, both conventional and DUROZ, are the P1 and P2 (Chambliss and Brahaney "B" respectively), although in some areas the P3 (Chambliss "C") may also be productive.

The clean limestone (top = blue line) and dolomitic limestone (top = purple line) on both the A-A' and B-B' cross-sections have similar characteristics, but there are some important differences between them. Both the clean and dolomitic limestones tend to be thickest in the north and ultimately pinches out on the southern part of the sections.

However, the top of the clean limestone is primarily restricted to the P4 and P5 intervals, only reaching upwards into the P3 in the northern part of each section. The upper limits of the dolomitic limestone is fairly well constrained to the P3 interval, until it ultimately pinches out towards the south, north of the clean limestone pinch out.

Horizontal San Andres Play

The horizontal San Andres depressuring of the upper residual oil zone (DUROZ) is the new productive play within western Yoakum County. It has been fifteen (15) years since the first horizontal San Andres well was completed, the Collins & Ware Inc. #808 Plains Unit, on February 10, 2004. However, it wasn't until the Apache Corporation #201H Brahaney Unit was drilled and completed on July 27, 2012 with the first 4,000 foot plus lateral that a steady to increasing number of horizontal San Andres DUROZ wells began to be drilled. Manzano LLC. was the first to begin full development of the horizontal DUROZ play with the #1H What A Mellon completed in April 2014. Appendix B is a table that shows the completions and production totals, proppant to fluid ratios, and oil and water cuts of the DUROZ wells through December 2018.

Figures 20 through 23, (abridged versions of Appendices C though F), depict first year production maps for wells completed in years 2016, and 2017, which are then overlain on the Pi Marker structure and total limestone isopach maps (respectively). It was hypothesized that either structural traps may aid in better production or that the dense limestone in the lower San Andres may create a barrier to a primary water productive zone. By looking at the oil cut percentage and its relationship to the Pi Marker and clean limestone isopach maps for these years, no observable trends can be noted. It also appears that the proppant ratio and oil cuts show no direct correlation to overall production. Although, even though there are not many in or around producing fields, the horizontal DUROZ wells that are there tend to have low to moderate (4% - 17%) oil cuts, as opposed to wells further away from the main productive fields (4% - 50% oil cuts)

Structural cross-section C-C' (Figure #) was created to determine where the horizontal DUROZ wells were being landed. The author does not have access to well logs for the majority of these wells, but the directional surveys were provided through the software vendor. In this fashion, a basic correlation between two wells with picked tops with correlation lines between them shows the relative landing zone of the horizontal wells. Although the raster coverage is lean and the structure varies between the correlation wells, cross-section C-C' does give a good indication of the landing points and orientations of the horizontal wells.

It appears that the primary landing zone for the DUROZ wells is between the top of the P1 (Chambliss) and the base of the P2 (Brahaney "B"), while most seem to land near the top of the P2 interval. A majority of the horizontal wells, as can be observed on Figure 5, are drilled in a north to south or south to north orientation, likely in the direction to take advantage of the principle northeast trending stresses caused by the Laramide Uplift or the potential northwesterly westerly fractures caused by the Laramide extension (Chuber and Pusey, 1972; Winfree, 1994).

FIGURE 20 – 2016 Horizontal San Andres Completions, First 12 Months Production on Total Limestone Isopach Map – Platang Area. For complete study area, please refer to Appendix C. (Folded Map)

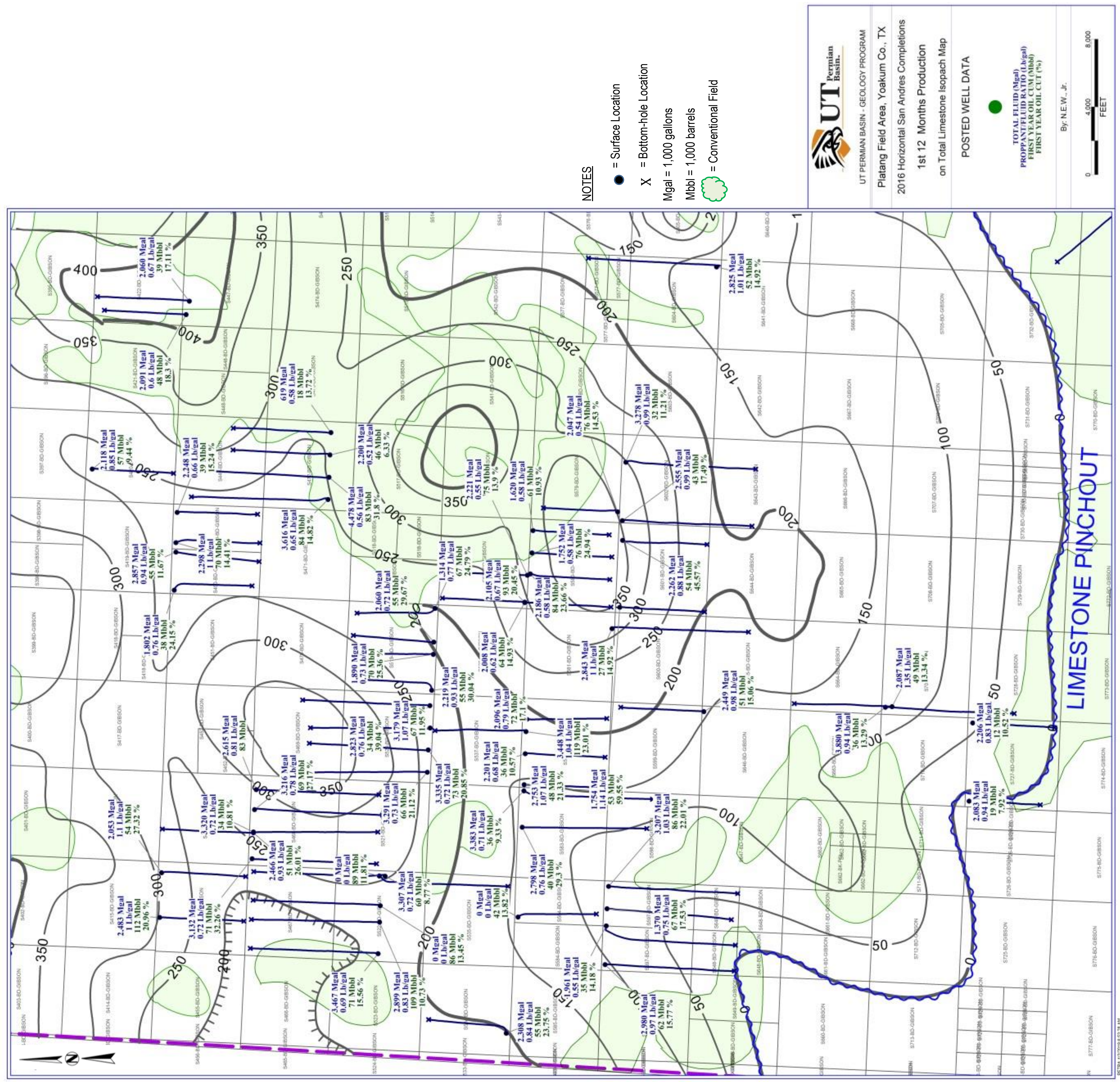

NOTES
= Surface Location
X = Bottom-hole Location
Mgal = 1,000 gallons
Mbbl = 1,000 barrels
= Conventional Field
UT Permian Basin
UT PERMIAN BASIN - GEOLOGY PROGRAM
Platang Field Area, Yoakum Co., TX
2016 Horizontal San Andres Completions
1st 12 Months Production
on Total Limestone Isopach Map
POSTED WELL DATA
TOTAL FLUID (Mgal)
PROPPANT/FLUID RATIO (Lb/gal)
FIRST YEAR OIL CUM (Mbbl)
FIRST YEAR OIL CUT (%)
By: N.E.W., Jr.
0 4,000 8,000
FEET
LIMESTONE PINCHOUT

FIGURE 21 – 2016 Horizontal San Andres Completions, First 12 Months Production on Pi Marker Structure Map – Platang Area. For complete study area, please refer to Appendix D. (Folded Map)

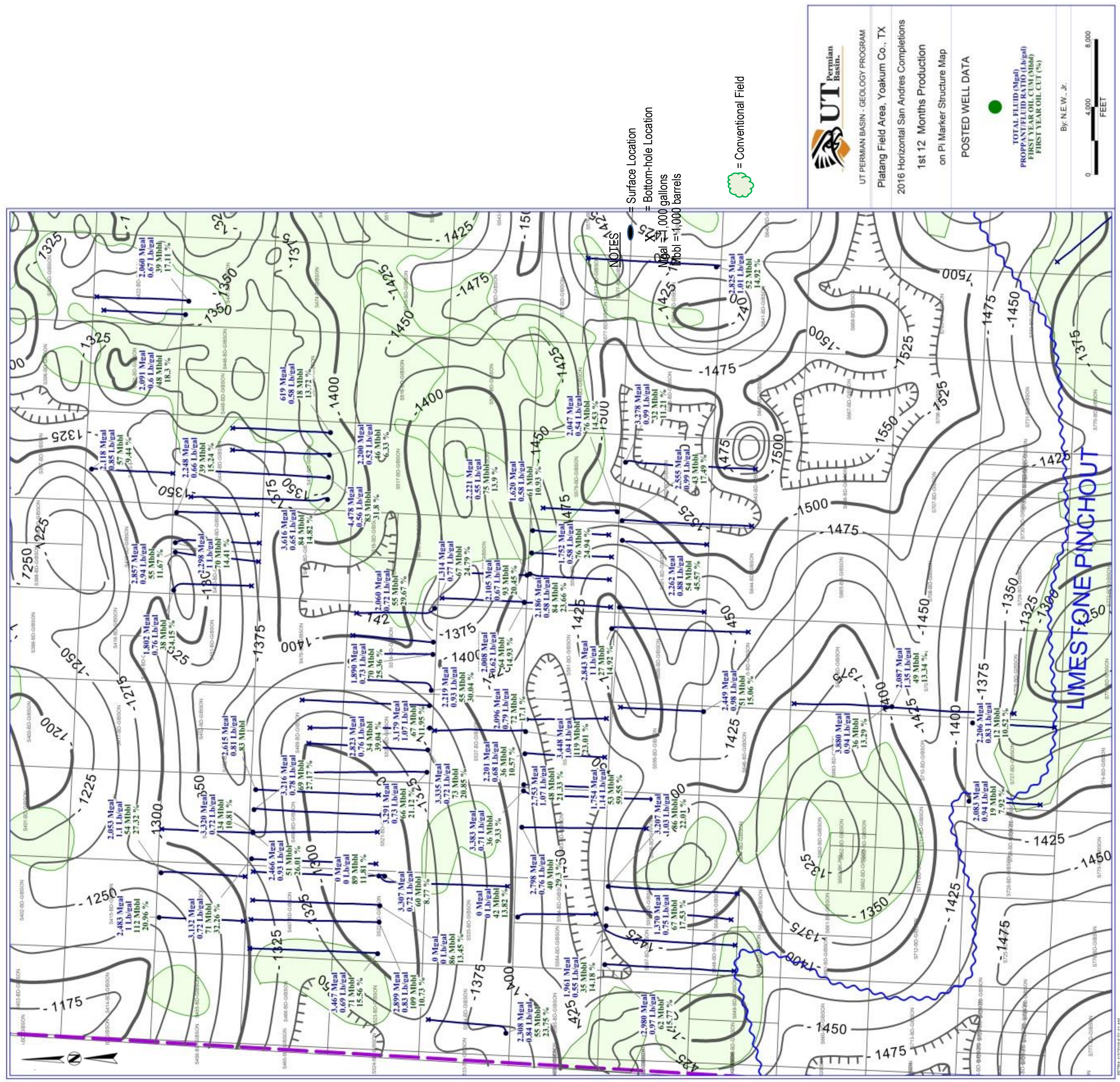

UT PERMIAN BASIN - GEOLOGY PROGRAM
Platang Field Area, Yoakum Co., TX
2016 Horizontal San Andres Completions
1st 12 Months Production
on Pi Marker Structure Map
POSTED WELL DATA
TOTAL FLUID (Mgal)
PROPPANT/FLUID RATIO (Lb/gal)
FIRST YEAR OIL CUM (Mbbl)
FIRST YEAR OIL CUT (%)
By: N.E.W., Jr.
0 4,000 8,000
FEET
NOTES
= Surface Location
= Bottom-hole Location
Mgal = 1,000 gallons
Mbbl = 1,000 barrels
= Conventional Field
LIMESTONE PINCHOUT

