

FORMATION EVALUATION OF LEONARDIAN STRATA WITHIN THE
NORTHERN SPRABERRY TREND, WEST TEXAS

by

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in

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EQUATION TERMINOLOGY

$\emptyset ND_{xp}$	= Neutron-density crossplot porosity (dec)
$\emptyset NS_{xp}$	= Neutron-sonic crossplot porosity (dec)
$\emptyset S$	= Sonic porosity (dec)
RhoMatApp	= Apparent matrix density (g/cc)
DTMatapp	= Apparent matrix travel-time (μ s/ft)
UMatApp	Apparent volumetric cross section (barns/electron)
U	= Volumetric cross section (barns/electron)
U_{fl}	= Volumetric absorption of fluid (barns/electron)
C_t	= Conductivity from deep-resistivity (milliSiemens)
R_t	= Deep resistivity (ohm-m)
C_{xo}	= Conductivity from shallow resistivity (milliSiemens)
R_s	= Shallow resistivity (ohm-m)
Napp	= Apparent N parameter (n/a)
Mapp	= Apparent M parameter (n/a)
BHT	= Borehole temperature (f)
SFT	= Mean surface temperature (f)
HSG	= Hydrostatic pressure gradient – assumed to be 465 (psi/ft)
V_{clGR}	= Clay volume derived from the gamma ray log (dec)
GR	= Gamma ray log response (api)
GR_{clean}	= Gamma ray response in a clean zone (api)
GR_{clay}	= Gamma ray response in a clay-rich zone (api)

EQUATION TERMINOLOGY - CONTINUED

Thor	= Thorium concentration (ppm)
$\text{Thor}_{\text{clean}}$	= Thorium concentration in a clean zone (ppm)
$\text{Thor}_{\text{clay}}$	= Thorium concentration in a clay-rich zone (ppm)
Vcl_{Thor}	= Clay volume derived from thorium concentration (dec)
ND_Vcl	= Clay volume derived from neutron-density separation (dec)
ρ_{fl}	= Fluid density (g/cc)
ρ_{ma}	= Matrix density (g/cc)
ρ_{b}	= Bulk density (g/cc)
$\emptyset\text{N}$	= Neutron porosity (dec)
$\emptyset\text{N}_{\text{ma}}$	= Matrix neutron response (dec)
$\emptyset\text{N}_{\text{fl}}$	= Fluid neutron response (dec)
NS_Vcl	= Clay volume derived from neutron-sonic separation (dec)
Δt	= Sonic travel-time ($\mu\text{s}/\text{ft}$)
Δt_{ma}	= Matrix travel-time ($\mu\text{s}/\text{ft}$)
Δt_{fl}	= Fluid travel-time ($\mu\text{s}/\text{ft}$)
$\Delta\log R_{\text{sonic}}$	= $\Delta\log R$ separation from sonic and resistivity logs (n/a)
$\Delta\log R_{\text{neutron}}$	= $\Delta\log R$ separation from neutron and resistivity logs (n/a)
$\Delta\log R_{\text{density}}$	= $\Delta\log R$ separation from density and resistivity logs (n/a)
R_{bl}	= Deep-resistivity value in organic-lean interval (ohm-m)
ΔT_{bl}	= Sonic-travel time in organic-lean and/or wet interval ($\mu\text{s}/\text{ft}$)
$\text{TOC}_{\text{Passey}}$	= Total organic carbon content from Passey method (wt%)

EQUATION TERMINOLOGY - CONTINUED

TOC_{bl}	= Background TOC levels in organic-rich rocks ~0.8 (wt%)
LOM	= Level of organic morphism (unitless)
C	= Passey scaling factor (n/a)
S_w	= Water saturation (dec)
a	= Tortuosity factor (n/a)
R_w	= Formation water resistivity (ohm-m)
n	= Saturation exponent (n/a)
m	= Cementation exponent (n/a)
R_o	= Wet rock resistivity (ohm-m)
$\Delta \log R_{Modified}$	= Separation from modified $\Delta \log R$ method (n/a)
$TOC_{Modified}$	= TOC from modified $\Delta \log R$ method (wt%)
$TOC_{Schmoker}$	= Total organic carbon content from Schmoker method (wt%)
Ts_1	= Schmoker numerator constant – published value of 154.497 (n/a)
Ts_2	= Schmoker subtraction constant – published value of 57.261 (n/a)
Δt_{Faust}	= Synthetic sonic log derived from true formation resistivity ($\mu s/ft$)
TOC_{Faust}	= TOC from the Faust method (wt%)
$\bar{M}$	= Vector of log responses
E	= matrix of endpoints to be solved for
$\bar{V}$	= Vector of unknown volumes
$\Phi S_o H$	= Hydrocarbon pore thickness (ft)
Φ_T	= Total porosity (dec)

EQUATION TERMINOLOGY - CONTINUED

H	= Height of specified interval (ft)
OOIP	= Oil in place (stock-tank barrels)
S_o	= Oil saturation (dec)
RF	= Recovery Factor (n/a)
B_o	= Oil volume factor (reservoir barrels per stock-tank barrel)

ABSTRACT

The Spraberry Trend is defined by oil and gas production associated with Permian age fine-grained siliciclastic and carbonate strata located within the Midland Basin of West Texas. Since its discovery, production within the Spraberry Trend has been inconsistent, and few petrophysical studies of these low permeability reservoirs exist to examine the reasons for this inconstancy. A modern petrophysical study of the Spraberry Trend will aid in understanding these rocks and in determining the unconventional reservoir potential of this strata in the northwestern Midland Basin.

The purpose of this research project is to complete a detailed petrophysical evaluation of Leonardian strata within Martin and Andrews counties of West Texas. Using public data from 50 wells and drill-core from two pilot wells, a petrophysical-workflow will document geologic heterogeneities throughout the study area. Petrophysical parameters of the Spraberry Trend will be determined through: 1) well-log data conditioning 2) deterministic and probabilistic well-log analysis 3) sedimentological core-descriptions 4) rock-to-log calibration 5) X-ray fluorescence analysis 6) stratigraphic analysis and 7) attribute mapping.

This project will demonstrate the importance of combining geologic knowledge and petrophysical attributes to better understand these rocks and to fully characterize them as unconventional reservoirs. Results from this project will compliment previous work completed on the Spraberry Trend by implementing modern petrophysical techniques to characterize an otherwise under-studied region of the Midland Basin. Oil companies and future researchers will be able to integrate data from this project to better understand the regional geology the Permian Basin and other unconventional reservoir targets.

CHAPTER 1

INTRODUCTION, OBJECTIVES, AND SIGNIFICANCE OF STUDY

Introduction

The Permian Basin¹ is a prolific hydrocarbon province that occupies ~120,000 square miles of land throughout West Texas and New Mexico (McGookey, 2013). Within this vast region, oil and natural gas have been produced from various subbasins and stratigraphic intervals since 1921 (Durham, 2011). In recent years, many petroleum operators have been exploring “stacked” pay zones, particularly, the Wolfberry play (Party, 2012).

Throughout West Texas, the Wolfberry play is composed of informal and formal units of the Wolfcampian and Leonardian Series of the Permian System: the Wolfcamp interval, the upper Leonard interval, the Dean Formation, the middle Leonard interval, and the Spraberry Formation (Hamlin and Baumgardner, 2012) (Figure 1). These units are composed of fine-grained siliciclastic and carbonate strata that can be observed in parts of the Midland, Delaware, and Val Verde Basins (Figure 2). This study will focus on the Leonardian Series located within the central region of the Midland Basin and defining the principle location of the Spraberry Trend.

The Spraberry Trend (Figure 2) is a northwest-southeast trending, subsurface-accumulation of deep-water submarine fan deposits that cover ~2,500 mi² of the Midland

¹ “Basin” is used in combination with a proper noun to indicate a geographic location, whereas “basin” is used to indicate a sedimentological depocenter, as suggested by Silver and Todd (1969).

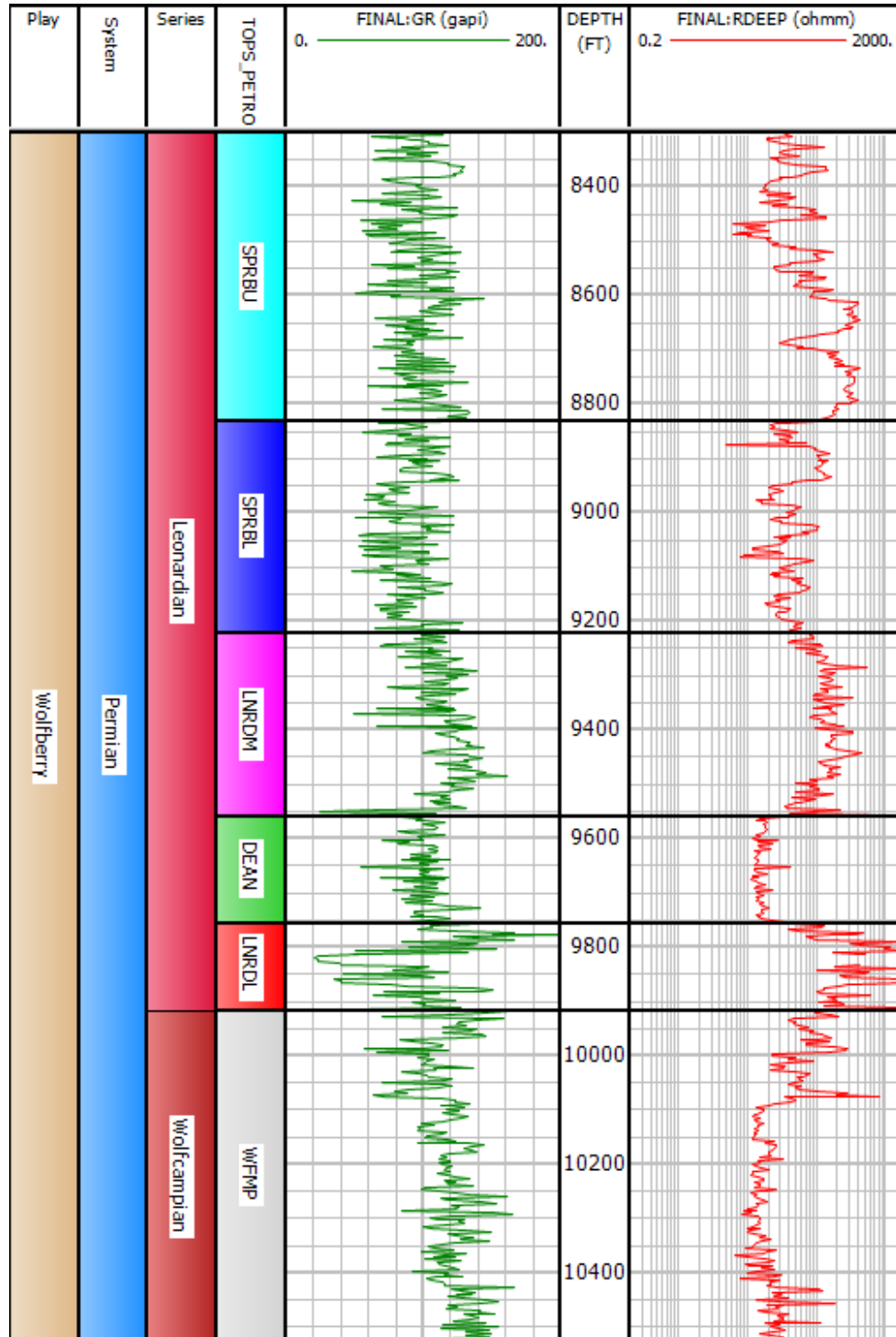


Figure 1. Stratigraphic ages, terminology, and typical gamma ray and resistivity responses of the rocks comprising Wolfberry play. SPRBU = Upper Spraberry, SPRBL = Lower Spraberry, LNRDM = Middle Leonard, LNRDL = Lower Leonard, WFMP = Wolfcamp.

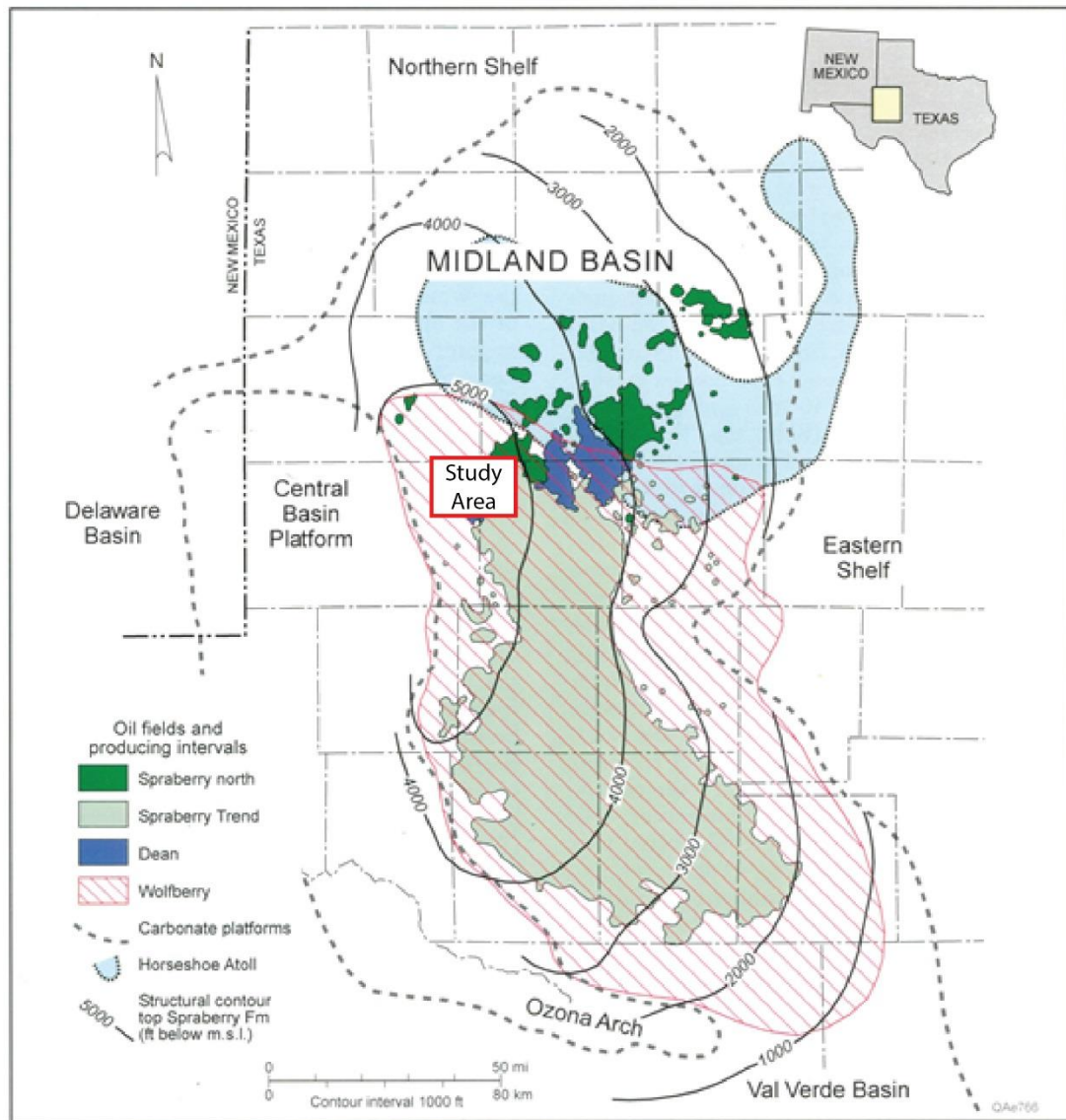


Figure 2. Map of the Midland Basin emphasizing the Wolfberry play and Spraberry Trend. Surrounding basins and platforms are also shown. Modified from Hamlin and Baumgardner (2012).

Basin (Tyler and Gholston, 1988). Reservoir intervals within this trend contain 10 billion of oil in place (Hamlin and Baumgardner, 2012), making the Spraberry Trend area the second largest oilfield in the United States based on proven reserves (Energy Information Administration, 2015). Hydrocarbons were first discovered by the Seaboard Oil Company in 1949 with the drilling and completion of the Lee No. 2-D well on Abner Spraberry's farm in Dawson County, Texas (Wilkinson, 1953). The Spraberry Field, and subsequently the Spraberry Trend, was named after the location of the aforementioned discovery well.

Since the discovery of the Spraberry Trend, conventional hydrocarbon production has been inconsistent due to geological heterogeneities and variations in completion practices associated with low permeability reservoirs within the Spraberry Formation, the middle Leonard interval, and the Dean Formation. According to Montgomery et al. (2000) modern reservoir analyses have been hindered by the lack of scientific studies conducted on the Spraberry Trend since the 1960's. Additionally, historical publications (McLennan and Bradely, 1951; Wilkinson, 1953; Schmitt, 1954) only characterize the Spraberry Trend from a conventional exploitation standpoint that do not incorporate quantitative petrophysical analyses. The terms "trend" and "play" are defined in the context of Petroleum Systems later in this thesis under the section pertaining to petroleum exploration terminology.

Objectives

The comprehensive objective of this study is to characterize the unconventional

reservoir potential of the northern Spraberry Trend within the Midland Basin by utilizing the following resources: public data from 50 *University of Texas Lands System* wells; core analyses and core descriptions from two Chesapeake Energy wells; LR Synergy's Interactive Petrophysics™ software and IHS's Petra® software. Characterization of Leonardian strata was accomplished by the implementation of three main objectives (Table 1):

- (1) Determine the reservoir potential of Dean-Spraberry strata in Andrews and Martin counties;
- (2) Document geological and petrophysical heterogeneities in these unconventional reservoirs;
- (3) Create predictive electrofacies models for these strata

Significance of Study

This project will characterize the petrophysical attributes of the Spraberry Formation, the middle Leonard interval, and the Dean Formation within Martin and Andrews Counties of West Texas. A detailed analysis of these units will improve the understanding of the Spraberry Trend throughout the Midland Basin. This project will also aid in regional and global understanding of unconventional reservoirs, by documenting well-to-well-petrophysical heterogeneities that are influenced by local geologic variation. The most important aspect of this project will be the documentation of a petrophysical-workflow for unconventional reservoirs. Future students and researchers will benefit from a modern petrophysical analysis of the Spraberry Trend.

Objectives	Questions	Methods
Determine the reservoir potential of the Spraberry Trend in Andrews and Martin counties	Can public data be used to calculate HIP values for the Spraberry, middle Leonard, and Dean intervals?	Well log correlation, formation evaluation, core-to-log calibration, cross section analyses, attribute mapping
Document geological and petrophysical heterogeneities in unconventional reservoirs	Are well-to-well heterogeneities mappable using a combination of petrophysical modeling and stratigraphic correlation?	Creation of deterministic and probabilistic petrophysical models, stratigraphic correlation, XRD and XRF analyses
Create predictive facies models	Can high-resolution core descriptions be used to create predictive facies models in the Spraberry Trend?	Core descriptions, well log cluster analysis

Table 1. Objectives, questions, and methods used to evaluate the Spraberry Trend within the northern Midland Basin.

CHAPTER 2

GEOLOGIC BACKGROUND

Regional Framework

The Permian Basin of West Texas and southeast New Mexico is an asymmetrical structural depression located along the southern edge of the North American craton (Dolton et al., 1979). This region can be sub-divided into subbasins, partitioning arches, and platforms (Figure 3) that include the: Marathon-Ouachita fold belt, Marfa Basin, Diablo Platform, Pedernal Massif, Matador Arch, and Bend Arch. Additionally, the central region of the Permian Basin includes the: Midland Basin, Central Basin Platform (CPB), Delaware Basin, Ozona Arch, Horseshoe Atoll, and Northern/Eastern shelves (Robinson, 1988).

The Permian Basin formed as an outgrowth of an ancestral feature known as the Tobosa Basin (Figure 4) (Galley, 1958). The Tobosa Basin was an intracratonic depression (Tyler and Gholston, 1988) that formed as a result of pre-Mississippian subsidence between the uplifts of the Pedernal Massif and Concho Arch (Figure 4) (Galley, 1958). This feature, and its associated carbonate shelves, became the depocenter for marine carbonates and fine grained terrigenous sediment. In-fill of the Tobosa Basin persisted from early Devonian to early Mississippian time (Galley, 1958; Robinson, 1988).

During Pennsylvanian time, West Texas and southeast New Mexico experienced intense structural deformation caused by continental collision of southern Laurasia with

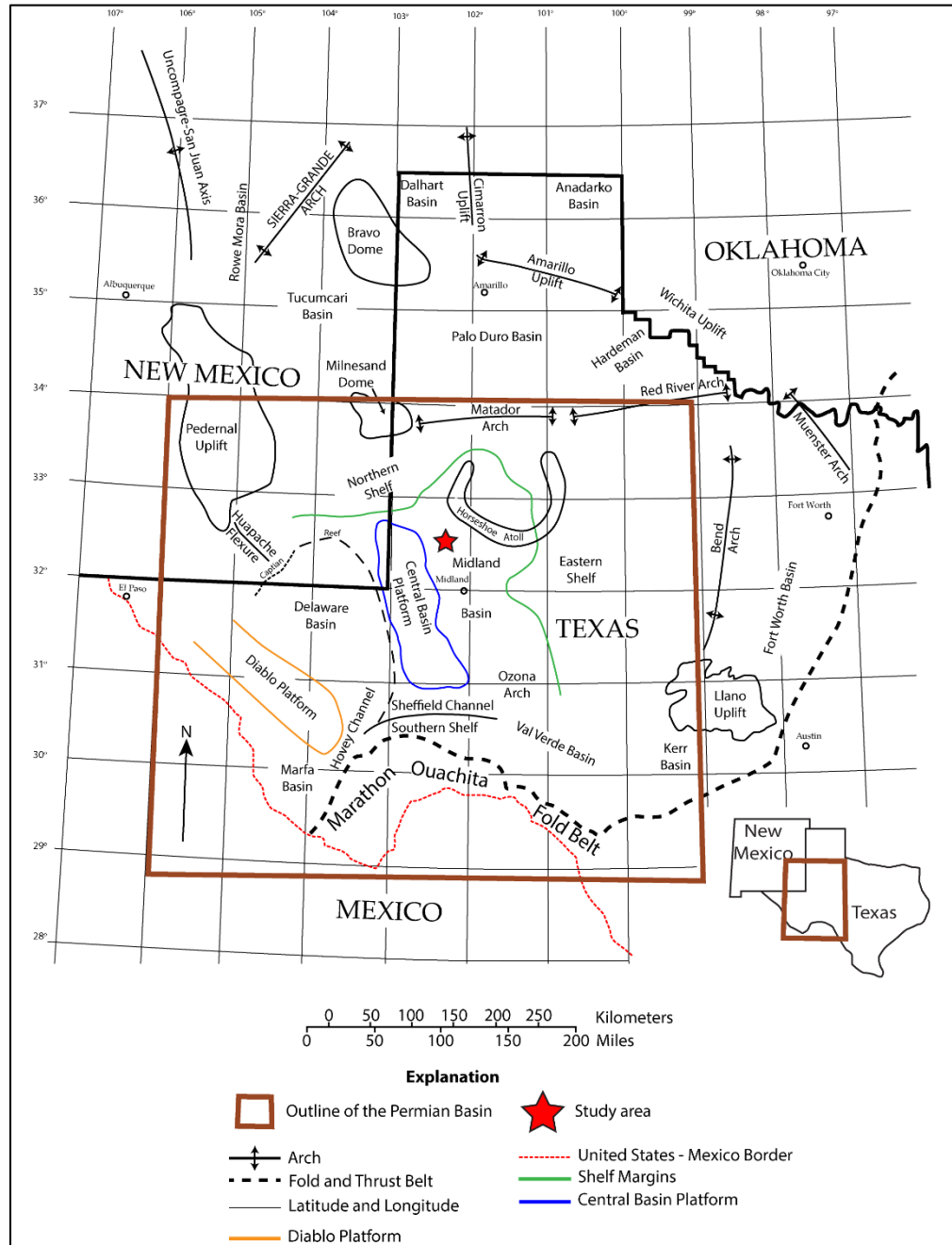


Figure 3. Prominent structural features that surround the study area. Modified from Dolton et al. (1979).

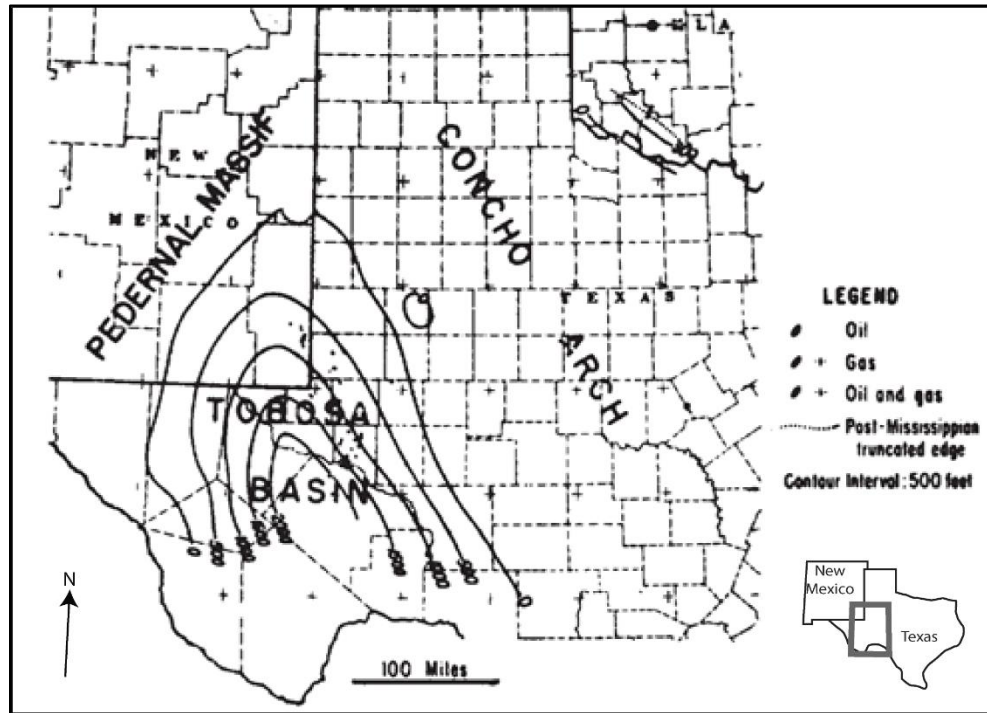


Figure 4. Outline of the Tobosa Basin. Modified from Galley (1958).

Gondwana, causing the Ouachita orogeny (Wicander and Monroe, 2010; McGookey, 2013). Structural deformation associated with the Ouachita orogeny formed the Marathon-Ouachita fold belt and uplifted the CBP and its subparallel counterpart, the Diablo Platform (McGookey, 2013). Associated crustal subsidence created the Midland and Delaware Basins (Figures 5-6) as part of a large east-west midcontinental (intracratonic) basin bordered by the Val-Verde foreland basin to the south, the Bend Arch to the east, the Pedernal Massif to the north, and the Diablo Platform to the southwest (Galley, 1958).

The onset of the Permian Period was marked by structural stability in West Texas and New Mexico (Galley, 1958). During the tectonically quiescent Permian Period, the central region of the Permian Basin continued to subside and thick shelf carbonates and

detrital deep-water siliciclastic rocks were deposited on the platforms and more basinal deep-water regions respectively (McGookey, 2013). Subsidence and sedimentation in the Midland and Delaware Basins continued until the end of the Permian Period (Robinson, 1988). Lastly, the Cenozoic Era ushered in an additional period of structural quiescence to West Texas and New Mexico. The region remained structurally stable until the Laramide orogeny of Late Cretaceous time (Wicander and Monroe, 2010). This event, and subsequent Tertiary orogenies, caused deformation of Paleozoic strata along the southwest edge of the Permian Basin (Galley, 1958). However, Paleozoic strata elsewhere in the basin maintained their approximate original depositional attitude and were minimally effected by regional tilting and local deformation (Galley, 1958).

Petroleum Exploration Terminology

For this study, the terms “play” and “trend” are used to group and describe the extent of subsurface strata within the study area. A petroleum play is an informal term that is defined herein as “a family of geologically similar fields, discoveries, prospects, and leads” (Rose, 2001). Additionally, a petroleum trend is an informal term that describes a broad area in which production occurs in a given play (Hamlin and Baumgardner, 2012). In subsequent sections of this thesis, geologic elements and petroleum system components of Wolfcampian and Leonardian strata will be defined.

Subsurface Stratigraphy of the Wolfberry Play

Within the Midland Basin, two Permian age provincial series: the Wolfcampian

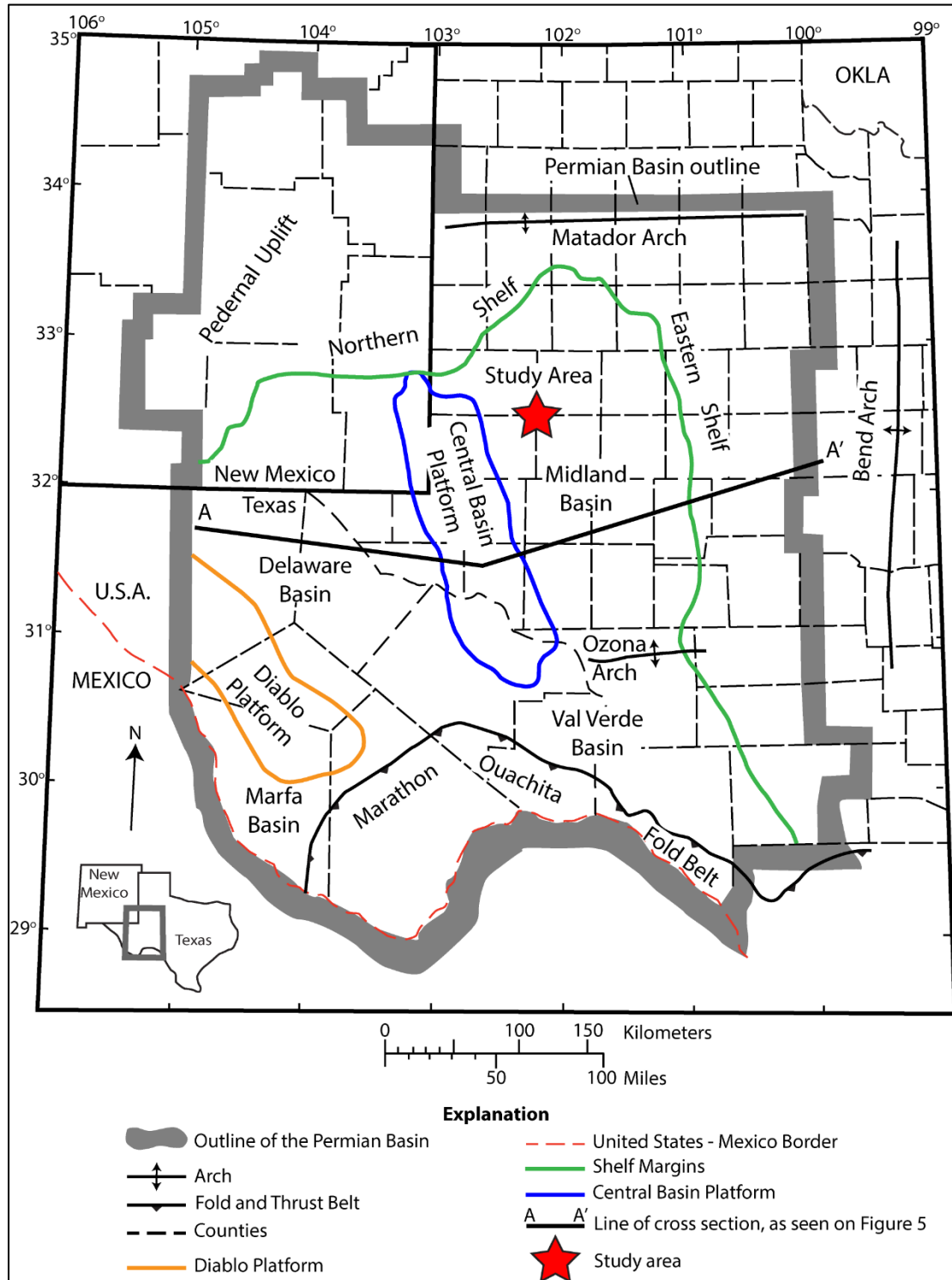


Figure 5. Outline of the Permian Basin and structural elements near the study area. Modified from Dolton et al. (1979).

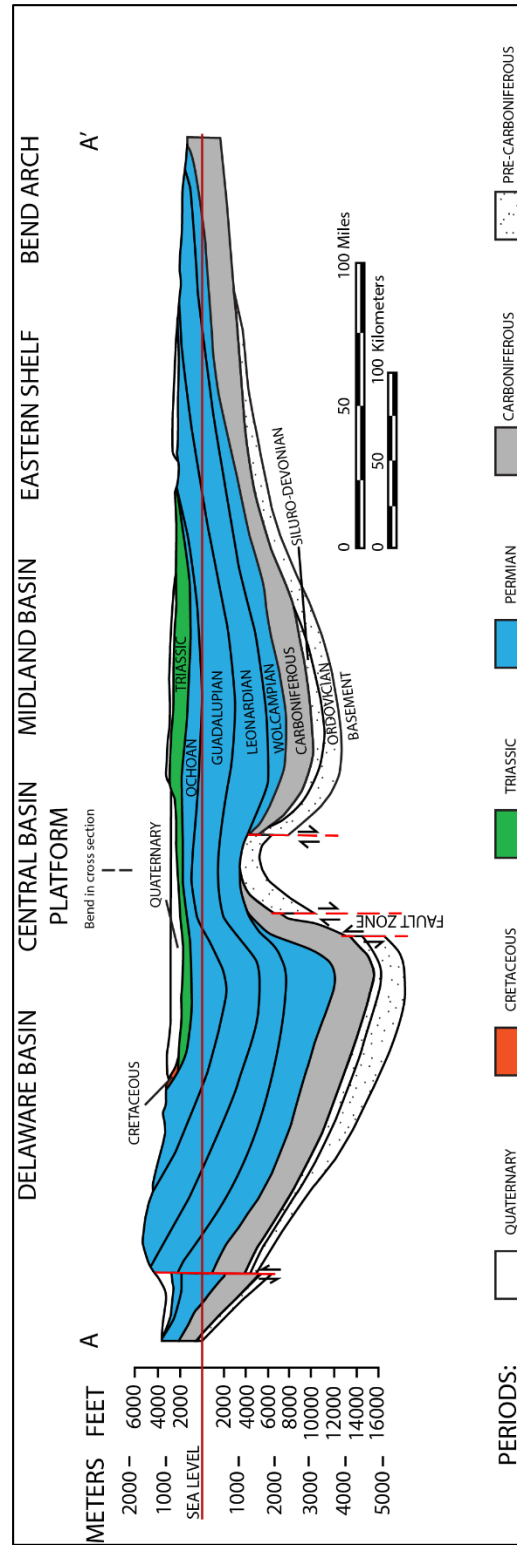


Figure 6. Generalized east-west geologic cross section of the study area. See figure 5 for location. Modified from Dolton et al. (1979).

Series and the Leonardian Series (Figure 7), are the focal point of Wolfberry exploitation (Hamlin and Baumgardner, 2012). For ease of identification, this study incorporates a nomenclature that consists of informal and formal subdivisions of the aforementioned series (Figure 7). Stratigraphic subdivisions used for this study include the: Wolfcamp interval², lower Leonard interval, Dean Formation, middle Leonard interval, and lower/upper Spraberry Formation. This study will focus on Dean-Spraberry strata found within the northern Spraberry Trend of the Midland Basin. Paleogeography, depositional mechanisms, and sedimentological characteristics associated with these units will be examined in the following sections.

Paleogeography

During Leonardian time, the Midland Basin was located ~15 degrees north of the equator (McGookey, 2013) (Figure 8). Due to its equatorial location and lack of siliciclastic input during highstands of sea-level, carbonate platforms, shelves, and reefs developed along the edges of the Midland Basin. According to McGookey (2013) the Permian Basin region was isolated from sediment sources and became sediment starved during Leonardian time. Sediment starvation within the Midland Basin favored cyclical deposition of basinal deep-water strata, including the Dean, middle Leonard, and Spraberry units during sea-level lowstands (Handford, 1981). These deep-water deposits display various lithologies and grain sizes that fluctuate temporally and spatially. Possible depositional mechanisms associated with these basinal units will be discussed below.

² Herein, interval refers to informal stratigraphic units whereas formation is applied to formal units as outlined by Hamlin and Baumgardner (2012).

System/ series		Midland Basin				Delaware Basin	Central Basin Platform	Composite sequence		
		Silver and Todd (1969)	Tyler and others (1997)	Hamlin and Baumgardner (2012)	This thesis					
Lower Permian	Kungurian	Upper Clear Fork		Upper Leonard	Upper Leonard	Cutoff	San Andres	Cs G1		
		Upper Spraberry	1U 2U 3U 4U 5U 6U	Upper Spraberry	Upper Spraberry			First Sand	Glorieta	Cs L5
			Middle Spraberry	1M 2M		Middle Spraberry	Second sand		Upper Clear Fork	Cs L4
				Lower Spraberry		3M 4M 5M 6M				
		Lower Spraberry	1L 2L		Middle Leonard	Middle Leonard		Tubb		
		Dean		Dean	Dean	Lower Clear Fork	Cs L2			
	Leonardian	Wolfcamp	Individual correlated sandstones	Lower Leonard	Lower Leonard	Wichita	Cs L1			
				Wolfcamp	Wolfcamp	Wolfcamp	Upper Wolfcamp	W3		
							Middle/lower Wolfcamp	W1-W2		
							Pennsylvanian	Cisco	Upper Penn	Upper Penn
	Canyon									
	Strawn									

Figure 7. Stratigraphic nomenclature of Wolfcampian and Leonardian series as well as underlying Pennsylvanian strata within the Midland Basin and surrounding areas. Modified from Hamlin and Baumgardner (2012).

Depositional Setting

Previous workers (Hanford, 1981; Tyler and Ghoston, 1988; Tyler, et al., 1997; Hamlin and Baumgardner, 2012) have extensively studied the depositional history and stratigraphic architecture of the Spraberry Trend. These authors have concluded that the Leonardian Series within the Midland Basin is composed of deep-water siliciclastic and carbonate strata. Handford (1981) developed a submarine-fan depositional model that is generally accepted as the probable depositional mechanism for basinal strata within the Midland Basin.

In his model, Hanford (1981) suggests that silt to sand-size siliciclastics, and detrital carbonates were deposited by turbidity currents, density flows, and suspension settling, while clay size sediments were deposited by hemipelagic sedimentation. The sedimentary character of individual units are outlined below.