FIGURE 22 – 2017 Horizontal San Andres Completions, First 12 Months Production on Total Limestone Isopach Map – Platang Area. For complete study area, please refer to Appendix E. (Folded Map)

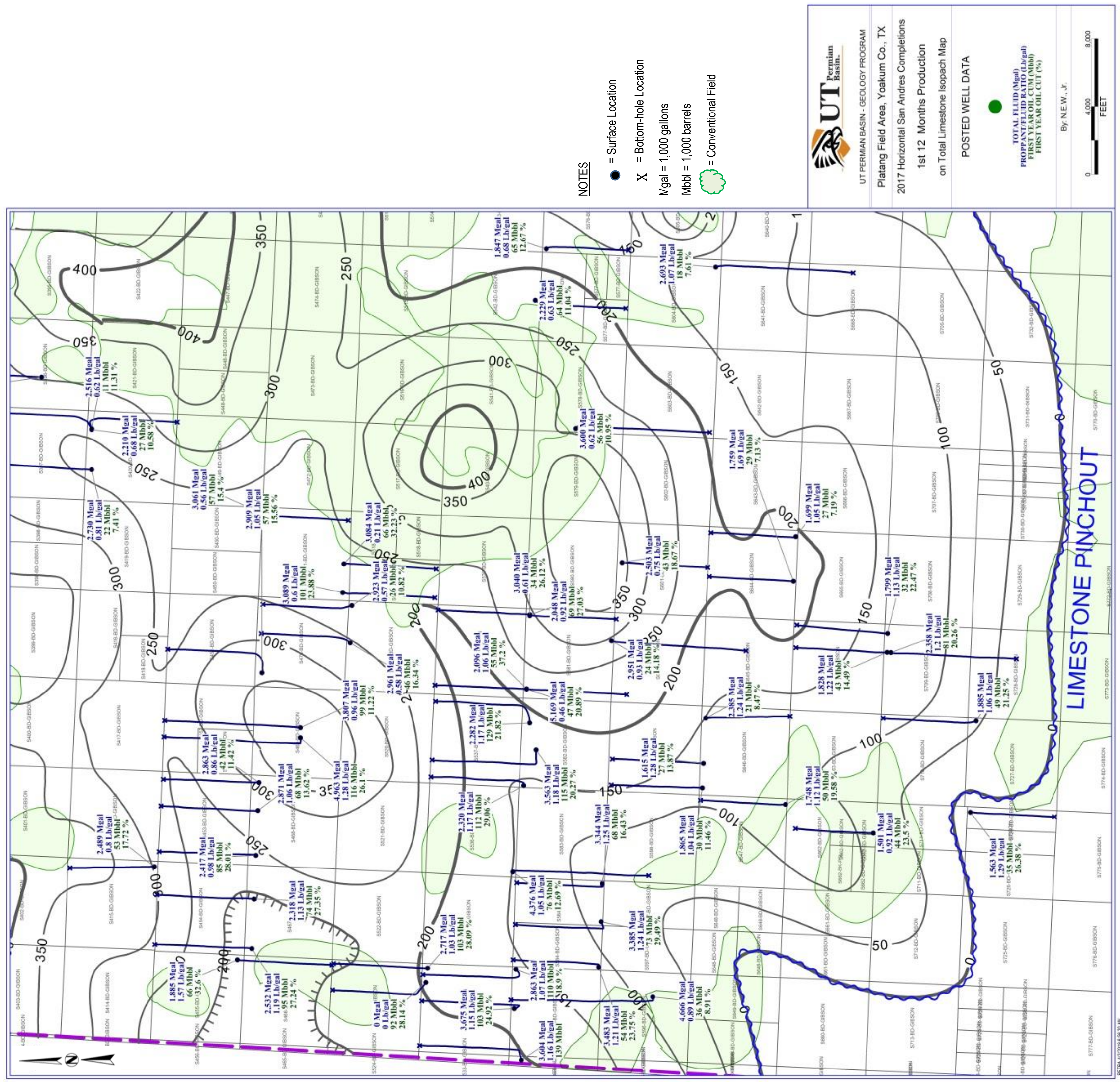

NOTES
= Surface Location
X = Bottom-hole Location
Mgal = 1,000 gallons
Mbbl = 1,000 barrels
= Conventional Field
UT Permian Basin.
UT PERMIAN BASIN - GEOLOGY PROGRAM
Platang Field Area, Yoakum Co., TX
2017 Horizontal San Andres Completions
1st 12 Months Production
on Total Limestone Isopach Map
POSTED WELL DATA
TOTAL FLUID (Mgal)
PROPPANT/FLUID RATIO (Lb/gal)
FIRST YEAR OIL CUM (Mbbl)
FIRST YEAR OIL CUT (%)
By: N.E.W., Jr.
0
4,000
8,000
FEET
LIMESTONE PINCHOUT

FIGURE 23 – 2017 Horizontal San Andres Completions, First 12 Months Production on Pi Marker Structure Map – Platang Area. For complete study area, please refer to Appendix F. (Folded Map)

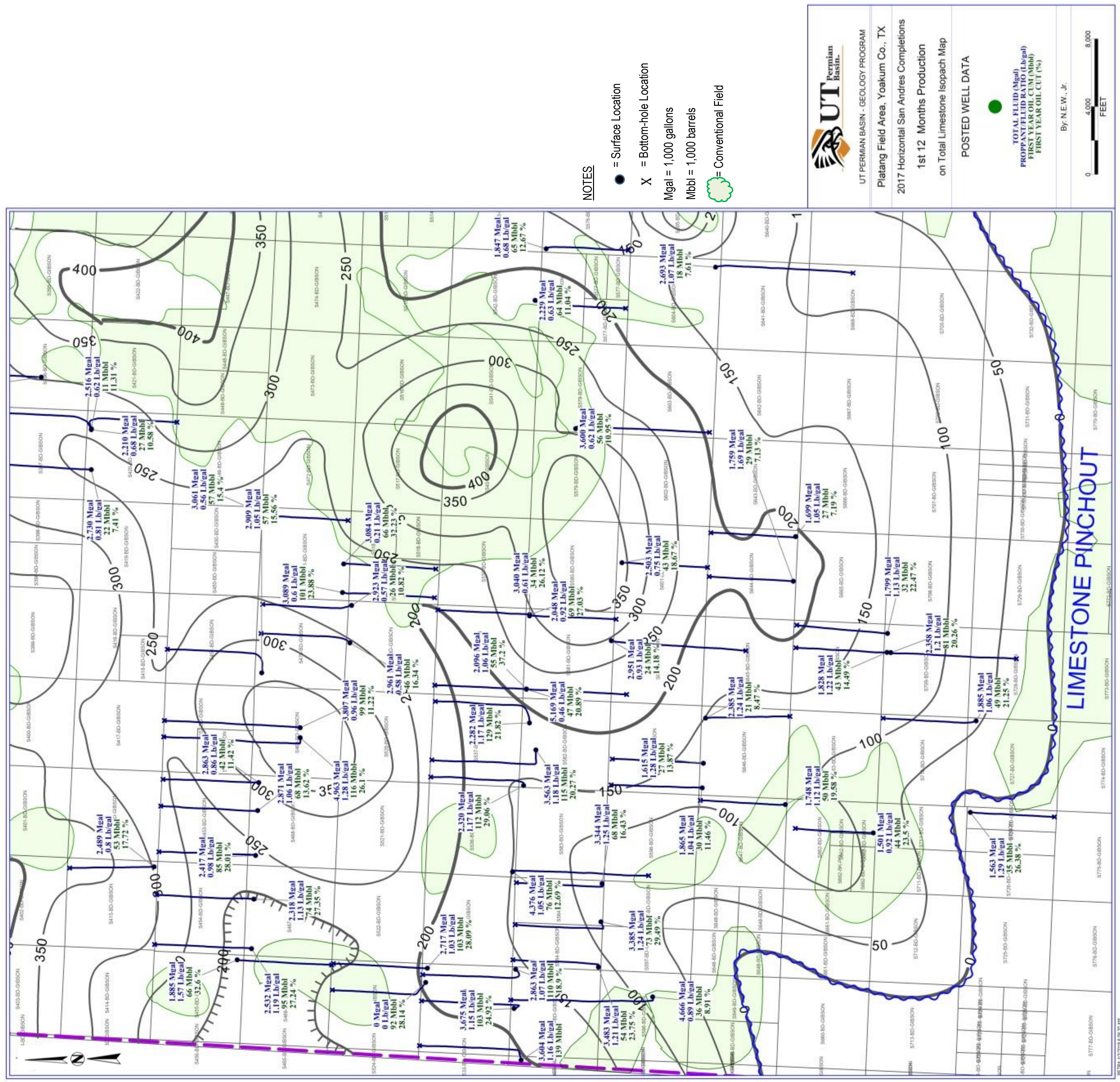
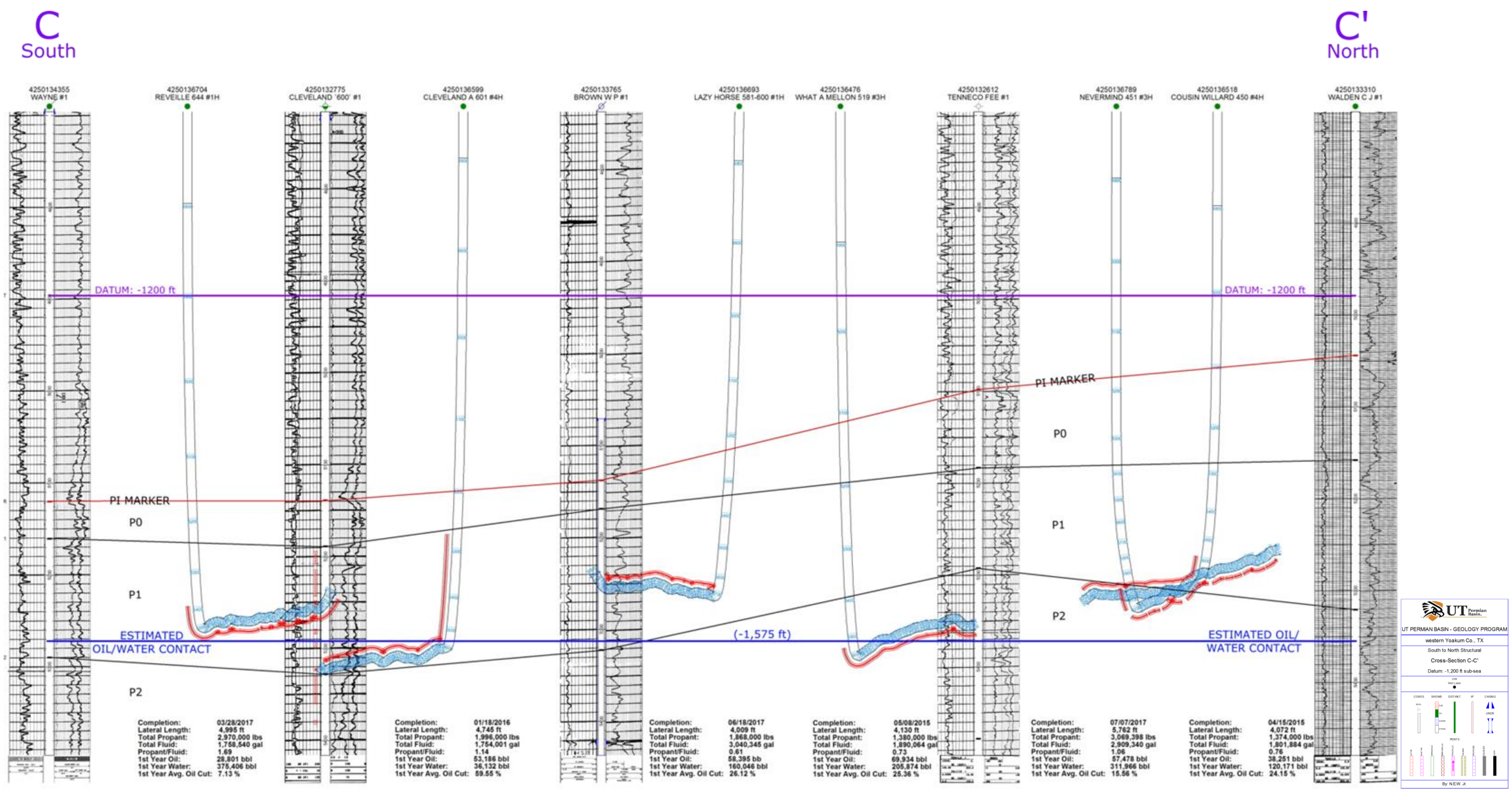

NOTES
= Surface Location
X = Bottom-hole Location
Mgal = 1,000 gallons
Mbbl = 1,000 barrels
= Conventional Field
UT Permian Basin.
UT PERMIAN BASIN - GEOLOGY PROGRAM
Platang Field Area, Yoakum Co., TX
2017 Horizontal San Andres Completions
1st 12 Months Production
on Total Limestone Isopach Map
POSTED WELL DATA
TOTAL FLUID (Mgal)
PROPPANT/FLUID RATIO (Lb/gal)
FIRST YEAR OIL CUM (Mbbl)
FIRST YEAR OIL CUT (%)
By: N.E.W., Jr.
0 4,000 8,000
FEET
LIMESTONE PINCHOUT

FIGURE 24 – South to North Structural Cross-Section C-C’, Flattened on -1,200 foot sub-sea. Horizontal wells are not crossing through each other or Vertical wells, but are due to the 2D depiction of 3D space.