Dean Formation

The Dean Formation, or the “Dean Sand,” as it is often referred to in the literature (McLennan and Bradley, 1951; Wilkinson, 1953, Schmitt, 1954), is a siliciclastic successions that is 100 to 200 feet thick (Hamlin and Baumgardner, 2012). This unit is primarily composed of interbedded siltstone, mudrock, and fine grained sandstone (Hamlin and Baumgardner, 2012).

Middle Leonard Interval

The middle Leonard interval is an informal unit that separates the Dean and Spraberry Formations. The majority of previous workers (McLennan and Bradley, 1951;



Figure 8. Paleogeographic reconstruction of the Middle Permian 275Ma. The red square represents the approximate location of the study area. Modified from Blakey et al. (2003).

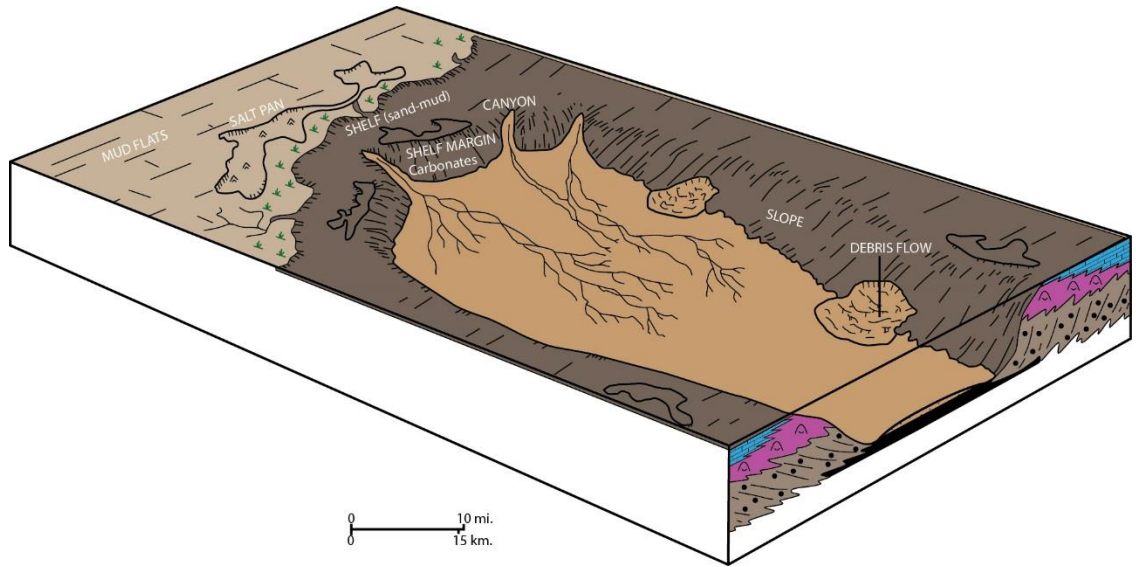


Figure 9. Block diagram illustrating inferred distribution of environments, geometry of deposits and channel patterns of the Midland Basin. Modified from Handford (1981).

Wilkinson, 1953) do not apply a name to this unit, but they demarcate a distinct separation between the Dean and Spraberry Formations on geophysical well-logs. However, Silver and Todd (1969) characterize the middle Leonard as belonging to the lower Spraberry Formation while Hamlin and Baumgardner (2012) demarcate the middle Leonard as a separate Leonardian unit between the Dean and Spraberry Formations. According to Hamlin and Baumgardner (2012) the middle Leonard interval is between 250-450 feet thick and is predominantly composed of calcareous mudrock.

Spraberry Formation

The Spraberry Formation, also referred to as the “Spraberry sandstone” in some literature (McLennan and Bradley, 1951; Wilkinson, 1953), is a unit that is ~1000 feet thick (Wilkinson, 1953). Although this unit is subdivided into lower and upper units

based on geophysical well-log response, the Spraberry Formation consists of interbedded sandstones, siliciclastic mudrocks, and calcareous mudrocks throughout both units (Hamlin and Baumgardner, 2012).

Dean-Spraberry Petroleum System

In petroleum exploration, the Total Petroleum System (TPS) concept (Magoon and Dow, 1994) plays a crucial role in defining geologic elements and processes that must be present to facilitate hydrocarbon accumulation. Elements of a TPS include the: source rock, reservoir rock, and seal rock (Figure 10) while TPS processes include trap formation, and hydrocarbon generation-migration-accumulation. Within the Spraberry Trend, components of the Dean-Spraberry Petroleum system can be assigned as followed:

Source Rock

Interbedded black shales are the predominant source rock within the Spraberry Trend (Handford, 1981). Additionally, Hamlin and Baumgardner (2012) report that organic-rich, oil-prone mudrocks are the primary source rocks for Leonardian strata within the Midland Basin. Source rocks in this study are immediately adjacent to siliciclastic reservoirs, making this a self-contained petroleum system (Robinson, 1988).

Reservoir Rock

Conventional reservoirs, units that can produce economic rates of hydrocarbons without stimulation (Passey et al., 2010), within the Spraberry Trend consist of muddy

siltstones, laminated sandstones, and muddy burrowed sandstones (Galloway et al., 1983).

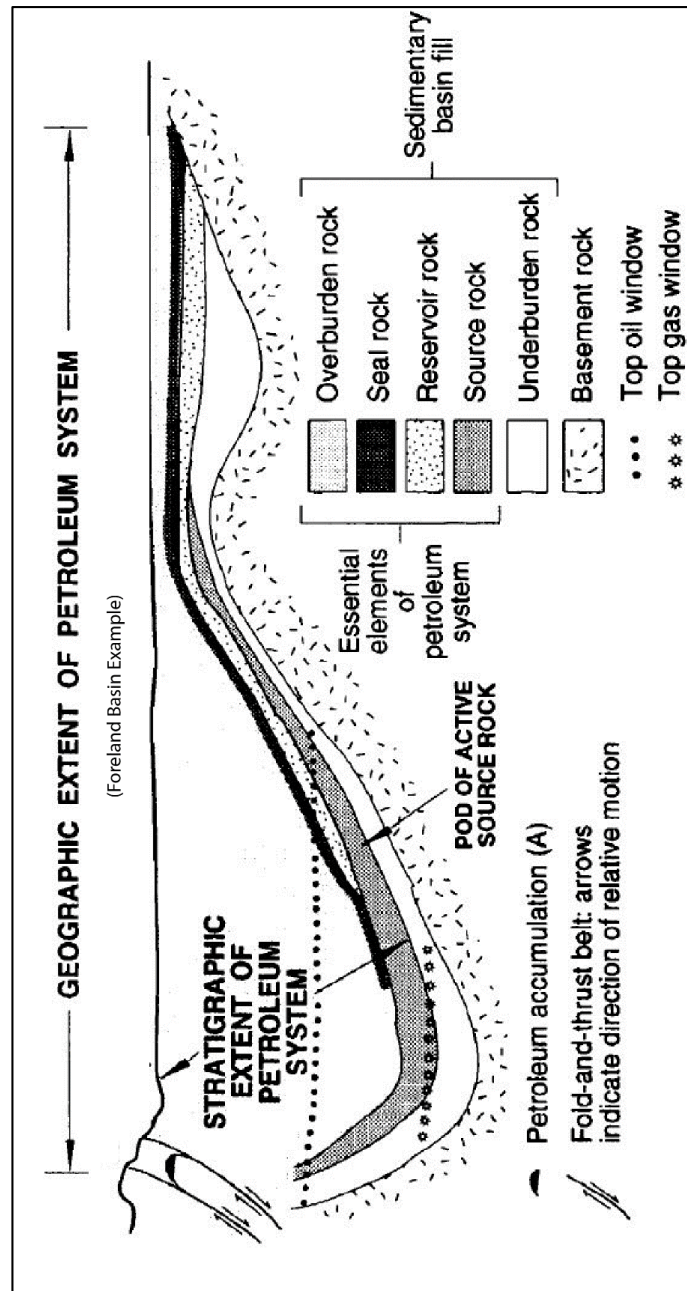


Figure 10. Example of a total petroleum system in a foreland basin setting. Modified from Magoon and Dow (1994).

Unconventional reservoirs, units that require stimulation to produce hydrocarbons at economic rates (Passey et al., 2010), within the Spraberry Trend consist of carbonaceous mudrock and organic-rich mudrocks interbedded between conventional reservoirs (Hamlin and Baumgardner, 2012). This juxtaposition of source rocks and reservoir rocks allows operators to exploit unconventional self-sourcing reservoirs and conventional reservoirs through the use of multistage hydraulic-stimulation (Hamlin and Baumgardner, 2012).

Seal Rock

Within the Spraberry Trend, there are a variety of seals including non-permeable shales, tight limestones, and porosity/permeability barriers between interbedded sequences (Robinson, 1988). Seal rock juxtaposition with reservoir rocks is very similar to the relationship between source rocks and reservoir rocks within the study area.

Traps

Stratigraphic traps are the predominant trap type in the Spraberry Trend (Galloway et al., 1983). According to Robinson (1988) pinch-outs and up-dip thinning are a common occurrence in the study area. Additionally, local anticlinal structures and comingled stratigraphic/structural traps are possible (Galloway et al., 1983; Robinson, 1988).

Generation-Migration-Accumulation

Due to the inter-bedded nature of source rocks, reservoir rocks, and seal rocks within the study area, hydrocarbon generation and accumulation most likely occurred

penecontemporaneously with reservoir development during Middle or Upper Permian time (Robinson, 1988). Timing of these events, and other Petroleum System components, can be illustrated by a timing chart (Figure 11). An important feature of the petroleum system timing-chart is the critical moment. The critical moment represents the inferred time at which all petroleum system components were present within a given play.

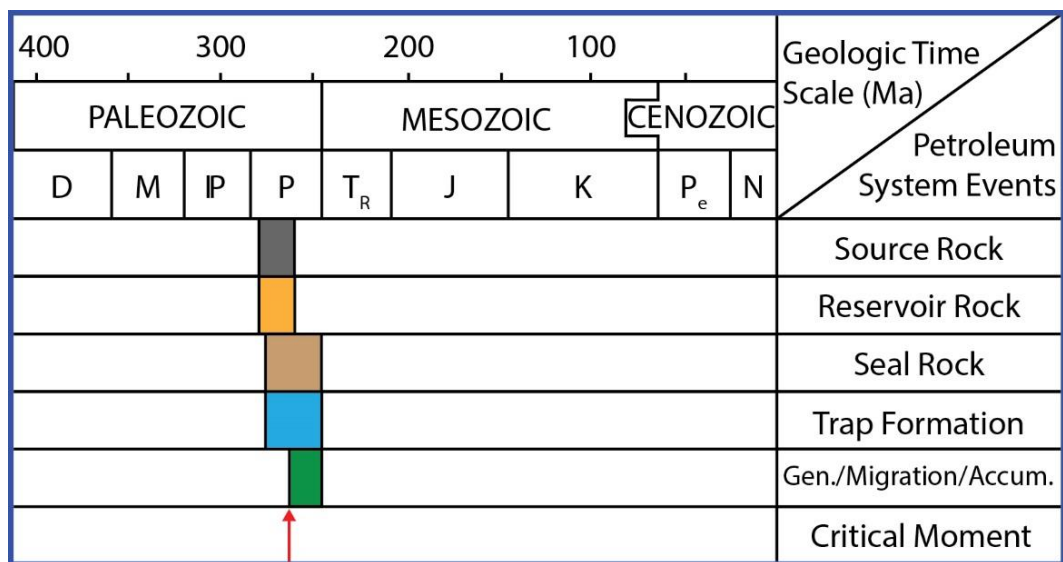


Figure 11. Timing chart for the Dean-Spraberry Play. Modified from Magoon and Dow (1994).

CHAPTER 3

CORE ANALYSIS

Introduction

In order to calibrate and place petrophysical analyses in a geologic context, subsurface drill-cores must be examined, described, and analyzed. Due to Chesapeake Energy's large presence within the study area, the author contacted members of Chesapeake Energy's Permian Basin team in search of available core data in the study area. Chesapeake Energy graciously provided analytical measurements as well as core-viewing and core description access for two subsurface drill-cores. These cores were collected from the University 7-17B #4 (4231736129) well and the Ralph Williams #4 (4231735100) well.

Once located, both cores were examined at Chesapeake Energy's *Core Research Center* in Oklahoma City, Oklahoma. The University 7-17 B #4 well contains slabbed core samples from the upper Spraberry and Dean Formations. Additionally, the Ralph Williams #4 well contains slabbed core samples from the middle Leonard interval, upper Spraberry Formation, and upper Leonard interval. Of the available core, the author described 502.5 feet of Dean, middle Leonard, and Spraberry zones.

Core Description

Grain size, sedimentary structures, contacts, unit thickness, and qualitative composition (where possible) were documented for the cored wells in this study. The fine

grained (silt to very-fine-sand) nature of these cores presented difficulties in distinguishing composition as well as textural information. Hydrochloric acid was used to distinguish siliciclastic intervals from calcareous intervals. All descriptions were compiled to create sedimentologically distinct lithofacies: “laterally equivalent bodies of sediment distinguished by lithological characteristics” (Boggs, 2006, p. 412). These lithofacies were then used to create electrofacies and predictive well-log models (Chapter 4, p. 64)

Lithofacies

A total of seven lithofacies (Table 1) were distinguished in the Dean Formation, middle Leonard, and upper Spraberry intervals. Lithofacies within these zones are generally interbedded and are very cyclic, often changing every 0.5-1.0 feet. Lithofacies within the cored intervals include siliciclastic mudrock (Figure 12), calcareous mudrock (Figure 13), laminated siltstone (Figure 14), convoluted siltstone (Figure 15), massive siltstone (Figure 16), structureless sandstone (Figure 17), and conglomeratic carbonate (wackestone) (Hamlin and Baumgardner, 2012) (Figure 18). Hydrodynamic interpretations and electrofacies models for these facies are presented in (Chapter 5).

Core Measurements

Chesapeake Energy provided a number of analytical core analyses for both the University 7-17B #4 and Ralph Williams #4 wells. These analyses include: quantitative X-ray diffractometry, including clay-mineral analyses; program pyrolysis, and Tight Rock Analyses (TRA), which includes: porosity, permeability and saturation

Facies Designation	Lithofacies	Grain Size	Sedimentary Structures	Notes
SMD	Siliciclastic mudrock	Clay	Structureless with rare mm-scale laminations along contacts	Pyrite is commonly found in this facies, especially near contacts
CMD	Calcareous mudrock	Clay	Structureless with rare mm-scale laminations along contacts	Generally appears slightly lighter in color than SMD facies
LMSST	Laminated siltstone	Silt	Planar tabular laminations to slightly inclined laminations	Varve-like laminations separated by mudrock, occasional flame structures
CSST	Convolute siltstone	Silt	Convolute/contorted laminations	No apparent orientation
MSST	Massive siltstone	Silt	Massive	Possible dish structures in portions of this facies
VFSS	Structureless sandstone	Very fine sand	Structureless	This facies is rare
CC	Conglomeratic carbonate	Clay matrix to pebble size detritus	Structureless	Detritus appears to be composed of shell fragments and crinoid stems

Table 2. Lithofacies descriptions from core analyses.

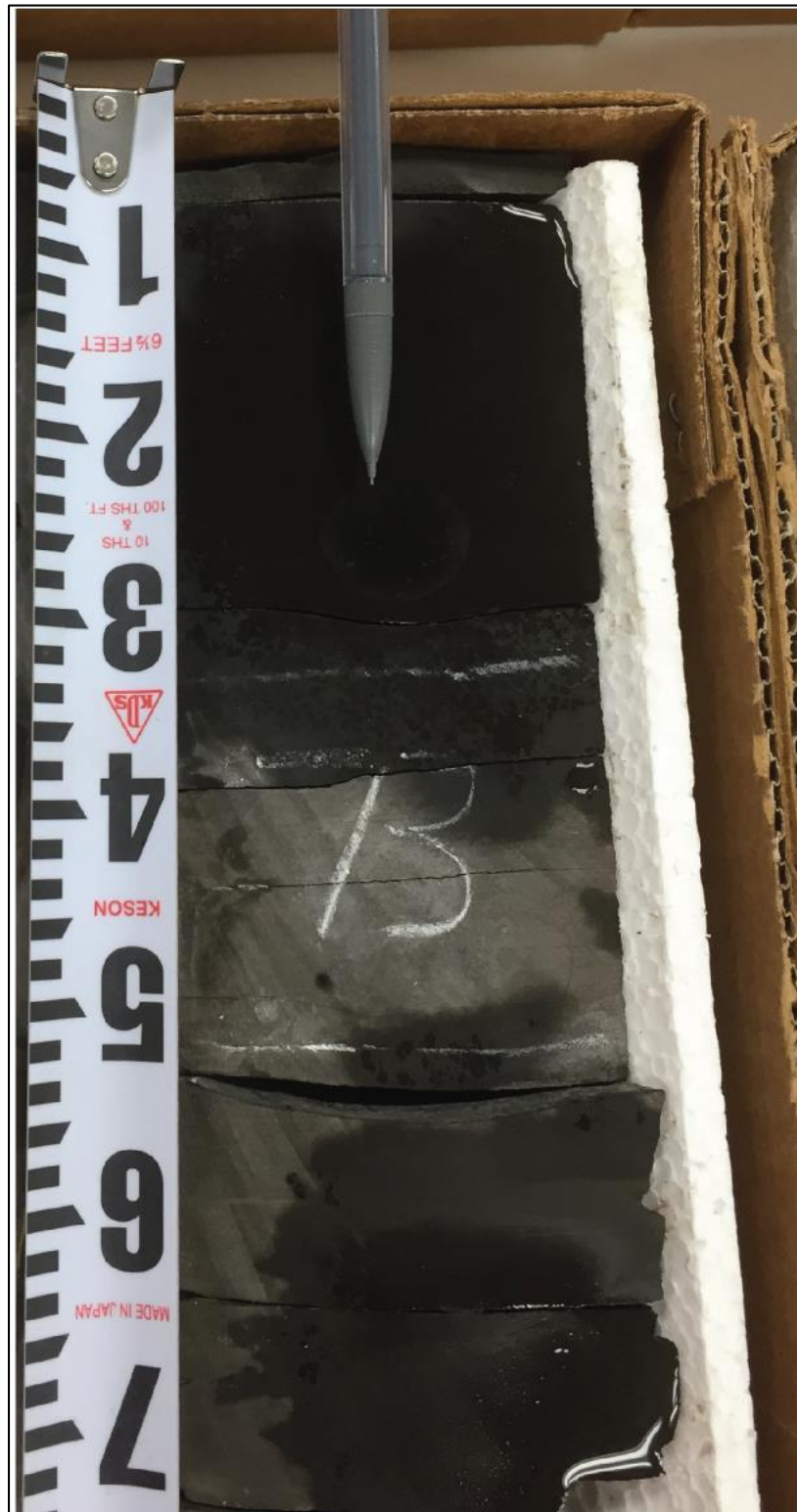


Figure 12. Siliciclastic mudrock facies (SMD).



Figure 13. Calcareous mudrock facies (CMD).



Figure 14. Laminated siltstone facies (LMSST).



Figure 15. Convoluted siltstone facies (CSST).



Figure 16. Massive siltstone facies (MSST).

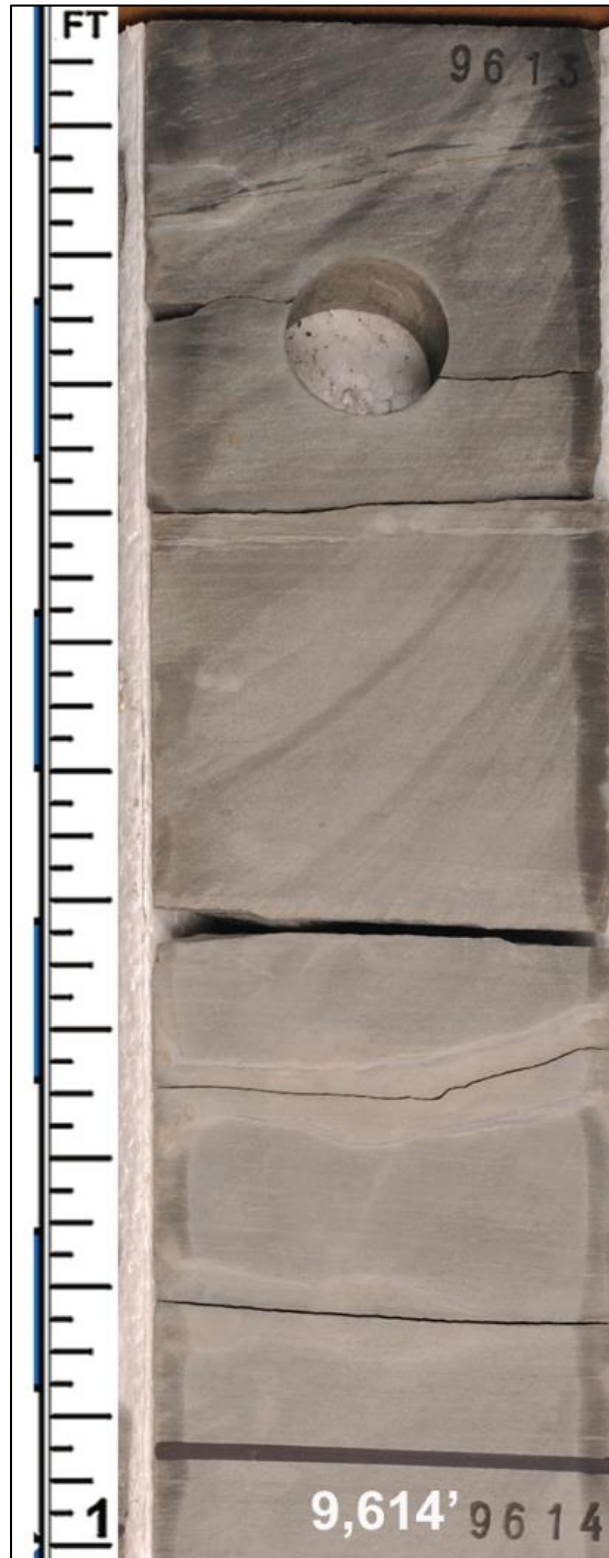


Figure 17. Structureless sandstone facies (VFSS).



Figure 18. Conglomeratic carbonate facies (CC).

measurements (Appendix A). Additionally, Chesapeake provided supplemental core photos, thin section photomicrographs, and scanning electron microscopy images. In conjunction with the quantitative analyses conducted by Chesapeake Energy, the author collected 231 X-ray fluorescence (XRF) measurements (Appendix A) from the Dean and Spraberry Formations in the University 7-17B#4 well. This well was chosen due to its close proximity to other wells in the study and time constraints during core viewing procedures.

XRF measurements were collected using a ThermoScientific Niton XL3t portable XRF analyzer (Figure 19). Forty four elemental concentrations (ppm) were analyzed using the “test all geo” mode. Each measurement required an acquisition time of 150 seconds and measurements were collected on two-foot and one-foot spacing. Due to the length of core analyzed and the relative facies homogeneity of the Dean Formation, a two-foot spacing was deemed adequate for measurements. However, the upper Spraberry Formation frequently oscillates between facies, deeming a one-foot sample spacing for this zone.

Core Calibration

Results from quantitative core analyses were incorporated into Interactive Petrophysics™ software and depth shifted to match subsurface gamma ray data (Chapter 4, p. 44). This routine ensures core descriptions and laboratory measurements are on depth with well log calculations. Subsequent petrophysical models were calibrated to match depth-shifted core data as closely as possible (Chapter 4).



Figure 19. Portable XRF analyzer used in this study.

CHAPTER 4

FORMATION EVALUATION

Introduction

Petroleum geology is an interdisciplinary subject that integrates data from multiple sources and incorporates interpretations from various disciplines. Data is collected from a variety of sources that include seismic surveys, gravity surveys, magnetic surveys, electromagnetic surveys (Kearey and Brooks, 1991, p. 1), mud logs and well logs (Johnson and Pile, 2006, p. 2). These data are analyzed by various scientists, including geologists, geophysicists, and petrophysicists. Geologists are responsible for delineating and mapping architectural elements of subsurface and surface strata. Geophysicists image the spatial and temporal distribution of subsurface strata. Petrophysicists characterize fluids, rocks, and fluid-rock interactions within subsurface strata and drill samples. This thesis will focus on the petrophysical characterization, or Formation Evaluation (FE), of the Spraberry, middle Leonard, and Dean intervals within Andrews and Martin counties.

Data Management

Petrophysical data is often collected by remote sensing devices known as open-hole wireline sondes (Hearst and Nelson, 1985, p. 43). These tools measure physical properties of strata surrounding a subsurface wellbore. Direct and indirect measurements from these devices provide quantitative data used for reservoir characterization. Once the

measurements are collected, all data must be compiled, organized, and edited. The following sections give a brief overview of the data management techniques employed in this study.

Data Acquisition

When a well is drilled, wireline tools are deployed periodically at predetermined depths or over the total depth of a well. In both instances, individual logging sondes are combined to form a tool-string that is connected to a cable and conveyed downhole by gravity (Figure 20). Once the logging sondes have reached their target depth, they are pulled to the surface via a logging truck (Figure 21). This portion of a logging job is known as a “logging run.” It is during this operation that petrophysical data is collected and displayed in the form of well logs³

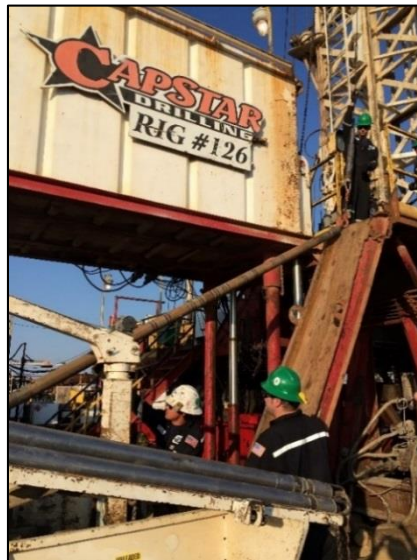


Figure 20. Service company employees constructing a wireline tool-string. In this scenario, the resistivity sonde is being hoisted to the drill-rig floor.

³ Herein, the term log refers to data recorded versus depth (or time) in graph form (Johnson and Pile, 2006, p.2).



Figure 21. Image of a wireline logging truck used to collect well-log data.

On deep wells, more than one logging run may be required to characterize the vertical extent, or zones of interest within the well. If this is the case, data from individual logging runs are spliced together to create a continuous “main pass” curve for each well log. Once the logs have been collected and/or spliced at the wellsite, service companies send the information as digital .LAS files to the well operator. These files contain data that enable geoscientists to evaluate the hydrocarbon potential of individual wells, leases, and/or fields. Pertinent data contained in .LAS files include: well name, well location, depths of each logging run, depth datum, service company information, a list of sondes used, and most importantly; values from individual well log measurements (Figure 22).

Data Integration

Public well files were the primary data used in this research project. As such, the University Lands *Well and Production Data Collection* was used to locate and acquire digital .LAS files for 50 wells spanning northeast Andrews and northwest Martin


```

~Version Information
VERS.                2.0:    CWLS log ASCII Standard -VERSION 2.0
WRAP.                NO:     One line per depth step
~Well Information Block
#MNM.UNIT            VALUE/NAME      DESCRIPTION
#-----
STRT.F               53.0000:  START DEPTH
STOP.F               10955.0000: STOP DEPTH
STEP.F               0.5000:  STEP DEPTH
NULL.                -999.25:  NULL VALUE
DMF.                 KB:      DRILL MEAS FROM
PDAT.                GL:      PERMANENT DATUM
UWI.                 42-317-36129: UNIQUE WELL IDENTIFIER
API.                 42-317-36129: API NUMBER
RANG.                N/A:     RANGE
TOWN.                N/A:     TOWNSHIP
SECT.                N/A:     SECTION
SON.                 7791040:  JOB NUMBER
CTRY.                USA:     COUNTRY NAME
PROV.                TEXAS:   PROVINCE
STAT.                TEXAS:   STATE NAME
IQVR.                R3.2.0:  WLIQ VERSION
SVCO.                Halliburton: SERVICECONAME
COMP.                CHESAPEAKE OPERATING, INC.: COMPANY
WELL.                UNIVERSITY 7-17B No. 4: WELL NAME
FLD.                 SPRABERRY (TREND AREA): FIELD NAME
LUL.                 ODESSA:  LOGGINGUNITLOC
CNTY.                MARTIN:  COUNTY NAME
RIG.                 PATTERSON 71: RIG NAME
FL1.                 660' FSL & 1,950' FEL: LOCATIONLINE1|
FL2.                 SECTION 17, BLOCK 7: LOCATIONLINE2
FL3.                 UNIVERSITY LANDS SURVEY: LOCATIONLINE3
DATE.                :       DATE
SRVC.                Halliburton: SERVICE COMPANY
LOC.                 :       LOCATION
LMF.                 KB:      LOG MEASURED FROM
APD.ft               18.0000:  DEPTH ABOVE PD
TVDS.ft              2943.0000: TVDSS CORRECTN
GVFD.g               1.0000:  GRAVITY FIELD
EGL.ft               2925.0000: GROUND ELEVATION
EPD.ft               2925.0000: ELEVATION
EKB.ft               2943.0000: KB ELEVATION
EDF.ft               2942.0000: DF ELEVATION
TDL.ft               10942.0000: TOTAL DEPTH (LOGGER)

```

Figure 22. Example of a well-log header found within a digital .LAS file.

counties of West Texas (Figure23). All wells were chosen based on location, well-log availability, and total depth values. Specifically, each well is located within blocks 6 and 7 of the UT Land's grid (Figure 23) contains gamma ray, resistivity, neutron porosity, bulk density, and photoelectric logs; and encompasses the upper Spraberry Formation through the base of the Dean Formation.

Once each well was located, individual .LAS files were imported into LR Senergy's Interactive Petrophysics™ (IP) software. Within IP, wells were labeled by well name and corresponding API number. Additionally, each well was geospatially referenced using latitudinal and longitudinal coordinates referenced to the NAD83

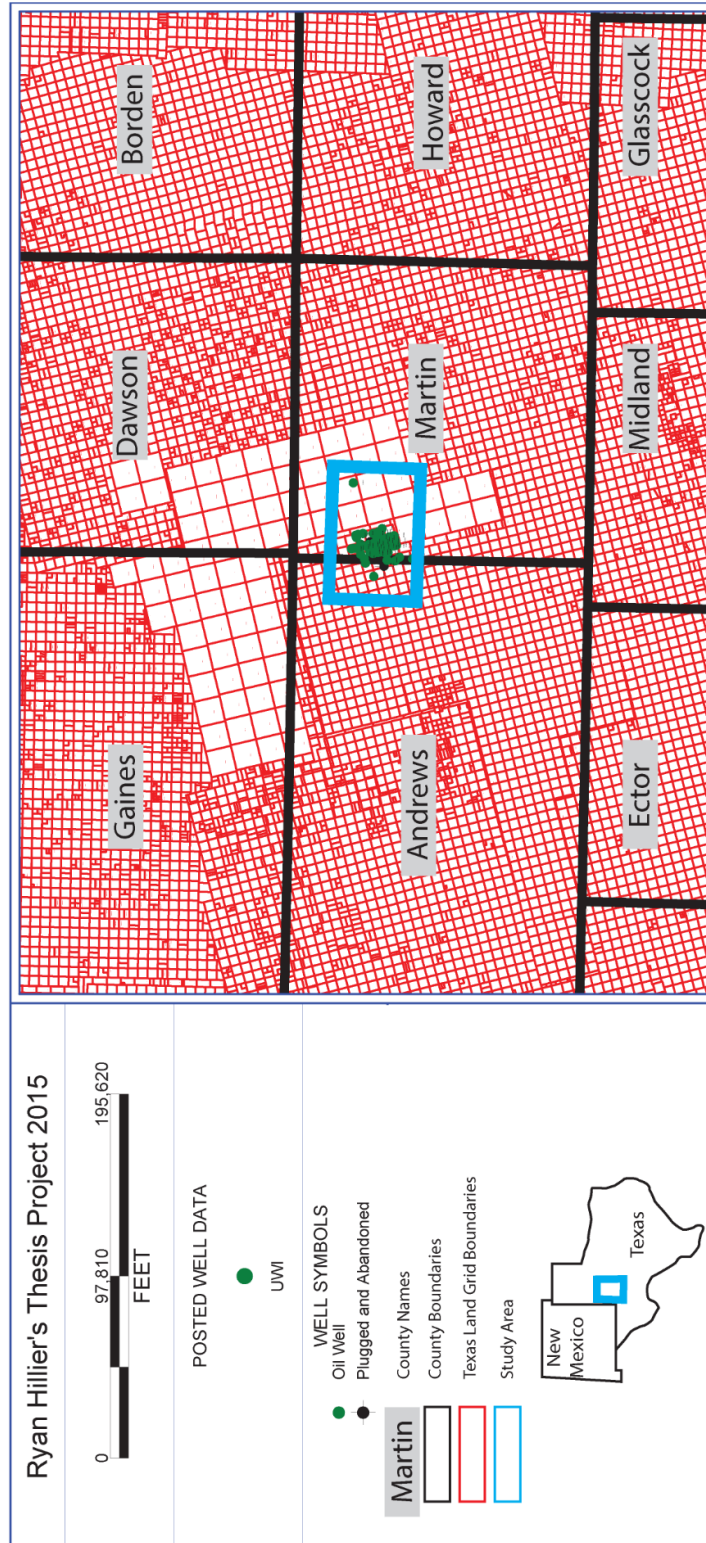


Figure 23. Overview map of study area.

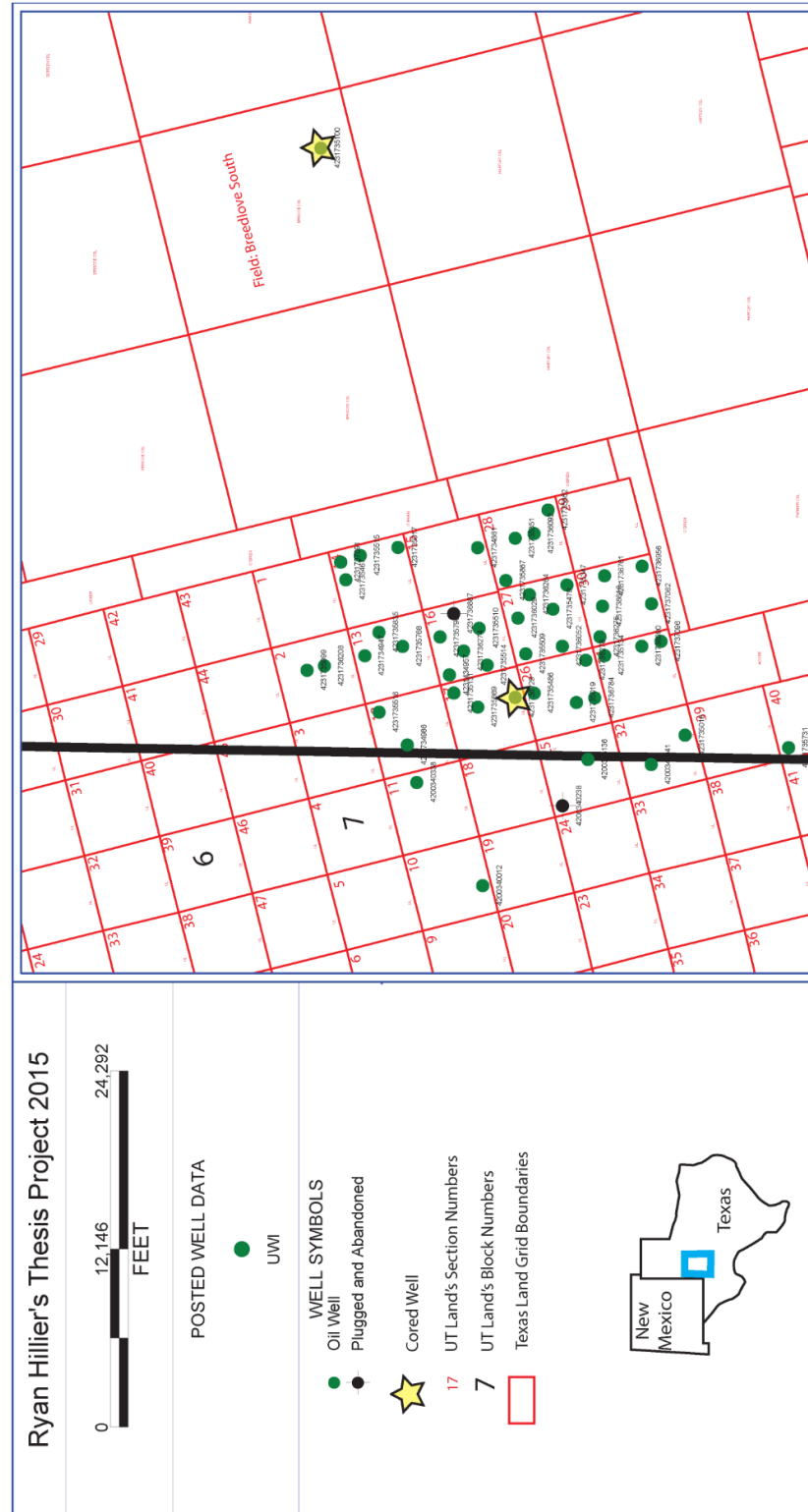


Figure 24. Inset map of study area and project wells.

Central Texas datum. Lastly, pertinent service company information, tool information, and logging parameters were noted for each well.

Stratigraphic Zonation

As outlined by Brooks and Montalvo (2012), top generation is the initial step in any petrophysical workflow. For this study, formal and informal sub-divisions of the Leonardian and Wolfcampian series within the Midland Basin were used to zone each well (Hamlin and Baumgardner, 2012). In order to achieve consistent and easily recognizable correlations, the author has chosen to incorporate nomenclature outlined by numerous workers (e.g., Silver and Todd, 1969; Tyler et al., 1997; Hamlin and Baumgardner, 2012) (Figure 7).

Using data presented by Hamlin and Baumgardner (2012), the University 40 #2 well was chosen as the reference well for stratigraphic zonation. This well was chosen based on three characteristics: 1) it is located within the study area; 2) it penetrates all intervals of interest; and 3) zonal depths are presented graphically and numerically by Hamlin and Baumgardner (2012).

Within IP, the University 40 #2 well was populated with tops using diagnostic well log deflections across each stratigraphic interval. Predominant deflections include: positive separation of the neutron porosity and density porosity curves, apparent increase in resistivity values, and noticeable gamma ray peaks and troughs (Figure 25). This step was crucial for subsequent stratigraphic correlations and zone-by-zone FE.