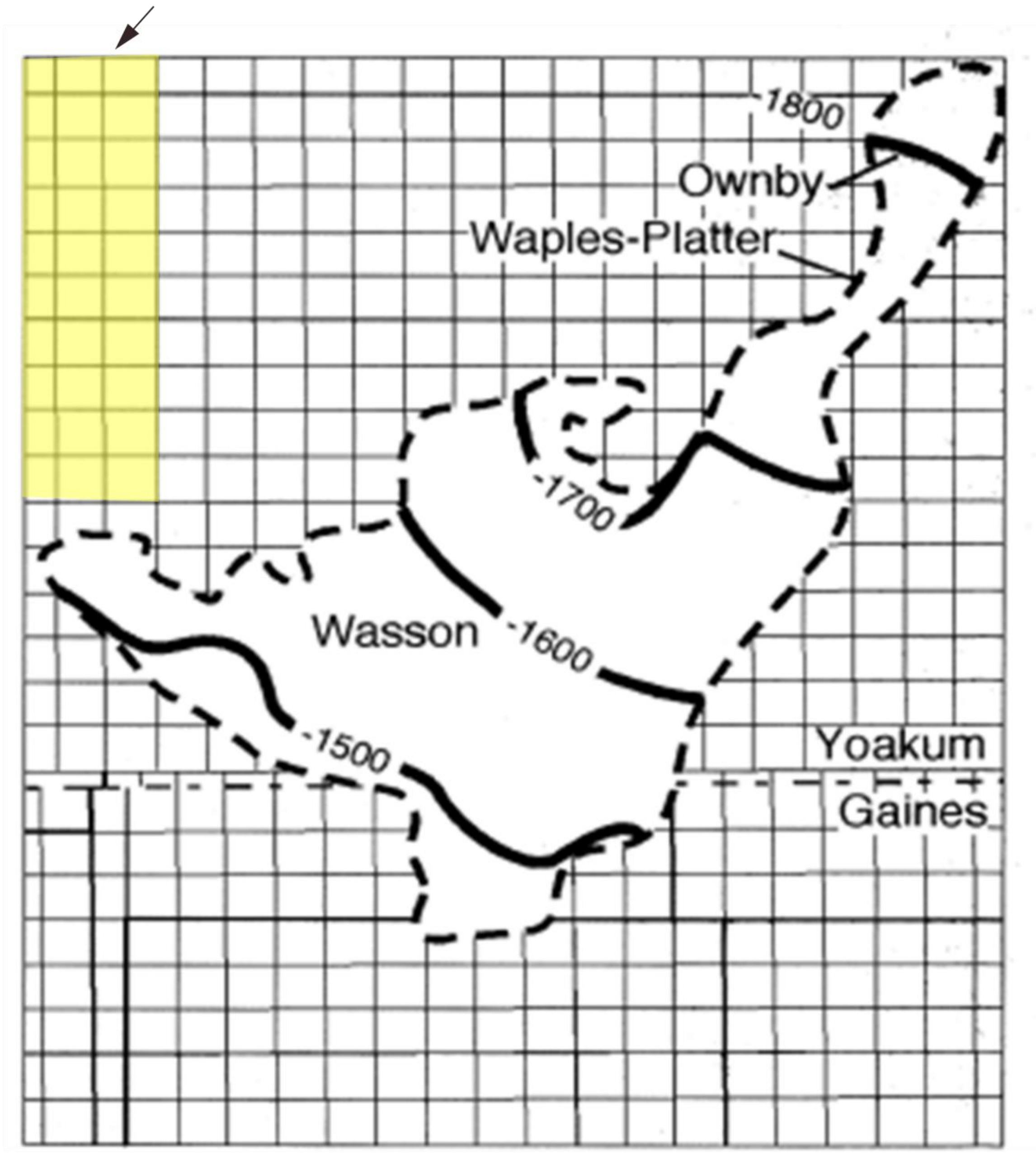


C
South
C'
North
4250134355
WAYNE #1
4250136704
REVEILLE 644 #1H
4250132775
CLEVELAND '600' #1
4250136599
CLEVELAND A 601 #4H
4250133765
BROWN W P #1
4250136693
LAZY HORSE 581-600 #1H
4250136476
WHAT A MELLON 519 #3H
4250132612
TENNECO FEE #1
4250136789
NEVERMIND 451 #3H
4250136518
COUSIN WILLARD 450 #4H
4250133310
WALDEN C J #1
DATUM: -1200 ft
DATUM: -1200 ft
PI MARKER
PI MARKER
P0
P0
P1
P1
P2
P2
ESTIMATED
OIL/WATER CONTACT
(-1,575 ft)
ESTIMATED OIL/
WATER CONTACT
Completion: 03/28/2017
Lateral Length: 4,995 ft
Total Propant: 2,970,000 lbs
Total Fluid: 1,758,540 gal
Propant/Fluid: 1.69
1st Year Oil: 28,801 bbl
1st Year Water: 375,406 bbl
1st Year Avg. Oil Cut: 7.13 %
Completion: 01/18/2016
Lateral Length: 4,745 ft
Total Propant: 1,996,000 lbs
Total Fluid: 1,754,001 gal
Propant/Fluid: 1.14
1st Year Oil: 53,186 bbl
1st Year Water: 36,132 bbl
1st Year Avg. Oil Cut: 59.55 %
Completion: 06/18/2017
Lateral Length: 4,009 ft
Total Propant: 1,868,000 lbs
Total Fluid: 3,040,345 gal
Propant/Fluid: 0.61
1st Year Oil: 58,395 bb
1st Year Water: 160,046 bbl
1st Year Avg. Oil Cut: 26.12 %
Completion: 05/08/2015
Lateral Length: 4,130 ft
Total Propant: 1,380,000 lbs
Total Fluid: 1,890,064 gal
Propant/Fluid: 0.73
1st Year Oil: 69,934 bbl
1st Year Water: 205,874 bbl
1st Year Avg. Oil Cut: 25.36 %
Completion: 07/07/2017
Lateral Length: 5,762 ft
Total Propant: 3,069,398 lbs
Total Fluid: 2,909,340 gal
Propant/Fluid: 1.06
1st Year Oil: 57,478 bbl
1st Year Water: 311,966 bbl
1st Year Avg. Oil Cut: 15.56 %
Completion: 04/15/2015
Lateral Length: 4,072 ft
Total Propant: 1,374,000 lbs
Total Fluid: 1,801,884 gal
Propant/Fluid: 0.76
1st Year Oil: 38,251 bbl
1st Year Water: 120,171 bbl
1st Year Avg. Oil Cut: 24.15 %
UT Permian Basin
UT PERMIAN BASIN - GEOLOGY PROGRAM
western Yoakum Co., TX
South to North Structural
Cross-Section C-C'
Datum: -1,200 ft sub-sea
UWI
Well Label
CORES
SHOWS
DST/WLT
IP
CASING
LINER
PERFS
By: N.E.W. Jr.

One interesting observation is that an estimated oil/water contact of -1,575 feet sub-surface was generated from logs and production information from within the Brahaney Field, and verified as being on trend to that of the Wasson Field as discussed in Brown (2002) (Figure 25). The oil/water contact is for conventional production purposes only, as it is understood that anything below this arbitrary contact would produce primarily water. For purposes of residual oil zone (ROZ) development this oil/water contact is what separates the conventional main pay zone (MPZ) above from the ROZ below (Figure 26). As shown on the C-C' cross-section (Figure 24), a majority of the horizontal wells seem to lie either above or at the estimated oil/water contact. When looking at the Platang Field wells in a 3D view (Figure 27), with the top of the Yellowhouse as the base and -1,575 ft sub-sea as a plane, one can observe the darker wells (deep red) that are above the plane of the estimated oil/water contact, versus the duller wells (dull red) that lie below the plane of the estimated oil/water contact. This shows that a majority of horizontal wells drilled are indeed above the MPZ-ROZ contact. It should be noted that, as discussed in Brown (2002), there is a regional dip of the oil/water contact to the northeast, as can be observed in the Wasson Field (Figure 25); however without more accurate data across Yoakum County's San Andres, it is difficult to accurately plot or predict the conventional oil/water contact for such a map of the ROZ.

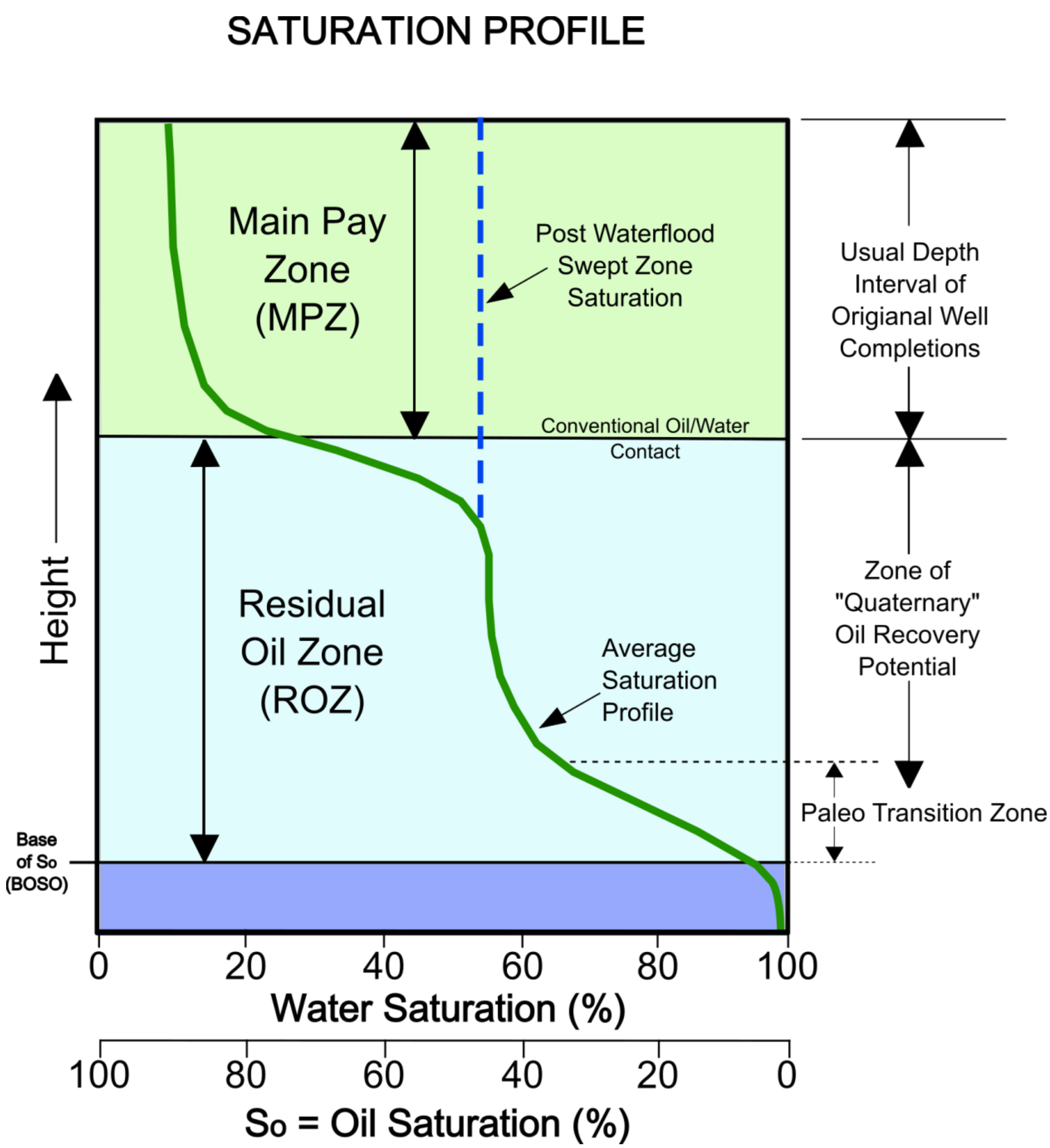
FIGURE 25 – Map depicting the tilted oil/water contact within the Wasson, Waples, Platter, and Ownby Fields of southern Yoakum County and Northern Gaines County, Texas. (Modified after Brown, 2001)

Platang Field (Horizontal San Andres DUROZ Play)



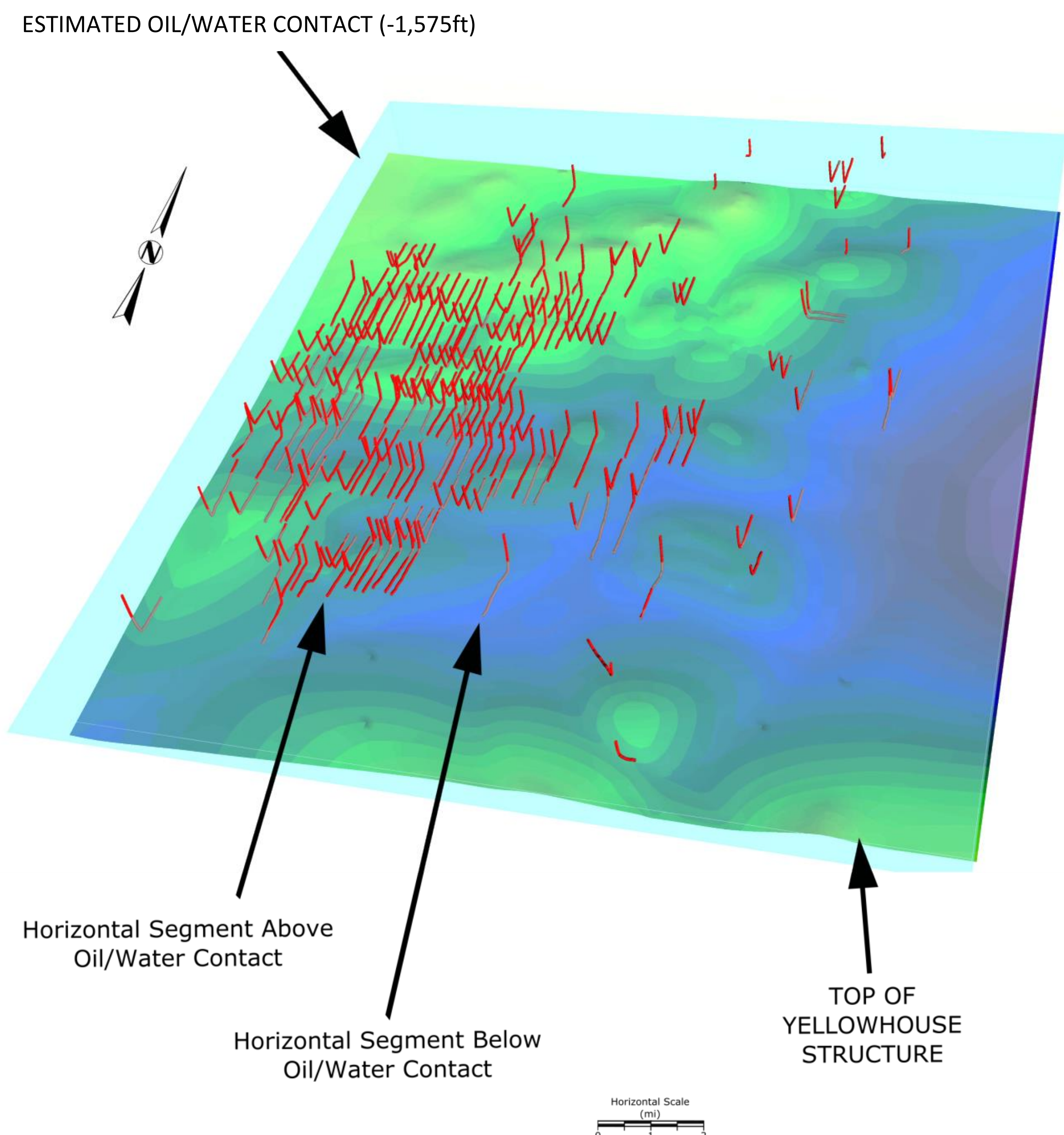
Modified after Brown (2001)

FIGURE 26 – Saturation profile of the Main Pay Zone (MPZ), and Residual Oil Zone (ROZ). (Modified after Melzer, 2016)



Modified after Melzer (2016)

FIGURE 27 – 3D representation of the Platang Field area, showing horizontal wells only. Where the bright right red wellbores lie above the Estimated Oil/Water Contact of -1575’, and the dull red wellbores lie below the contact.


ESTIMATED OIL/WATER CONTACT (-1,575ft)
N
Horizontal Segment Above Oil/Water Contact
Horizontal Segment Below Oil/Water Contact
TOP OF YELLOWHOUSE STRUCTURE
Horizontal Scale (mi)
0
1
2

CHAPTER 6 - Discussion

Structures

There are three types of structures, which include 1) Regional, 2) Paleo-Tectonic, and 3) Local, that have been observed in Figures 12 and 13 (Yellowhouse Structure Map and Pi Marker Structure Map, respectively). Regional structures include those that were formed due to the geometry at time of deposition (i.e. carbonate ramp, regional dip). Paleo-Tectonic structures are present, which include 1) those that are caused either due to a paleogeograhic structure causing the formation of a similar structure at time of deposition (i.e. Wolfcamp Shelf Edge, Abo Reef Trend); 2) structures caused due to tectonism either during or after deposition (i.e. Ouachita-Marathon Fold Belt formation, Laramide uplift, Laramide extension); or 3) a combination of the two (i.e. Wasson Field structure). Finally, there are local structures which form due to the primary environment of deposition, biologic carbonate forming elements or bathymetry/topography of the area (i.e. West D8A Field, Janice Field, etc.), or result from surface exposure and erosion.

Regional structure elements can be difficult to observe, especially when evaluating a relatively small area. However, one of the advantages of this study is that it is sub-regional and incorporates a large enough area (approximately 400 square miles) in order to see the effect of regional structure. The structure most readily observable is the broad carbonate ramp which strikes southwest to northeast and regionally dips towards the south-southeast, prograding toward the Midland Basin (Figure 12). The up-dip beginning of the carbonate ramp system is roughly some 40 miles north of the Wasson Field (Silver and Todd, 1981; Ramondetta 1982a & b), with the Wasson Field located at the approximate lower San Andres shelf margin. As can be observed on the two primary cross-sections A-A' and B-B' (Figures 17 and 18 respectively), the progradation of the lower San Andres shelf margin was caused by contemporaneous subsidence (Elliot and Warren, 1989). Wasson Field and the northern study area within the regional sabkha environment structural highs, during times of high stands were likely below sealevel, and thus were able to build shallow marine carbonate deposits; however, during low stands, these areas were likely exposed with areas of evaporite deposition and erosion (Pitt and Scott, 1981; Danielli, 1995; Sarg, 2001; Brown, 2002). These exposure surfaces and evaporite deposits became important in in both reservoir generation and destruction, due to: the formation of karst, potential for dolomitization through reflux reactions, and the creation of seals through formation of thick beds of evaporites (Sarg, 2001). The lowest structural areas, even during low stands, may still have been below sea-level, and thus never were exposed to anhydritic sabkha formation, and the limestone was not dolomitized. The area just north of limestone pinch out (north of the Wasson Field boundary, Figure 15) shows evidence on the wireline logs that little to no anhydrite was deposited from the top of the Yellowhouse through top of the P4, while there appears to be tight anhydrite intervals that overlies the top of the P3 through top of the P1 intervals across the study area.

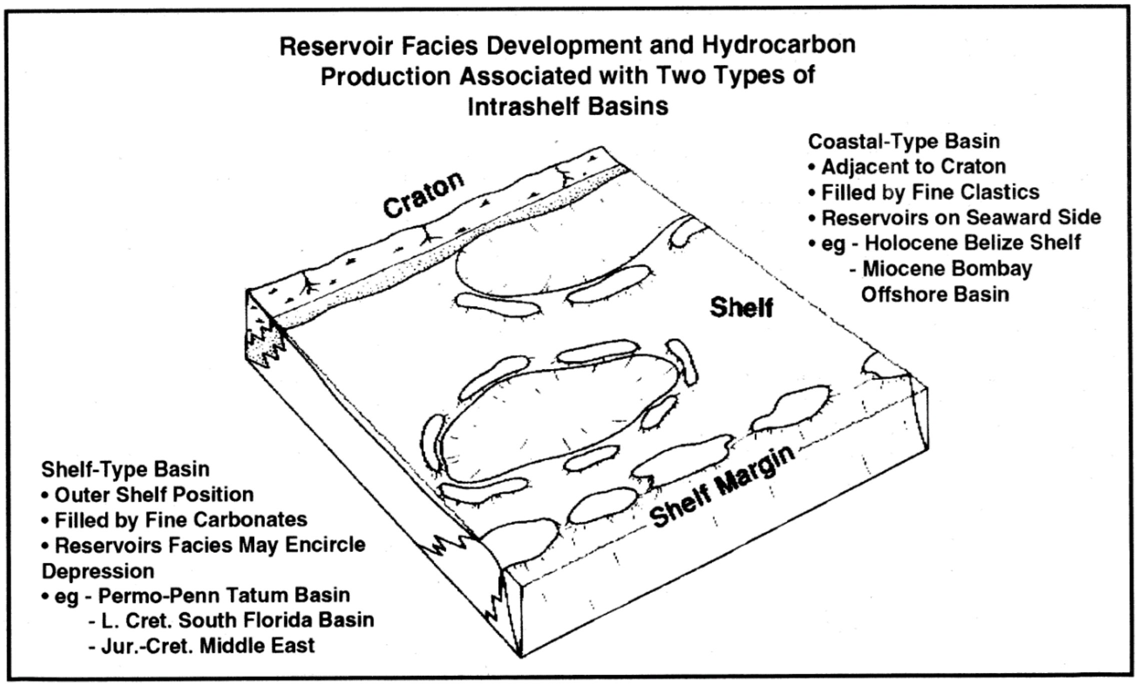
Paleo-Tectonic structures may be more important for large scale petroleum prospects because of their relative size and potential for creating conditions favorable to trapping oil and gas. However, finding new paleo-tectonic prospects in the modern era is rather difficult, because a majority of the largest structures have already been discovered and produced. The paleotopographic highs that formed within the study area are related to the deep Wolfcamp Shelf edge, as well as the Leonardian Abo Reef trend, which ultimately allowed for the creation of the Wasson Field high and the lower San Andres shelf margin. Along the paleo high, while subsidence was still occurring during highstand periods, biota that were favored by more light and higher wave or current energies was able to grow and prosper, thus building the Wasson Field structure (a series of stacked barrier-bank to outer ramp deposits [Winfree, 1995]). On the other hand, tectonism during the time of deposition of the lower San Andres allowed for the subsidence of the Midland Basin, and the occasional uplift of certain areas (i.e. Wasson Field [Trentham, R., personal communication from K. Winfree]), which created the conditions for larger structures to form. However, post-depositional tectonics (Laramide uplift) likely raised already elevated areas, or created new highs through activation of deep faults (Dutton et. al., 1993; Winfree, 1995). Within the study area, the Laramide Uplift compression was directed to the northeast, which is the direction in which most of the smaller structures can be observed trending on the Yellowhouse Structure Map (Figure 12). As already discussed, both paleotopographic and tectonic forces may aid in the creation of structural highs from time of deposition through post deposition.