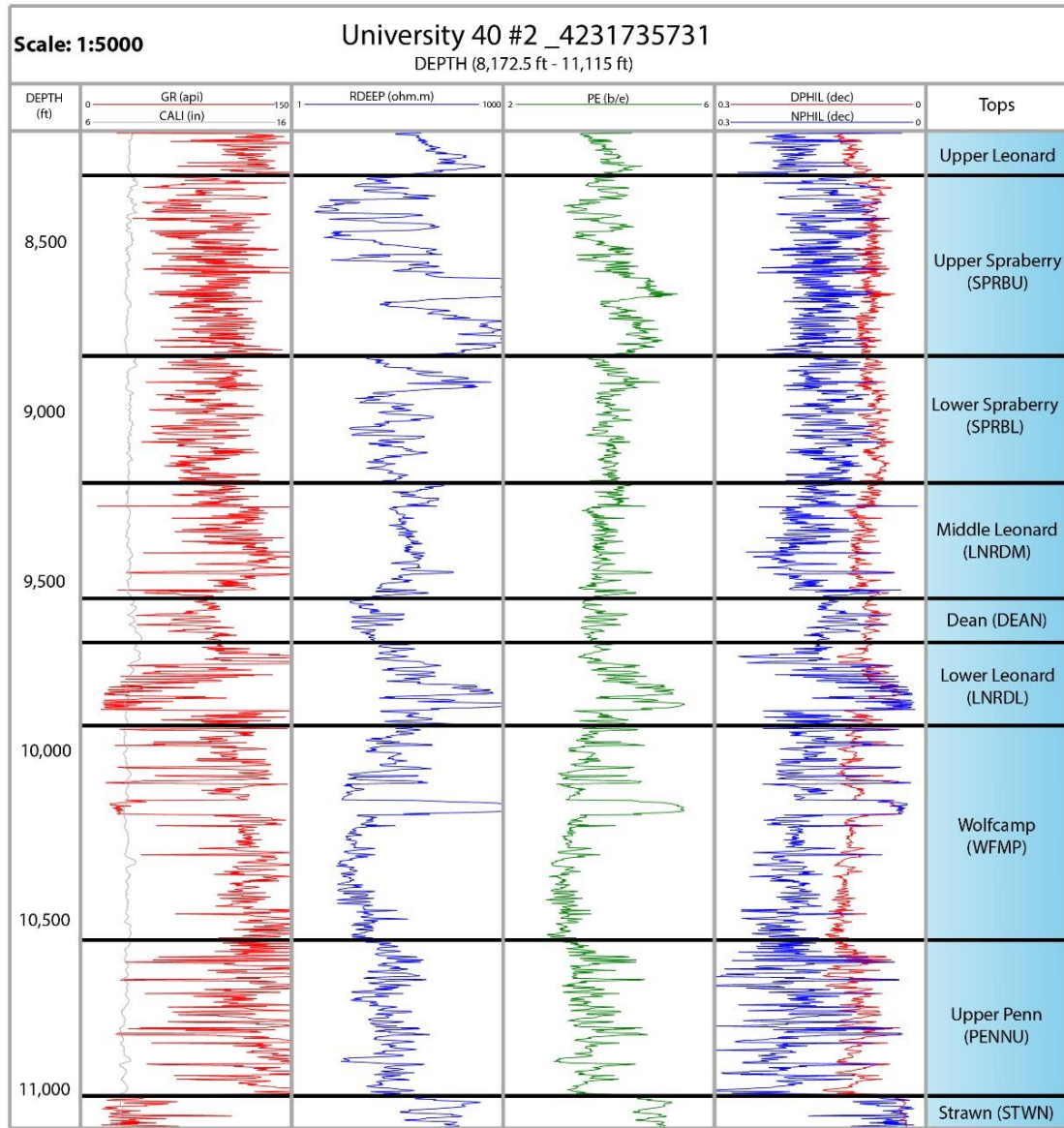


Figure 25. Type well used for stratigraphic zonation. Stratigraphic boundaries were assigned to conform with those presented by Hamlin and Baumgardner (2012).

Data Conditioning

Prior to conducting quantitative FE procedures, quality control and normalization was performed on all petrophysical well logs. Due to wellbore instability, tool anomalies, and random error, subsurface data must be analyzed for any extraneous and/or erroneous values. According to Smith (2011), well-log data editing and conditioning is often overlooked or over simplified. In order to provide a robust petrophysical analysis, this study incorporated three data-conditioning techniques used to organize, examine, and in some cases, rectify raw well-log data. These techniques include: 1) log mnemonic standardization; 2) depth shifting; and 3) log editing, which will be individually discussed below.

Log Mnemonic Standardization

Due to the large number of wellsite service companies and the wide variety of wireline tools used to characterize wellbores, individual well logs are designated by company mnemonics rather than names. This identification scheme is cumbersome and counterproductive when comparing multiple wells within a study area. In order to achieve consistent results, a standardized nomenclature, developed by Apache Corporation, was implemented across all wells within this study.

The Apache scheme standardizes tool names by binning individual curves into pre-determined sets (Table 3). This task was accomplished by examining each well header to determine the correct logs to be incorporated from each well. Once the curve sets were populated with the appropriate well logs, each curve was re-named based on

Set Name	Contents
WLRAW	Raw wireline curves from LAS files
EDIT	Depth shifted and edited curves
MLR	Calculated curves from IP's multi-linear regression module
EVAL	Quantitative curves
CCORE	Conventional core data
XRF	X-ray fluorescence data
Msol	Calculated curves from IP's mineral solver module
FLUIDS	Calculated curves from IP's fluids module
OStCap	Calculated curves from IP's oil-storage module
ZJUNK	"Junk" curves that will not be used in final analyses
FINAL	All curves that will be used in final petrophysical analyses

Table 3. Curve sets and organizational hierarchy used in this study.

Logging Tool	Operational Mnemonics				
	Baker Hughes	Halliburton	Schlumberger	Weatherford	This Study
Bulk Density	ZDEN	RHOB	RHOZ	RHOB	RHOB
Caliper	CALX	CALI	HCAL	CALI	CALI
Compressional Sonic	DT24	BCS	SLT	CPSL	DTC
Deep Lateral Resistivity	RD	LLD, RT90	RLA5	RLLD	RDEEP
Density Correction	ZCOR	DRHO	HDRA	DRHO	DRHO
Neutron Porosity (Limestone Matrix)	CNC	NPHI	TNPH	NPHI	NPHIL
Photoelectric Effect	PE	PE	HPEFZ	PEF	PE
Shallow Lateral Resistivity	RS	LLS, RT 10	RLA1	RLLS	RSHAL
Total Gamma Ray	GR	GR	HGR	GR	GR
Uranium Corrected Gamma Ray	KTH	GRKT	HCGR	GRS	GRKTH

Table 4. Wireline nomenclature encountered in this study. For simplicity, all curves were renamed according to tool function, rather than service company identifiers.

tool measurements rather than service company mnemonics (Table 4). In this way, each curve set acts as an organizational system by incorporating curves that serve a specific petrophysical function during FE. This organizational system allows data to be displayed consistently and efficiently across all log plots and cross sections within a given project.

Depth Shifting

Once raw wireline curves were labeled and incorporated into the appropriate sets, depth shifting was performed. According to Hearst and Nelson (1985, p. 42), individual well logs may contain depth discrepancies due to wellbore instabilities. During data acquisition, wireline tools may become stuck against the wellbore wall, causing the logging cable to stretch. Zangwill (1982) describes two scenarios in which cable stretch affects depth data: 1) positional data is skewed due to inaccurate depth measurements that are based on cable length; and 2) velocity data is skewed between individual sondes on a single tool string. Both scenarios must be considered and accounted for to achieve meaningful petrophysical calculations at depth.

In order to rectify the aforementioned errors, all well logs in this study were depth shifted to a pre-determined standard: the gamma ray log. The gamma ray log was chosen as the depth standard because it is often used to locate perforation intervals during well completion and stimulation operations (E. Vosburgh, Apache Corporation, verbal communication, June 5, 2015). If all quantitative formation evaluation is on-depth with the main-pass gamma ray log, zones of interests will be accurately located during subsequent well interventions and completions.

Using the interactive depth shift module in IP, individual curves were overlain on

the gamma ray curve (Figure 26). By means of local geological and petrophysical knowledge, each curve was scaled to represent diagnostic deflections across all well logs. If discrepancies were present, individual logs were squeezed and stretched between chosen deflections points on the gamma ray curve and the corresponding shift curve.

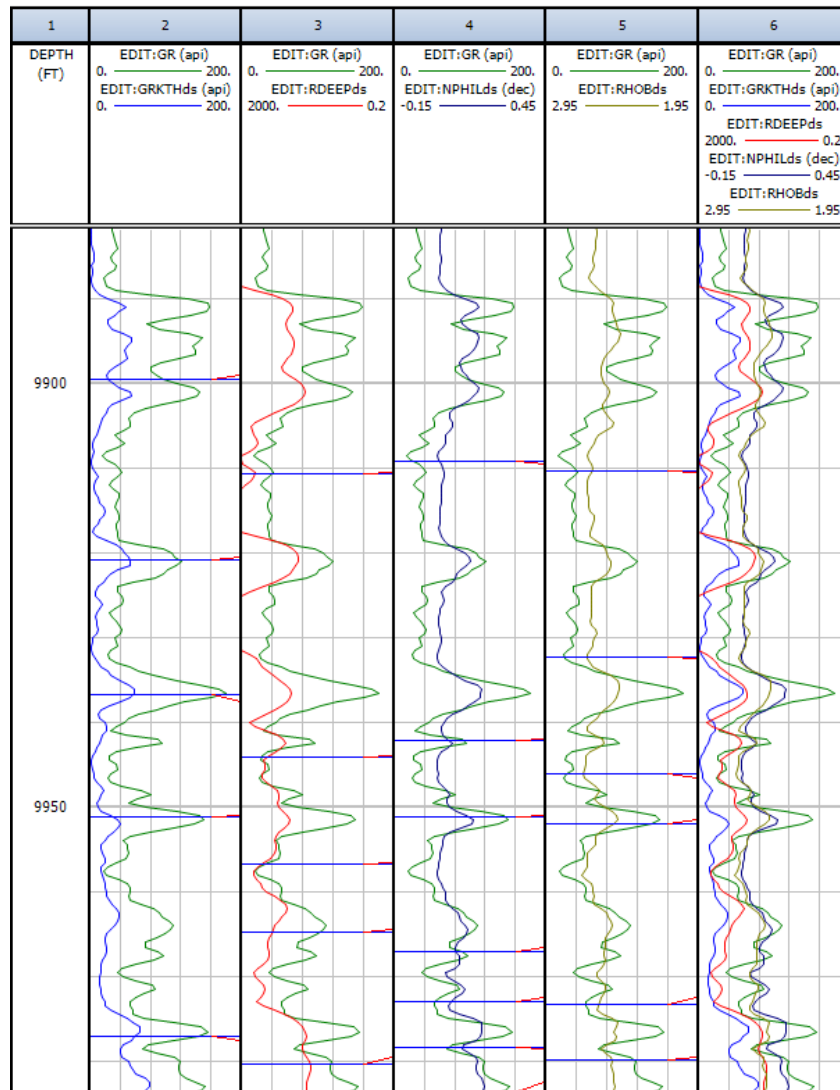


Figure 26. Depth-shifting module in Interactive Petrophysics™. The gamma ray log is presented in all tracks (green curve). Additionally, depth, uranium-corrected gamma ray, deep resistivity, neutron porosity, and bulk density logs are presented in tracks one through five. Track six displays all logs simultaneously. The horizontal blue lines in tracks two through five represent depth-shifting points.

Once the main curves from each tool were shifted, (e.g., uranium-corrected gamma ray, deep resistivity, neutron porosity, and bulk density) supplementary curves were shifted to these “parent” curves. Supplementary curves include: density correction, caliper, photoelectric effect, shallow resistivity, and all components of the spectral gamma ray curve, (e.g., potassium, thorium, and uranium concentrations).

Log Editing

Upon completing the appropriate depth shifts, a series of interpretive log editing techniques (Ausburn, 1977) were used to control the quality of individual log data on a well-to-well basis. A quote by Ausburn (1977) sums up the plight of log editing: “Everyone who has worked quantitatively with well logs recognizes that it is not uncommon for portions of well-log data to contain data that may be significantly different from the true, in situ formation properties.” Through the use of crossplot analyses, multi-linear regression, and well-log normalization, the author was able to locate and rectify extraneous data throughout each well as followed by the methods of Farnan and McHattie (1984). Once invalid data was identified, interlog relationships were used to create pseudo data across problematic zones. This crucial and sometimes tedious routine enabled the author to achieve consistent petrophysical calculations in subsequent steps.

Crossplot Analysis: To begin the editing workflow, a series of interactive crossplots were used to examine log data across individual stratigraphic zones (Figure 27). When log data is displayed in this manner, temporal and spatial patterns are easily

recognizable. Using published literature on the Spraberry Trend (Tyler and Gholston, 1988; Tyler, et al., 1997; Hamlin and Baumgardner, 2012) in conjunction with caliper logs and density correction logs, acceptable lithological and petrophysical parameters were distinguished for each zone of interest.

Once the data was examined, user-defined polygons (Figure 27) were created to display data in log plot space and crossplot space simultaneously. Through an iterative process of selection and examination, acceptable crossplot values were converted into petrophysical flags (Figure 28). These data flags were then incorporated as discriminators in subsequent multi-linear regression procedures used to create pseudo data over zones of wellbore instability.

Multiple Linear Regression: Once questionable data was identified, pseudo well-log data was constructed using the multi-linear regression (MLR) module in IP (Figure 29). Within this module, four to five well logs were used as inputs to predict the response of curves containing questionable data. Petrophysical flags and restricted training intervals were incorporated to achieve the highest correlation coefficients possible. Through an iterative process, the author repeated the above steps until robust regression models were created. Once these models were created, pseudo data was merged with edited data using IP's user formula and interactive curve splice modules (Figures 28 and 30).

The aforementioned procedures were also implemented when sonic travel-time curves were absent from wells. In this situation, a nearby well containing sonic data was used to create and calibrate MLR models. Resulting equations were used to populate

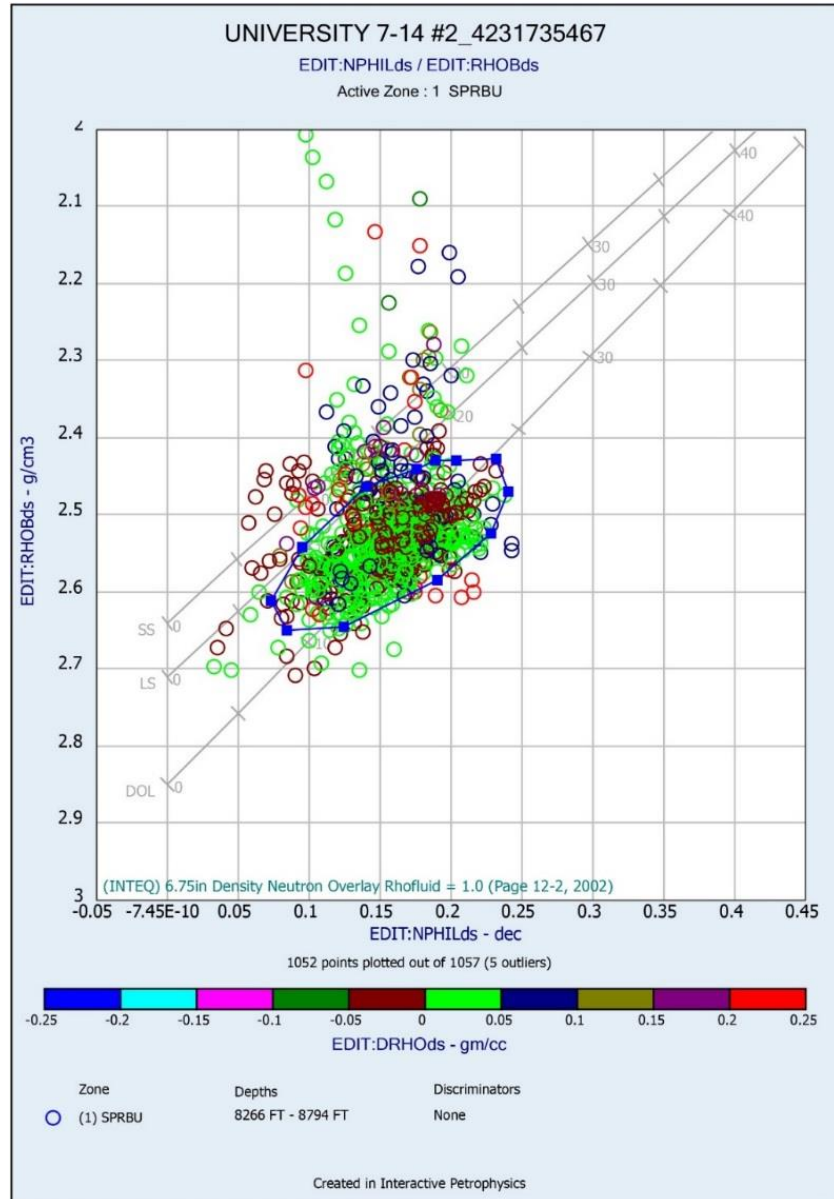


Figure 27. Example of an interactive crossplot used to QC well-log data. The blue polygon represents user-defined data selection and the gray lines represent chart-book lithology markers. RHOBds is a depth-shifted bulk density log, NHIPLds is a depth-shifted neutron porosity log, and DRHODs is the depth-shifted density correction log.

synthetic data in wells lacking sonic-log data based on the relationship of sonic travel-time to known well-log parameters in the well of interest for which synthetic data is created.

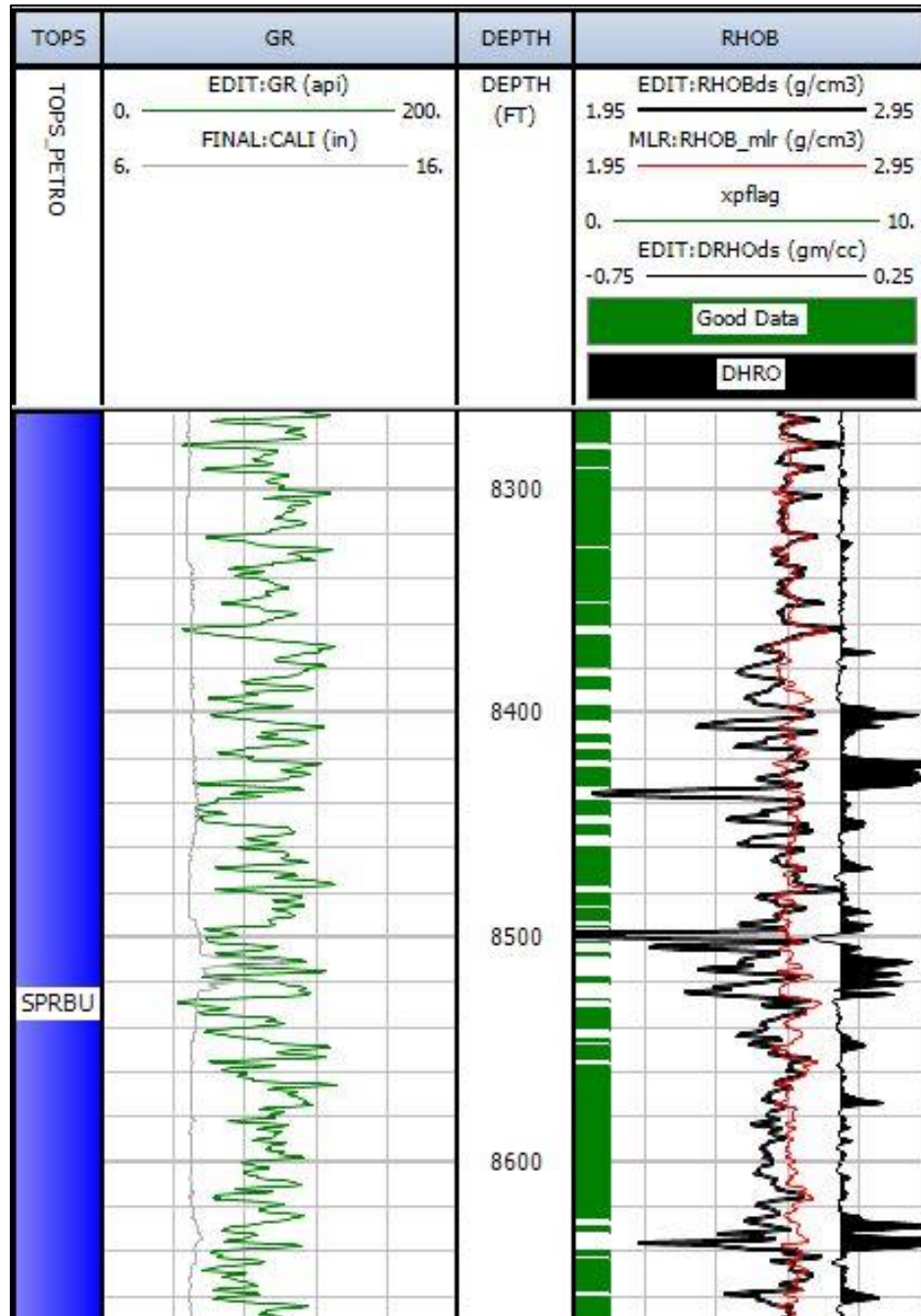


Figure 28. Log plot used to display petrophysical flags and pseudo-data created by multiple-linear regression. For this well, SPRBU marks the upper Spraberry, GR is the gamma ray log, CALI is the caliper log, DEPTH is measured depth, RHOBds is the depth-shifted bulk density log, RHOB_mlr is a synthetic bulk density log created from MLR, xpflag represents acceptable data obtained from crossplot analyses, and DRHODs is the density correction log.

	Use	Default	Log	Well	We
Curve Name				1	2
Well Name	→	↓		(72) University 7-28B #2_4231735351	
Curve to Predict	→	✓	RHOB	EDIT:RHOBds	
Input Curve 1	→	✓	GR	EDIT:GR	
Input Curve 2	→	✓	RDEEPds	✓ EDIT:RDEEPds	
Input Curve 3	→	✓	THORds	EDIT:THORds	
Input Curve 4	→	✓	PE	EDIT:PEds	
Input Curve 5	→				
Input Curve 6	→				
Input Curve 7	→				
Input Curve 8	→				
Use Well	→		for Model Build	✓	
Top Interval			for Model Build	8717	
Bottom Interval			for Model Build	8815	
Use Well	→		for Model Run	✓	
Top Interval			for Model Run	8298	
Bottom Interval			for Model Run	8844	
Show Plot			for Model Run	Show Plot	
Discriminator	→	Crv 1	NDFlag	xpFlag	
Discriminator	→	Crv 2	PassTOC	PEdFlag	

Advanced Well Select Get Depths from Zones ☐ Use Custom Plot Format

Report Multi-Well Plot Reset form Load model Save model Close Help

Figure 29. MLR module used to create pseudo well-log data.

User-defined formula - UNIVERSITY 7-16 #4_4231735796 : MLR_RHOB_edit.frm

Discriminator logic (optional)

If depth $\geq$ 8292 and depth $\leq$ 8564

Formula

then MLR:RHOB_mlr

Formula

else EDIT:RHOBds

☐ Clip Resultant curves Minimum value : 0.003 Maximum Value :

Result Curve MLR:RHOB_edit Units Top TOPS_PETRO - SPRBU (Top)

Curve Type Numeric Bottom TOPS_PETRO - PENNU (Bottom)

Output Set Check for null data ☒ Auto Save ☐

Information Comment

Run Load Formula Save Formula Clear Close Help

Figure 30. User formula used to combine edited curves and pseudo well-log data.

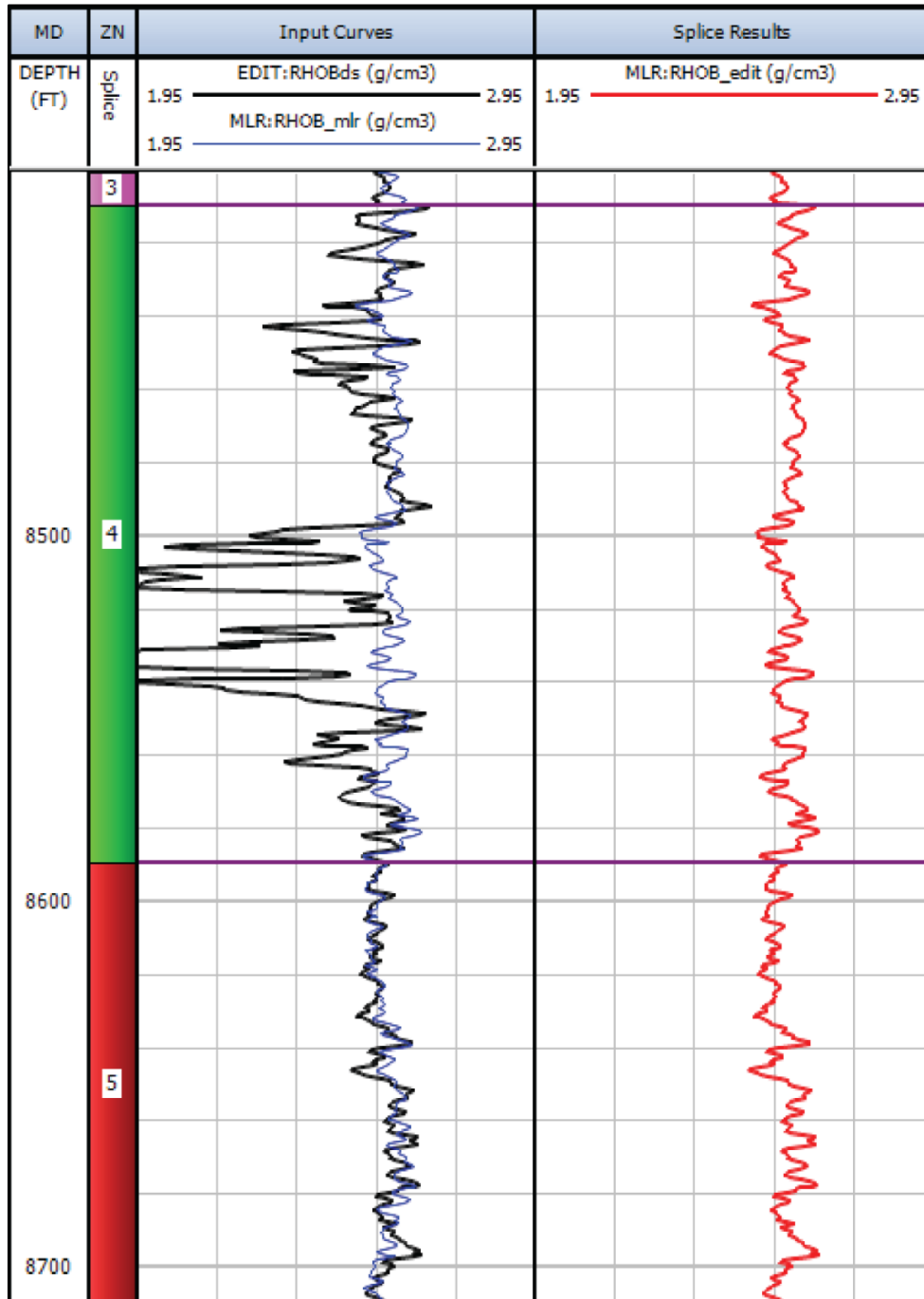


Figure 31. Curve splice module used to merge edited data. Tracks one and two contain depth and zone information, track three contains input curves, and track four contains the resulting spliced curve. DEPTH is measured depth, Splice represents zones created for the splice module, RHOBds is the depth-shifted bulk density log, RHOB_mlr is a synthetic bulk density log created by multiple-linear regression, RHOB_edit is the edited bulk density log that contains a combination of depth-shifted data and synthetic data.

Log Normalization: Well log normalization is the final step in data conditioning prior to quantitative FE. According to Shier (2004, p. 269),

“Any well log curve may be considered as the sum of a signal (actual rock properties), random noise (including random variations in the count rates for the nuclear tools), and systematic errors. Well log normalization is the process of eliminating systematic errors from well log curves.”

Using the histogram module in IP (Figure 31) key well logs (Cluff and Holmes, 2013) were normalized, including the gamma ray, bulk density, neutron porosity, and photoelectric curves. As outlined by Shier (2004) and Cluff and Holmes (2013), gamma ray logs and neutron porosity logs were normalized by utilizing a two-point gain and offset, while the bulk density and photoelectric logs were normalized using a one-point linear shift.

The aforementioned corrections were applied using three methods within IP; statistical two-point gain and offset normalization (Cluff and Holmes, 2013), statistical one-point offset normalization (Shier, 2004), and/or interactive one or two point normalization. The statistical method of log normalization adjusts chosen percentiles of un-normalized curves to reference curves in a type well. Shier (2004) mentions the 10th and 90th percentiles as a common range to shift well logs. These values were used as a starting point for the statistical normalization method employed in this study. In some cases, a narrower range of the 5th and 95th percentiles was employed to match the reference curves in the type well. In both cases, the low-shoulder and/or the high-shoulder of each well log was used to examine the validity of each shift. The overall goal of each normalization procedure is to shift the un-normalized curve such that it is encased within the envelope of the matching curve in the type well. If both statistical approaches

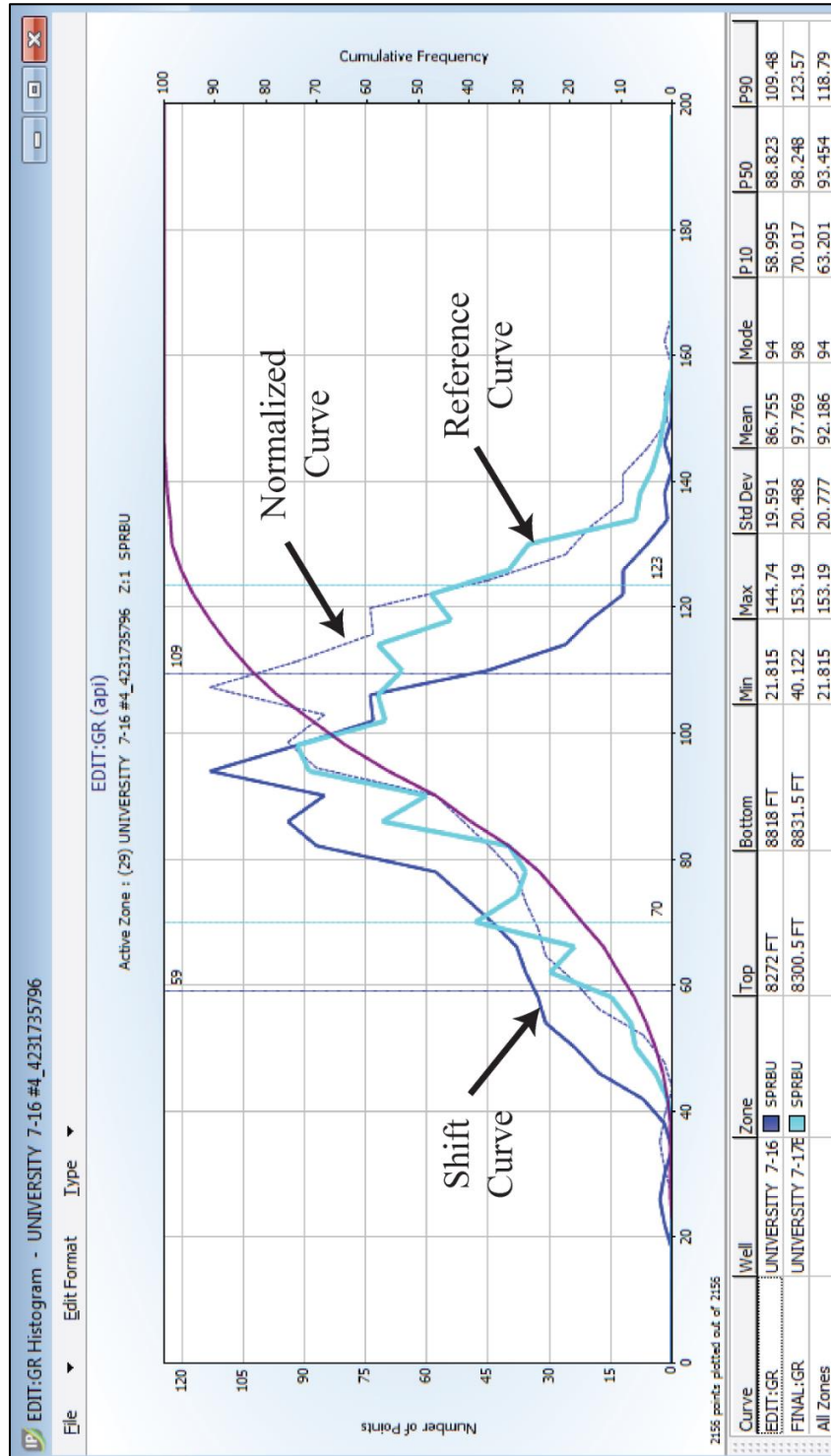


Figure 32. Histogram module used to normalize well logs. In this example the shift curve is the gamma ray log to be normalized, the reference curve is the gamma ray log located in the type well, and the normalized curve is the resulting normalized gamma ray log.

were unsatisfactory, an interactive one or two point normalization procedure was used. In this method, the author chose a representative point along the low and/or high shoulders of each well log and moved the shift curve appropriately.

Deterministic Petrophysical Calculations

Once all preparatory procedures were complete, matrix parameters, fluid properties, clay volumes, and total organic carbon content (TOC) were calculated using a deterministic workflow similar to those presented by previous workers (e.g., Sondergeld et al., 2010; Brooks and Montalvo, 2012; Glorioso and Rattia, 2012; Cluff and Holmes, 2013). However, specific equations and methodologies may vary slightly based on trial/error and the author's experience. In either case, deterministic and probabilistic techniques were implemented throughout various stages of this study.

Matrix Parameters

To begin the petrophysical workflow, preliminary porosity and lithology indicators were calculated. Using equations published by Asquith and Krygowski (2004, p. 37-51) crossplot porosities, sonic porosity, apparent matrix density, apparent matrix travel-time, matrix volumetric cross-section, conductivity, M, and N were determined using equations shown below. These parameters are important for obtaining a "first look" lithological interpretation and an initial porosity calculation for subsequent models. Additionally, subsurface temperature and pressure profiles were determined using equations (11-12). Formation temperature and pressure are important parameters for subsequent calculations involving fluid properties and resistivities.

$$\emptyset ND_{xp} = \frac{1}{2} * (\emptyset D + \emptyset N) \quad (1)$$

$$\emptyset NS_{xp} = \frac{1}{2} * (\emptyset S + \emptyset N) \quad (2)$$

$$\emptyset S = \frac{\Delta t - \Delta t_{ma}}{\Delta t_{fl} - \Delta t_{ma}} \quad (3)$$

$$RhoMatApp = \frac{\rho_b - (\emptyset ND_{xp} * \rho_{fl})}{1 - \emptyset ND_{xp}} \quad (4)$$

$$DTMatApp = \frac{\Delta t_{ma} - (\emptyset NS_{xp} * \Delta t_{fl})}{1 - \emptyset NS_{xp}} \quad (5)$$

$$UMatApp = \frac{U - \emptyset ND_{xp} * U_{fl}}{1 - \emptyset ND_{xp}} \quad (6)$$

$$U = Pe * (\rho_b + 0.1883) * 0.93423 \quad (7)$$

$$C_t = 1000 * R_t^{-1} \quad (8)$$

$$C_{xo} = 1000 * R_s^{-1} \quad (9)$$

$$Napp = \frac{\emptyset N_{fl} - \emptyset N}{\rho_b - \rho_{fl}} \quad (10)$$

$$Mapp = \frac{\Delta t_{fl} - \Delta t}{P_b - P_{fl}} * 0.01 \quad (11)$$

$$\text{Formation Temperature (F)} = \frac{BHT - SFT}{\text{Depth (ft)}} \quad (12)$$

$$\text{Formation Pressure (Psi)} = \text{Depth (ft)} * HSG \quad (13)$$

Fluid Properties

After initial matrix parameters were determined, IP's unconventional reservoir module was used to calculate fluid properties across all stratigraphic zones. This interface allowed the author to determine dynamic sonic travel-time and density parameters for oil and water, on a well-to-well basis. Fluid properties in this module are calculated based on

algorithms presented by Burke and Curtis (2000). A list of input parameters and output curves for these calculations can be found in (Appendix B).

Clay Volume

One of the most crucial steps in any petrophysical routine is determining the amount of clay minerals present within the formation(s) of interest. According to Asquith and Krygowski (2004, p. 125), the presence of clay minerals (Figure 33) can cause log-derived water saturations and porosities to be erroneous. Hydroxyls within the clay crystal lattice and/or interstitial water between phyllosilicate layers can cause porosity logs to overestimate the total porosity of a given unit volume (Figure 34). Additionally, the negative surface charge associated with clay minerals can cause cations to become adsorbed to clay platelets (Figure 33). This relationship causes clay minerals to conduct electrical current, effectively lowering resistivity values obtained from well logs.

Within the petrophysical community, log analysts either compute volume of shale (V_{sh}) or volume of clay (V_{cl}). For this study, the author chose to compute V_{cl} for two reasons: 1) shale volume implies constituents of clay minerals as well as fine-grained quartz and feldspars in a given unit volume (Boggs, 2006, p. 140), whereas clay volume implies the volume of clay minerals present in a given unit volume; and 2) probabilistic mineral-models require bulk mineral volumes as inputs, therefore, clay volumes can be directly used in volumetric calculations.

Clay volumes in this study were determined by taking the minimum clay volume derived from multiple deterministic methods. These methods incorporated single clay indicators derived from thorium concentration and gamma ray response, and double-clay

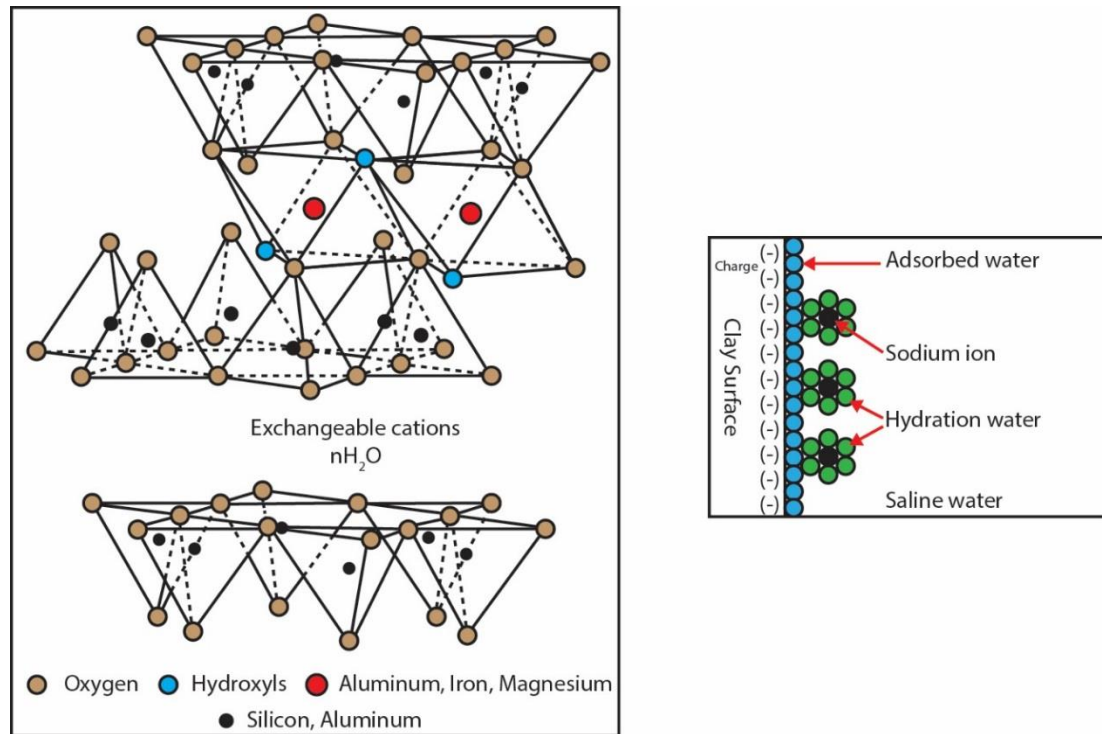


Figure 33 Diagrammatic sketches of a swelling clay-mineral (Smectite) and the clay surface-water relationship of negatively charged clay minerals. Modified from Grim (1962) and Clavier et al, (1984).