Localized structures can be defined as small non-regional structures that encompass a relatively small area (i.e. pinnacle reef, embayment, reentrant, etc.) Many localized structures tend to form along a trend, or as can be observed on the Yellowhouse Structure map (Figure 12) a “string-of-pearls”. These trends form because the conditions are optimal within a specific water depth, light concentration, wave/current/tidal energies, or thermal region (Scholle et. al., 1983) for biota to grow in mounded communities (i.e. barrier reef); or non-biologic carbonates , such as ooids, to precipitate, typically in high energy environments (i.e. carbonate shoals). However, as the mounds/shoals form and grow, low areas are also created, and if these embayments and recesses get closed off, smaller sub-basins, or intrashelf basins, may form (Grover Jr., 1992, 1993a & b). If these intrashelf basins are large enough, they may control a significant area of oil production within the shelf margin, either from the development of structural highs, or by deposits within the intrashelf basin itself (Grover Jr., 1992, 1993a & b). Two requirements for an intrashelf basin are 1) there appears to be two shelf margins, an inner margin which is what rings the intrashelf basin, and an outer margin that is the regional shelf margin, and 2) that the mounds/shoals (and or production) tend to form at least an articulate shape around the intrashelf basin (Figure 28) (Grover Jr., 1992, 1993a & b). Two types of intrashelf basins exist, the coastal basin – which form close to the craton and are filled primarily with siliclastics, and the shelf basin which occurs on the outer part of a shelf and generally is filled with fine carbonate sediments (Grover Jr., 1992).

An example of a carbonate shelf basin within the larger Permian Basin is the Tatum Basin in Lea County, New Mexico (Figure 1) which was in existence from early Pennsylvanian through Wolfcampian when it finally became filled (Grover Jr., 1993b; Silver and Todd, 1969). There may be some question as to whether areas of the Northern and Northwest Shelf, especially within the study area, may be considered as intrashelf basin. The productive fields that surround the study area (Figure 5), tend to follow from north to south along the western edge of the study area, and then wrap around the south with West D8A and Wasson Fields. However, this may only meet partial criteria for an intrashelf basin which is the articulate shape of productive mounds/shoals. The Wasson Field being part of the shelf margin is problematic; although Wasson is so large that if both “margin mounds” were to have grown together to form the field, then the first criteria of having two shelf margins may still be met. Another issue is that this study does not encompass a large enough area to fully explore if such shelf basins, on the relative scale of the Tatum Basin, exist.

The Pi Marker Structure (Figure 13) is significantly different than that of the Yellowhouse Structure (Figure 12) in multiple ways, yet similar regional trends are still observable. While the Yellowhouse structure has a “string-of-pearls” look to the smaller structural elements, the Pi Marker has a more meandering look. One possibility is that the Pi Marker sits atop a major exposure surface (see Figure 4). The erosional processes that sculpted the upper G4 interval would also have allowed the silt rich low stand Pi Marker to be deposited in erosional lows, and therefore the surface looks structurally controlled. Although some elements remain intact (i.e. Wasson Field, northern study area dip), there was loss of the trending structures.

FIGURE 28 – Block Diagram depicting both Costal and Shelf-Type intrashelf basins (Retrieved from Grover Jr., 1992).



Retrieved from Grover Jr. (1992)

Limestone and Dolomite Occurrence

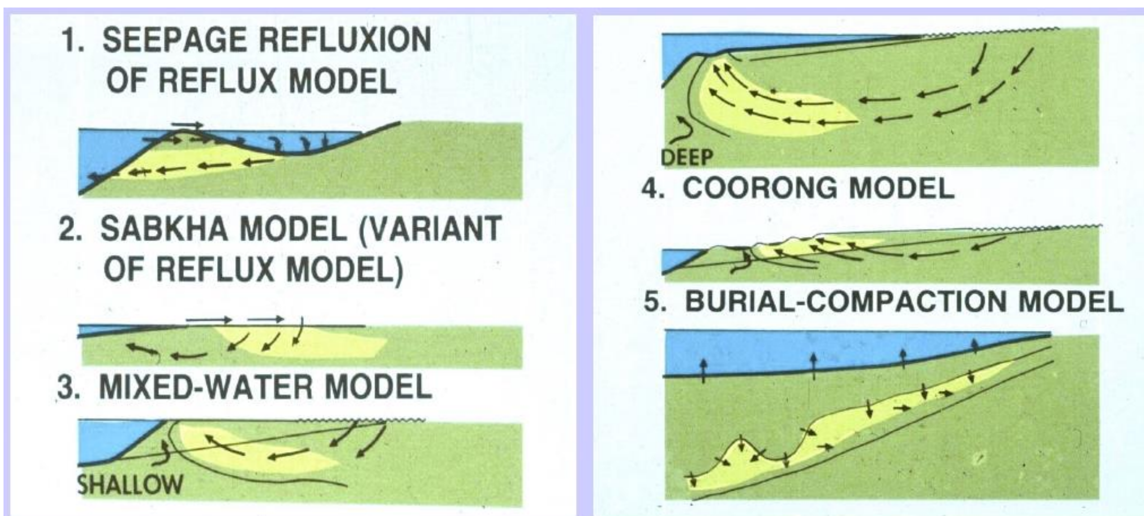
As has been observed on the clean limestone, total limestone, and primary cross-sections A-A' and B-B' (Figures 15, 16, 17, and 18, respectively), a massive limestone exists across the majority of the study area, which pinches out roughly five miles from the southern bounds of the study area, the Yoakum-Gaines County border. This limestone lies above the Yellowhouse dolomite interval (L8) and extends at maximum thickness into the P3 (Brahaney "B", G3 [Kerans, 2006]). It is primarily composed of dense to medium crystaline mudstone to grainstone (as observed on sample/strip logs), argillaceous in part, and contains significant chert and deeper outer-shelf marine fossils (i.e. crinoids, brachiopods, bryozoa, fusulinids). This type of deposit is what would be expected for the outer-shelf at the time of maximum flood (G2) P4 (see Figure 3) or p3 interval. This Major sea level rise resulted in the shelf as far north as Cochran County to be in deeper open marine environment which did not drop low enough for progradation of the shelf to progress far enough for intertidal deposits to start forming. This overall sea-level drop can be observed occurring (in the form of evaporite deposits) at the upper P3 (G3) through P0 (G4) sequences throughout much of the study area (see cross-sections; Figures 17 and 18).

As mentioned earlier, limestone forms under shallow marine conditions with either the presence of a healthy of biota or through non-biologic precipitation, which means any limestone observed must have formed within the marine environment. Through the post-depositional process of dolomitization, limestone is replaced (recrystallized) with dolomite through the chemical interaction with magnesium rich brine water (dolomite saturated) under the proper kinetic conditions (Mazzullo, 1998; Machel, 2004). What is observed within the study area (see cross sections; Figures 17 and 18) is that limestone is both underlain and overlain by dolostone. Pitt and Scott (1981) said specifically of limestone underlain by dolostone: “This lateral gradation as well as the general stratigraphic position in depositional cycles of dolomite above and limestone below implies that dolomite was formed from calcite or aragonite penecontemporaneously with the deposition of calcareous sediments.“ This concept is the basis of the reflux and sabkha-reflux models. Lindsay (2018) proposes that a hybrid model of the reflux model may be used, and would involve later stage dolomitization. The hybrid model is a reflux-mechanical compaction dolomitization model in which sub-surface brines with high concentrations of magnesium (Mg^{2+}) move downslope due to the pressure of the overburden (compaction) above. But as Machel (2004) iterates, no one true model for dolomitization may explain the full extent of the dolomite or dolostones observed in modern times.

The sabkha-reflux model of dolomitization best describes the primary process by which the San Andres dolostones of the Northern Shelf formed, primarily due to the region’s arid conditions at time of deposition. Machel (2004) explains: “The magnesium for dolomitization is supplied synsedimentarily (penecontemporaneously) by seawater that is propelled periodically onto the lower supratidal zone and along remnant tidal channels by strong onshore winds. The seawater has normal to slightly elevated salinity… but become significantly evaporated beyond gypsum saturation on and within the supratidal flats, through which it refluxes via its increased density, similar to flow in the reflux model” (see Figure 29). The sabkha model may be the best to explain why the limestone that lies above the Yellowhouse has not been dolomitized. The sabkha and reflux models suggest that any limestone that had never experience high salinity as the source of dolomitization fluids (remained at near open marine salinities), are immediately underneath the brine source and has low permeabilities (and thus low flow rates), and areas furthest from the brine source with low permeabilities may not dolomitize (Garcia-Fresca et. al., 2012). The dense argillaceous mudstone to wackestones observed on the strip/sample and mud logs would be low permeability, low flow rate limestones, explaining one possible reason for why they have not been dolomitized.

Conversely, the limestone does not thicken as it approaches the shelf-margine nor does it remain equally isopachous; instead the limestone tends to thin significantly to the south and pinches out near the northern border of the Wasson Field (Figures 15 and 16). A modern analog to the Wasson Field may be drawn to that of the Bahamas (Trentham, 2018). However, the Bahamas have no significant dolomites, and are primarily limestone with some aragonite (Whitaker and Smart, 2007), and Machel (2004) states that dolomite is fairly rare in the Holocene (modern day) environments. It is proposed that when exposed, the Wasson Field structure was more an isolated sabkha-like feature, and less a “tropical island”. If that were the case, then sabkha-reflux would have occurred from the isolated reflux fluid, generating features resulting in the limestones on and near the structure to become dolomitized during low stands, while also allowing other areas to

FIGURE 29 – Diagram depicting various models of dolomitization (retrieved from Machel, 2008).



Retrieved from Machel (2008)

remain limestone. This model, however, does not account for the thin limestone areas observed away from the limestone pinch out.

There is another explanation that may fit all criteria as well as the patterns of limestone to dolomite observed on the limestone isopach maps (Figures 15 and 15). The entire study area, especially around the Wasson Field, was known to have been tectonically active during and after deposition of the San Andres Formation (Dutton et. al., 1993; Winfree, 1994). The stresses of differential compaction during periods of sedimentation, especially on the Wasson Field structure, would have caused fractures to form in the limestone. These would be separate from the regional Laramide compression and subsequent post-Laramide extension events that also formed fractures, as observed by Winfree (1994). These early fractures could have extended into deeper formations, allowing for the dewatering of the deeper formations and ultimately the dolomitization (especially if the post-Ouachita waters were saturated to dolomite) of areas surrounding the fractures. As observed on Figure 19, the surface lineaments tend to trend or align with the thinnest clean limestone areas (Figure 15). This could be evidence that even though faults may not have penetrated through the San Andres that the stresses caused by their activation and the flexuring during the San Andres could have caused fractures, at least in part. It is also possible that the tectonic activity caused pore pressures to rise to a level where hydrofracturing occurred (Magara, 1981). In any of these cases, fractures created a pathway of migration that would not otherwise occur within or between sediment types, and thus the movement of water or hydrocarbon into these formations would likely affect the formations themselves.

Once the limestones have been fractured and post-Ouachita waters start to move upward due to the pressure differential, the areas with greatest potential for dolomitization would be thinnest at the base site of the fracturing while thickening (like a funnel or plume) upward and away from the base fracture. Any lithologies with porosity and permeability would allow for the post-Ouachita waters to infiltrate and potentially result in early dolomitization, while the tighter limestone would take longer to react and be dolomitized. These patterns of clean limestone, dolomitized limestone, and dolomite occurrences tend to match what is being observed within the study area (Figures 15 and 16). This model would also explain the occurrence of the dolomitized limestone that overlays the clean limestone, where the upper portions of the limestone at time of deposition were more porous due to being higher in section at the time of deposition while the San Andres shelf was prograding. In turn, when the fractures formed, and the deeper dolomitizing fluids moved through, these more porous limestones either 1) allowed for dolomite cements to form within the limestone matrix, 2) partly dolomitize or recrystallize the limestone into proto-dolomite, or 3) a combination of these two. This fits with the burial model of dolomitization as discussed by Machel (1999, 2004).

Water was the first fluid to move through the fractures, as oil generation would either not have started or would have been beginning by the time of the Laramide compression event. Dolomitization would have been occurring long before oil would have moved into the San Andres and potentially interrupted the dolomitization processes (Trentham, 2018; Machel, 2004). Oil accumulation, though is another important mark of the fractured limestone hypothesis. A majority of the observed oil reservoirs are along the periphery (or isopachous slopes) of the limestones identified (Figures 15 and 16), where oil collected primarily in structural highs and structural noses (Figure 14). It is reasonable to believe that the structures in which the oil is trapped may have been partly formed or affected by the fracturing that occurred. Since this is the case, the producing structures would be either directly above the thinnest clean limestones or along the fold axis of the deeper active faults. The seal for trapped oil then becomes the anhydritic dolomites or sabkha anhydrites located in either the P0 (G4), or those associated with the Upper San Andres. However, if there were not fractures within the lower San Andres, the likelihood that oil would have reached beyond the Wasson Field structure is questionable. Fractures within the San Andres, especially northward beyond the shelf margine, would allow for oil to be expelled when structurally and stratigraphically a seal should have occurred (Wilkinson et. al., 1991).