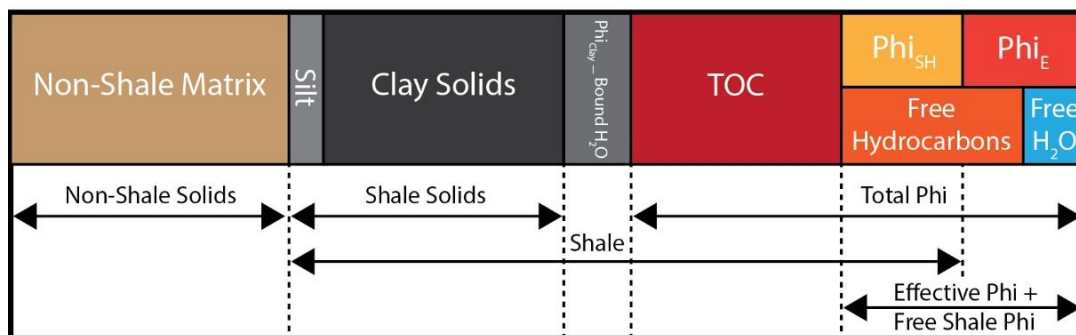


Figure 34. Schematic of an idealized petrophysical unit volume. Modified from Cluff and Holmes (2013).

indicators derived from neutron-density and sonic-density relationships. Equations from the IP clay module are as follows:

$$V_{clGR} = \frac{GR - GR_{clean}}{GR_{clay} - GR_{clean}} \quad (14)$$

$$V_{clThor} = \frac{Thor - Thor_{clean}}{Thor_{clay} - Thor_{clean}} \quad (15)$$

$$ND_Vcl = \frac{(\rho_{fl} - \rho_{ma}) * (\phi_N - \phi_{N_{ma}}) - (\rho_b - \rho_{ma}) * (\phi_{N_{fl}} - \phi_{N_{ma}})}{(\rho_{fl} - \rho_{ma}) * (\phi_{N_{clay}} - \phi_{N_{ma}}) - (\rho_{clay} - \rho_{ma}) * (\phi_{N_{fl}} - \phi_{N_{ma}})} \quad (16)$$

$$NS_Vcl = \frac{(\rho_{fl} - \rho_{ma}) * (\Delta t - \Delta t_{ma}) - (\rho_b - \rho_{ma}) * (\Delta t_{fl} - \Delta t_{ma})}{(\rho_{fl} - \rho_{ma}) * (\Delta t_{clay} - \Delta t_{ma}) - (\rho_{clay} - \rho_{ma}) * (\Delta t_{fl} - \Delta t_{ma})} \quad (17)$$

Equations (14-17) were manipulated using the interactive clay-volume module within IP. This module allowed the author to manually enter clay parameters which were then altered using interactive crossplots (Figure 35). Individual models were iteratively modified to match core data as closely as possible. See (Appendix B) for clay module parameters and calibrated results.

Total Organic Carbon Content

Total Organic Carbon (TOC) is the term used to describe the amount of carbon bound in organic compounds within a rock (Glorioso and Rattia, 2010). According to Bohacs et al. (2013) the main constituents of TOC are kerogen which is insoluble in organic solvents and bitumen which is soluble in organic solvents. During burial, kerogen undergoes conversion and hydrocarbons are generated. Kerogen type, in conjunction with thermal maturity, dictates the type of hydrocarbons generated (McCarthy et al., 2011). In order to fully characterize the petrophysical unit volume (Figure 34), TOC must be

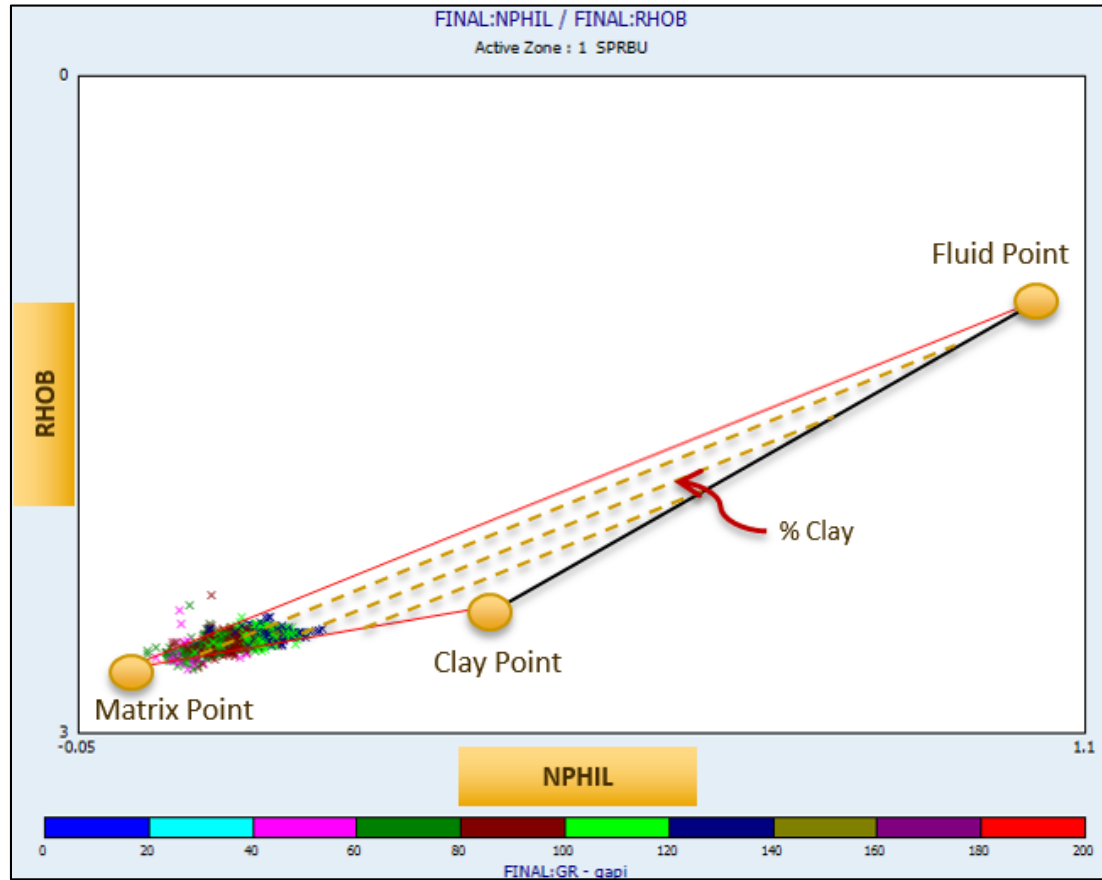


Figure 35. Example of an interactive neutron-density crossplot used to solve for clay volume. The matrix point represents the bulk density and neutron porosity endpoints for an assumed limestone matrix (2.71 and 0, respectively). The fluid point represents the bulk density and neutron porosity readings in water (1.0 and 1.0, respectively). The clay point is determined interactively to match core derived clay volumes. These endpoints are incorporated into equation 16 to partition the data cluster into % clay as artistically represented by the dashed golden lines.

accounted for and quantified in both conventional and unconventional petroleum exploration. Generally, TOC is estimated using conventional well-log analysis techniques in conjunction with laboratory geochemistry.

In unconventional petroleum exploration, TOC estimation from well-logs is a keystone step in characterizing self-sourcing reservoirs. As a “quick-look” approach, log based TOC estimations are used to identify organic-rich zones, which are flagged as possible horizontal drilling target intervals. Once targets are identified, TOC values are incorporated into petrophysical models to obtain kerogen corrected porosities, and if necessary, adsorbed gas content (Glorioso and Rattia, 2010; Quirein et al., 2010; Sondergeld et al., 2012).

TOC values in this study were ascertained by averaging the results of three deterministic log-analysis techniques: 1) the Modified $\Delta\log R$ method; 2) the Schmoker method; and 3) the Faust method. As with previously discussed petrophysical parameters, calculations were calibrated to core. Calibrated models were then used as references for subsequent calculations in wells lacking core data. Methodologies and procedures for each technique are discussed below.

The $\Delta\log R$ Method: The $\Delta\log R$ method is an empirical technique that was developed by Passey et al. (1990) that incorporates porosity logs, deep-resistivity logs, and thermal maturity information to quantify weight percent TOC in a given unit volume (equations 18-21). This method relies on the assumptions that: 1) organic matter causes an apparent increase in porosity values because TOC occupies pore space and displays

similar well log responses as formation fluids, and 2) in-situ hydrocarbons cause an increase in formation resistivity values (Passey et. al., 1990) (Figure 36).

$$\Delta \log R_{\text{sonic}} = \log_{10} \left(\frac{R_T}{R_{bl}} \right) + 0.02 * (\Delta t - \Delta t_{bl}) \quad (18)$$

$$\Delta \log R_{\text{neutron}} = \log_{10} \left(\frac{R_T}{R_{bl}} \right) + 4.0 * (\phi N - \phi N_{bl}) \quad (19)$$

$$\Delta \log R_{\text{density}} = \log_{10} \left(\frac{R_T}{R_{bl}} \right) - 2.50 * (\rho_b - \rho_{bl}) \quad (20)$$

$$TOC_{\text{Passey}} = TOC_{bl} + \Delta \log R * 10^{(2.297 - 0.1688 \text{ LOM})} * C \quad (21)$$

This study implements a modified version of the $\Delta \log R$ method that was developed by Eric Vosburgh at Apache Corporation. The modified $\Delta \log R$ technique incorporates a common FE plotting technique known as an “ R_o ” overlay (Figure 36, pg. 63). This overlay uses a derivation of the Archie (1942) water saturation equation that enables log analysts to determine “wet-rock” resistivity over zones containing water-filled porosity (equation 22). This technique assumes water resistivity (R_w) is equal to formation resistivity (R_t) if water saturation (S_w) is 100% across low resistivity zones.

Using these assumptions, “wet” resistivity baselines were chosen for each stratigraphic zone in this study. Once baseline values were established, R_o curves were created by incorporating neutron-density crossplot porosities and m/a values (i.e., 2 and 1 respectively) into equation (22).

In a similar manner to the approaches outlined by Passey et al. (1990), calculated. R_o curves were used to represent resistivity values over organic-lean zones. When R_o is plotted against R_t , both curves align in organic-lean intervals and separate in zones

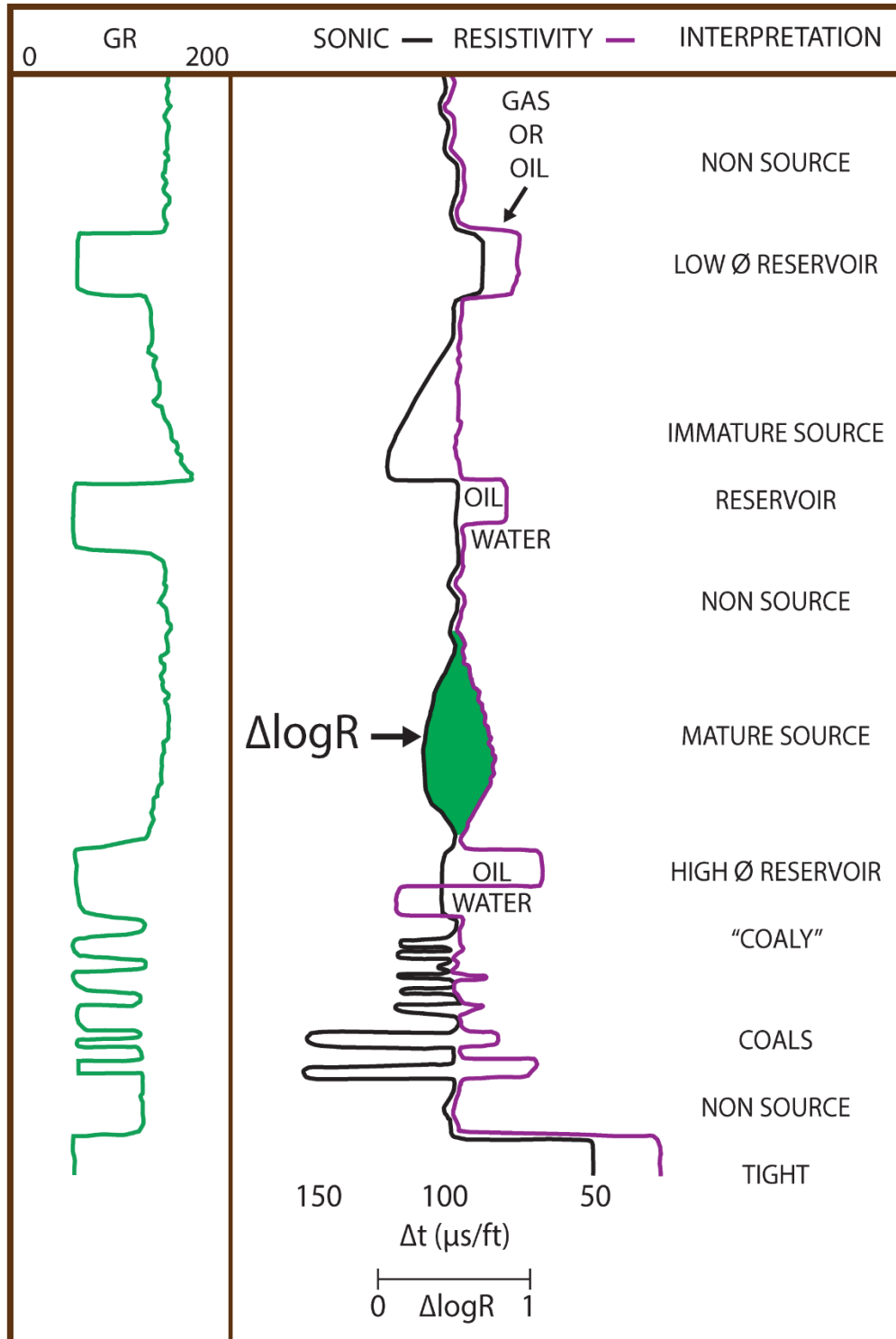


Figure 36. Schematic depiction of features observed on a $\Delta \log R$ overlay. Modified from Passey et al. (1990).

containing organic matter and/or hydrocarbons (Figure 37, pg. 66). In this way, the amount of $R_o - R_t$ separation becomes the $\Delta\log R$ term in equations (24-25).

$$S_W = \left(\frac{a * R_W}{\emptyset^m * R_t} \right)^{\frac{1}{n}} \quad (22)$$

$$R_o = \frac{a * R_T}{(\emptyset N D_{xp})^m} \quad (23)$$

$$\Delta\log R_{\text{Modified}} = \log_{10} \left(\frac{R_T}{R_o} \right) \quad (24)$$

$$\text{TOC}_{\text{Modified}} = \text{TOC}_{\text{bl}} + \Delta\log R_{\text{Modified}} * 10^{(2.297 - 0.1688 \text{ LOM})} * C \quad (25)$$

When using any forms of the $\Delta\log R$ method, thermal maturity must be taken into consideration. The LOM term in the $\Delta\log R$ method refers to Level of Organic Metamorphism, a concept introduced by Hood et al. (1975). LOM is a maturity scale that relates numerous forms of maturity data collected through various laboratory measurements (i.e., vitrinite reflectance analysis, program pyrolysis, and thermal alteration indices). For this study, vitrinite reflectance measurements collected by Chesapeake Energy suggests an LOM of 10 should be used.

The Schmoker Method: In contrast to previously discussed techniques, the Schmoker method (Schmoker, 1979) establishes a relationship between a single input, bulk density, and TOC. According to (Schmoker, 1979; Herron, 1991; Sondergeld et. al, 2010) organic matter causes bulk density measurements to read low in comparison to other volumetric components (i.e., quartz, calcite, etc.). Using this observation, Schmoker (1979) derived an empirical equation (24), as presented by Herron (1991), that estimates TOC from bulk density logs.

$$\text{TOC}_{\text{Schmoker}} = \frac{\text{Ts}_1}{\text{P}_b} - \text{Ts}_2 \quad (26)$$

Due to the empirical nature of the Schmoker method, the author manipulated the Ts_2 constant to achieve a best-fit correlation to core-derived TOC data. For consistency, the Ts_1 constant was not manipulated during calibration. Instead, a published value of 154.497 (Herron, 1991) was used in all Schmoker TOC calculations.

The Faust Method: The third method of TOC calculation in this study incorporates a resistivity-sonic overlay technique similar to the aforementioned $\Delta\log R$ method (Passey et al., 1990). The Faust method implements a re-scaled resistivity log that is derived from velocity-resistivity relationships outlined by Faust (1953). Using equation (27), the author created synthetic resistivity transforms that were plotted against sonic travel-time curves. Equation (28) was then used to calculate TOC values from positive curve separation in zones containing TOC and/or hydrocarbons. The Faust_c term in equation (28) was manipulated to calibrate curve separation to core-derived TOC values. Typical Faust_c values in this study range between 8-10.

$$\Delta T_{\text{Faust}} = \frac{513}{(\text{Depth} * R_t)^{0.1666}} \quad (27)$$

$$\text{TOC}_{\text{Faust}} = \frac{\Delta \text{Faust}}{\text{Faust}_c} \quad (28)$$

Electrofacies Analysis:

Electrofacies are a sub class of facies that connect well logs to geologic attributes. Doveton (1994) defines electrofacies as “the set of log responses which characterizes a bed and permits it to be distinguished from others.” In general, electrofacies are used to

predict the possible lithological variation between cored wells and non-cored wells as an aid in identifying reservoir intervals (Gupta and Johnson, 2002). This study incorporates electrofacies as an additional measure of geologic heterogeneity between wells.

Model Preparation: The University 7-17B #4 well was chosen as the training well for the predictive facies model implemented in this study. As such, the Dean and upper Spraberry Formations were used as training intervals. The other cored well in this study, the Ralph Williams #4 well, was not incorporated as a training well because the author believes this well is too distant to the main cluster of wells in this study. Additionally, the Ralph Williams #4 well is not located on the *University Land* grid.

Prior to model construction, core-derived Lithofacies were assigned top and bottom depths. Additionally, a numerical code, qualitatively based on grain size, was used to represent the seven facies found in the cored intervals (e.g., a value of one represents siliciclastic mudrock and a value of 7 represents conglomeratic carbonate). This information was uploaded to IP and depth shifted to create facies profiles for each zone. Facies profiles for both cored wells are presented in (Figures 38-41).

Model Implementation: Within IP, the Self Organizing Maps (Kohonen, 2001) module was used to create a predictive facies model. The model was trained over the Dean and Spraberry Formations using four well logs: gamma ray, neutron porosity, bulk density, and photoelectric factor. Through trial and error, it was determined that the most accurate results were achieved using a map width of 50, 750,000 training iterations, and a learning rate of 0.1. Furthermore, the author grouped the various siltstone facies into one

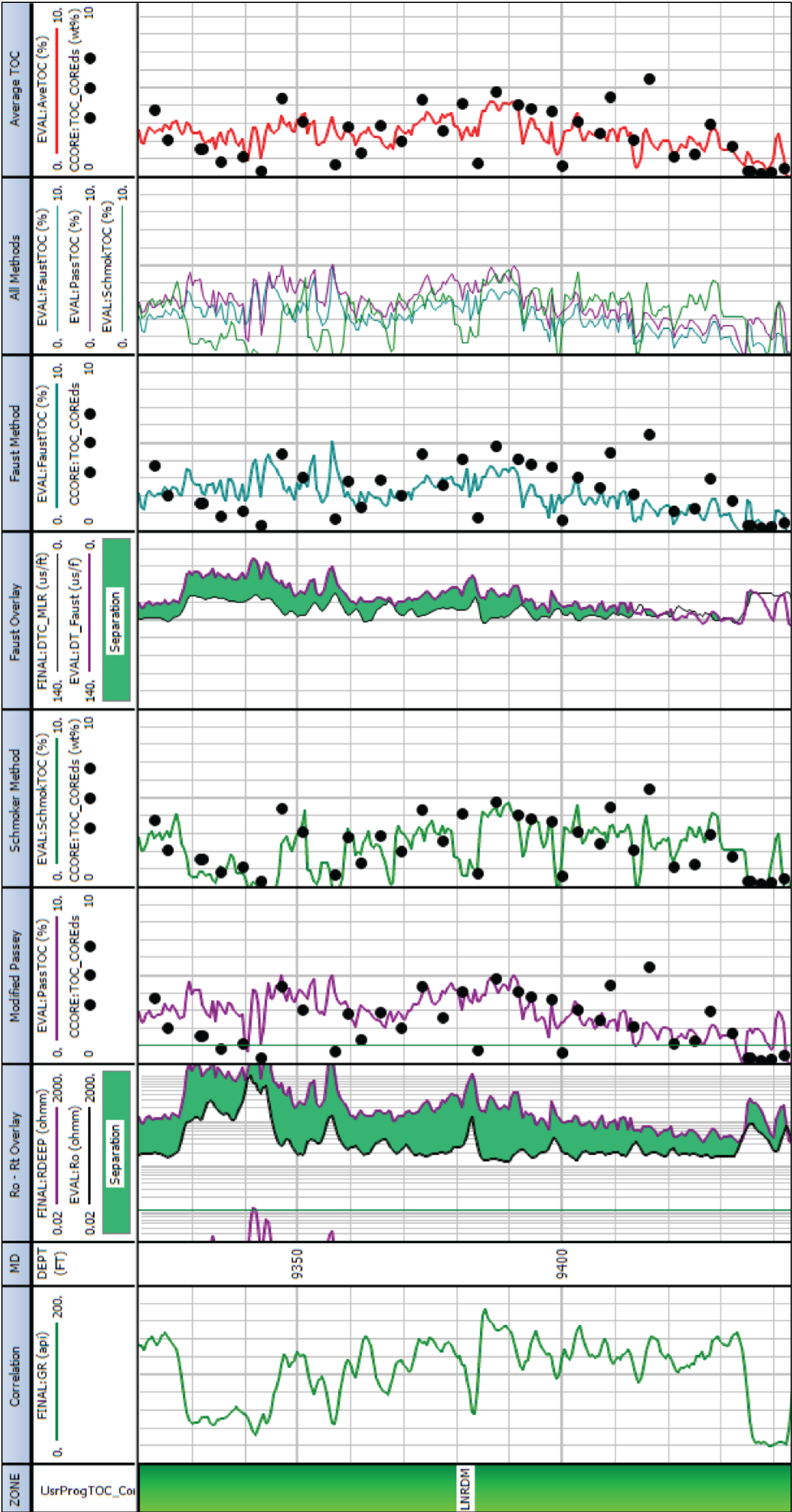


Figure 37. Core-calibrated TOC models and associated overlays for the middle Leonard interval within the Ralph Williams #4 well. Track titles correspond to each method and resulting curves. See equations 18-28 and table 4 for specific calculations and input curves incorporated in each method.

learning rate of 0.1. Furthermore, the author grouped the various siltstone facies into one calibration facies. Due to the vertical resolution of most well logs, thin interbedded successions of a similar lithology will generally be averaged out. Once the model was trained, electro facies were populated across wells lacking core data. Model results will be discussed in the proceeding chapter.

Probabilistic Petrophysical Calculations

The final and most difficult step in FE is calculating compositional and fluid constituents within a given unit volume (i.e., mineral volumes, porosity, water saturation, and oil saturation). These components can be solved for individually, using deterministic approaches, or simultaneously, using probabilistic techniques. A workflow similar to the one presented in (Figure 42) provides a probabilistic volumetric assessment for strata in this study. Many workers (Burke et al., 1967; Doveton, 1984; Mitchell and Nelson, 1988) have documented the advantages of using statistical log analysis techniques in lithologically-complex settings. In wellbores that penetrate multiple facies, deterministic log-analysis techniques do not accurately predict porosity or fluid saturations (Burke et al., 1967). Doveton (1994) states: “for more complex rock types, compositional analysis by traditional crossplot methods is more challenging because of the increased number of components that must be incorporated.” For these reasons, the author employed IP’s stochastic mineral solver to construct volumetric models for each well.

Inversion Models

Many log analysis software packages contain probabilistic modules. Although

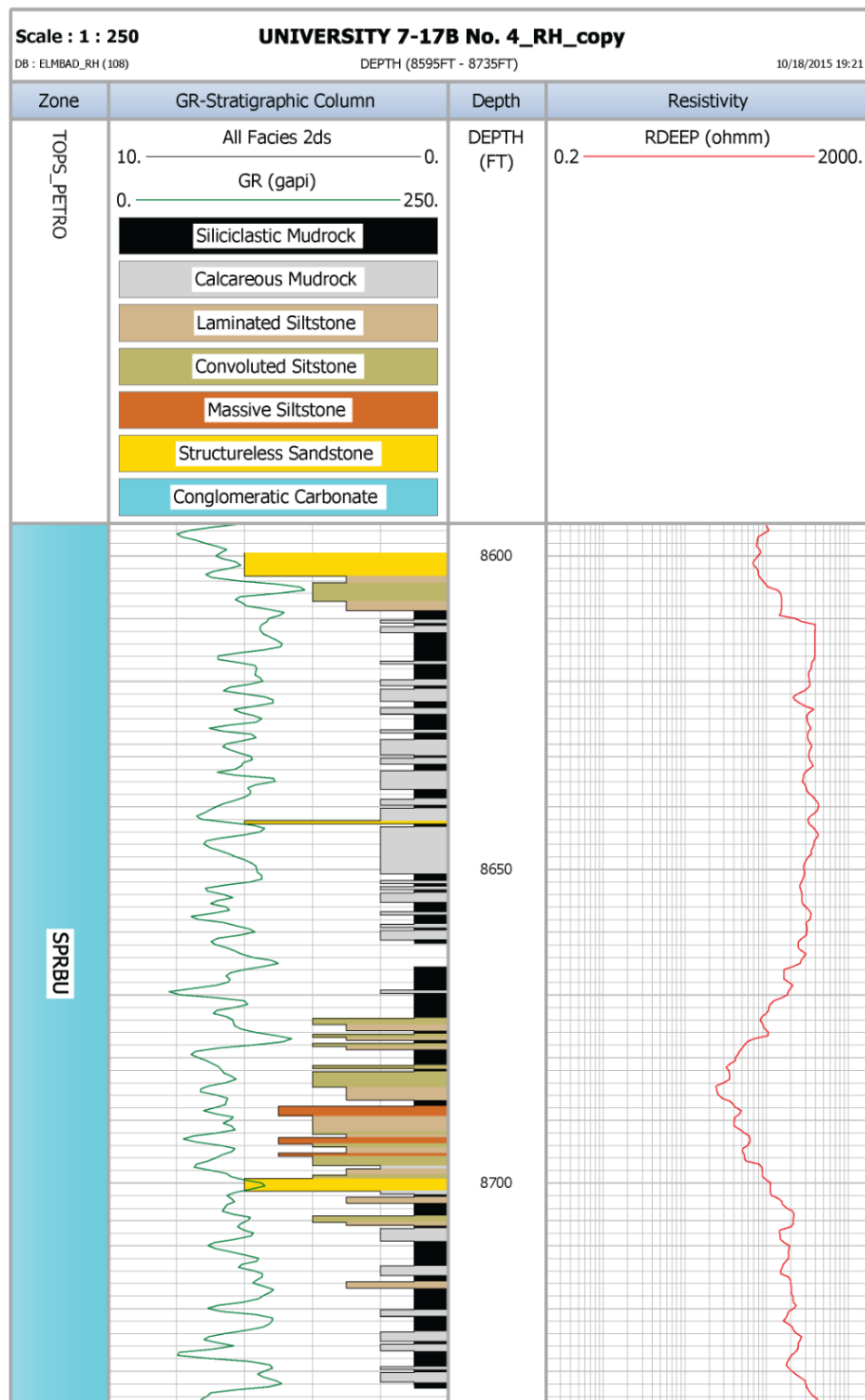


Figure 38. Facies profile for the upper Spraberry Formation: University 7-17B #4 Well.

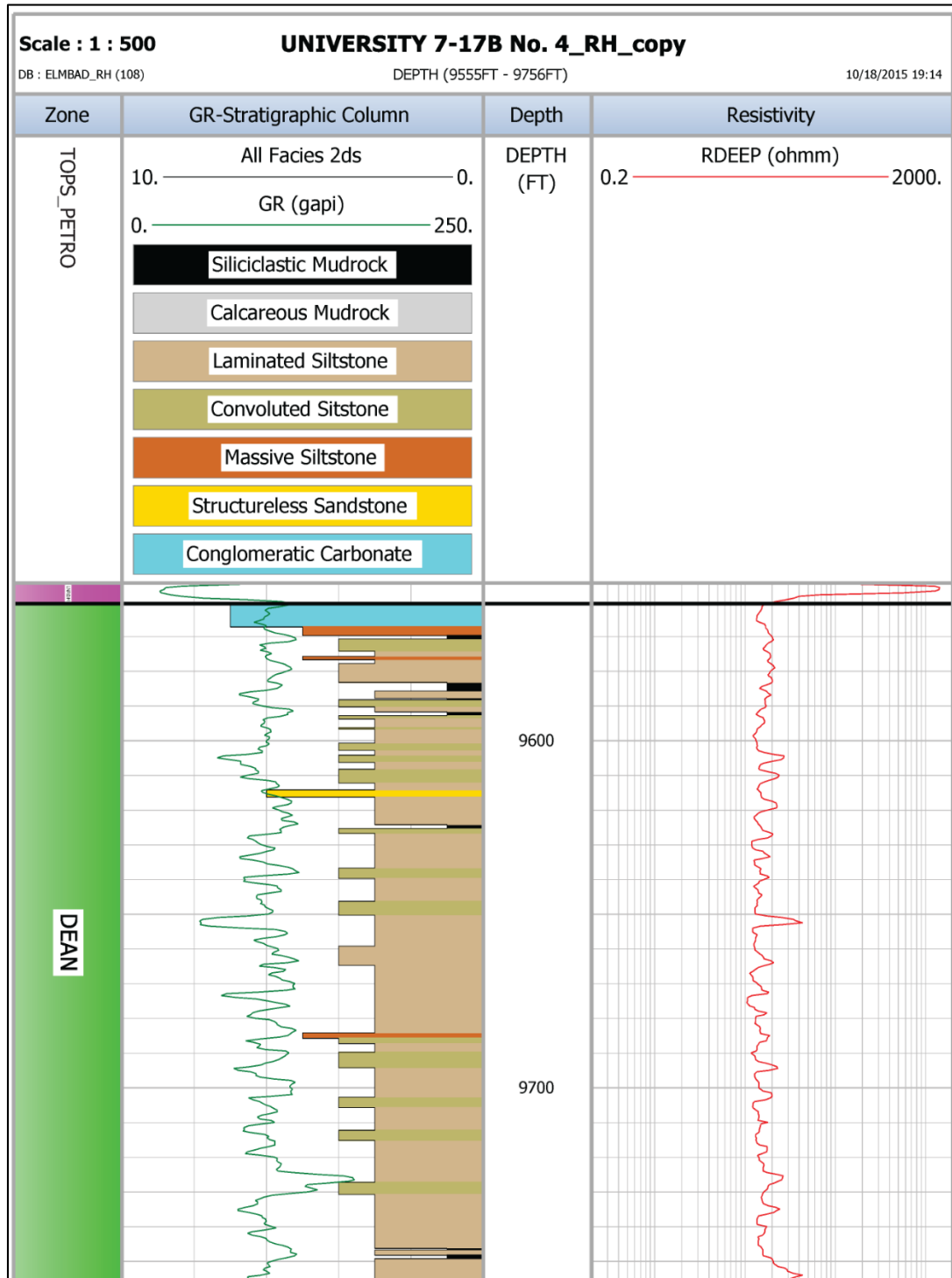


Figure 39. Facies profile for the Dean Formation: University 7-17B #4 Well.

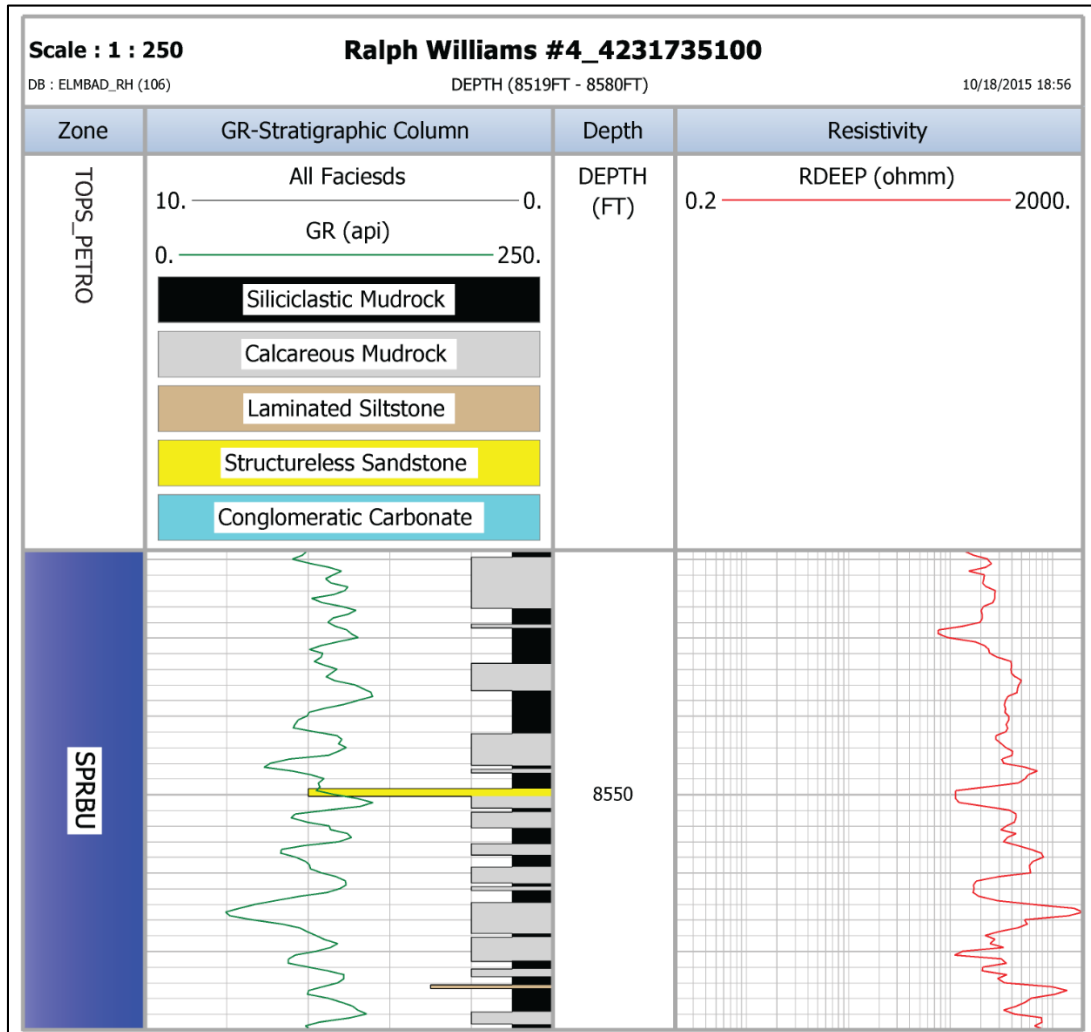


Figure 40. Facies profile for the upper Spraberry Formation: Ralph Williams #4 Well.

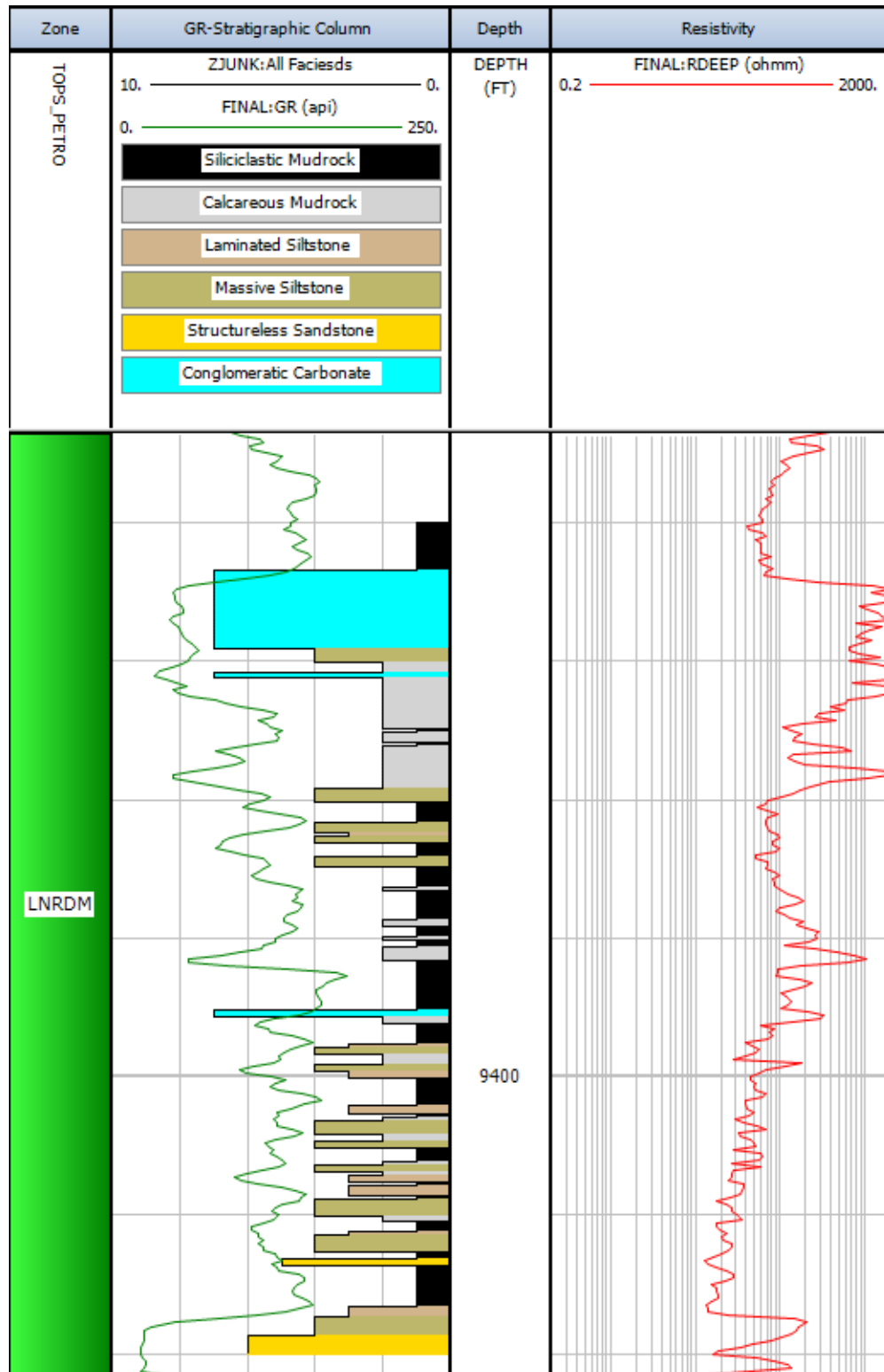


Figure 41. Facies profile for the middle Leonard interval: Ralph Williams #4 Well.

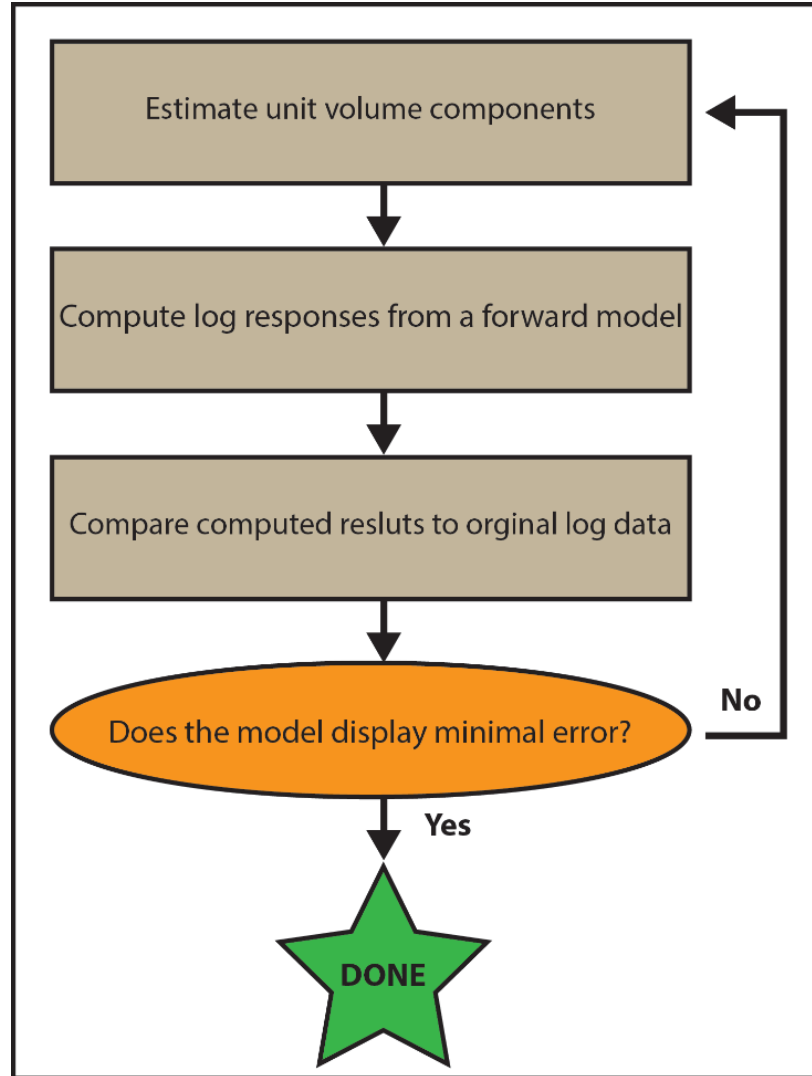


Figure 42. Flowchart of probabilistic inversions. Modified from Cluff and Holmes (2013).

slightly different, the underlying principles are similar: well-log data and tool response parameters. Mathematically, this procedure can be written in matrix form (Mitchell and Nelson, 1988):

$$\bar{M} = E \bar{V} \quad (29)$$

Using forward models, equation (29) can be solved using singular value decomposition⁶ (Press et al, 1986). This technique combines normalized down-hole logging measurements and assumed volumetric constituents, to create theoretical tool responses (Mitchell and Nelson, 1994). If the assumed volumetric constituents are 1) present within the formation; and 2) accounted for correctly, theoretical log responses will match original log data. Conversely, if volumetric parameters are assumed incorrectly, theoretical tool responses will not match down-hole data. The overall goal of probabilistic modeling is to minimize the difference between reconstructed log responses and original log data (Mitchell and Nelson, 1988).

Volumetric Models

For this project, well-to-well probabilistic models were created and employed in four stages: 1) primary component integration, in which forward models were populated with volumetric constituents, log data, and statistical confidence parameters; 2) supplementary component integration, in which porosity and saturation methodologies were selected and calculation parameters were specified; 3) model execution, in which individual models were created and examined; and 4) model adjustment, in which input parameters were adjusted and reconfigured. The methods associated with each of these stages are discussed below.

Primary Component Integration: During this stage, a “grid” (Figure 43) is

⁶ Given the breadth of this study, an in-depth mathematical investigation of singular value decomposition is outside the scope of this project. Readers are referred to Press et al. (1986); Mitchell and Nelson, (1988) for further information on this topic.

constructed that contains data to be used during forward modeling. These data include a list of well logs to be implemented during calculations, the statistical confidence given to each well log as determined by tool calibration charts, a list of volumetric parameters to be solved for, and a list of idealized well-log responses that correspond to each of the unknown components.

Volumetric parameters for this project were chosen to represent likely minerals and fluids found within the Spraberry Trend. In probabilistic modeling, the total number of solvable endpoints is limited by the number of well logs (i.e., equations) available. Due to the complex lithologies encountered in this study, the combination of minerals and fluids exceeds the number of well logs collected in each well. This situation creates an underdetermined system that requires n linear-equations to solve for $n+1$ components (Mitchell and Nelson, 1988). For this study, eight components: clay, quartz, calcite, dolomite, pyrite, TOC, oil⁷, and water were solved for, using seven equations: bulk density, neutron porosity, sonic travel-time, volumetric cross section, TOC, clay volume, and a model unity function. It should be noted that the TOC and clay-volume inputs were calculated deterministically (see p. 56-64) prior to model construction, in order to achieve robust solutions. This method of deterministic input-is outlined by Mitchell and Nelson (1988, p. 8).

Upon completing the component and equation setup, volumetric endpoints and confidence intervals were incorporated into the model grid. Static mineral endpoints for quartz, calcite, dolomite, and pyrite were populated with values presented by Ellis et al.

⁷ Oil was chosen based on program pyrolysis data provided by Chesapeake Energy.

(1958), while “auto” endpoints were determined during the inversion process of the model execution stage. Clay endpoints were obtained during previous clay-volume analyses (p. 56-58) and TOC endpoints were populated with commonly observed values outlined by (Sondergeld et al., 2010; Cluff and Holmes, 2013). Fluid endpoints were populated with dynamic values that were previously calculated using IP’s fluid module (p. 52). Initial confidence intervals for well-log derived equations were chosen based on calibration errors associated well-log measurements (E. Vosburgh, personal communication, May, 2014). Deterministically derived equations and unity functions were as tightly constrained as possible, to minimize error. During the model execution stage, these constraints were modified, if necessary, to achieve satisfactory results.

Supplementary Component Integration: Prior to generating forward models, porosity inputs and water saturation methodologies must be stipulated. For this study, water saturation was calculated using Archie’s equation (equation 22, page, 60). Deep resistivity and forward model-derived total porosity were the preferred input curves for Archie’s equation. Additionally, values of 2.2, 2, and 1 were chosen as initial inputs for Archie’s cementation exponent, saturation exponent, and tortuosity component, respectively (m , n , and a in Archie’s equation). During additional forward modeling these parameters were manipulated to match core-derived water saturation trends as closely as possible.

Model Execution: The main purpose of this stage is quality control. Once an inversion is initiated, it is crucial to examine the results (Figure 44) to make sure the

model did not fail during execution. If the inversion was unsuccessfully executed, each input component must be examined for possible mistakes and/or missing data.

Conversely, if the model was successfully created, the total statistical error of the model is examined and problematic zones are noted. Once problematic intervals have been determined, it is often necessary to adjust inversion inputs to achieve satisfactory results.

Model Adjustment: The final stage in probabilistic modeling is model adjustment. This is accomplished through an iterative process of model modification and subsequent model execution. If problematic zones are identified during the model execution stage, three techniques are used to optimize results: 1) manipulation of model constraints, in order to better visualize results; 2) modification of deterministic inputs; 3) adjustment to volumetric endpoints; and 4) determination of dynamic water saturation parameters.

As with many other FE techniques, visual inspection of data plays a key role in probabilistic modeling. Due to the number of variables that can be adjusted in a forward model, it is crucial to narrow-down the parametric possibilities causing inversion mismatch. One way to achieve this task, is by loosening model constraints and running a subsequent inversion (Figure 45). This technique highlights the match or mismatch between reconstructed curves and input curves.

From this plot, an analyst can generally determine if TOC values and/or clay-volumes need to be recalculated to achieve an optimal solution between reconstructed curves and input values. However, if these curves are manipulated, it is crucial to simultaneously update the TOC and clay endpoints within the original model grid. This will allow ensuing model executions to predict correct endpoints. Additionally, other

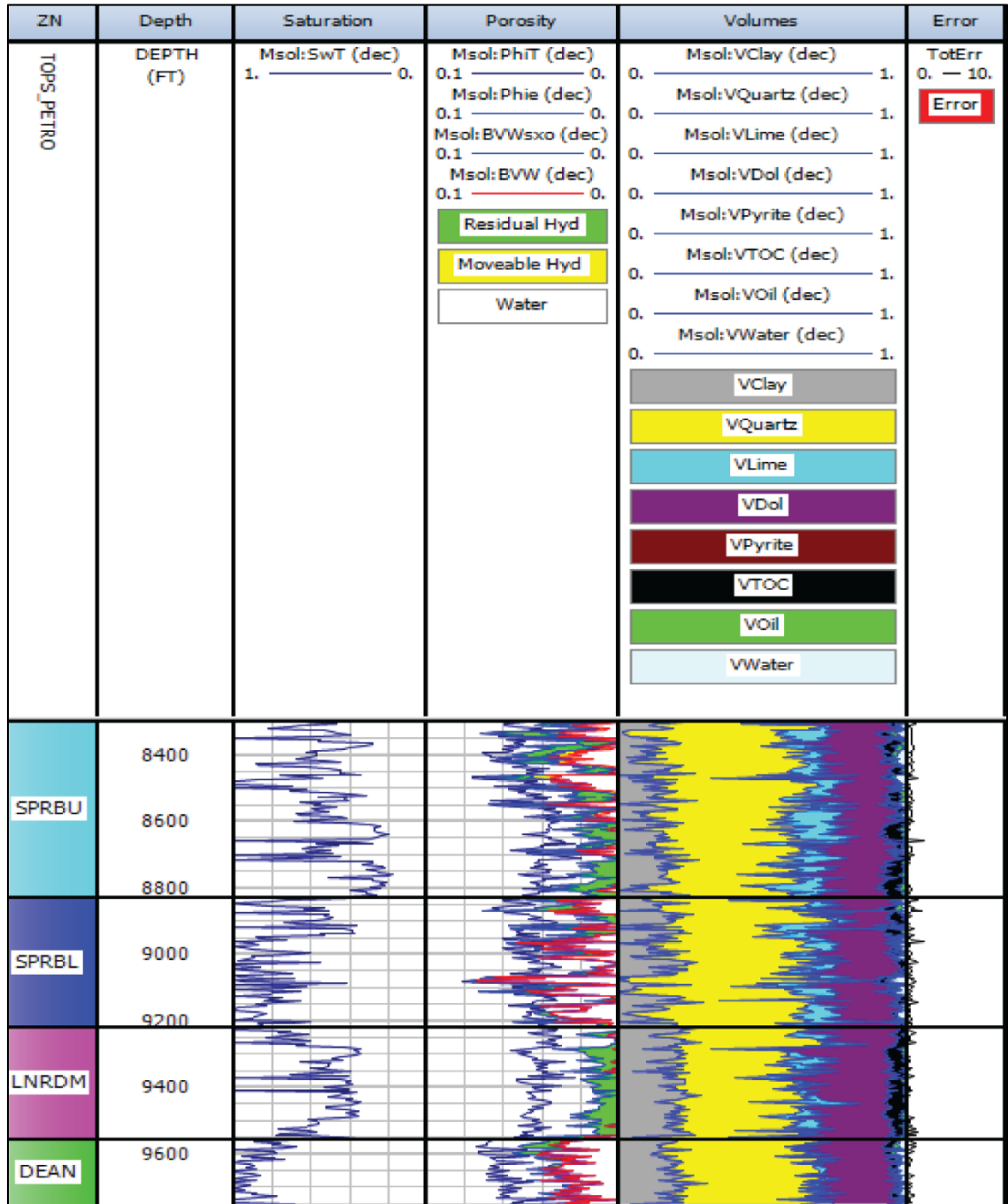


Figure 44. Example of a probabilistic model from the University 7_17B#4 well. Tracks one and two contain zone and depth information. Tracks three through six contain model derived water saturation, porosity, unit volume components, and total error, respectively.

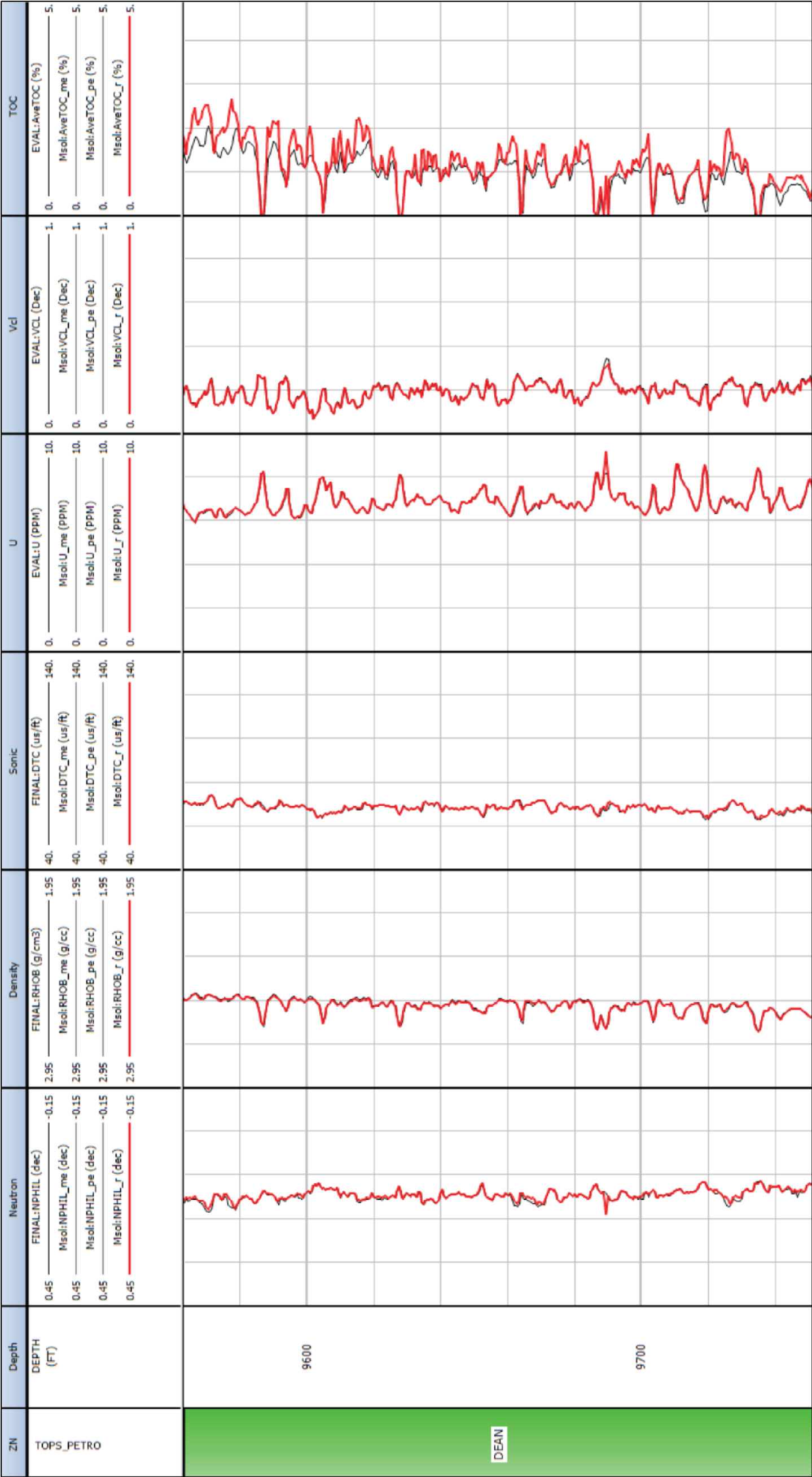


Figure 45. Probabilistic curve reconstructions for the University 7-17B #4 well. The red curves represent reconstructed well logs and the black curves are input well logs (each curve corresponds to the track titles in this plot). Notice the slight mismatch between the original and reconstructed logs in the TOC track.

volumetric endpoints may also need to be adjusted to accurately predict re-computed curves.

Once the above steps have been executed, water saturation inputs must be updated to coincide with inversion-based porosity results. This is accomplished by graphically solving Archie's equation with a Pickett plot (Pickett, 1973) (Figure 46). In the absence of electrical laboratory measurements, Pickett plots are used to obtain water saturation values by estimating Archie parameters: m , R_w , and n using the following equation:

$$\log_{10}(\phi) = \log_{10}(a * R_w) - \frac{1}{m} * \log_{10}(R_t) - n * \log_{10}(S_w) \quad (30)$$

Within this study, Archie parameters were determined using IP's interactive Pickett plot module that incorporates total porosity, deep resistivity, and Archie parameters on a logarithmic crossplot. This module allowed the author to solve Archie's equation by placing the "water bearing line" (Pickett, 1973) along the southwest edge of the data cloud, as described by Asquith and Krygowski (2004, p. 121). Once the water-bearing line was positioned, the slope of the line, which determines the value of the cementation exponent (m), was manipulated to best fit the data trend on the Pickett plot (E. Vosburgh, Apache Corporation, verbal communication, June, 2014). Using a tortuosity (a) value of one, the water-bearing line was extrapolated to intersect the y-axis of the Pickett plot. The point of intersection demarcates the value of formation water resistivity (R_w). Once these features were established, the saturation exponent (n) was iteratively manipulated until calculated water saturation values matched the general trends of core-derived water saturation. Upon determining water saturation values, a final

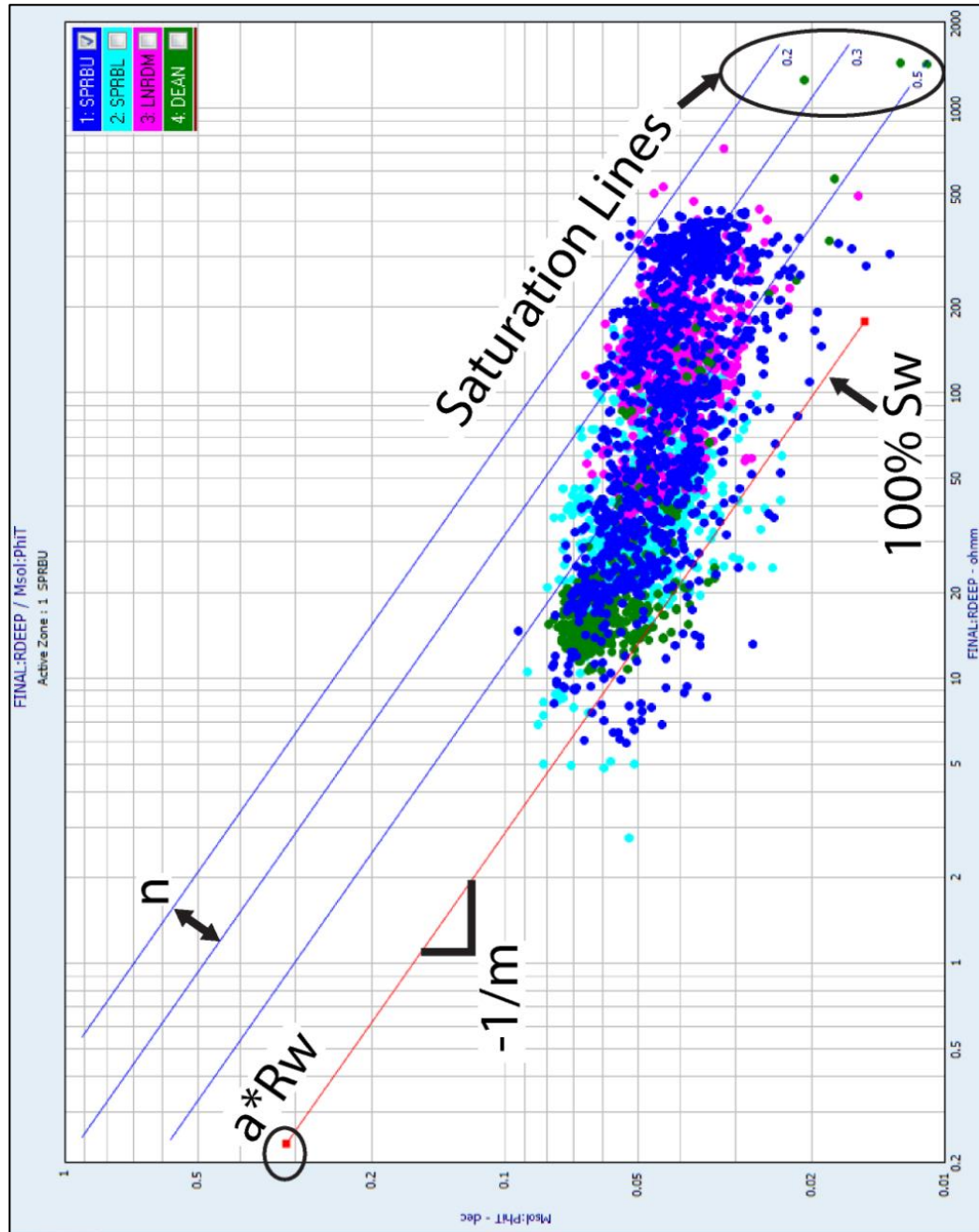


Figure 46. Example of a logarithmic resistivity-porosity crossplot (Pickett plot) used to graphically solve Archie's water saturation equation. The red line represents an interactively determined water-bearing line that displays a slope of $-1/m$ (cementation exponent) and a y-axis intercept of $a \cdot R_w$ (tortuosity x water resistivity). If tortuosity (a) is assumed to be one, formation water resistivity (R_w) can be determined from the plot. Additionally, water saturation values can be assigned to the data cloud if a value for the saturation exponent (n), is assumed. See equation (30) for details.

model was generated using iteratively derived parameters. If individual model results were acceptable and total error was minimized, the model was considered satisfactory and probabilistically derived- petrophysical attributes were used in successive volumetric summations and attribute mapping.

Cutoff and Summations

The final step in Formation Evaluation is identifying target intervals and calculating volumetric parameters on a zone-to-zone basis. This is accomplished by assigning cutoff values to key petrophysical play drivers (Brooks and Montolvo, 2012) and calculating curve statistics across each zone of interest. For this study, two types of zones were identified: “net Pay,” and “reservoir.” Zonation procedures are discussed below.

Petrophysical Flags:

As with previously discussed methods, petrophysical flags were implemented to visually represent zones of interest across the Spraberry, lower Leonard, and Dean intervals within this study. Two types of petrophysical flags: pay and reservoir, were used as discriminators during curve summation and averaging techniques. Individual parameters associated with these flags are discussed herein.

Pay Flags: Pay flags were calculated by assigning static cutoff values to water saturation, total porosity, and clay volume curves. Pay flags were assigned to intervals with the following criteria: water saturation values below 75%, total porosity values

above 2% and clay volumes below 50 %. These criteria are important because water saturation is used to distinguish possible oil-bearing zones, porosity values are used to discriminate tight carbonate stringers and clay volume is used to distinguish ductile intervals from more rigid intervals (E. Vosburgh, personal communication, September, 2015)

Reservoir Flags: Reservoir flags were obtained in a similar manner as pay flags. The main difference between the two flags is the static cutoff value assigned to water saturation. For an interval to be considered a reservoir interval, water saturation values must be below 50%. All other parameters were kept constant between both flags.

Hydrocarbon Pore Thickness

Within the cutoff and summation module, the above petrophysical flags were used to calculate hydrocarbon pore thickness (Φ_{SoH}) (equation 31), also known as hydrocarbon pore volume, across each of the stratigraphic intervals in this study. It should be noted that original oil in place (OOIP) values (equation 32) are generally calculated from hydrocarbon pore thickness. However, due to the lack of subsurface pressure and fluid phase information within the study area, the author could not determine the oil volume expansion factor (B_o) or the recovery factor (RF) in equation (32) (Asquith and Krygowski, 2004, p. 166). As such, hydrocarbon pore thickness is used as “reservoir potential” in subsequent attribute mapping.

$$\Phi_{SoH} = \Phi_T * (1 - S_w) * H \quad (31)$$

$$OOIP = \frac{7758 * A * h * \phi * S_o * RF}{B_o} \quad (32)$$

Final Product

Petrophysical well-log plots are generally used to present Formation Evaluation results. These plots typically show deterministic calculations, probabilistic results, and petrophysical flags. If available, core data is also presented to represent overall the overall core-to-log match (Figure 47).

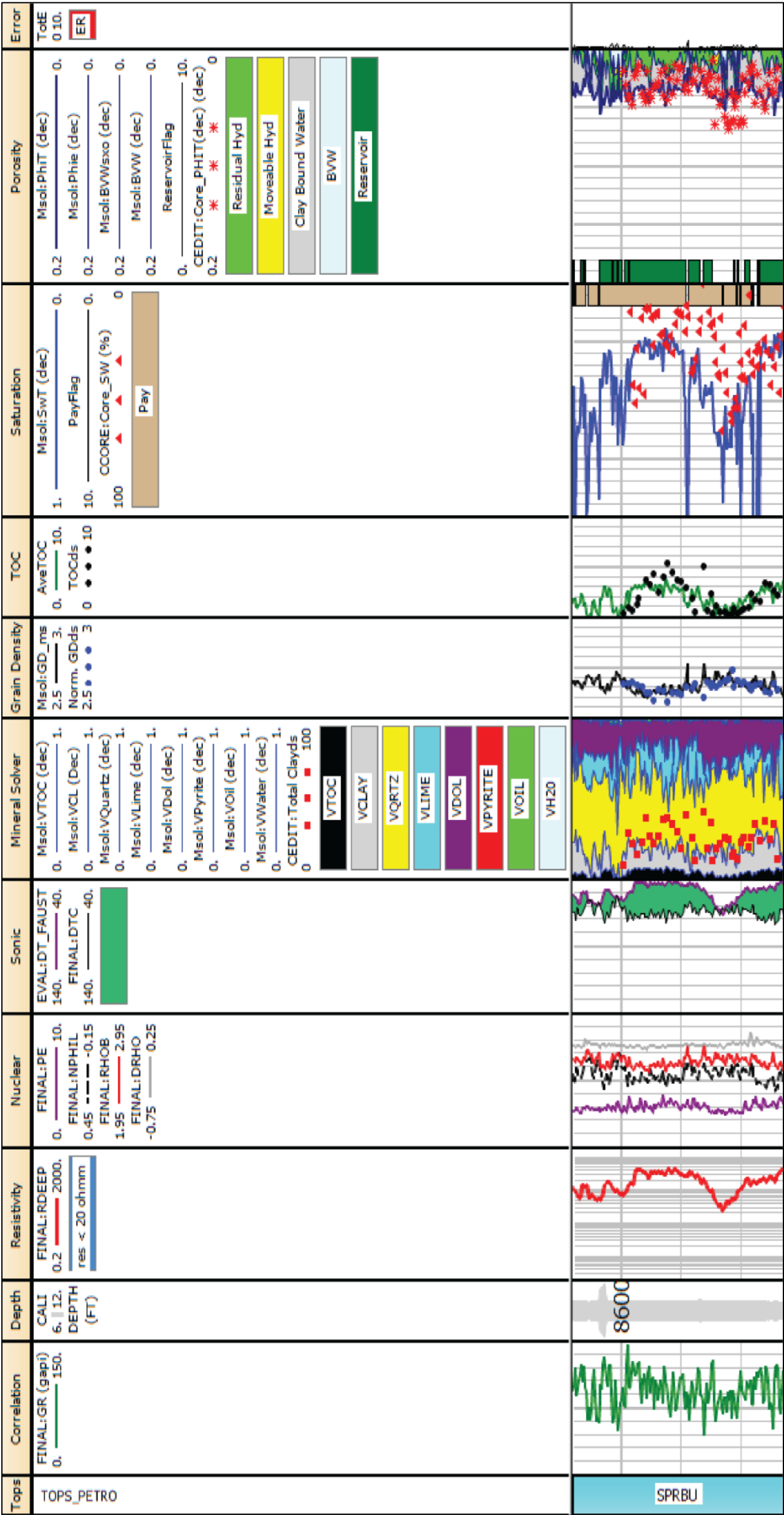


Figure 47. Final Petrophysical plot. Tracks one through five contain zone, gamma ray, depth, resistivity, photoelectric, neutron porosity, bulk density, and density correction information, respectively. Track six contains a Faust overlay that indicates possible organic-rich zones. Track seven contains probabilistically determined unit-volume components and core-derived clay volume. Tracks eight and nine contain core-calibrated grain density and TOC curves, respectively. Track 10 contains core-calibrated water saturation values and pay flags. Track 11 contains core calibrated porosity values and reservoir flags. Lastly, track 12 contains the total error associated with the corresponding probabilistic model for this well.

CHAPTER 5

RESULTS

Introduction

The goal of this chapter is to present qualitative observations and quantitative results from core characterization and Formation Evaluation aspects of this study. Information in this chapter will be presented in two segments: geologic interpretation and petrophysical interpretation. These segments will elucidate the overarching objective of this study: characterization of the unconventional reservoir potential of Leonardian strata within the northern Spraberry Trend.

Geologic Interpretation

A multifaceted analysis of subsurface drill core allowed the author to frame this study in a geologic context. As such, three aspects of core characterization will be discussed below: 1) hydrodynamic processes associated with core-derived lithofacies, 2) results from core-calibrated electrofacies modeling; and 3) chemostratigraphic variations observed from XRF analysis

Hydrodynamic Processes

Lithofacies described in this study closely match those presented by (Hamlin and Baumgardner, 2012; Handford, 1981; Tyler et al., 1997). As such, these publications were used as the foundation for hydrodynamic interpretations within this study. Inferred

hydrodynamic processes for each lithofacies will be presented below. A brief discussion of depositional environments will follow.

Siliciclastic Mudrock (SMD): Siliciclastic mudrocks within this study were deposited by suspension settling (Hamlin and Baumgardner, 2012). Additionally, the presence of organic matter and pyrite indicate these rocks were deposited in an anoxic environment (Pufahl, 2010).

Calcareous Mudrock (CMD): This facies, like the siliciclastic mudrock facies discussed above, was deposited by suspension settling (Hamlin and Baumgardner, 2012). Interbedded sequences of CMD and SMD indicate a fluctuation between carbonate mud and siliciclastic mud components during deposition of Leonardian strata.

Laminated Siltstone (LMSST): Laminated siltstone is very abundant throughout the cored intervals described in this study. According to Hamlin and Baumgardner, (2012) LMSST is the most abundant Leonardian lithofacies in the Midland Basin. This key facies was deposited by suspension settling (Hamlin and Baumgardner, 2012)

Convolute Siltstone (CSST): Contorted laminae in this facies represents rapid deposition by turbidity currents (Posamentier and Walker, 2006). Additionally, this facies may be developed through soft-sediment deformation (Handford, 1981).

Massive Siltstone (MSST): The structureless nature of this lithofacies indicates secondary dewatering of beds during compaction (Posamentier and Walker, 2006). Structureless lithofacies are typically associated with high-density turbidity currents.

Structureless Sandstone (VFSS): According to Hamlin and Baumgardner, (2012) this lithofacies was deposited by intermediate to high-density turbidity currents. It should be noted that a limited number of faint dish-structures were observed within the VFSS facies. These features indicate secondary fluid escape features (Posamentier and Walker, 2006) formed during compaction.

Conglomeratic Carbonate (CC): The presence of this facies was limited within the cores described. This lithofacies was deposited by cohesive slumps, slides, and/or debris flows (Hamlin and Baumgardner, 2012).

Discussion: Core-derived lithofacies and facies associations, in conjunction with previous work by (Handford, 1981; Tyler and Gholston, 1988, Tyler et al., 1997; Hamlin and Baumgardner, 2012), indicate Leonardian units within this project were deposited in a deep-water submarine fan complex by hemipelagic sedimentation, turbidity currents, density flows, and debris flows. Within the broad scope of submarine fan deposits, the aforementioned lithofacies are similar to those found in thin-bedded turbidites located along proximal portions of submarine fan deposits (Prothero and Schwab, 2014, p. 204-205). This observation is consistent with the interpretation by Hamlin and Baumgardner (2012) that suggests Andrews and Martin counties of West Texas are located within a large turbidite lobe.

In summary, the repetitious nature of submarine fan deposits within the two drill cores document microscopic reservoir heterogeneity (i.e., pore-to-pore) (Alpay, 1972). Lateral and vertical permutations of these facies can create well-to-well heterogeneity

(macroscopic) and fieldwide/regional heterogeneity (megascopic) (Alpay, 1972). In the absence of outcrop data, subsurface drill cores are key exploration tools for describing the heterogeneous nature of lithofacies associated with submarine fan deposits.

Electrofacies Analysis

The Self Organizing Maps (SOM) module (Chapter 4, page 62) provided robust electrofacies prediction for the Dean and upper Spraberry Formations. Within the University 7-17 B#4 training well, the SOM facies model correctly predicted 97.7% of the core-derived lithofacies within the Dean Formation (Figure 48). Additionally, the SOM facies model correctly predicted 91.89% of the core derived lithofacies within the upper Spraberry training interval (Figure 49). These agreeable predictions allowed the author to populate electrofacies in nearby wells lacking core data.

Due to the inferred north-northwest sediment source of the Spraberry Trend (Hanford, 1981; Tyler et al., 1997), electrofacies were incorporated in wells occupying strike and dip orientations within the study area. Using procedures outlined by Mulholland (1994), east-west (strike oriented) and north-south (dip oriented) cross sections were constructed (Figures 50-51)

Discussion

Within the strike oriented cross section (Figure 50), modeled electrofacies for both the Dean and Spraberry Formations display increased sandstone content to the west and increased siliciclastic mudrock to the east. Geologically, this might be an indication

of a submarine channel or another submarine-fan lobe located to the west of the study area. Additional drill core and well logs are needed to test this hypothesis.

The dip cross section of electrofacies (Figure 51) displays an increase in mudrock and siltstone facies from north to south. Additionally, the model shows a decrease in sandstone from north to south in both the Dean and upper Spraberry Formations. Geologically, this agrees with a northern sediment source. Distal, fine grained sediments would deposited to the south, which is what the model is showing. As previously discussed, additional core data and well logs are needed to test this hypothesis

X-ray Florescence

Within this study, XRF elemental analyses were converted to oxides (Sarraf, 1990) to qualitatively illustrate chemostratigraphic variations in the cored intervals within the University 7-17B #4 well⁸. It should be noted that an attempt was made to convert XRF oxides to normative mineralogy using procedures outlined by Rosen and Abbasov (2003). However, it was determined that uncertainties associated with assigning normative values to unknown mineral phases and assigning unknown clay-mineral species were too large to create an accurate model. Additionally, preliminary XRF-derived mineralogy overestimated mineralogy acquired by XRD analyses. For these reasons, the author chose to incorporate XRD mineralogy for deterministic and probabilistic model calibration.

⁸ It should be noted that XRF measurements cannot distinguish ferrous and ferric oxidation states of iron. However, the total elemental concentration of iron was converted to both oxidation states in an attempt to produce normative mineral components from XRF data. Additional wet chemical analysis would be needed to quantify oxidation states within this data set.

Discussion

Overall, XRF data trends appear to match lithofacies and electrofacies variations within the cored well (Figures 48-49). Decreases in SiO_2 and increase in CaO mimic fluctuations between siliciclastic facies and carbonate facies, respectively. Additionally, iron oxides show a positive correlation with increases in mudrock facies, possibly indicating the presence pyrite or iron-bearing carbonate muds within these facies. Lastly, Al_2O_3 data concentrations remain relatively constant across all faces. This may be due to a relative lack in feldspathic minerals within individual facies.

Petrophysical Interpretation

The cutoff and summation module in IP (Chapter 4, page, 82) was used to calculate zonal averages (arithmetic) for individual wells in the study area. This module also enabled study-wide averages to be determined for each zone of interest (Table 5). In both instances, three deterministically-derived parameters were averaged: unit thickness, clay volume, and TOC content. Additionally, three probabilistically-derived parameters were averaged: total porosity, water saturation, and hydrocarbon pore thickness.