Another dolomitization event that is rather important to the formation of the Residual Oil Zone (ROZ) occurred during the Laramide compression and Basin and Range extension periods. The formation of the Guadalupe and San Andres Mountains (west of the study area) were formed during the Basin and Range event. The exposure of the San Andres Formation allowed for the influx of meteoric derived waters to flush through the subsurface (Brown, 2002; Lindsay, 1998, 2018; Trentham et al., 2012; Trentham, 2017; West, 2014a & b), which in turned allowed for dolomitization to occur (Machel, 2004). The amount of water flowing through the San Andres, which is still occurring today, causes a hydraulic head to form, which not only allowed for the vast majority of oil once contained within the San Andres ROZ interval to be pushed/flushed out, but for the evolution and current state of the tilted oil/water contact (Figure 25) (Brown, 2002; Lindsay, 1998; West 2014a & b).

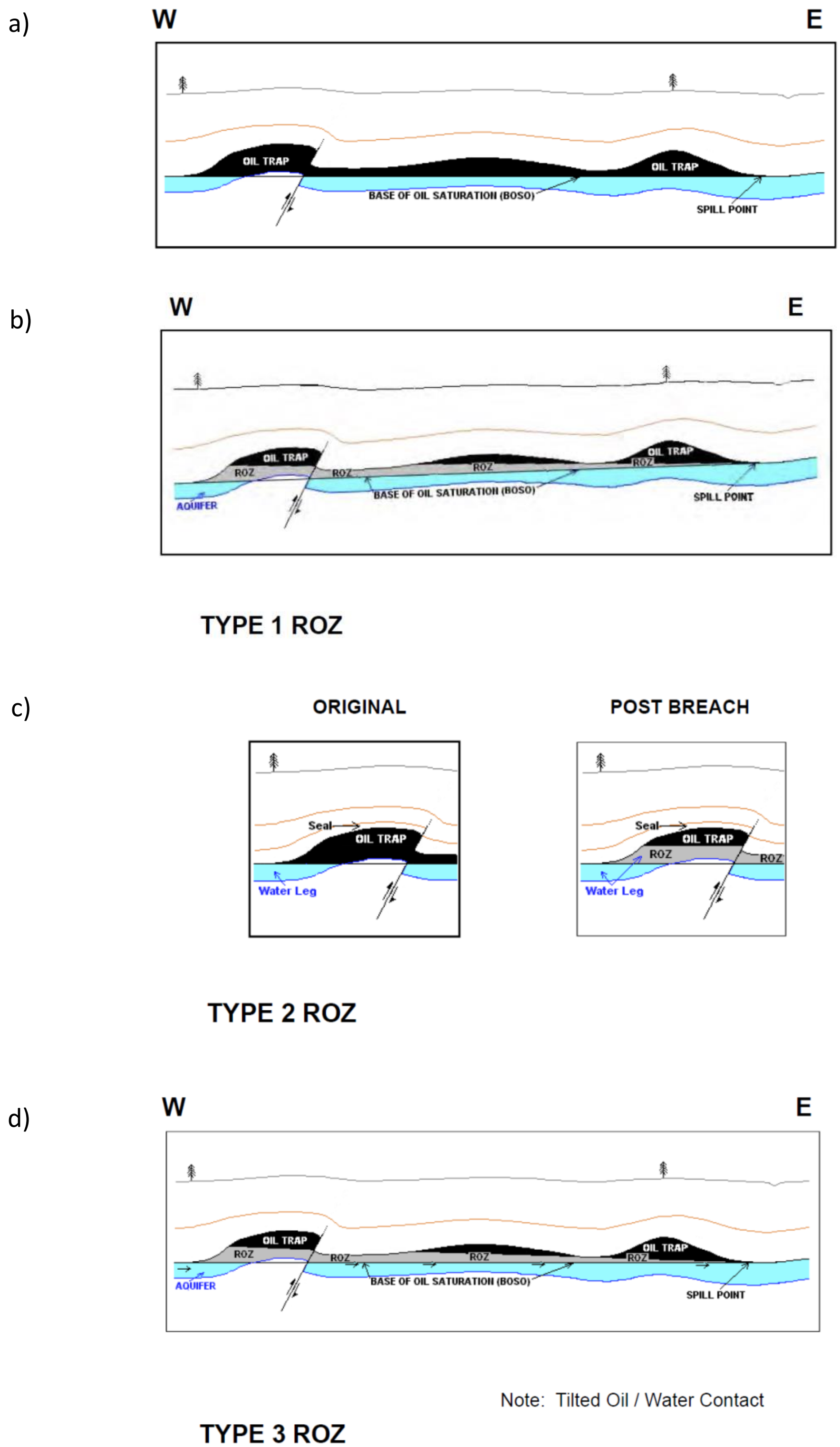
DUROZ Horizontal Play

The San Andres Formation of western Yoakum County, Texas, has been an area of active horizontal drilling and depressuring of the upper residual oil zone (DUROZ) for the past five plus years. During that time, the CO_2 Flooding Conference and later the CO_2/ROZ Conference has been an event where ideas and case studies have been presented and discussed on the (DU)ROZ of Yoakum and other Counties in Texas and elsewhere (Allison and Melzer, 2017; Hall, 2016, 2017, 2018; Hawthorne et. al., 2018; Kinder Morgan, 2018; Smith, 2015; Stedman, 2018; Taylor, 2017; Trentham and Melzer, 2011; Vance, 2014; West, 2014b; Worral and Hanagan, 2016). Although these studies are informative and useful for the general trends of the industry and general evolution of specific fields, few geologic significant insights have been provided. This section will use these conference presentations in order to help explain the findings and observations made throughout this study.

To begin with, the Residual Oil Zone (ROZ) is an oil saturated reservoir interval in which meteoric derived waters flushed through for all intents and purposes water-flooding the zone, leaving behind oil not recoverable by primary production methods (a.k.a. "Mother-Nature's Waterflood") (Trentham et. al., 2012). The ROZ play in Yoakum County, and most of west Texas is considered a Type 3 ROZ, or one in which there is a tilted oil/water contact due to the uplift and exposure of reservoir rock to meteoric derived waters (Figure 30). The DUROZ play, entails depressuring a longer lateral length of the San Andres (rather than CO_2 injection in and around vertical San Andres wells in thr typical ROZ play) so that the gasses trapped within the oil would be allowed to expand, making the oil less viscus and able to move (Figure 31). Manzano, LLC (who sold their Yoakum County rights to Steward Energy II, LLC in 2016) was the first to truly test the DUROZ concept starting with the drilling of the #1H What A Mellon 519 well in March of 2013.

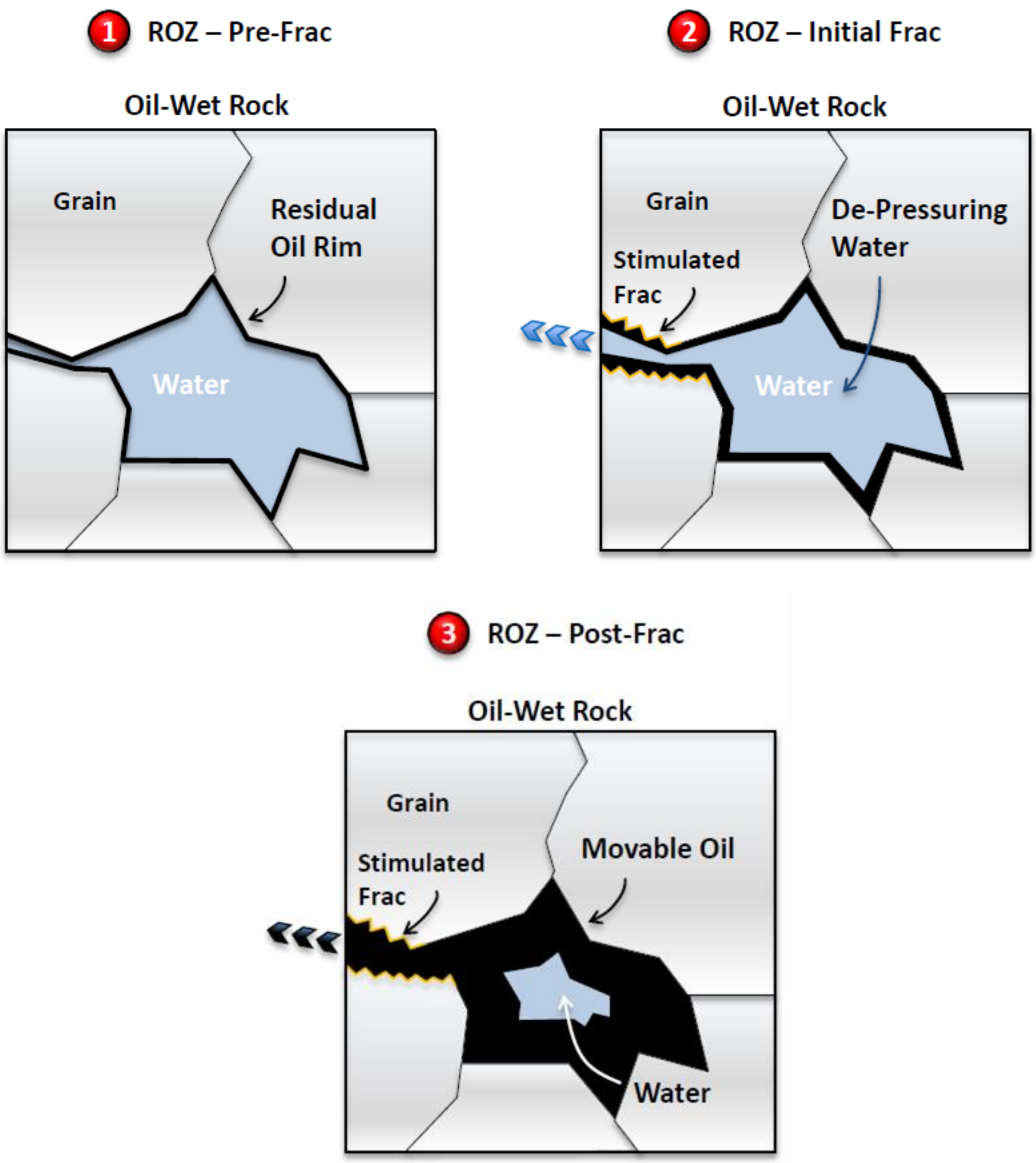
As observed in this study on the C-C' cross-section and 3D map (Figures 24 and 27, respectively), it appears that a majority of the wells may not be "landing" (the point at which the borehole goes horizontal, which starts at approximately 85° from vertical) within the ROZ proper, but instead in a tighter main pay zone (MPZ). Although it has been noted that a tilted oil/water contact exists across the study area, and all of the remaining Northern Shelf, the author did not have the resources to accurately plot this contact across the study area. The areas away from the conventional fields may have an elevated oil/water contact as compared to the primary producing fields. This increasing thick water zone could occur if the porosity and permeability from the MPZ fields are such that capillary pressures, and smaller pore throats, allow for water to draw higher into the section than in the more porous and permeable conventional MPZ fields. If this is the case, then many of the horizontal DUROZ wells may be below, or cross, the traditional oil/water contact.

FIGURE 30 – a. Diagram depicting pre-existing conditions. b. Type 1 ROZ: Westward regional tilt and migration of oil leaving behind an ROZ. c. Type 2 ROZ: Pre and Post breach of reservoir, showing ROZ formation after migration of oil along fault and reseal. d. Type 3 ROZ: Meteoric derived waters flush through reservoir creating tilted oil/water contact, leaving behind ROZ. (Modified after Melzer, 2012)



Modified after Melzer (2012)

FIGURE 31 – Diagram depicting oil emplacement and swelling during DUROZ operations. 1) Water pressure compresses gasses and oil, only water able to move. 2) Frack operations occur, and dewatering/depressuring begins. 3) Depressuring has reached level where gasses are able to swell and “inflate” oils; oil is not able to be produced.



Modified after Taylor (2017)

These observations bring up some questions on the definition of what has been considered the depressuring of the upper residual oil zone (DUROZ). Does a horizontal well that is landed in a tight MPZ, yet is hydraulically fractured (fracked) into the ROZ, still considered DUROZ well? Is a well that is landed at the upper limit of the ROZ and is fracked and produced from both the MPZ and ROZ still a DUROZ well? Here the author will try to provide a definition for some of the most common cases:

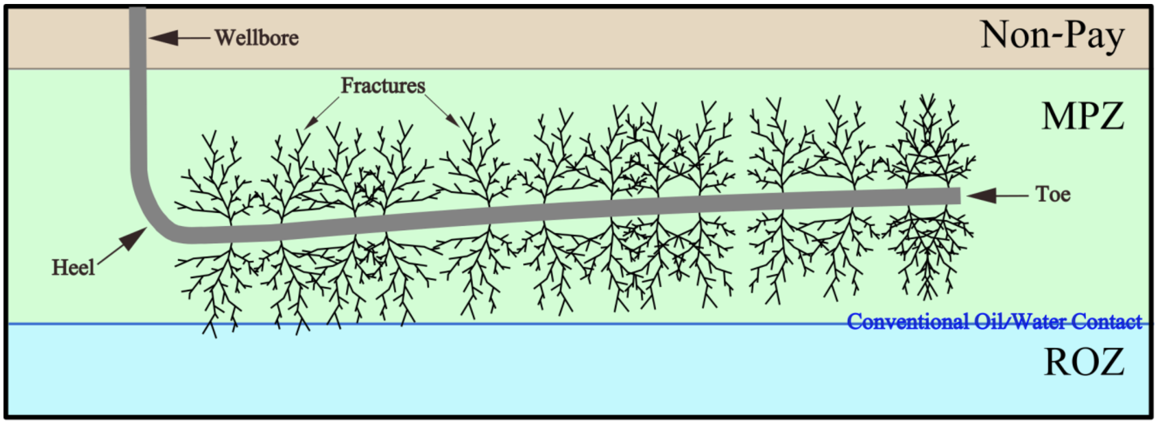
1) A well with the lateral drilled and completed in the Main Pay Zone, but with few fracks reaching the conventional oil/water contact (into the Residual Oil Zone [ROZ]), resulting in little to no production from the ROZ. This should be considered as a Main Pay (MP) well. (see Figure 32a)
2) A well with the lateral drilled and completed near the conventional oil/water contact with fracks extending into both the Main Pay Zone (MPZ) and Residual Oil Zone (ROZ), with production coming from both zones. This should be considered a Mixed Conventional and Residual Oil Zone (MCROZ) well. (see Figure 32b)
3) Horizontal well with the lateral drilled and completed below the conventional oil/water contact, with little to no fracks that extend into the Main Pay Zone (MPZ), and little to no production from the MPZ. This should be considered as a Residual Oil Zone (ROZ) well. (see Figure 32c)

Qualifiers may also be added to this nomenclature and abbreviations where applicable, but may not be necessary where it is understood. For example "Depressuring the Upper" or "DU" may be added to the Main Pay or Residual Oil Zone (i.e. depressuring the upper main pay [DUMP], depressuring the upper residual oil zone [DUROZ]); however, neither may necessarily be needed for the Mixed Pay Residual Oil Zone (MCROZ) since it is already understood that depressuring would be the primary production technique, and there is no upper or lower level to this type of well. Some refinement may need to be made at a later date, if contributions from the Main Pay and ROZ may ever be determined, but for now this should further assist in visualizing the landing zone and completions associated with horizontal conventional drilling and production. With these new definitions, it would appear that the majority of the horizontal San Andres wells are primarily mixed conventional and residual oil zone (MCROZ) rather than strictly DUROZ or MP producers.

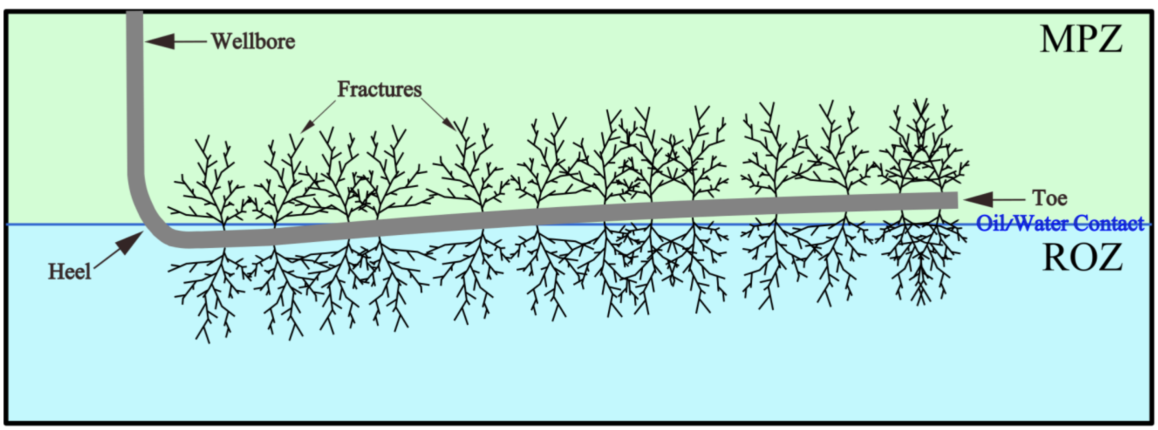
While reviewing the first 12 month production of the horizontal San Andres wells for years 2016 and 2017 (Figures 20 through 23, and Appendices C through F), no correlation between the completion nor the environment could be determined. This is likely due to the wide range of landing points, variations in straightness of the horizontals, toe (end of the horizontal segment) up or down (as compared to the heal [curve]), completion techniques, horizontal lengths, and other factors. The other factors for why the DUROZ/MCROZ play does not have correlative production is that the play is still relatively new (being only roughly 6 years old), drilling/completion techniques have not been perfected (technology is still advancing), and our understanding of the play is still in its infancy. Steward II LLC. (Stedman, 2018) provided a chart in their latest CO2/ROZ Conference presentation that demonstrated how their Bronco/Platang area wells have evolved through 2017 (Table 2). Only if and when a large enough set of wells are drilled to the same relative stratigraphic or structural depth, drilled the same length, and completed the same way, would a better pattern between the formation (i.e. DUMP, MCROZ, DUROZ) and production appear; however, that is not the case, and will not be for the foreseeable future. Another factor that complicates the correlative nature of the depressuring play is that every new well drilled near another producing well already has a partially depressured reservoir to start from allowing for faster oil production than the one previous (Stedman, 2018). Also, the landing point of the horizontal San Andres wells tends to be at too great a distance above the clean limestone so that no barrier to vertical flow of water can be established. However, the dolomitic limestone which does exist in the upper P3 (Brahaney “C”) in areas of this study may have an effect on the production of the lower landing DUROZ wells. Since the dolomitic limestone would tend to have lower porosity, it may help facilitate a partial barrier to the deeper water zones once the well is fracked, thus allowing for better control of frack length and an overall lower water cut. To paraphrase Hall (2018), zones with slightly lower porosities (dolomitic limestones) may be better to land in than those with the highest porosities (dolostones) because it may prevent the instant access to the “big water” that resides deeper in the San Andres.

Another observation made based on the first 12 month production maps (Figures 20 through 23, and Appendices C though F) is that, in general, wells that are nearest or within existing conventional fields tend to have lower oil cuts than those further away from existing fields. Firstly, the initial production and drawdown of the conventional main pay zone (MPZ) does not produce only oil and water, but gas as well. The

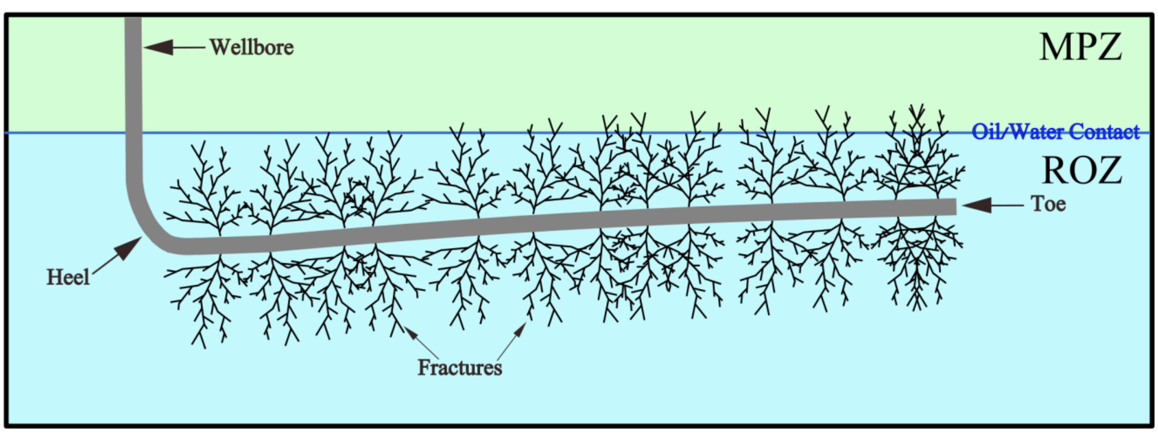
FIGURE 32 – Diagrams depicting landing zones, and associated production from stimulated fractures. a. Figure depicting Main Pay (MP) production. b. Figure depicting Mixed Conventional and Residual Oil Zone (MCROZ) production. c. Figure depicting Residual Oil Zone (ROZ) production.



a) Main Pay (MP)



b) Mixed Conventional and Residual Oil Zone (MCROZ)



c) Residual Oil Zone (ROZ)

TABLE 2 – Steward II LLC.'s evolution of horizontal drilling and stimulation in the Bronco/Platang Fields of western Yoakum County, TX. (Retrieved from Stedman, 2018)

<table>
<tr><th>Gen</th><th>Date</th><th>Lateral Length</th><th>Stage Count</th><th>Stage Spacing</th><th>100 Mesh</th><th>Proppant Mesh</th><th>Proppant Mass</th><th>Slickwater %</th><th>Linear %</th><th>X-link %</th><th>Gel Loading</th></tr>
<tr><td>Pre-ACQ</td><td>Oct-16</td><td>4100</td><td>13</td><td>315</td><td rowspan="3">45,000</td><td rowspan="5">30/50</td><td rowspan="5">145,000</td><td>45%</td><td>40%</td><td>15%</td><td rowspan="4">12#</td></tr>
<tr><td>1.1</td><td>Nov-16</td><td rowspan="6">5000</td><td>14</td><td>357</td><td>35%</td><td>15%</td><td>50%</td></tr>
<tr><td>1.2</td><td>Feb-17</td><td>16</td><td>313</td><td rowspan="2">25%</td><td rowspan="2">20%</td><td rowspan="3">55%</td></tr>
<tr><td>2.1</td><td>Mar-17</td><td>18</td><td>278</td><td>7,500</td></tr>
<tr><td>2.2</td><td>Apr-17</td><td rowspan="3">20</td><td rowspan="3">250</td><td rowspan="3">5,000</td><td rowspan="3">20%</td><td>25%</td><td rowspan="2">15#</td></tr>
<tr><td>3.1</td><td>Jun-17</td><td rowspan="2">20/40</td><td rowspan="2">205,000</td><td rowspan="2">0%</td><td rowspan="2">80%</td></tr>
<tr><td>3.2</td><td>Dec-17</td><td>18#</td></tr>
</table>

- Lateral Length – increased by moving surface locations off-lease
- Stage Count – gradually increased – room for more?
- 100 Mesh – reduced to minimum needed to reduce near wellbore tortuosity
- Proppant Size – can easily pump either 30/50 or 20/40 but 20/40 is more readily available
- Fluids – gradually shifted to fully cross-linked proppant laden fluid
- Gel – a more robust gel system creates more frac width, reducing need for sweeps

Retrieved from Stedman (2018)

processes involved in primary production will ultimately depressurize the MPZ, potentially to the “minimum miscibility pressure” (MMP) (“miscible fluids mix in any ratio without forming two phases” – Hawthorn, et. al., 2018) of light natural gasses (LNGs) within the reservoir. Take ethane (C2) for example: once the reservoir pressures drop to the minimum miscibility pressure of ethane, it will preferentially turn to a gas which will allow it to travel more easily through the pore-throats of the reservoir (Hawthorn et. al, 2018; Melzer, 2017). This is the same is true for each of the light natural gases, but each varies according to their particular chemical properties (Hawthorn et. al., 2018).

After multiple years of production and depressurization of the main pay zone, secondary recovery (water-flooding) of the reservoir may be sought to help increase reservoir pressures as well as push remaining retrievable oil towards production wells. Water injection may help increase the overall reservoir pressure, and may even be able to over-pressurize the reservoir (increase beyond native non-produced pressures). However, with the loss of light natural gasses (lower Gas to Oil Ratio [GOR]), the remaining oil has become heavier (lower API gravity) and more viscous (less likely to flow). This will in turn cause less oil to be produced than initially expected in a secondary recovery attempt. However, for horizontal wells (i.e. DUMP, MCROZ, DUROZ) trying to maximize recovery within an already productive field, the effects of the initial depressurization of the reservoir may be detrimental to overall production. Due to the loss of light natural gasses (which the depressuring wells depend on), the oil may not have enough gas to swell the oil in order to make it movable. The lower GOR and API of the oil will ultimately lead to higher water production. What may be observed in these cases (especially in and around secondary recovered fields) is a “pressure shadow”, the impact of depressuring during primary production and subsequent re-pressuring during water flooding. Figure # tries to help visualize this pressure shadow effect. Further research into this concept is needed.