Zonal Results

The remainder of this chapter will present general log-analysis observations, cross sections, equal thickness (isochore) maps, hydrocarbon thickness maps, and a brief synapses of unconventional reservoir potential of units in this study. Observations and results will be discussed zone-by-zone in stratigraphic order, starting with the Dean

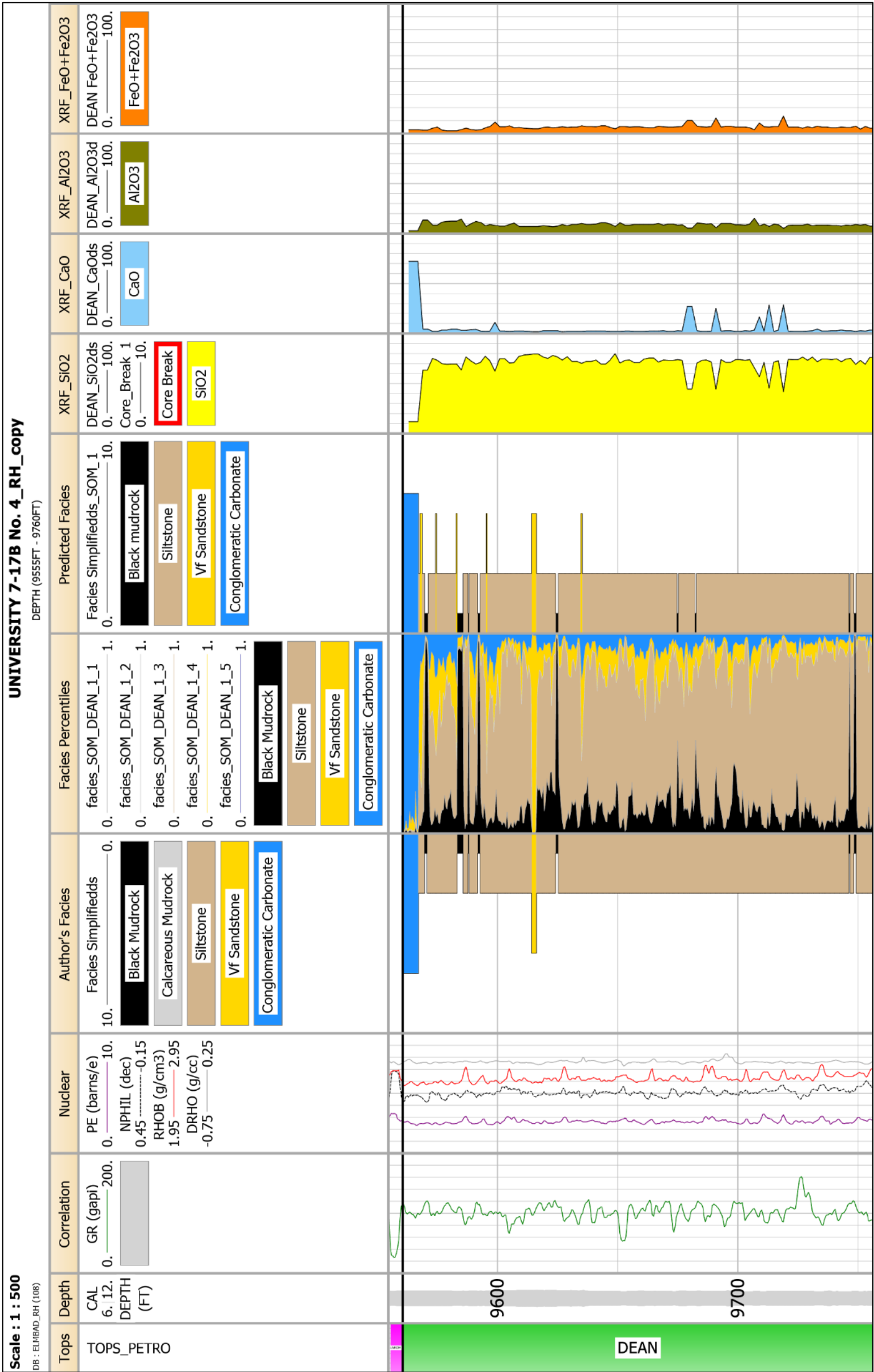


Figure 48. Electrofacies model results and XRF measurements for the Dean Formation. Tracks one through four contain: zone, depth, gamma ray, photoelectric, neutron porosity, and bulk density data. Track five displays core-derived lithofacies. Tracks six and seven display electrofacies obtained using IP's SOM module. Lastly, tracks eight through eleven contain elemental oxides derived from handheld XRF measurements.

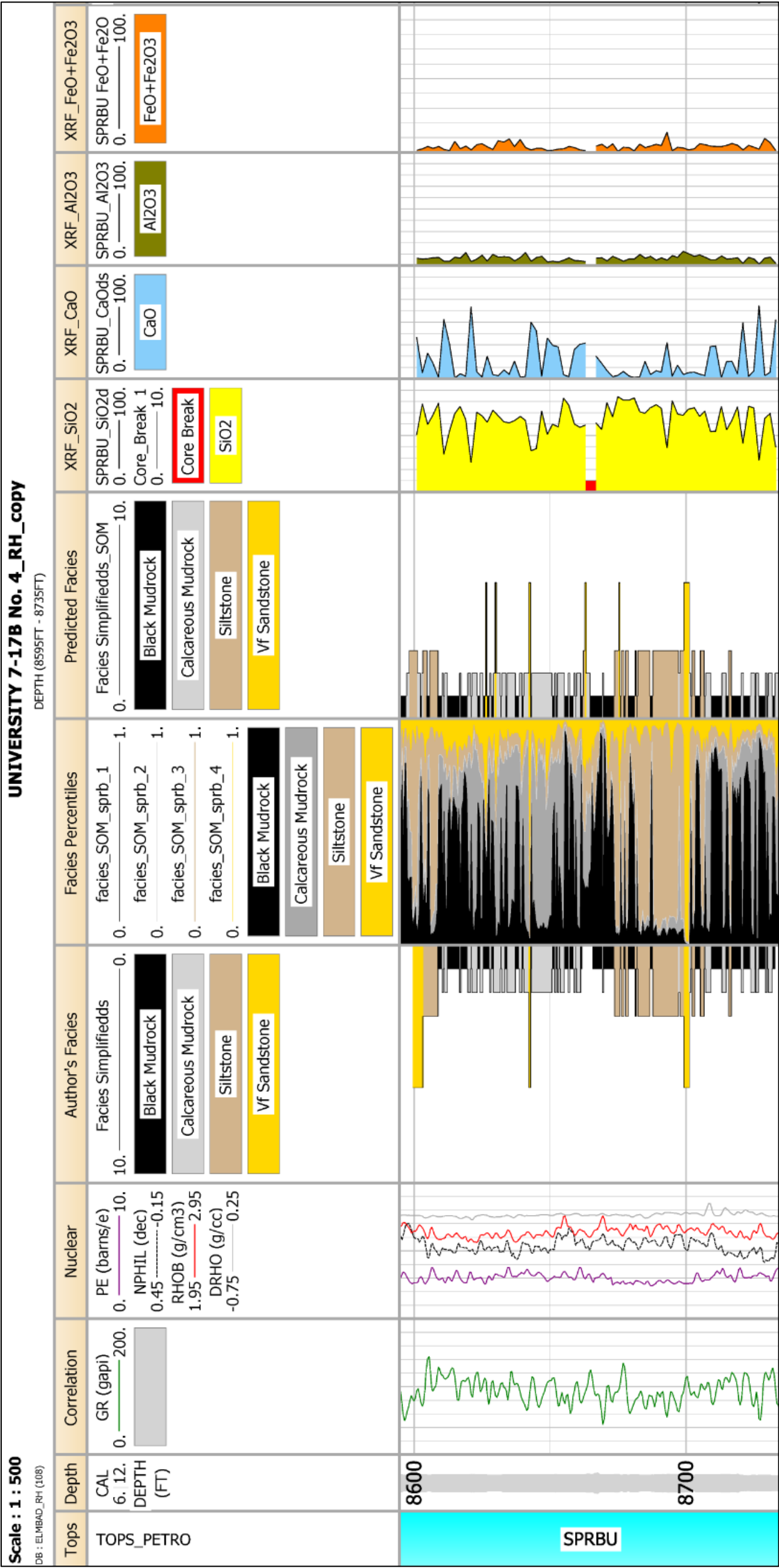


Figure 49. Electrofacies model results and XRF measurements for the upper Spraberry Formation. Tracks one through four contain: zone, depth, gamma ray, photoelectric, neutron porosity, and bulk density data. Track five displays core-derived lithofacies. Tracks six and seven display electrofacies obtained using IP's SOM module. Lastly, tracks eight through eleven contain elemental oxides derived from handheld XRF measurements.

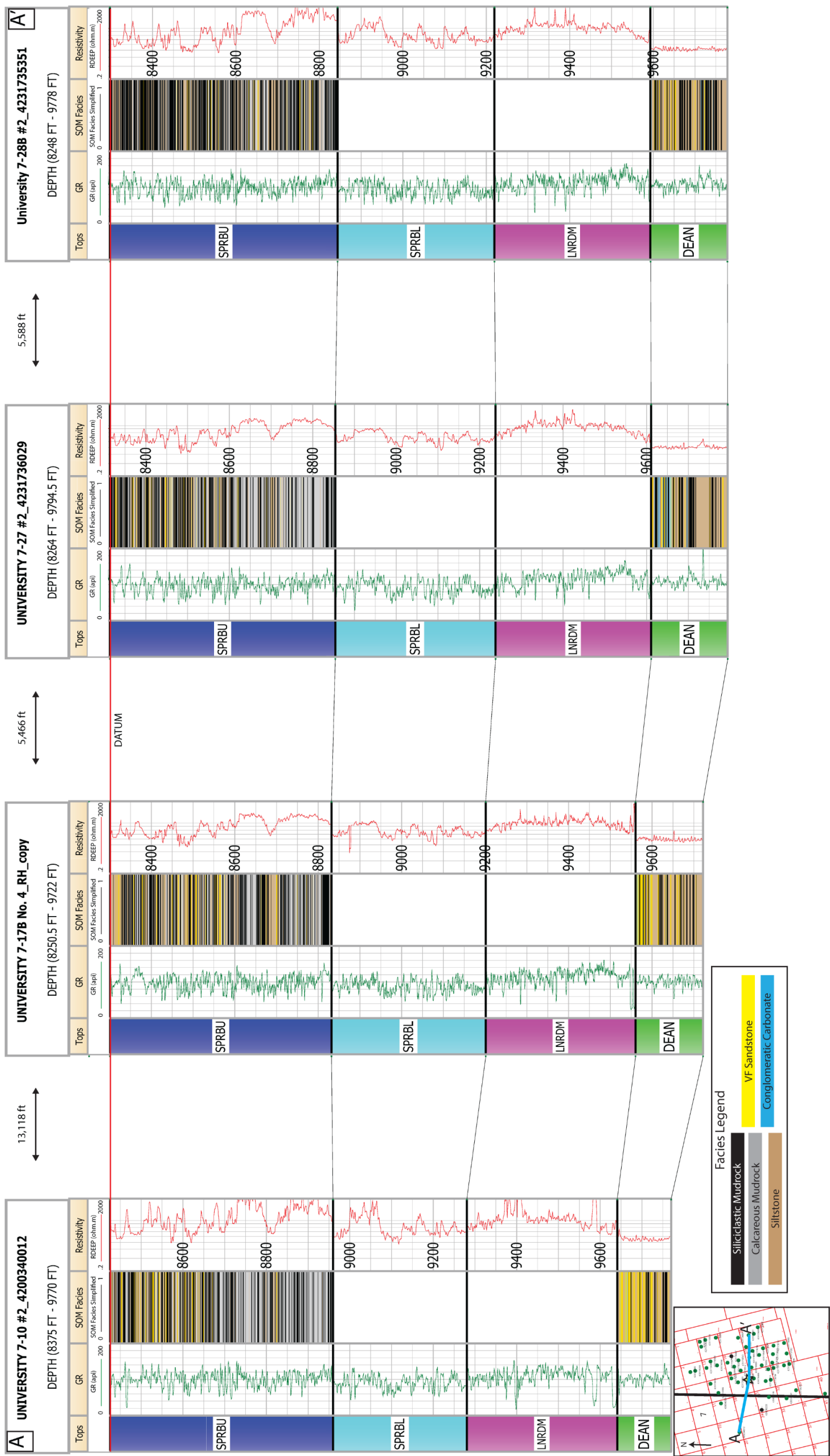


Figure 50. Strike oriented cross section illustrating gamma ray response, electrofacies, and resistivity response for Leonardian units in this study.

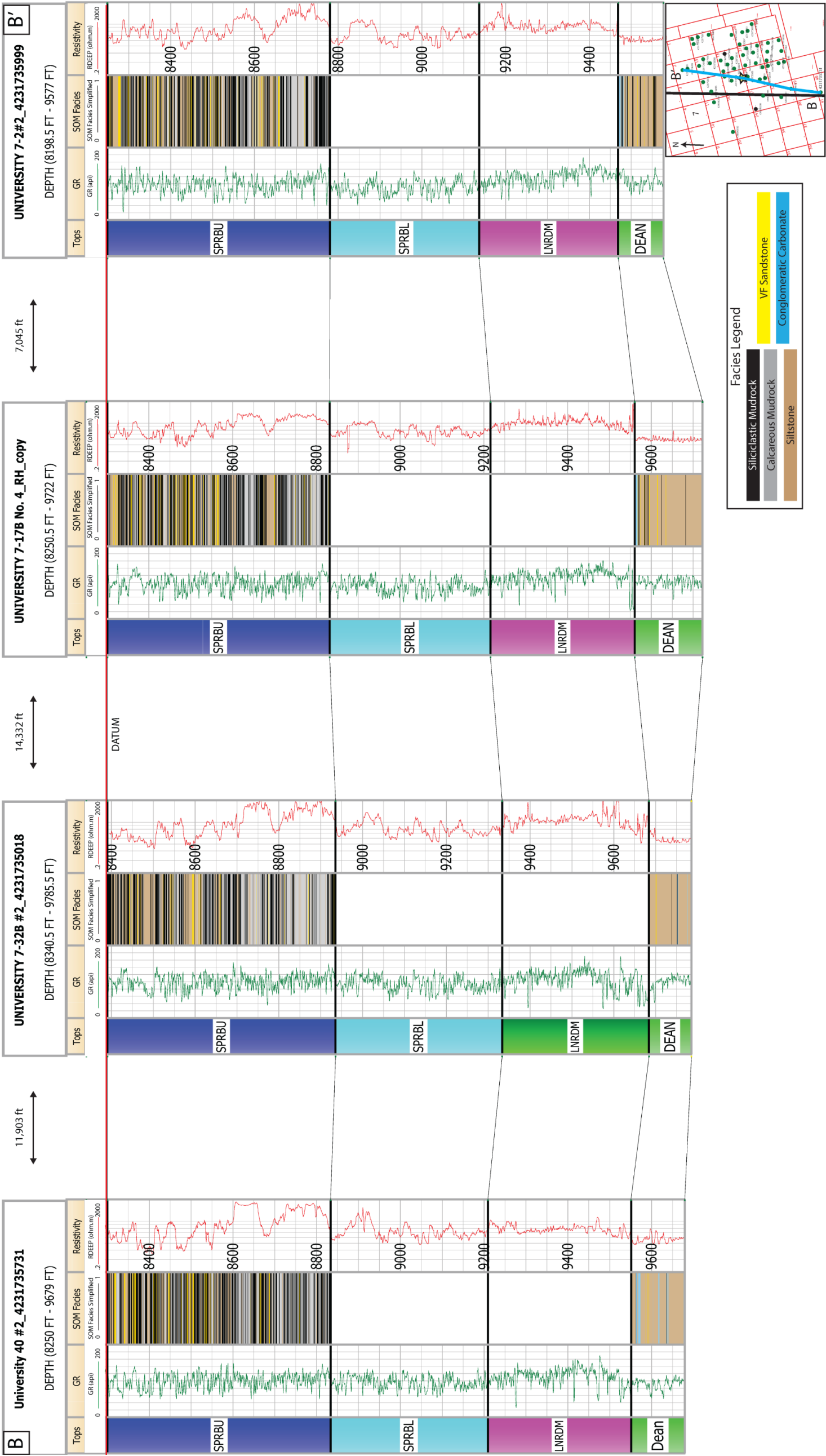


Figure 51. Dip oriented cross section illustrating gamma ray response, electrofacies, and resistivity response for Leonardian units in this study.

Formation and ending with the upper Spraberry Formation. In addition to the results discussed herein, Appendix D presents supplemental attribute maps, which illustrate subsea structural contours, clay volume, TOC content, total porosity, and water saturation for each interval.

Dean Formation

The Dean Formation, as well as overlying units, is generally distinguishable by resistivity log response (Figures 52-53). Within the study area, the Dean Formation exhibits a relatively flat resistivity profile consisting of low resistivity values; typically less than or equal to 10 ohm-m. The gamma ray signature of the Dean Formation appears relatively constant with minor bell shape (gradual increase in values) and funnel shape (gradual decrease in values) profiles (Figures 52-53). Unlike other units in this study, the gamma ray values for the Dean Formation occupy a narrow range between 75 api and 120 api.

Figure 53 shows that the Dean Formation thickens to the east while thinning to the west. Additionally, the Dean Formation appears to display a sinuous, channel-like feature in the central portion of the study area. Consequently, values of increased hydrocarbon pore thickness (Figure 55) appear to coincide with this channel feature as well as structural highs within the study area (Appendix D).

Middle Leonard Interval

In contrast to the Dean Formation, the middle Leonard interval is characterized by a serrated, cylindrical (relatively symmetrical increase and decrease) resistivity profile

Average Parameters	Dean Formation	Middle Leonard Interval	Lower Spraberry Formation	Upper Spraberry Formation
Gross Thickness (ft)	168.2	361.0	371.5	540.6
SoPhiH (ft)	0.8	8.8	5.6	11.2
Vcl (%)	19.3	19.8	13.8	14.9
TOC (wt%)	1.0	2.3	1.2	1.8
PhiT (%)	7.6	5.2	5.8	5.6
Sw (%)	86.3	52.0	69.9	59.3

Table 5. Average petrophysical results obtained during this study.

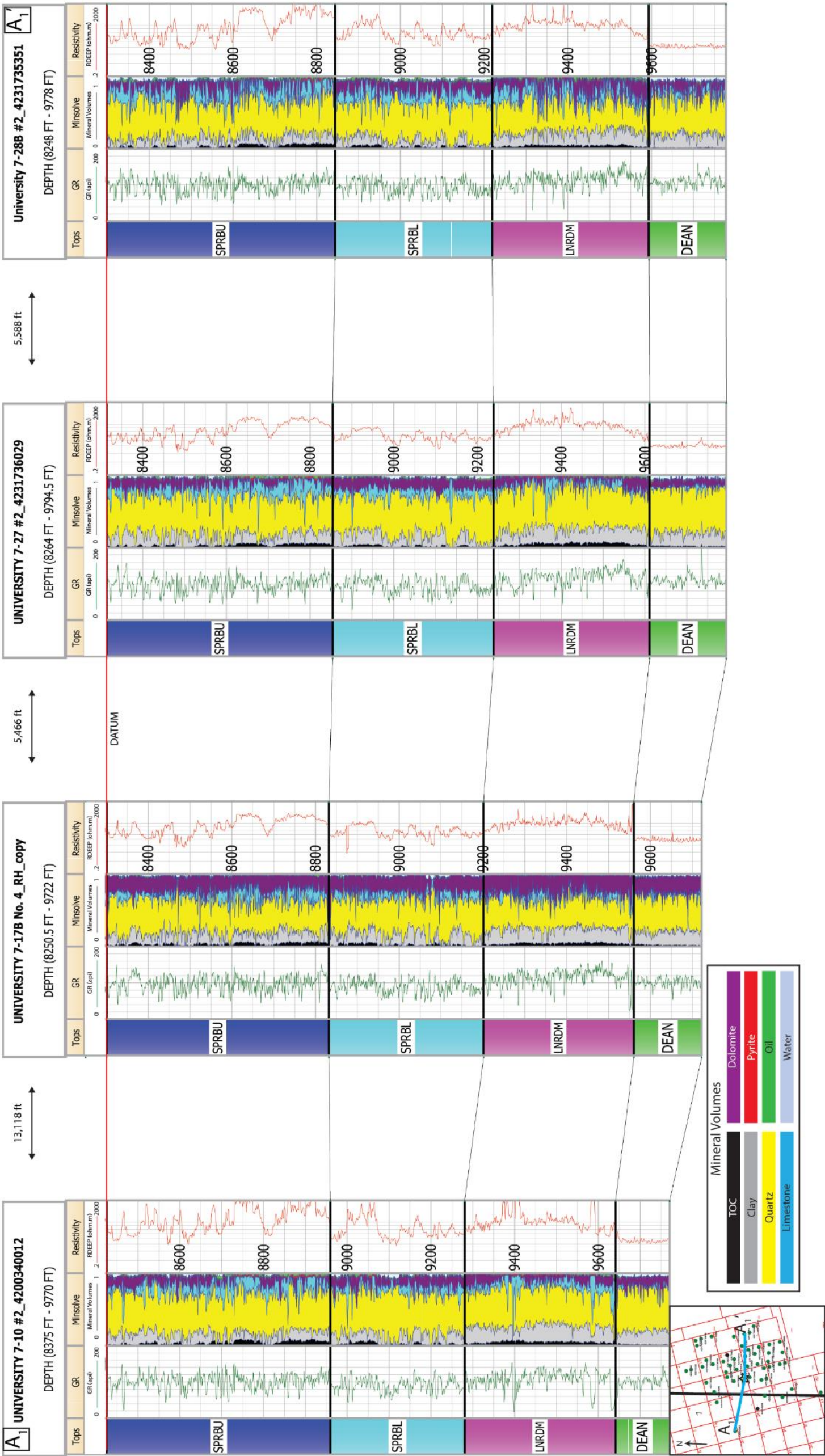


Figure 52. Strike oriented cross section illustrating gamma ray response, probabilistic mineral volumes, and resistivity response for Leonardian units in this study.

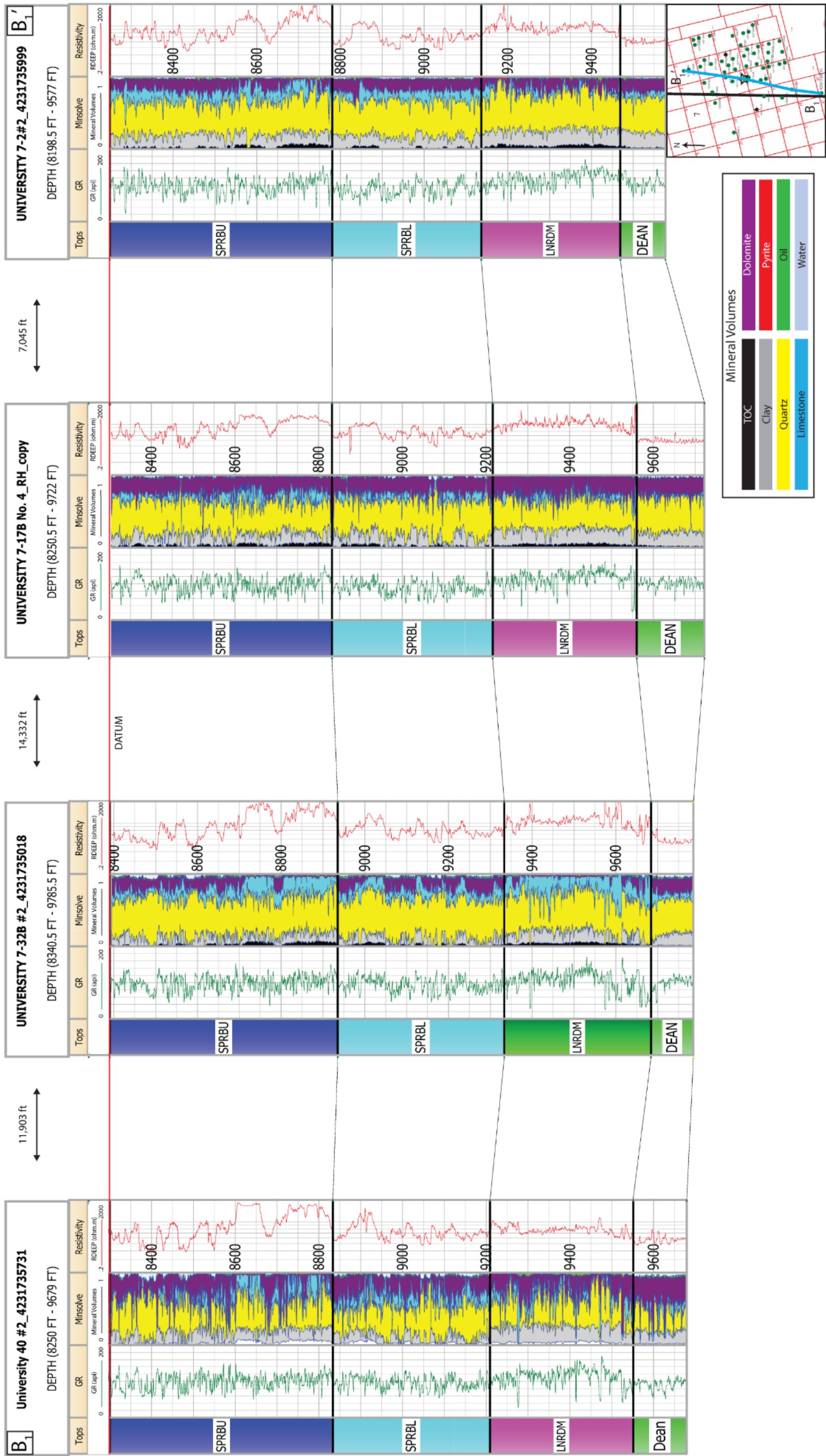


Figure 53. Dip oriented cross section illustrating gamma ray response, probabilistic mineral volumes, and resistivity response for Leonardian units in this study.

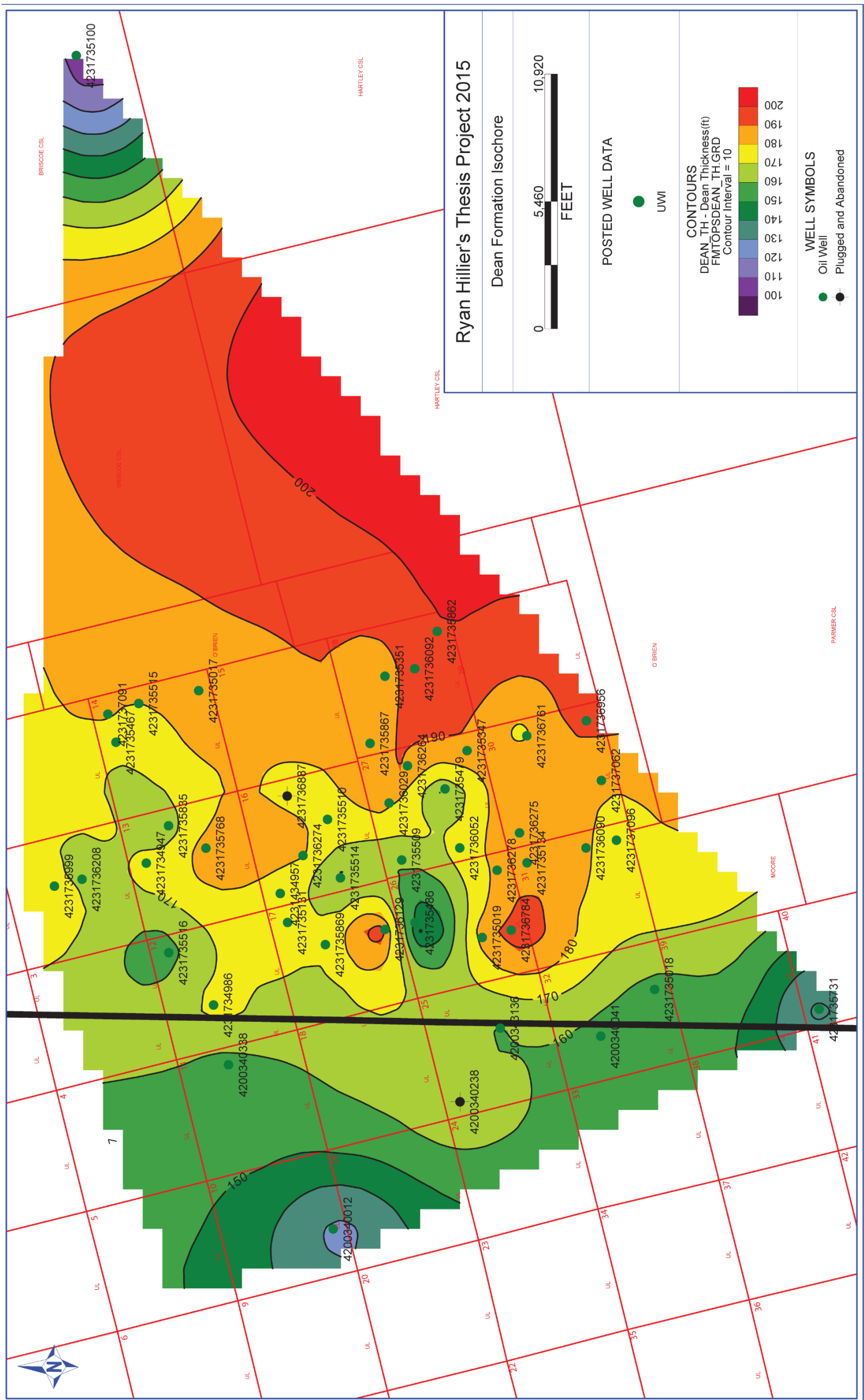


Figure 54. Equal thickness map of the Dean Formation

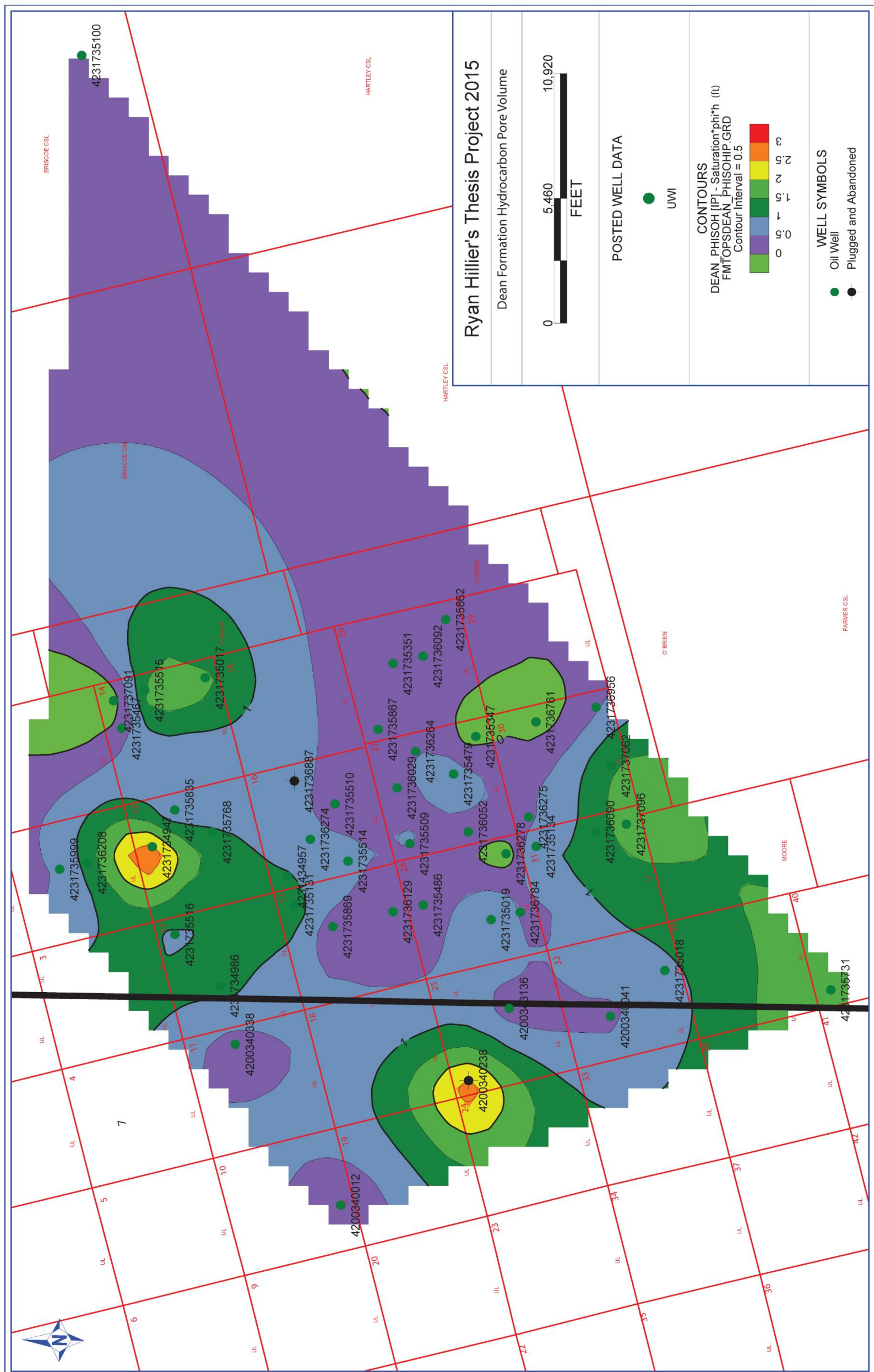


Figure 55. Map showing hydrocarbon pore thickness for the Dean Formation.

that generally ranges in values from 30 ohm-m to values in excess of 1000 ohm-m (Figures 52-53). The gamma ray signature of this zone is generally a broad funnel shape composed of smaller funnel profiles. In general, gamma ray values within middle Leonard interval are higher than underlying and overlying units (Figures 51-52). Maximum values exceed ~150 api near the base of the interval and minimum values are ~75 api near the top of the unit.

Within the study area, the middle Leonard interval appears to thicken from west to east (Figure 56) in a similar manner to the Dean Formation. Additionally, thicknesses contours display ~north-south trend, much like those of the Dean Formation. However, fluctuations in hydrocarbon pore thickness appear to trend northeast-southwest across the study area (Figure 57). Overall, this unit displays relatively high hydrocarbon thicknesses values compared to other Leonardian units in this study

Lower Spraberry Formation

Resistivity and gamma ray characteristics of the lower Spraberry Formation are noticeably different than those of the underlying middle Leonard interval. Resistivity curves in this unit commonly display a series of bell and funnel shapes throughout the interval (Figures 52-53). Typical resistivity values in this formation range from ~10 ohm-m to ~120 ohm-m. Additionally, the gamma ray profile of this formation is commonly blocky with minor funnel and bell shapes (Figures 52-53). Values for the gamma ray curve range between ~40 api and ~120 api within the lower Spraberry Formation.

The lower Spraberry Formation marks a change in direction of thickness contours from underlying Leonardian units. Contours in this interval show a pronounced northeast-

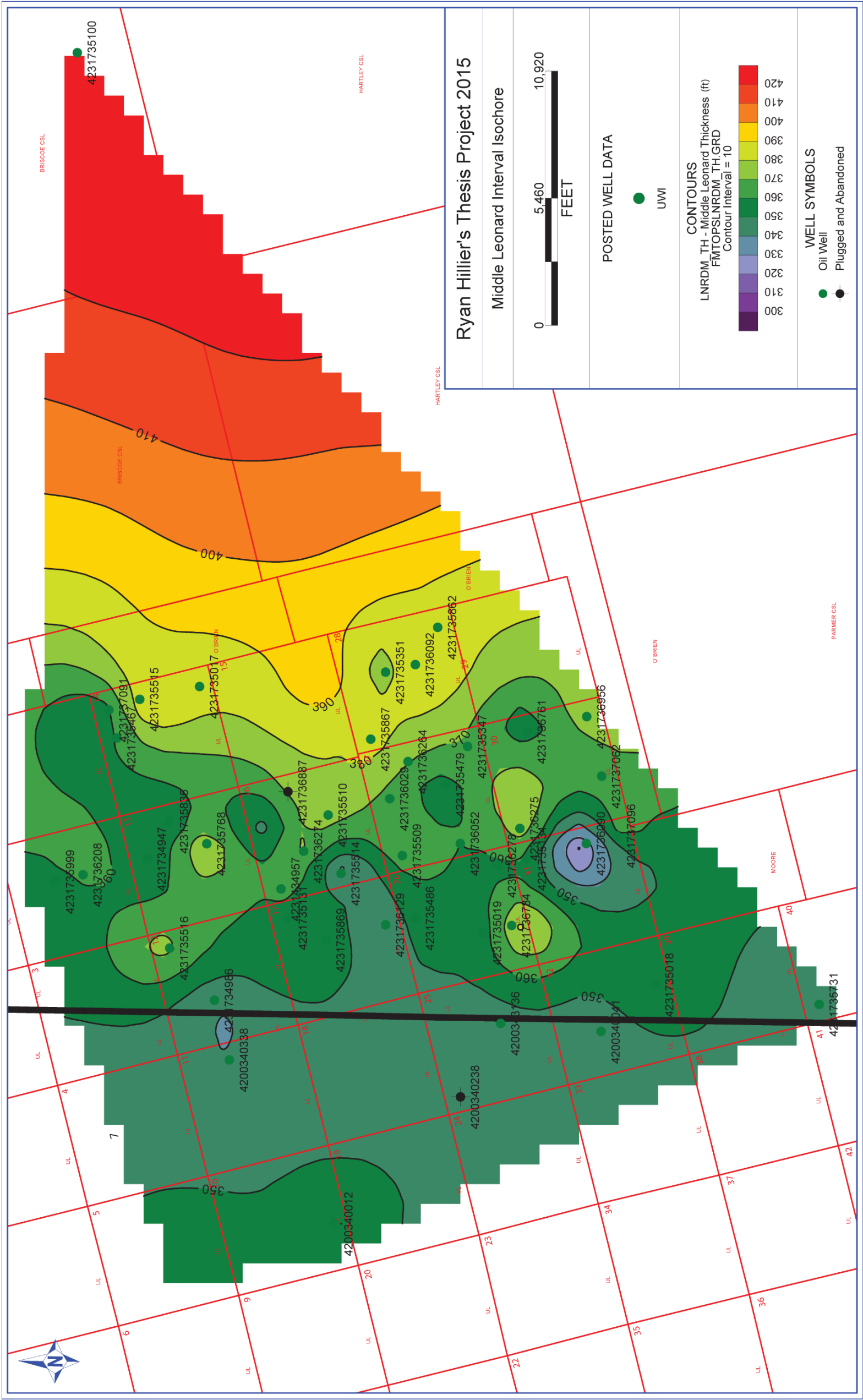


Figure 56. Equal thickness map of the middle Leonard interval

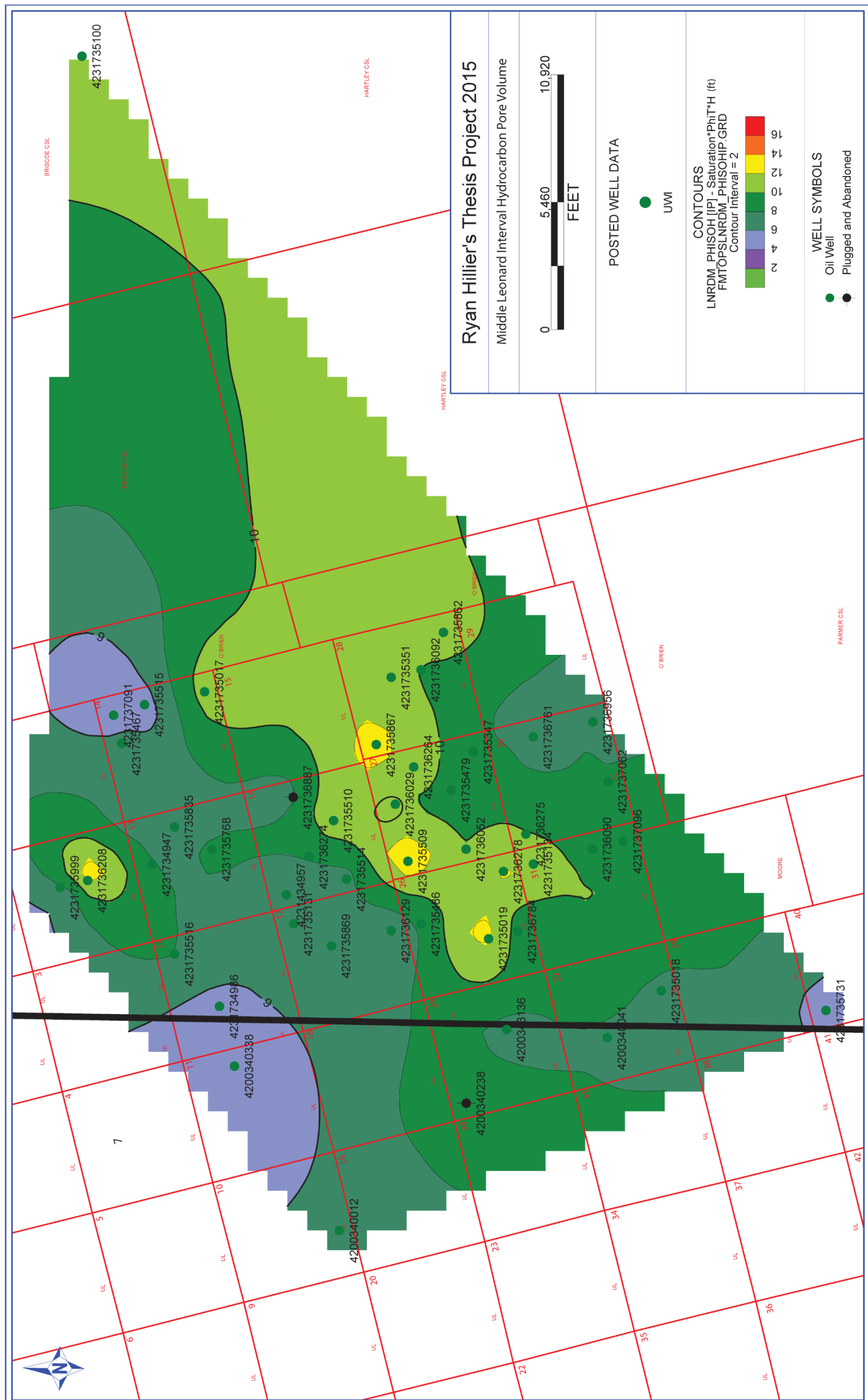


Figure 57. Map showing hydrocarbon pore thickness for the middle Leonard interval.

southwest trend that represents an overall thickening to the southeast, (Figure 58) In addition, there appears to be a sinuous thickness pattern in the central portion of the study area that contains isolated zones of increased thickness. Hydrocarbon pore thicknesses within this unit appear to fluctuate irrespectively to thickness contours (Figure 59).