When viewing the results around the conventional producing fields, especially those undergoing water floods (Wasson and Brahaney in particular; Appendices C through F), the effects of the initial gas and pressure loss can be observed. The horizontal DUROZ/MCROZ wells within or near these field have upwards of 50% the oil cuts (if not less) than those further away, with a few exceptions. This may be cause by a pressure shadow. This false security provided by the pressure of the reservoir should be recognized and planned for, although more research is required.

As for the wells with greater oil cuts in and around the productive fields (and even throughout the area of study), there are multiple explanations for why they have better oil cuts and initial production: 1) insufficient reporting, in which multiple wells at one point did not have “water produced” reported, thus artificially increasing oil cut; and, 2) landing point and stimulation techniques, where a horizontal landed higher with less aggressive stimulation may have lower chances of producing water, especially to start. Although the “insufficient reporting” statement, in itself, is a slight misnomer for this study, in that the Texas Railroad Commission (TRRC) does not require quantity of produced water to be reported and recorded. Instead, the water that gets reported is based on a calculation from the biannual production tests that are reported to the TRRC,

FIGURE 33 – Diagram depicting potential reservoir pressures and effects from various stages of production. a. Native pressures, pre-production. b. Pressures post primary production, pre-secondary production (waterflood). c. Pressures during secondary recovery (waterflood).

Minimum Miscible Pressures used (demonstration purposes only, not real reservoir numbers):

Methane (C1):	1500 psi
Ethane (C2):	1200 psi
Propane (C3):	900 psi
Butane (C4):	600 psi

a)
b)
c)

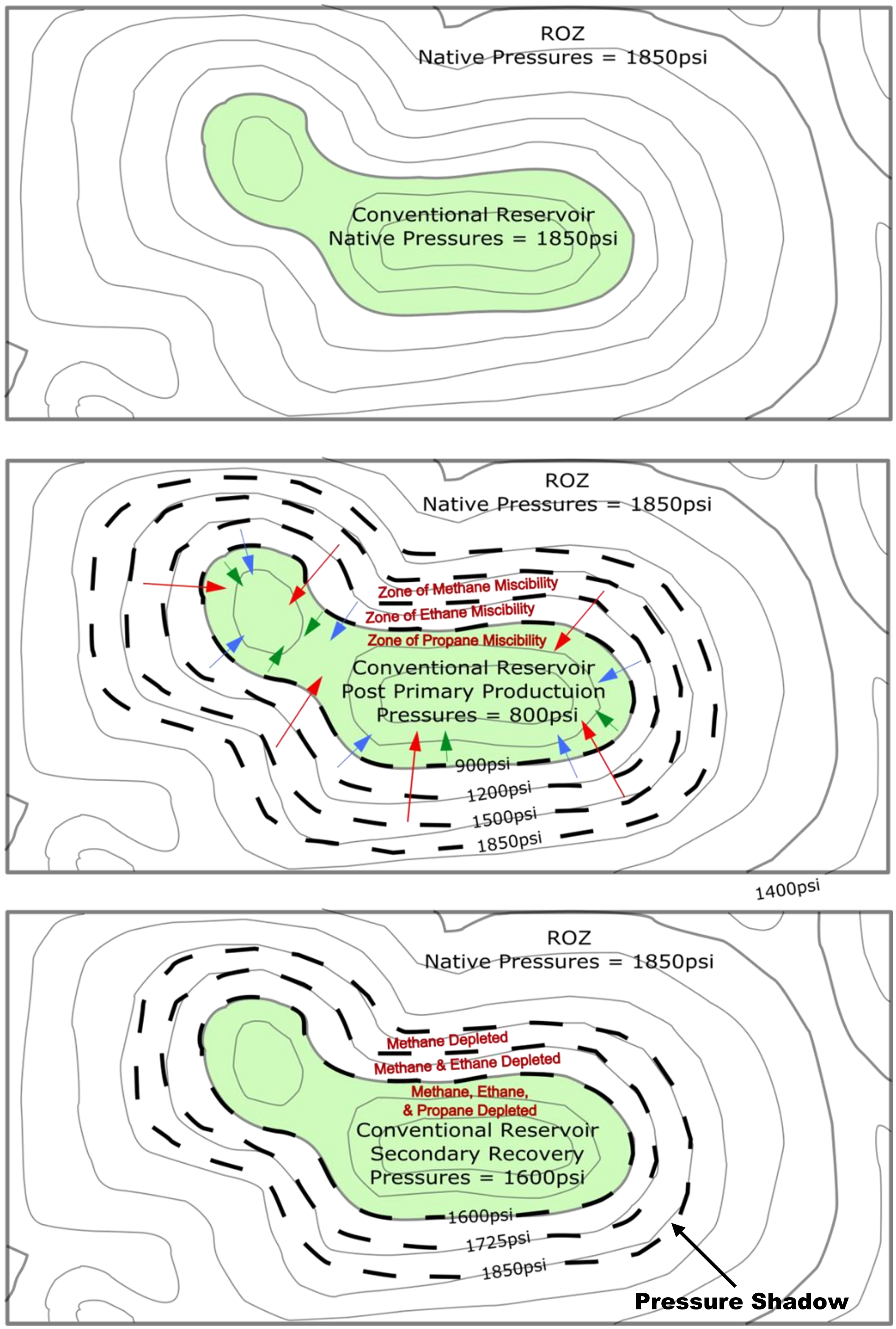


*Figure is concept only; numbers used are for demonstration and not from an actual reservoir.

in which the "water produced" is based on the percentage of oil/gas/water from the production test and amount of oil and/or gas produced from the well in a given month after the test. If an error was made in the test, or water produced was not recorded or improperly reported on the production test, then no water or improper water amounts will be "produced" from a well for at minimum a six month period.

The importance of native pressures may be significant. If pressure shadows continue to hinder production for the DUROZ/MCROZ around and within conventional main pay fields then an alternative may need to be developed, but as of now the horizontal development within these conventional fields is still young and insufficient data has been gathered. This may lead credence to drilling and completing horizontal DUROZ/MCROZ wells near smaller fields where no water floods have occurred, or in areas that seem to have a main pay zone (MPZ) but has been determined too tight to produce (greenfields). Since these areas would either suffer from lower to no pressure loss, there would be no pressure shadow to contend with. As Hall (2018) suggested, completing in tighter rock may aid in producing more oil, with proper stimulation, and would prevent access to the deeper water intervals. As long as reservoir quality rock is present, and oil or gas shows prevalent, the only question then becomes: "How tight is too tight?"

CHAPTER 7 - Conclusions

The limestone that lies above the Yellowhouse dolomite was deposited during the San Andres maximum sea level during the Guadalupian 1 and 2 (G1 & G2), which correlates to the McKnight Shale and the El Centro Member of the Cutoff Formation. The evidence for this has been found in the sample/strip and mud logs where the descriptions confirm a deep open marine limestone. The clean limestone at the top of the Yellowhouse is upwards of 358 feet, while total limestone thickness is upwards of 395 feet in nothern Yoakum County, Texas. The limestone pinches out approximately five miles north of the Yoakum-Gaines county border.

The gradient of dolomitization/recrystallization of the limestone (both clean and dolomitic) is not consistent; instead there are multiple areas of thinning and thickening across the study area. The best explanation for these thicks and thins are fractures caused by the Laramide compression and Basin and Range extension events. These fractures likely enabled a pathway of migration for deeper basinal fluids, saturated with magnesium rich fluids, to migrate into the San Andres. During this basement dewatering, the upper limestone was converted to dolomitic limestone, and ultimately into dolostone (in part) over time. As for the DUROZ play in western Yoakum County, no correlation between the thickness of limestone and production could be observed, primarily due to the depths at which the limestone occurs as compared to where the horizontal wells are being landed and hydrocarbons are being produced.

It has been observed that the majority horizontal DUROZ wells were not necessarily landing below the conventional oil/water contact and in the ROZ, but instead landing above in a tighter relatively uneconomic main pay zone (MPZ). This lead to a new definition termed the “Mixed Conventional and Residual Oil Zone” (MCROZ), in which significant production is likely from both the MPZ and the ROZ. A redefinition of wells landing in the MPZ with little to no ROZ production to being termed “Main Pay” (MP), while sells landing below the conventional oil/water contact with little to no production from the MPZ will continue to be termed Residual Oil Zone (ROZ). The descriptors of “Depressurizing”, “Upper”, or any other term deemed necessary could still be placed in front of these three terms for better definition.

Also, it was observed that there seems to be little to no effect on the DUROZ/MCROZ wells due to structure or thickness of the lower San Andres or clean limestone, but likely this is related to where the well is landed and the type of stimulation. However, wells landed in proximity to conventional fields being water flooded tend to have lower oil cuts. This may be due to a pressure shadow produced after the initial dissolved gasses were removed and water flooding began. Since gas is a main driver for producing from the DUROZ the initial loss of gas may allow for lower gravity (thicker) oil and thus more water to be produced. Drilling MP or MCROZ wells starting in a tighter reservoir may help increase oil productivity by diminishing overall water cut.

Recommendations for Further Research

This research was the first step in producing a better geological understanding of an area with both renewed and growing interest: Yoakum County, Texas. However, there are still many questions that need to be answered, especially new ones resulting from this study. These areas for further study are:

1) Mapping the limestone above the Yellowhouse formation to the west into Lea County, New Mexico and east including the rest of Yoakum County, Texas.
2) Determining through limestone mapping studies, in conjunction with this study, if the Tatum Basin and/or another intrashelf basin existed during the San Andres time.
3) Establishing a regional oil/water contact across the non-productive part of the Northwest and Northern Shelves, and determining its regional dip.
4) Describing core taken through the lower San Andres, especially those that intersect the limestone intervals to better define the environment of deposition.
5) Describing core taken through the lower San Andres, especially in or near, and intersect, the Limestone thins to determine if fractures exist, and what impact they may have in the dolomitization of the lower San Andres.
6) Evaluating the effects of "pressure shadows" on infield and nearfield horizontal drilling and production.

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APPENDIX A

APPENDIX B

APPENDIX C

Please Refer to Folded Map on Back Cover:

2016 Horizontal San Andres Completions, First 12 Months Production on Total Limestone Isopach Map.

APPENDIX D

Please Refer to Folded Map on Back Cover:

2016 Horizontal San Andres Completions, First 12 Months Production on Pi Marker Structure Map.

APPENDIX E

Please Refer to Folded Map on Back Cover:

2017 Horizontal San Andres Completions, First 12 Months Production on Total Limestone Isopach Map.

APPENDIX F

Please Refer to Folded Map on Back Cover:

2017 Horizontal San Andres Completions, First 12 Months Production on Pi Marker Structure Map.

Vita

Norman E. Wells, Jr. was born February 22, 1981 in Garfield Heights, Ohio (suburb of Cleveland), United States to Norman E. Wells, Sr. (Father) and Diane Wells (Mother). He started a Bachelor of Arts Degree in Geology in August of 1999 at Miami University (Oxford, Ohio), and graduated in May of 2003. Norman's first geological job was as a Mud Logger for GeoSite, Inc. based out San Angelo, TX in which he worked for two years in the Fort Worth Basin (Barnett Shale), Permian Basin, and Anadarko Basins (Cleveland Sandstone). He left Texas for Ohio, where he worked for approximately one year as an Environmental Technician for Bureau Veritas N.A., then moved to Charlotte, North Carolina, where he was a Staff Scientist for Delta Consultants (an environmental firm). Norman was laid off in 2010, when he moved back to Texas and started working for GeoSite, Inc. as a Mud Logger/Geologic Consultant for another 2 years, before hiring on with Berger Geosciences (B-Geo) as a Marine Geologist III. Norman's primary function at B-Geo was to observe and record shallow geohazards prior to a risor being connected to the rig. He was able to work in the Caspian Sea off of Baku, Azerbaijan, South China Sea off of Brunei, and the Gulf of Mexico off of Luisiana. In 2013, Norman began working in Midland, Texas for McClure Oil Company, Inc. as an Operations Geologist, where he resides till this day. Norman received his Master of Science in Geology on May 11, 2019. This thesis was typed by Norman E. Wells, Jr.