Upper Spraberry Formation

The resistivity profile for this unit is very diagnostic (Figures 52-53). Two cylindrical zones are found near the base of the unit that often display minimum values of ~20 ohm-m and maximum values in excess of 2000 ohm-m. The resistivity profile of the upper half of this unit is generally serrated and ranges in values from ~10 ohm-m to ~130 ohm-m.

Within this unit, the gamma ray log typically displays a profile that distinguishes the lower and upper portions of this interval (Figures 52-53). The lower half of the upper Spraberry Formation often shows distinct cylindrical profiles. In contrast, the upper portion of the upper Spraberry Formation is characterized by a combination of funnel and bell shaped responses. Gamma ray values throughout the upper Spraberry Formation are typically between ~50 api and 150 api

The upper Spraberry Formation displays a thickness pattern that is unlike the other units in this study. Thickness values are quite consistent across the study area, except for the central portion of the study area (Figure 60). In this region, thickness contours form a bulbous feature that expands to the northwest. However, hydrocarbon pore thickness values do not appear to coincide with thickness patterns (Figure 61). Overall,

this unit displays higher hydrocarbon pore thickness values than any of the underlying units within this study.

Final Remarks

Of the units characterized in this study, the Middle Leonard interval and the lower ~200 feet of the upper Spraberry Formation display the most favorable petrophysical results (i.e., increased hydrocarbon thickness values, increased TOC content, and relatively low water saturation values). As such, these units would be considered the most likely unconventional reservoirs within this study.

Conversely, the Dean Formation and the lower Spraberry Formation are the least favorable target intervals within the study area. Both units display relatively high water saturation values, lower TOC content than other units, and relatively low hydrocarbon pore thickness values. However, the lower Spraberry Formation often displays a zone (~100 feet thick) near the top of the interval, that shows lower water saturation values and higher TOC values than the rest of the interval. This zone is a potential reservoir interval.

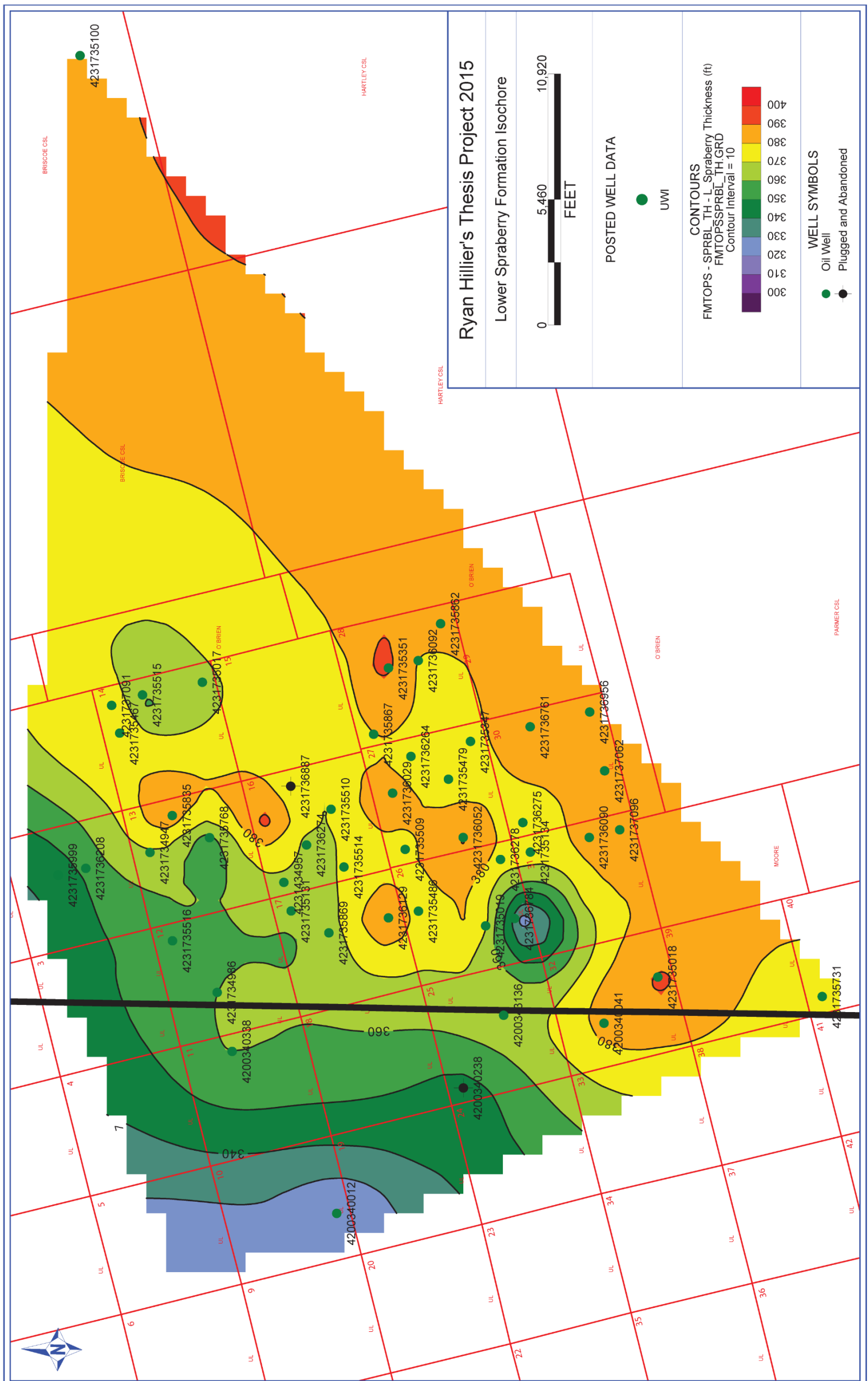


Figure 58. Equal thickness map of the lower Spraberry Formation.

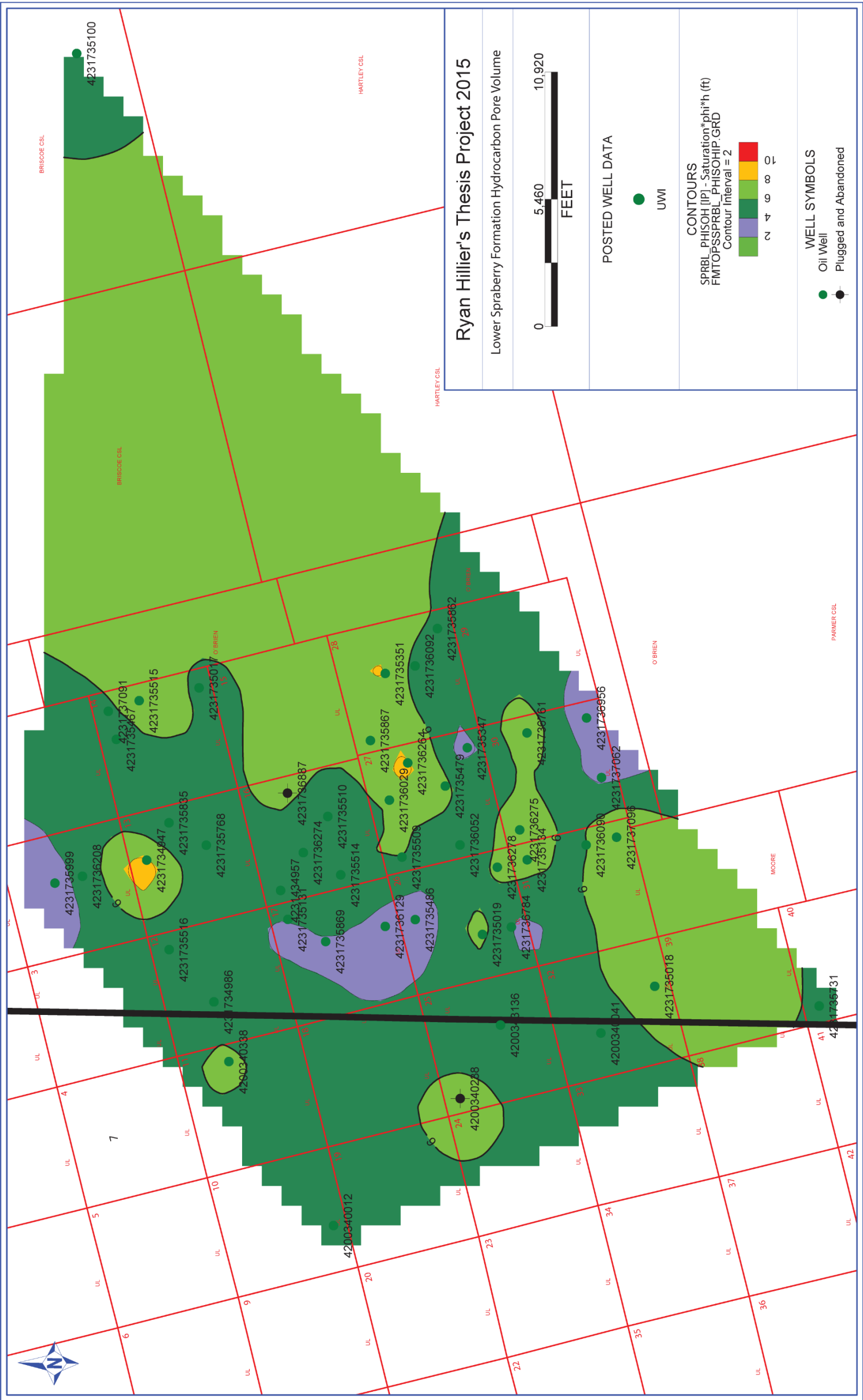


Figure 59. Map showing hydrocarbon pore thickness for the lower Spraberry Formation.

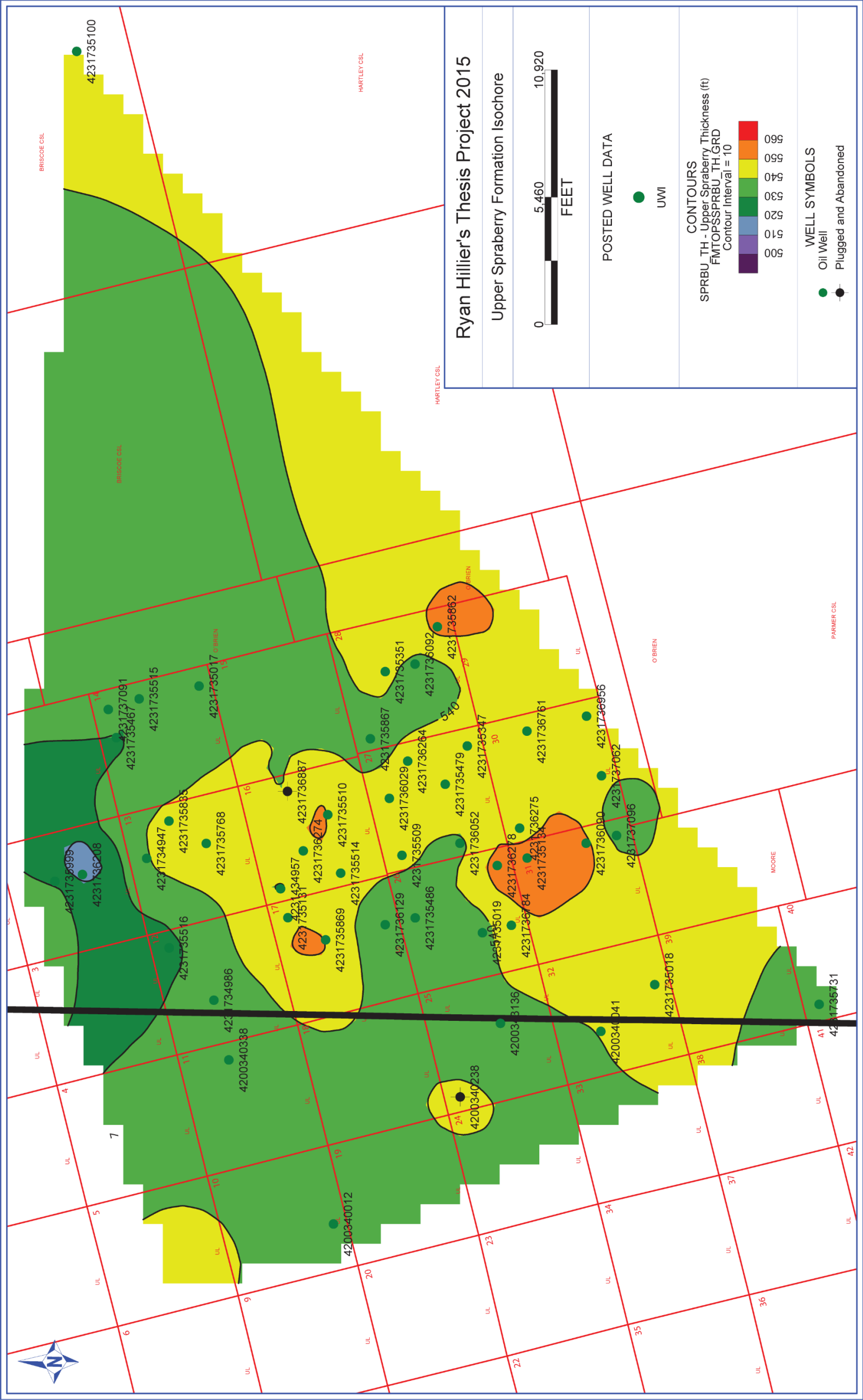


Figure 60. Equal thickness map of the upper Spraberry Formation.

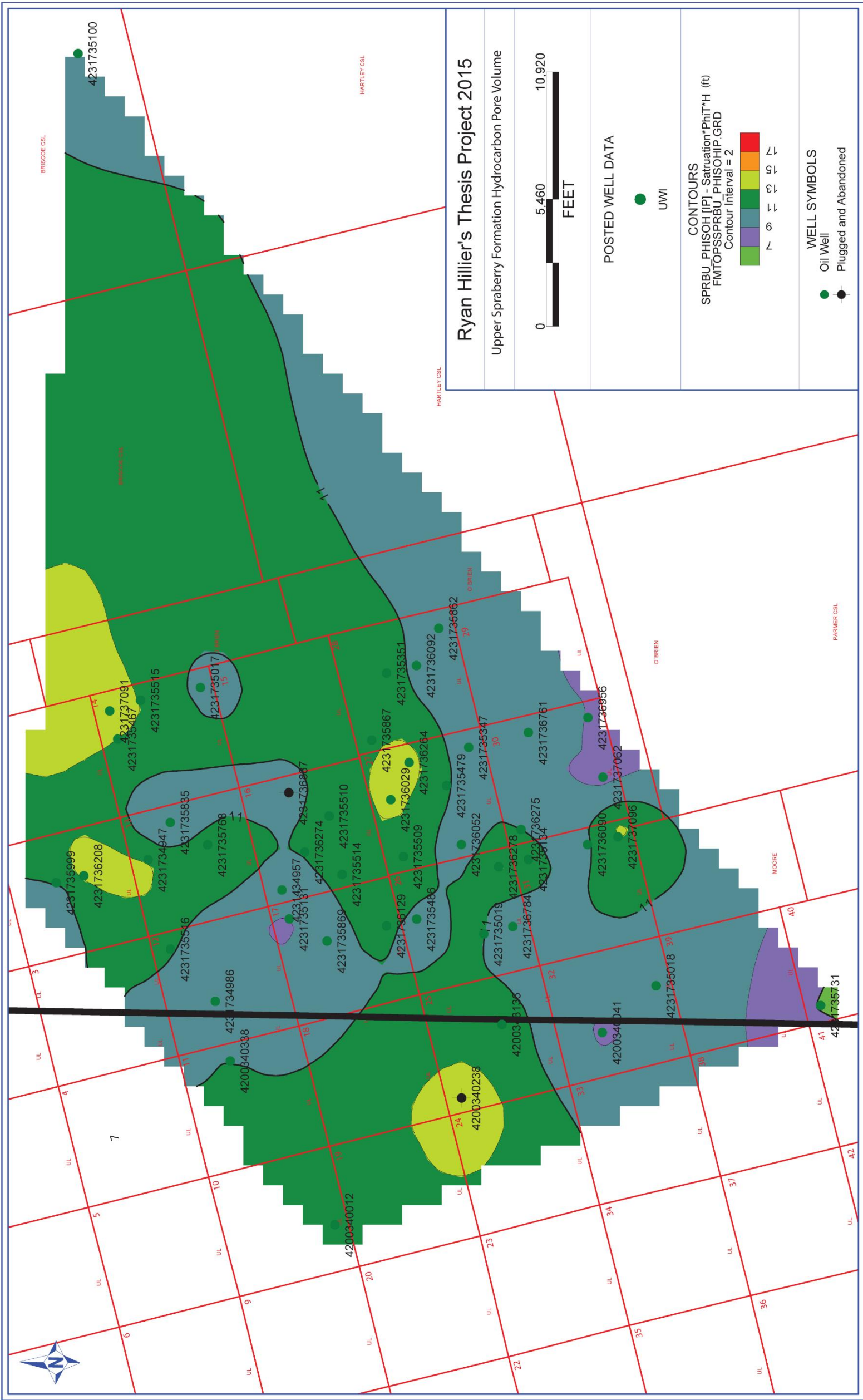


Figure 61. Map showing hydrocarbon pore thickness for the upper Spraberry Formation.

CHAPTER 6

SUMMARY AND FUTURE WORK

Summary

The overarching goal of this thesis was to evaluate the unconventional reservoir potential of Leonardian strata within the northern Spraberry Trend of the Midland Basin. By implementing data from two subsurface drill cores and 50 geophysical well logs, the author was able to estimate hydrocarbon pore thicknesses for the Dean Formation, middle Leonard interval, lower Spraberry Formation, and upper Spraberry Formation within the study area.

This was accomplished by assimilating a multifaceted approach that combined qualitative core descriptions, quantitative core analyses, deterministic petrophysical modeling, and probabilistic petrophysical modeling. Furthermore, the author: 1) characterized and mapped key petrophysical play drivers (Brooks and Montalvo, 2012) within the study area; 2) documented core-derived lithofacies; 3) integrated log-based electrofacies; and 4) documented well-to-well petrophysical heterogeneities throughout the study area.

Data from this study show that Dean-Spraberry strata contain hydrocarbons and represent potential drilling targets on a local scale. Individual reservoir intervals can be distinguished vertically from petrophysical log plots and laterally from attribute maps. Results from this study justify continued exploration of Leonardian strata on a regional scale within the northern Midland Basin.

Future Work

Petrophysical models and geologic interpretations from this research project could be further constrained by incorporating: 1) additional subsurface data; 2) quantitative laboratory and field-based sample analyses; and 3) risk assessments. A brief overview of these topics are discussed herein.

Additional Subsurface Data

Supplemental well log data could be used to characterize geomechanical properties and porosity values of target intervals. Within the study area, integration of dipole sonic logs (i.g., sondes that record both compressional and shear travel-times) would aid in determining geomechanical properties (e.g., Poisson's ratio and Young's modulus) and anisotropy (Brie et al., 1998) of Wolfberry strata. According to Brie et al. (1998) these components are crucial for reservoir development because they help predict formation strength, which can be used to improve well placement strategies and reservoir production.

Additionally, nuclear magnetic resonance (NMR) well logs could be used to obtain lithology independent porosities (Akkurt et al., 2008). Lithology independent porosity calculations would supplement porosities obtained from density, neutron, and sonic logs. Furthermore, NMR porosities would aid in distinguishing free-fluid, clay-bound water, and capillary-bound water within a given unit volume (Akkurt et al., 2008). These components could be used to further constrain volumetric models.

Laboratory Measurements

Water saturation calculations could be better constrained if electrical component analyses are conducted on drill core and/or cuttings samples, in addition to well-site water chemistry tests. Further laboratory and well-site measurements would provide supplementary controls on log-based water saturation estimations through the determination of Archie (1942) water saturation parameters: R_w , m , n , and a .

Moreover, subsurface well tests would further constrain fluid chemistry and flow rates (Aghar et al., 2007). These analyses would aid in determining *in-situ* fluid properties and volumetric expansion factors (Aghar et al., 2007). These data could be combined with hydrocarbon pore thickness data to calculate hydrocarbon-in-place values.

Risk Assessment

A Monte-Carlo uncertainty analysis could be used to validate results obtained in the study. This type of sensitivity analysis would document errors associated with individual petrophysical parameters used in deterministic and probabilistic models. Data obtained from this procedure could then be used to refine volumetric model inputs. Constrained inputs would provide more robust petrophysical models.

Lastly, economic factors could be combined with geological/petrophysical data to assign exploration risk (Rose, 2001). This procedure could be used to justify or negate future exploration within the Spraberry Trend. Ultimately, this type of evaluation would determine the overall unconventional reservoir potential of the Spraberry Trend within the study area.

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APPENDICES

APPENDIX A

SUPPLEMENTAL CORE DATA

X-ray Diffraction Analyses:

Quantitative Mineralogy:

To prepare the samples for X-ray powder diffraction analysis (XRD), a small portion of each sample (~1.6 g) was mixed with 1.0- μm corundum (Al_2O_3) internal standard in the ratio 80% sample to 20% corundum by weight. Each sample was then ground under acetone in a McCrone Micronizing mill (fitted with an agate grinding set) for 10 minutes. This produced a sample with an average particle size of less than 5 μm and ensured thorough mixing of sample and internal standard. The fine particle size is necessary to ensure adequate particle statistics and to reduce primary extinction and other sample-related effects (Bish and Reynolds 1989; Klug and Alexander 1974).

All diffraction patterns were collected on a Bruker D4 X-ray powder diffractometer using $\text{CuK}\alpha$ radiation and a Bruker VANTEC position sensitive detector, from $2-70^\circ 2\theta$, using $\sim 0.04^\circ$ steps, and counting for at least 1s/step. Samples were all back-pack mounted.

Mineral abundances were determined using FULLPAT, a quantitative X-ray powder diffraction (QXRD) program and method, originally developed in the Earth and Environmental Sciences Division at Los Alamos National Laboratory (Chipera and Bish, 2002; Chipera and Bish, 2013). FULLPAT matches entire patterns including the background, and utilizes a least-squares refinement to optimize the fitting of the library standards to the observed pattern. The advantage of FULLPAT over other QXRD methods is that amorphous components are now explicitly analyzed by fitting the entire background. FULLPAT no longer requires that the amorphous abundance be constrained as the difference from 100% (i.e. amorphous abundance = 100% - sum of phases abundances for the crystalline phases). Like the traditional RIR method but unlike the other full-pattern methods, all library standards and samples are mixed with corundum as an internal standard to compensate for matrix effects so that an unconstrained analysis can be made. Fitting of entire patterns alleviates many of the problems encountered with the traditional RIR methods of quantitative analyses (see Bish and Chipera, 1988; 1995 for a more complete discussion). FULLPAT has an advantage over the Rietveld method (Bish and Howard, 1988) in that the Rietveld method requires that a crystal structure be known for all the phases and that the phases all exhibit 3-dimensional order – which is not the case for most clay minerals.

Clay Mineral Analyses:

Clay mineral analyses are conducted by disaggregating an aliquot of sample suspended in de-ionized water with an ultrasonic probe for about 10 minutes. Sample is then

centrifuged to sediment out the larger than 1.0 μ m fraction. The <1.0 μ m fraction, which is still in suspension, is then vacuum filtered onto a silver-membrane filter. Samples are solvated overnight in an ethylene-glycol atmosphere inside of an oven held at 80°C and then X-rayed from 2–34°2 θ , using ~0.04° steps, and counting for at least 1s/step. Clay expandability is determined by comparing the patterns to calculated patterns generated by the NEWMOD computer program written by Robert Reynolds, Jr. Details of these analyses can be found in Moore and Reynolds (1989).

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XRD Data (Normalized to sum to 100 wt%) - University 7-17B #4														
Sample ID	Depth	Quartz	K-spar	Plagioclase	Apatite	Pyrite	Calcite	Dolomite	Total Wt%	Mixed Clays	Illite+Mica	Chlorite	Total Clays	Total
1	8607.3	43.8	4.3	18.3	0.8	0.4	11.0	12.6	91.2	0.6	7.7	0.5	8.8	100
3	8611.7	44.6	3.8	15.8	0.8	1.9	1.1	3.3	72.3	4.1	23.1	0.5	27.7	100
5	8614.6	56.4	3.0	12.0	1.0	1.7	1.3	2.6	78.7	3.1	17.8	0.3	21.3	100
7	8619.2	47.4	2.9	7.7	1.6	1.8	21.0	2.0	85.7	1.7	12.6	0.1	14.3	100
9	8623	54.6	2.6	10.5	0.4	2.4	2.5	2.7	77.6	3.4	18.5	0.5	22.4	100
11	8626.4	38.5	2.1	9.0	3.4	2.7	2.7	2.5	64.5	6.9	28.1	0.5	35.5	100
13	8629.8	39.4	2.7	11.0	1.2	1.9	11.6	3.7	74.8	3.3	21.4	0.5	25.2	100
15	8633	43.0	1.9	6.7	2.3	1.2	17.2	3.3	79.9	3.6	16.2	0.3	20.1	100
17	8637.3	47.2	3.5	11.7	2.1	2.4	2.4	3.0	74.8	3.9	20.9	0.5	25.2	100
19	8640.9	33.8	2.0	10.1	1.7	3.0	6.7	4.3	65.5	5.9	28.1	0.5	34.5	100
21	8644.8	41.5	2.5	8.8	0.5	2.3	0.9	2.9	64.9	4.6	30.0	0.5	35.1	100
23	8648.7	30.1	2.2	8.3	2.8	4.0	14.0	2.5	68.3	6.0	25.2	0.5	31.7	100
25	8653.4	40.9	2.0	7.4	1.0	2.8	11.5	2.5	72.0	4.1	23.9	0.0	28.0	100
27	8656.4	32.6	1.9	6.9	1.9	1.6	30.5	2.9	81.9	3.5	14.6	0.0	18.1	100
29	8660.6	29.0	2.7	11.2	5.8	3.3	4.0	4.2	62.9	5.3	31.3	0.5	37.1	100
31	8665.6	53.2	2.8	10.4	0.5	2.0	2.4	2.3	75.4	4.5	19.7	0.3	24.6	100
33	8667.8	34.7	2.7	12.2	0.8	0.5	35.6	1.7	88.6	2.3	9.0	0.0	11.4	100
35	8675.7	32.1	2.3	8.7	3.9	2.6	4.3	3.0	61.9	7.0	30.7	0.5	38.1	100
37	8678.2	44.4	2.3	11.5	0.4	1.3	18.4	2.7	81.6	3.7	14.6	0.0	18.4	100
39	8681.4	42.8	3.0	12.8	0.7	2.8	1.0	1.4	66.7	6.3	26.9	0.0	33.3	100
41	8683.2	57.6	3.1	12.7	0.8	0.5	2.2	11.4	88.6	2.8	8.5	0.0	11.4	100
43	8686.2	56.9	2.9	13.6	0.4	1.5	1.6	3.8	81.7	3.6	14.2	0.5	18.3	100
45	8688.5	51.6	3.2	15.9	0.6	1.1	1.8	4.1	78.8	2.5	18.4	0.3	21.2	100
47	8693.2	47.4	3.2	15.0	0.6	1.6	1.5	5.4	75.2	2.6	22.2	0.0	24.8	100
49	8696.6	45.6	3.0	15.3	0.5	1.3	1.6	8.7	76.2	2.8	20.9	0.0	23.8	100
51	8698.8	20.8	5.0	11.2	1.0	0.9	9.0	38.5	86.9	1.1	12.1	0.0	13.1	100
53	8700.6	56.4	4.5	16.7	0.6	1.2	2.1	2.1	84.4	1.2	14.2	0.3	15.6	100
55	8703.3	47.9	2.8	15.6	0.7	0.6	3.1	16.7	87.7	1.7	10.6	0.0	12.3	100
57	8706.6	49.7	3.3	15.9	0.7	1.3	2.0	3.9	77.4	3.6	19.0	0.0	22.6	100
59	8709.5	50.0	2.4	13.1	0.4	1.4	1.3	5.6	74.9	3.8	20.9	0.3	25.1	100
61	8712.9	55.2	2.9	11.6	0.6	1.0	6.0	2.2	80.3	5.0	14.4	0.3	19.7	100
63	8715.3	35.1	2.1	10.3	1.7	1.2	18.4	4.2	75.2	3.7	20.6	0.5	24.8	100

65	8719.2	44.0	3.3	11.5	0.7	1.7	1.9	2.5	67.1	6.8	25.7	0.5	32.9	100
67	8723	40.2	2.4	9.9	1.5	1.4	11.5	9.2	77.6	4.9	17.5	0.0	22.4	100
69	8726.8	32.0	3.3	7.4	10.7	3.4	2.4	3.8	66.4	9.6	23.8	0.2	33.6	100
71	8731	37.1	1.6	6.4	1.5	1.3	22.9	2.8	76.7	5.9	16.9	0.5	23.3	100
73	8734.4	43.3	2.1	9.5	0.7	4.2	2.8	2.9	68.0	8.8	22.6	0.5	32.0	100
75	8738.2	40.4	0.5	1.9	0.7	0.6	39.7	1.6	87.7	0.0	12.3	0.0	12.3	100
1	9567.9	6.6	1.5	3.9	1.0	0.3	46.9	33.2	93.7	0.0	6.3	0.0	6.3	100
4	9570.9	40.7	2.3	12.6	0.7	2.4	0.9	5.0	66.3	6.6	26.7	0.5	33.7	100
9	9575.9	49.3	2.6	12.6	0.5	1.6	1.3	4.3	73.0	2.6	24.0	0.5	27.0	100
22	9588.5	49.4	2.6	11.9	0.5	1.1	0.2	6.7	73.6	3.1	22.4	1.0	26.4	100
35	9601.1	42.7	2.4	11.3	0.8	1.5	0.3	5.1	64.9	5.6	28.5	0.9	35.1	100
53	9619.95	50.5	2.5	13.5	0.6	1.4	0.2	6.2	75.5	3.1	20.5	0.9	24.5	100
64	9630.3	18.9	1.5	5.0	0.7	1.1	0.0	56.8	84.8	1.7	13.0	0.5	15.2	100
74	9640.85	49.2	3.1	11.3	0.5	1.2	0.1	4.9	71.0	2.2	25.9	1.0	29.0	100
85	9651.3	16.7	2.8	6.4	0.7	0.6	0.5	57.8	85.6	2.6	11.2	0.5	14.4	100
89	9655.9	51.7	2.6	13.0	0.5	1.3	0.1	6.8	76.7	1.9	20.4	1.0	23.3	100
93	9659.9	49.5	2.4	13.1	0.5	1.4	0.3	5.6	73.4	2.9	22.5	1.2	26.6	100
97	9663.7	40.1	2.2	11.5	0.7	1.3	0.4	16.8	73.4	2.8	23.1	0.8	26.6	100
109	9675.2	39.8	2.4	10.1	0.4	1.9	0.1	5.4	61.8	4.8	32.5	0.9	38.2	100
120	9686.2	48.6	2.8	12.4	0.4	1.1	0.2	4.8	70.8	3.0	25.3	1.0	29.2	100
131	9697.8	50.4	2.8	12.6	0.4	1.1	0.2	5.7	73.6	2.1	23.8	0.5	26.4	100
138	9704.21	47.0	2.4	11.7	0.6	1.3	0.3	9.1	73.0	2.3	24.2	0.5	27.0	100
147	9713.70	17.8	1.9	5.8	0.9	0.5	0.0	57.1	84.2	2.6	12.8	0.5	15.8	100
156	9722.5	45.0	2.2	12.9	0.6	1.4	0.2	14.1	77.0	1.7	20.8	0.5	23.0	100
168	9734.6	46.3	2.6	10.9	0.4	1.7	0.3	5.8	68.9	2.7	27.5	0.8	31.1	100
178	9744.2	47.7	2.7	12.1	0.5	1.6	0.9	5.9	72.0	3.3	23.9	0.8	28.0	100
171	9751.8	48.3	2.6	13.1	0.6	1.8	1.4	6.8	75.3	2.5	21.2	1.0	24.7	100
173	9755.7	45.3	2.4	12.2	0.0	1.6	0.8	6.0	69.3	3.6	26.1	1.0	30.7	100
192	9758.9	46.2	2.7	12.0	0.4	2.3	1.1	5.0	70.5	4.4	24.1	1.0	29.5	100
175	9759.84	45.0	2.3	11.8	0.6	2.3	1.7	5.5	70.3	3.7	24.9	1.1	29.7	100
177	9763.86	47.9	2.6	12.3	0.8	1.8	2.1	7.2	75.4	3.4	20.0	1.2	24.6	100
179	9766.68	42.9	2.2	11.8	0.9	1.9	2.0	13.2	75.6	3.9	19.5	1.0	24.4	100
181	9769.72	42.7	2.8	10.5	0.8	2.9	0.4	3.0	65.0	5.5	28.3	1.2	35.0	100

Appendix A: XRD Data (Normalized to sum to 100 wt%) - Ralph Williams #4														
Sample ID	Depth	GRAND TOTAL	Non-Clay Total	Clay Total	Quartz	K-spar	Plag.	Apatite	Pyrite	Calcite	Dolomite	Illite/Smectite	Illite+Mica	Chlorite
1	7950.9	100	51.6	48.4	34.6	0.9	5.6	0.4	3.3	0.0	2.5	8.7	39.7	0.0
3	7955	100	91.7	8.3	6.1	0.2	3.1	0.6	0.7	71.5	8.8	0.0	8.3	0.0
5	7958.86	100	92.9	7.1	14.4	0.2	3.0	0.7	0.7	63.5	9.4	0.0	7.1	0.0
7	7963.28	100	85.4	14.6	12.7	0.1	3.3	0.4	0.8	39.7	27.5	0.0	14.6	0.0
9	7967.08	100	51.3	48.7	34.8	0.7	6.2	0.2	3.8	0.1	2.7	8.5	40.2	0.0
11	7971.26	100	51.0	49.0	35.9	0.3	4.6	0.0	3.1	0.0	2.4	8.8	40.2	0.0
13	7974.94	100	52.5	47.5	31.7	0.3	4.7	2.2	4.0	0.1	3.6	12.0	35.5	0.0
15	7979.2	100	55.6	44.4	36.6	0.6	6.0	3.1	3.2	0.0	2.3	8.9	35.5	0.0
17	7982.98	100	52.8	47.2	37.3	0.3	3.8	0.2	3.8	0.1	2.3	11.7	35.4	0.0
19	7987.26	100	59.1	40.9	40.1	0.2	4.9	0.0	3.4	0.0	4.9	9.9	30.9	0.0
21	7990.92	100	58.0	42.0	34.4	0.6	5.0	5.0	4.1	0.2	4.0	9.1	32.8	0.0
23	7994.64	100	72.9	27.1	28.7	0.4	5.3	14.2	3.8	8.0	8.0	3.4	23.7	0.0
25	7999.32	100	54.7	45.3	34.1	0.5	6.7	0.5	4.7	0.7	3.6	10.5	34.8	0.0
27	8003	100	49.9	50.1	31.6	0.7	5.5	0.1	4.0	0.0	2.5	8.4	41.7	0.0
29	8006.92	100	89.3	10.7	9.2	0.9	4.8	1.2	1.5	16.1	54.2	0.0	10.7	0.0
31	8520.8	100	65.1	34.9	37.8	0.4	4.3	3.0	2.1	10.0	2.9	6.2	28.4	0.3
33	8524.76	100	65.2	34.8	40.5	1.2	6.0	1.1	2.1	6.3	3.8	7.6	26.8	0.3
35	8529.08	100	54.9	45.1	37.2	0.5	6.0	0.3	3.1	1.7	3.2	5.6	38.9	0.5
37	8533.5	100	72.5	27.5	35.9	2.2	4.8	3.7	2.1	17.2	1.9	0.0	27.2	0.3
39	8536.92	100	57.1	42.9	38.9	0.4	5.8	0.3	3.0	0.0	1.8	3.2	39.3	0.3
41	8540.22	100	56.4	43.6	38.5	0.5	6.1	0.2	3.6	0.0	2.3	0.0	43.3	0.3
43	8545.16	100	66.4	33.6	35.5	0.2	5.9	3.2	2.8	12.1	2.6	3.2	30.2	0.2
45	8548.94	100	92.4	7.6	16.5	0.1	1.9	1.0	0.7	68.9	1.5	0.0	7.6	0.0
47	8553.16	100	47.9	52.1	32.2	1.1	5.6	0.2	3.5	0.0	0.7	3.6	48.3	0.2
49	8556.94	100	73.4	26.6	34.7	0.3	4.2	3.2	2.2	22.1	3.0	5.8	20.6	0.2
51	8561.58	100	67.3	32.7	33.3	0.4	7.0	1.7	3.2	14.0	3.0	2.7	29.8	0.2
53	8565	100	64.7	35.3	37.8	0.5	6.8	0.9	2.7	9.9	3.5	5.2	30.0	0.2
55	8569.7	100	51.7	48.3	34.1	0.5	7.6	0.1	2.9	0.1	2.2	6.6	41.0	0.6
57	8572.54	100	74.3	25.7	32.7	0.2	8.1	0.9	3.3	22.8	4.0	4.7	20.8	0.2
59	8576.3	100	67.5	32.5	47.5	0.6	7.7	0.2	2.4	3.2	2.6	5.0	27.3	0.3
61	9321.3	100	52.7	47.3	33.6	1.0	6.7	0.3	3.1	0.1	4.2	7.8	39.4	0.1

63	9323.8	100	69.4	30.6	50.5	0.8	7.6	0.5	2.7	2.2	3.1	4.4	26.1	0.2
65	9329.2	100	88.1	11.9	33.2	0.1	3.4	0.8	0.7	34.2	14.2	0.0	11.9	0.0
67	9332.9	100	93.7	6.3	27.5	0.2	2.2	0.4	0.7	59.4	2.6	0.0	6.3	0.0
69	9337.4	100	90.5	9.5	21.2	0.2	2.8	0.4	0.7	60.7	3.3	0.0	9.5	0.0
71	9341	100	96.5	3.5	11.0	0.2	1.6	0.6	0.2	80.8	1.7	0.0	3.5	0.0
73	9344.86	100	68.3	31.7	38.7	1.0	5.4	1.4	2.1	8.7	6.6	3.6	28.0	0.1
75	9348.36	100	64.3	35.7	47.4	1.3	6.3	0.2	2.9	0.3	3.0	4.8	30.7	0.2
77	9351.8	100	61.4	38.6	44.2	0.9	6.0	0.3	2.4	0.4	4.2	8.2	30.4	0.0
79	9354.54	100	93.7	6.3	4.8	1.1	3.0	1.4	0.3	9.6	72.8	0.0	6.3	0.0
81	9356.9	100	72.8	27.2	37.7	1.3	6.9	0.5	2.5	15.9	5.3	4.1	22.9	0.2
83	9359.6	100	66.2	33.8	48.7	1.5	8.3	0.2	2.3	0.6	3.3	5.5	28.1	0.2
85	9362.62	100	55.8	44.2	29.3	0.5	8.0	1.9	3.4	4.5	5.2	8.1	35.8	0.3
87	9366.3	100	59.7	40.3	35.0	1.1	9.1	0.4	2.8	0.2	9.2	6.6	33.5	0.2
89	9370.4	100	56.9	43.1	33.9	1.2	7.4	0.2	2.5	0.1	7.3	7.8	35.2	0.2
91	9374.5	100	65.8	34.2	42.7	0.5	7.5	0.6	2.8	4.9	4.3	6.1	27.8	0.3
93	9378.46	100	62.8	37.2	36.8	0.9	7.3	0.3	4.6	5.3	3.6	5.0	32.0	0.2
95	9381.7	100	93.7	6.3	13.2	0.1	2.3	1.4	0.8	72.8	2.3	0.0	6.3	0.0
97	9385.06	100	68.0	32.0	36.2	0.7	6.6	0.4	3.0	11.5	4.6	0.0	31.7	0.3
99	9389	100	63.4	36.6	43.9	1.2	6.8	0.3	2.7	0.8	3.6	3.3	33.0	0.3
101	9391.5	100	71.1	28.9	40.9	0.6	6.2	2.6	2.8	10.0	4.2	3.2	25.3	0.4
103	9395.74	100	65.0	35.0	39.0	0.7	8.6	0.8	2.2	4.9	5.1	4.1	30.6	0.3
105	9397.48	100	93.6	6.4	14.2	0.2	3.5	0.6	0.6	63.1	10.8	0.0	6.4	0.0
107	9400.6	100	67.4	32.6	45.2	1.4	7.5	0.4	2.5	3.0	4.2	3.0	29.4	0.3
109	9404.9	100	70.3	29.7	51.7	1.3	7.0	0.1	2.3	1.6	3.9	3.4	26.0	0.3
111	9407.1	100	73.4	26.6	36.6	0.6	7.6	1.0	1.6	15.1	6.2	3.8	22.7	0.2
113	9411.54	100	63.4	36.6	43.8	1.0	6.4	0.3	2.4	0.5	6.9	3.7	32.6	0.3
115	9415.12	100	57.4	42.6	29.8	0.9	7.6	1.8	3.5	2.4	5.8	4.8	37.5	0.3
117	9419.4	100	56.7	43.3	40.8	0.6	6.7	0.2	1.8	0.1	5.3	0.0	43.1	0.2
119	9423.26	100	60.2	39.8	43.7	1.1	7.6	0.2	2.9	0.3	3.1	5.7	33.8	0.3
121	9426.84	100	63.6	36.4	44.9	1.1	7.3	0.3	2.3	1.2	3.6	6.3	29.7	0.4
123	9430.6	100	54.5	45.5	40.5	0.7	6.4	0.2	2.6	0.1	2.3	5.3	39.9	0.3
125	9433.3	100	92.4	7.6	69.6	1.6	8.8	0.4	0.5	7.1	4.0	1.2	6.4	0.0
127	9435.36	100	95.9	4.1	9.6	0.3	2.1	0.2	0.1	4.4	79.0	0.0	4.1	0.0
129	9437.46	100	97.3	2.7	5.7	0.7	2.2	0.6	0.1	5.5	82.3	0.0	2.7	0.0
131	9439.7	100	97.5	2.5	10.0	0.6	2.0	0.4	0.0	6.0	78.1	0.0	2.5	0.0

Pyrolysis Data - University 7-17B #4									
vTPH (S1) = Volatile Total Petroleum Hydrocarbons (n TOC = Total Organic Carbon pTPH (S2) = Kerogen yield HI = Hydrogen Index cTemp = calculated temperature (Rock Eval) PI = Production Index tTemp = true temperature (Rock Eval temp + 39)									
SAMPLE ID	Depth	vTPH (S1)	pTPH (S2)	S1+S2	cTemp	tTemp	TOC	HI	PI
1	8607.28	0.63	0.66	1.29	433.9	472.9	0.25	266.13	0.488
3	8611.70	0.82	3.31	4.13	448.9	487.9	0.96	344.79	0.199
5	8614.64	1.09	2.27	3.36	444.0	483.0	0.61	369.71	0.324
7	8619.16	0.72	5.15	5.87	446.5	485.5	1.24	415.32	0.123
9	8620.00	2.73	7.97	10.70	445.4	484.4	1.89	421.69	0.255
11	8626.36	2.64	16.27	18.91	447.9	486.9	3.60	451.94	0.140
13	8629.80	2.25	14.17	16.42	447.1	486.1	3.24	437.35	0.137
15	8633.04	2.42	18.71	21.13	448.7	487.7	4.22	443.36	0.115
17	8637.28	2.70	10.05	12.75	445.6	484.6	2.48	405.24	0.212
19	8640.92	2.67	16.15	18.82	446.4	485.4	3.90	414.10	0.142
21	8644.80	3.91	25.01	28.92	446.2	485.2	5.37	465.74	0.135
23	8648.68	2.68	16.58	19.26	446.4	485.4	4.40	376.82	0.139
25	8653.44	2.43	16.01	18.44	447.9	486.9	3.71	431.54	0.132
27	8656.40	1.61	13.28	14.89	449.6	488.6	3.53	376.20	0.108
29	8660.60	2.10	11.44	13.54	447.3	486.3	2.81	407.12	0.155
31	8665.60	2.49	7.00	9.49	447.2	486.2	1.88	372.34	0.262
33	8667.80	0.82	1.51	2.33	440.8	479.8	0.49	311.34	0.352
35	8675.70	2.02	21.73	23.75	444.8	483.8	4.93	440.77	0.085
37	8678.16	1.19	2.61	3.80	436.8	475.8	0.65	404.02	0.313
39	8681.40	1.40	9.24	10.64	446.6	485.6	2.27	407.05	0.132
41	8683.24	0.84	0.95	1.79	436.9	475.9	0.27	347.99	0.469
43	8686.16	2.09	4.20	6.29	443.6	482.6	1.00	420.00	0.332
45	8688.46	0.81	1.52	2.33	442.6	481.6	0.46	330.43	0.348
47	8693.16	0.31	1.12	1.43	447.2	486.2	0.42	266.03	0.217
49	8696.64	0.15	0.40	0.55	444.4	483.4	0.21	193.24	0.273
51	8698.76	0.33	0.63	0.96	444.3	483.3	0.36	174.03	0.344
53	8700.64	1.29	2.55	3.84	445.0	484.0	0.79	324.02	0.336
55	8703.26	1.15	0.95	2.10	420.3	459.3	0.26	369.65	0.548

57	8706.60	1.23	2.08	3.31	443.2	482.2	0.62	334.41	0.372
59	8709.50	1.24	2.57	3.81	447.5	486.5	0.79	324.91	0.325
61	8712.86	1.01	2.87	3.88	446.8	485.8	0.86	334.89	0.260
63	8715.34	1.55	9.01	10.56	447.6	486.6	2.29	393.45	0.147
65	8719.16	2.38	7.05	9.43	448.5	487.5	1.67	422.16	0.252
67	8723.00	1.78	5.79	7.57	447.6	486.6	1.52	380.92	0.235
69	8726.82	2.80	13.35	16.15	447.7	486.7	3.37	396.14	0.173
71	8730.96	1.58	11.09	12.67	450.7	489.7	3.15	352.06	0.125
73	8734.42	3.00	9.39	12.39	447.1	486.1	2.60	361.15	0.242
75	8738.16	1.95	7.19	9.14	454.4	493.4	2.15	334.42	0.213
1	9567.90	0.92	0.62	1.54	415.8	454.8	0.28	222.22	0.597
4	9570.90	3.38	5.43	8.81	450.1	489.1	1.76	308.52	0.384
9	9575.90	3.13	3.10	6.23	430.3	469.3	0.80	387.02	0.502
22	9588.50	2.16	3.23	5.39	446.9	485.9	1.13	285.84	0.401
35	9601.10	3.01	3.14	6.15	434.2	473.2	0.87	359.27	0.489
53	9619.95	2.74	2.61	5.35	426.8	465.8	0.67	392.48	0.512
64	9630.30	1.01	1.60	2.61	446.2	485.2	0.81	198.27	0.387
74	9640.85	2.06	2.34	4.40	419.8	458.8	0.64	368.50	0.468
85	9651.30	0.11	0.12	0.23	444.7	483.7	0.17	71.43	0.478
89	9655.90	2.64	2.41	5.05	424.6	463.6	0.72	336.59	0.523
93	9659.90	2.42	2.32	4.74	421.8	460.8	0.65	359.69	0.511
97	9663.70	0.56	0.80	1.36	439.1	478.1	0.33	245.40	0.412
109	9675.20	1.83	4.44	6.27	453.0	492.0	1.73	256.65	0.292
120	9686.20	1.63	2.00	3.63	416.0	455.0	0.56	360.36	0.449
131	9697.80	1.92	2.26	4.18	423.1	462.1	0.55	407.94	0.459
138	9704.20	2.28	2.14	4.42	420.5	459.5	0.61	350.82	0.516
147	9713.70	0.12	0.13	0.25	444.4	483.4	0.17	77.38	0.480
156	9722.50	1.54	1.68	3.22	425.8	464.8	0.64	261.68	0.478
168	9734.60	1.19	2.11	3.30	451.2	490.2	0.92	230.60	0.361
178	9744.20	1.32	1.65	2.97	439.8	478.8	0.65	253.85	0.444
192	9758.85	1.11	1.88	2.99	448.9	487.9	0.81	233.25	0.371

Appendix A: Pyrolysis Data - Ralph Williams #4												
vTPH (S1) = Volatile Total Petroleum Hydrocarbons (mg/g)					TOC = Total Organic Carbon							
pTPH (S2) = Kerogen yield					S3 (CO2) = Amount of CO2 produced during pyrolysis of Kerogen							
cTemp = calculated temperature (Rock Eval)					HI = Hydrogen Index				OI = Oxygen Index			
tTemp = true temperature (Rock Eval temp + 39)					PI = Production Index							
SAMPLE ID	Depth	vTPH (S1)	pTPH (S2)	S1+S2	S3 (CO2)	cTemp	tTemp	TOC	HI	OI	PI	
Ralph Williams #4 SN 1	7950.90	3.08	15.86	18.94	0.46	445.3	484.3	4.27	371.255	10.768	0.1626	
Ralph Williams #4 SN 3	7955.00	0.87	1.52	2.39	0.47	434.9	473.9	0.76	199.397	61.656	0.364	
Ralph Williams #4 SN 5	7958.86	1.30	1.96	3.26	0.41	436.7	475.7	0.90	216.742	45.339	0.3988	
Ralph Williams #4 SN 7	7963.28	1.00	1.96	2.96	0.51	438.4	477.4	0.87	224.41	58.392	0.3378	
Ralph Williams #4 SN 9	7967.08	2.06	9.41	11.47	0.32	444.8	483.8	2.90	324.259	11.027	0.1796	
Ralph Williams #4 SN 11	7971.26	2.75	18.31	21.06	0.30	446.2	485.2	4.68	391.574	6.4157	0.1306	
Ralph Williams #4 SN 13	7974.94	3.39	22.32	25.71	0.45	445.4	484.4	5.71	391.03	7.8837	0.1319	
Ralph Williams #4 SN 15	7979.20	2.67	16.01	18.68	0.35	445.6	484.6	3.93	407.587	8.9104	0.1429	
Ralph Williams #4 SN 17	7982.98	3.07	18.87	21.94	0.30	444.7	483.7	4.99	377.853	6.0072	0.1399	
Ralph Williams #4 SN 19	7987.26	4.51	21.60	26.11	0.72	445.9	484.9	5.54	389.61	12.987	0.1727	
Ralph Williams #4 SN 21	7990.92	3.70	18.12	21.82	0.43	443.4	482.4	4.74	382.278	9.0717	0.1696	
Ralph Williams #4 SN 23	7994.64	4.92	17.14	22.06	0.70	442.1	481.1	4.70	364.914	14.903	0.223	
Ralph Williams #4 SN 25	7999.32	2.69	13.58	16.27	0.45	442.7	481.7	3.98	341.463	11.315	0.1653	
Ralph Williams #4 SN 27	8003.00	3.69	20.78	24.47	0.62	444.7	483.7	5.39	385.743	11.509	0.1508	
Ralph Williams #4 SN 29	8006.92	1.06	3.84	4.90	0.65	437.6	476.6	1.49	257.2	43.537	0.2163	
Ralph Williams #4 SN 31	8520.80	2.50	16.89	19.39	0.73	446.2	485.2	4.42	381.868	16.505	0.1289	
Ralph Williams #4 SN 33	8524.76	2.65	16.20	18.85	0.39	445.3	484.3	4.19	386.266	9.299	0.1406	
Ralph Williams #4 SN 35	8529.08	2.48	8.55	11.03	0.52	445.7	484.7	2.77	309.111	18.8	0.2248	
Ralph Williams #4 SN 37	8533.50	2.98	17.68	20.66	0.41	445.7	484.7	4.61	383.348	8.8899	0.1442	
Ralph Williams #4 SN 39	8536.92	4.70	26.07	30.77	0.31	446.2	485.2	6.91	377.225	4.4856	0.1527	
Ralph Williams #4 SN 41	8540.22	4.58	20.76	25.34	0.29	444.8	483.8	5.27	393.629	5.4987	0.1807	
Ralph Williams #4 SN 43	8545.16	3.26	15.04	18.30	0.37	444.4	483.4	3.99	376.754	9.2685	0.1781	
Ralph Williams #4 SN 45	8548.94	1.72	5.30	7.02	0.38	444.0	483	1.74	304.598	21.839	0.245	
Ralph Williams #4 SN 47	8553.16	2.85	16.22	19.07	0.30	447.4	486.4	4.43	366.305	6.7751	0.1494	
Ralph Williams #4 SN 49	8556.94	4.01	12.49	16.50	0.72	445.4	484.4	3.76	332.535	19.169	0.243	
Ralph Williams #4 SN 51	8561.58	2.52	17.62	20.14	0.41	445.9	484.9	4.58	384.548	8.9481	0.1251	
Ralph Williams #4 SN 53	8565.00	2.47	7.83	10.30	0.68	444.9	483.9	2.59	302.667	26.285	0.2398	

Ralph Williams #4 SN 55	8569.70	2.84	14.95	17.79	0.36	446.5	485.5	4.04	370.324	8.9175	0.1596
Ralph Williams #4 SN 57	8572.54	1.85	7.27	9.12	0.38	444.7	483.7	2.22	327.33	17.109	0.2029
Ralph Williams #4 SN 59	8576.30	2.90	11.18	14.08	0.39	446.3	485.3	3.09	361.929	12.625	0.206
Ralph Williams #4 SN 61	9321.30	1.72	10.05	11.77	0.16	449.2	488.2	3.71	271.255	4.3185	0.1461
Ralph Williams #4 SN 63	9323.80	1.57	4.37	5.94	0.22	444.3	483.3	2.01	217.629	10.956	0.2643
Ralph Williams #4 SN 65	9329.20	1.79	3.59	5.38	0.36	443.6	482.6	1.53	234.641	23.529	0.3327
Ralph Williams #4 SN 67	9332.90	0.69	1.59	2.28	0.41	442.2	481.2	0.78	204.003	52.605	0.3026
Ralph Williams #4 SN 69	9337.40	0.67	2.12	2.79	0.41	443.2	482.2	1.09	195.212	37.753	0.2401
Ralph Williams #4 SN 71	9341.00	0.22	0.29	0.51	0.37	435.3	474.3	0.30	97.4135	124.29	0.4314
Ralph Williams #4 SN 73	9344.86	3.38	13.24	16.62	0.22	447.3	486.3	4.37	302.767	5.0309	0.2034
Ralph Williams #4 SN 75	9348.36	2.56	8.11	10.67	0.15	447.8	486.8	3.05	265.814	4.9164	0.2399
Ralph Williams #4 SN 79	9354.54	0.37	0.79	1.16	0.60	439.2	478.2	0.67	118.317	89.861	0.319
Ralph Williams #4 SN 81	9356.90	2.22	6.96	9.18	0.35	446.2	485.2	2.79	249.821	12.563	0.2418
Ralph Williams #4 SN 83	9359.60	1.76	3.27	5.03	0.22	436.1	475.1	1.29	253.685	17.067	0.3499
Ralph Williams #4 SN 85	9362.62	2.28	7.07	9.35	0.23	445.9	484.9	2.87	246.084	8.0056	0.2439
Ralph Williams #4 SN 87	9366.30	1.66	4.76	6.42	0.37	443.5	482.5	1.96	242.486	18.849	0.2586
Ralph Williams #4 SN 89	9370.40	3.24	12.06	15.30	0.2	448.5	487.5	4.34	278.072	4.6115	0.2118
Ralph Williams #4 SN 91	9374.50	2.47	6.40	8.87	0.25	446.6	485.6	2.54	252.465	9.8619	0.2785
Ralph Williams #4 SN 93	9378.46	3.20	9.76	12.96	0.24	442.8	481.8	4.08	239.45	5.8881	0.2469
Ralph Williams #4 SN 95	9381.70	0.75	1.27	2.02	0.51	438.5	477.5	0.73	174.666	70.142	0.3713
Ralph Williams #4 SN 97	9385.06	4.22	14.74	18.96	0.36	446.8	485.8	4.78	308.626	7.5377	0.2226
Ralph Williams #4 SN 99	9389.00	3.73	11.50	15.23	0.19	446.3	485.3	4.01	287.069	4.7429	0.2449
Ralph Williams #4 SN 101	9391.50	3.30	10.04	13.34	0.35	445.8	484.8	3.77	266.384	9.2863	0.2474
Ralph Williams #4 SN 103	9395.74	2.69	9.96	12.65	0.37	447.6	486.6	3.62	275.062	10.218	0.2126
Ralph Williams #4 SN 105	9397.48	0.40	0.92	1.32	0.36	438.2	477.2	0.60	153.692	60.14	0.303
Ralph Williams #4 SN 107	9400.60	2.73	7.59	10.32	0.26	451.3	490.3	3.04	249.507	8.547	0.2645
Ralph Williams #4 SN 109	9404.90	2.41	5.95	8.36	0.26	445	484	2.43	244.655	10.691	0.2883
Ralph Williams #4 SN 111	9407.10	3.17	12.92	16.09	0.42	447.5	486.5	4.43	291.385	9.4723	0.197
Ralph Williams #4 SN 113	9411.54	1.91	4.69	6.60	0.27	443.6	482.6	2.03	230.58	13.274	0.2894
Ralph Williams #4 SN 115	9415.12	3.05	14.96	18.01	0.3	446.7	485.7	5.47	273.592	5.4865	0.1694
Ralph Williams #4 SN 117	9419.40	0.91	2.05	2.96	0.35	441.2	480.2	1.13	181.577	31.001	0.3074
Ralph Williams #4 SN 119	9423.26	1.06	2.75	3.81	0.26	435.9	474.9	1.26	218.427	20.651	0.2782
Ralph Williams #4 SN 121	9426.84	1.89	7.83	9.72	0.29	448.7	487.7	2.95	265.874	9.8472	0.1944

Appendix A: TRA DATA - University 7-17B #4 Well																					
Sample ID	Depth, feet	A-R		A-R minus		Dry										Expandable		Bound		Pressure-	
		Bulk Density	Density	Oil Density	Density	Grain Density	Porosity	Water Saturation	Gas Saturation	Mobile Oil Saturation	Gas Filled Porosity	Clay	Water	% of BV	Hydrocarbon Saturation	Clay	Water	% of BV	Clay	Water	Decay Perm
1	8607.28	2.640	2.685	2.686	2.690	2.690	2.0	12.2	85.5	2.3	1.7	0.3	0.4	1.2	0.000109						
2	8609.40	2.580	2.621	2.623	2.646	2.646	3.1	43.7	51.1	5.2	1.6	0.5	1.0	4.4	0.000098						
3	8611.70	2.575	2.626	2.627	2.664	2.664	4.1	51.7	46.4	1.9	1.9	0.7	1.3	4.1	0.000095						
4	8612.66	2.560	2.635	2.638	2.658	2.658	4.2	28.1	68.1	3.7	2.8	0.3	1.1	2.4	0.000060						
5	8614.64	2.565	2.627	2.631	2.669	2.669	4.8	45.0	48.6	6.3	2.3	0.5	1.0	3.0	0.000169						
6	8616.90	2.544	2.589	2.593	2.600	2.600	2.4	15.1	72.3	12.6	1.7	2.1	2.1	7.6	0.000120						
7	8619.16	2.624	2.648	2.649	2.664	2.664	1.9	47.4	48.3	4.3	0.9	0.3	1.4	1.7	0.000078						
8	8620.24	2.510	2.532	2.537	2.541	2.541	1.4	11.2	61.8	27.0	0.9	0.6	3.4	5.1	0.000131						
9	8623.00	2.552	2.634	2.640	2.649	2.649	3.9	11.4	78.7	9.9	3.1	0.5	2.1	3.7	0.000574						
10	8625.26	2.520	2.604	2.610	2.622	2.622	4.3	15.1	75.9	9.0	3.2	0.4	2.7	4.5	0.000562						
11	8626.36	2.516	2.576	2.590	2.614	2.614	4.5	26.9	51.4	21.7	2.3	0.4	2.9	4.8	0.000274						
12	8627.60	2.598	2.636	2.641	2.646	2.646	2.0	13.5	71.2	15.3	1.4	0.3	2.1	2.4	0.000169						
13	8629.80	2.534	2.604	2.613	2.623	2.623	3.8	13.0	71.2	15.8	2.7	0.4	1.8	4.2	0.000269						
14	8630.70	2.550	2.629	2.640	2.653	2.653	4.3	13.3	68.8	17.9	3.0	0.4	1.4	4.3	0.000390						
15	8633.04	2.500	2.542	2.555	2.570	2.570	3.4	22.0	49.0	29.0	1.6	0.1	3.3	2.9	0.000268						
16	8634.84	2.533	2.585	2.591	2.603	2.603	3.1	21.5	65.9	12.6	2.0	0.6	2.7	2.7	0.000475						
17	8637.28	2.543	2.590	2.596	2.610	2.610	3.0	26.0	61.0	13.0	1.8	0.6	2.6	4.3	0.000444						
18	8639.30	2.513	2.534	2.544	2.555	2.555	2.1	27.5	39.5	33.0	0.8	0.2	2.8	4.1	0.000118						
19	8640.92	2.514	2.568	2.582	2.600	2.600	4.0	23.1	52.6	24.4	2.1	0.2	2.8	5.2	0.000202						
20	8642.80	2.548	2.568	2.574	2.583	2.583	1.7	30.2	46.7	23.1	0.8	0.4	2.1	3.4	0.000167						
21	8644.80	2.425	2.473	2.496	2.513	2.513	4.4	17.6	43.4	39.0	1.9	0.0	3.3	5.4	0.000367						
22	8647.22	2.515	2.559	2.567	2.574	2.574	2.6	12.3	65.0	22.7	1.7	0.4	2.5	4.3	0.000101						
23	8648.68	2.492	2.561	2.571	2.581	2.581	3.9	12.8	69.4	17.8	2.7	0.6	3.2	5.3	0.000235						
24	8650.44	2.577	2.598	2.604	2.608	2.608	1.4	14.0	58.3	27.7	0.8	0.2	2.2	2.2	0.000181						
25	8653.44	2.521	2.560	2.569	2.580	2.580	2.7	20.8	57.1	22.1	1.5	0.5	2.7	4.6	0.000165						
26	8654.86	2.589	2.622	2.628	2.632	2.632	1.8	9.8	68.5	21.7	1.2	0.2	1.7	2.4	0.000169						
27	8656.40	2.550	2.579	2.583	2.588	2.588	1.6	14.1	67.5	18.4	1.1	0.4	1.2	2.9	0.000157						
28	8659.34	2.510	2.547	2.557	2.581	2.581	3.5	38.5	41.7	19.8	1.5	0.6	3.2	6.5	0.000212						
29	8660.60	2.583	2.622	2.629	2.650	2.650	3.1	36.6	47.5	16.0	1.5	0.6	2.2	5.9	0.000192						

30	8662.64	2.546	2.592	2.603	2.625	3.7	32.6	48.2	19.1	1.8	0.6	2.3	6.0	0.000410
31	8665.60	2.542	2.598	2.599	2.609	2.8	21.2	77.2	1.5	2.2	0.5	2.1	3.6	0.000441
32	8666.32	2.524	2.573	2.579	2.587	2.7	15.8	70.1	14.1	1.9	0.6	2.6	4.2	0.000222
33	8667.80	2.638	2.682	2.683	2.683	1.7	0.0	97.3	2.7	1.6	0.2	0.5	1.0	0.000063
34	8673.30	2.550	2.591	2.592	2.596	1.9	12.2	83.7	4.1	1.6	0.8	2.3	3.9	0.000270
35	8675.70	2.504	2.547	2.555	2.565	2.8	18.2	60.5	21.3	1.7	0.7	3.1	5.6	0.000146
36	8677.00	2.539	2.602	2.611	2.623	3.7	17.3	66.2	16.5	2.4	0.3	1.4	3.2	0.000088
37	8678.16	2.616	2.672	2.673	2.684	2.8	22.7	75.7	1.6	2.1	0.4	1.0	2.4	0.000064
38	8679.36	2.595	2.628	2.631	2.644	2.2	34.2	58.5	7.3	1.3	0.5	1.5	3.9	0.000154
39	8681.40	2.561	2.611	2.617	2.644	3.9	39.5	50.4	10.1	1.9	0.6	1.6	5.3	0.000276
40	8682.14	2.613	2.651	2.652	2.669	2.5	40.4	57.9	1.8	1.5	0.5	0.8	3.2	0.000057
41	8683.24	2.642	2.665	2.666	2.669	1.1	14.9	77.8	7.3	0.9	0.4	0.3	1.6	0.000067
42	8684.86	2.566	2.621	2.625	2.698	6.5	63.1	32.3	4.7	2.1	6.2	1.1	8.8	0.000613
43	8686.16	2.548	2.610	2.615	2.633	3.7	28.1	63.9	8.1	2.4	0.4	1.2	3.4	0.000068
44	8687.66	2.546	2.578	2.583	2.601	2.6	38.4	46.9	14.7	1.2	1.2	1.3	6.2	0.000234
45	8688.46	2.553	2.616	2.618	2.657	4.8	47.0	49.8	3.2	2.4	0.6	0.4	3.3	
46	8691.58	2.633	2.673	2.676	2.715	3.9	55.9	38.4	5.7	1.5	0.5	0.2	3.9	
47	8693.16	2.583	2.643	2.644	2.704	5.8	59.7	39.6	0.8	2.3	0.4	0.3	3.6	
48	8695.52	2.590	2.669	2.670	2.732	6.4	53.4	45.9	0.7	3.0	0.3	0.0	2.3	
49	8696.64	2.598	2.686	2.689	2.751	6.9	49.9	47.8	2.3	3.3	0.4	0.0	3.6	
50	8698.12	2.566	2.638	2.641	2.701	6.3	53.3	43.2	3.5	2.7	0.5	0.1	3.8	
51	8698.76	2.718	2.799	2.800	2.815	3.8	21.6	77.2	1.2	2.9	0.5	0.0	2.4	
52	8699.76	2.586	2.648	2.652	2.677	4.0	34.3	58.1	7.6	2.3	1.4	0.9	6.1	
53	8700.64	2.525	2.610	2.616	2.660	6.1	40.5	53.3	6.3	3.3	0.5	0.9	3.1	
54	8701.76	2.606	2.684	2.685	2.722	5.0	40.8	57.6	1.6	2.9	1.4	0.3	6.9	
55	8703.26	2.642	2.735	2.736	2.750	4.2	18.3	80.6	1.1	3.4	0.2	0.6	1.2	
56	8705.16	2.595	2.686	2.692	2.743	6.5	42.1	51.8	6.0	3.4	0.6	0.0	5.3	
57	8706.60	2.583	2.678	2.689	2.724	6.1	29.9	58.3	11.9	3.5	0.4	0.2	3.5	
58	8708.10	2.655	2.718	2.720	2.722	2.5	5.4	91.4	3.2	2.3	0.2	0.0	0.9	
59	8709.50	2.572	2.663	2.676	2.717	6.4	33.9	53.8	12.3	3.4	0.2	0.3	3.5	0.000491
60	8710.50	2.571	2.616	2.625	2.652	3.8	39.4	44.7	15.9	1.7	0.3	1.0	4.3	0.000231
61	8712.86	2.586	2.640	2.641	2.656	3.0	29.4	67.9	2.7	2.0	0.6	0.9	2.5	0.000231
62	8714.24	2.601	2.632	2.633	2.646	2.0	36.2	59.8	4.0	1.2	0.7	1.5	3.3	0.000094
63	8715.34	2.588	2.625	2.626	2.635	2.0	27.0	69.1	4.0	1.4	0.9	1.8	4.0	0.000113

64	8716.66	2.582	2.607	2.608	2.615	1.4	29.4	67.5	3.1	1.0	0.9	1.5	3.5	0.000168
65	8719.16	2.546	2.605	2.617	2.648	4.7	35.8	47.9	16.4	2.3	0.6	0.8	5.3	0.000413
66	8720.86	2.629	2.664	2.669	2.679	2.2	24.2	61.3	14.4	1.3	0.2	0.5	2.2	0.000201
67	8723.00	2.604	2.653	2.665	2.687	3.7	29.1	49.6	21.3	1.8	0.3	0.7	4.2	0.000292
68	8725.50	2.563	2.609	2.620	2.656	4.5	43.9	38.8	17.4	1.7	0.7	1.1	6.0	0.000230
69	8726.82	2.582	2.648	2.665	2.697	5.2	31.1	47.9	21.0	2.5	0.4	2.1	5.7	0.000278
70	8728.80	2.518	2.551	2.560	2.580	3.1	36.1	41.1	22.8	1.3	0.3	2.4	4.5	0.000197
71	8730.96	2.559	2.584	2.593	2.604	2.1	27.2	44.6	28.2	1.0	0.3	1.8	3.4	0.000125
72	8733.46	2.557	2.593	2.600	2.630	3.6	47.1	39.1	13.8	1.4	1.1	1.6	6.3	0.000182
73	8734.42	2.554	2.599	2.616	2.634	3.8	22.9	46.6	30.5	1.8	0.9	1.4	5.7	0.000410
74	8737.06	2.549	2.585	2.599	2.607	2.7	10.6	52.3	37.1	1.4	0.1	1.3	2.6	0.000204
75	8738.16	2.568	2.599	2.605	2.609	1.7	8.9	68.5	22.6	1.2	0.2	1.2	1.8	0.000145

Appendix A: TRA DATA - Ralph Williams #4 Well																	
Sample ID	Depth, feet	A-R		A-R minus		Dry		Porosity	Water Saturation	Gas Saturation	Mobile Oil Saturation	Gas Filled Porosity	Expandable		Bound	Bound	Pressure-Decay
		Bulk Density	Density	Density	Oil Density	Grain Density	gms/cc						% of BV	% of PV			
1	7950.9	2.448	2.474	2.486	2.600	6.27	69.00	16.86	14.14	1.06	1.04	0.91	7.13	0.000069			
3	7955.0	2.667	2.703	2.707	2.718	1.63	2.77	80.50	16.73	1.31	0.18	0.32	1.20	0.000066			
5	7958.9	2.654	2.697	2.704	2.714	2.14	6.30	74.74	18.96	1.60	0.29	0.22	1.13	0.000107			
7	7963.3	2.701	2.727	2.732	2.753	1.75	29.38	52.50	18.12	0.92	0.57	0.26	1.78	0.000065			
9	7967.1	2.504	2.536	2.544	2.648	6.36	70.82	19.64	9.54	1.25	1.48	0.08	8.07	0.000054			
11	7971.3	2.431	2.459	2.469	2.593	6.13	68.51	18.66	12.83	1.14	0.91	0.49	7.07	0.000153			
13	7974.9	2.422	2.459	2.472	2.605	6.32	61.21	23.50	15.30	1.48	1.10	0.25	6.73	0.000129			
15	7979.2	2.460	2.506	2.516	2.649	6.95	62.46	26.43	11.11	1.84	0.91	0.00	6.45	0.000127			
17	7983.0	2.440	2.490	2.501	2.623	6.62	56.59	30.09	13.32	1.99	1.03	0.33	6.81	0.000113			
19	7987.3	2.417	2.454	2.471	2.570	5.96	52.79	25.67	21.53	1.53	0.85	0.66	6.14	0.000154			
21	7990.9	2.447	2.480	2.495	2.631	6.38	62.10	21.22	16.69	1.35	1.05	0.08	5.83	0.000087			
23	7994.6	2.488	2.518	2.538	2.665	6.26	57.90	19.09	23.00	1.20	1.04	0.08	5.70	0.000077			
25	7999.3	2.492	2.528	2.539	2.657	6.24	64.39	22.98	12.64	1.43	1.20	0.00	6.63	0.000083			
27	8003.0	2.418	2.481	2.495	2.636	7.63	53.14	33.10	13.76	2.53	1.29	0.25	6.65	0.000151			
29	8006.9	2.716	2.771	2.776	2.818	2.94	21.23	67.26	11.51	1.98	0.75	0.09	2.11	0.000104			
31	8520.8	2.508	2.534	2.544	2.630	3.27	46.25	31.18	22.57	1.02	1.11	0.00	4.59	0.000175			
33	8524.8	2.500	2.541	2.552	2.637	3.87	38.10	41.73	20.16	1.61	0.99	0.00	4.75	0.000118			
35	8529.1	2.552	2.588	2.599	2.676	4.60	53.92	29.89	16.18	1.38	1.56	0.09	6.66	0.000095			
37	8533.5	2.517	2.555	2.567	2.637	3.31	28.05	45.30	26.66	1.50	1.20	0.34	3.42	0.000119			
39	8536.9	2.398	2.442	2.459	2.573	5.21	39.78	34.76	25.46	1.81	1.68	0.89	5.44	0.000111			
41	8540.2	2.418	2.466	2.483	2.535	4.58	29.67	41.89	28.44	1.92	1.39	2.70	6.32	0.000117			
43	8545.2	2.496	2.538	2.552	2.613	4.06	34.79	41.62	23.59	1.69	1.04	1.01	4.35	0.000138			
45	8548.9	2.616	2.644	2.652	2.659	1.61	0.64	66.45	32.91	1.07	0.29	0.62	1.64	0.000173			
47	8553.2	2.479	2.514	2.526	2.605	4.85	54.06	28.78	17.15	1.40	1.29	1.43	7.12	0.000130			
49	8556.9	2.530	2.576	2.594	2.626	4.02	25.58	44.71	29.71	1.80	0.93	1.29	3.82	0.000120			
51	8561.6	2.512	2.557	2.568	2.598	3.03	17.11	58.28	24.60	1.76	1.13	1.62	4.39	0.000081			
53	8565.0	2.552	2.589	2.599	2.647	3.83	44.06	36.60	19.34	1.40	1.24	0.61	5.68	0.000064			
55	8569.7	2.512	2.546	2.558	2.598	3.54	38.41	37.89	23.69	1.34	1.90	1.02	7.81	0.000118			
57	8572.5	2.596	2.630	2.638	2.668	2.76	32.96	46.54	20.49	1.28	0.52	0.50	3.47	0.000066			

59	8576.3	2.542	2.576	2.588	2.626	3.34	34.05	39.95	26.00	1.33	1.00	1.21	4.61	0.000071
61	9321.3	2.525	2.564	2.571	2.659	5.01	59.40	30.41	10.19	1.52	1.66	0.26	7.33	0.000052
63	9323.8	2.551	2.603	2.610	2.674	4.80	48.80	41.38	9.81	1.99	1.08	0.17	4.35	
65	9329.2	2.599	2.650	2.658	2.685	2.96	16.65	64.87	18.48	1.92	0.70	0.29	1.79	
67	9332.9	2.643	2.678	2.681	2.682	1.74	12.89	74.76	12.35	1.30	1.06	0.90	1.08	0.000056
69	9337.4	2.644	2.675	2.679	2.680	1.59	14.06	72.87	13.07	1.16	1.37	1.86	0.66	
71	9341.0	2.662	2.699	2.700	2.700	1.47	0.61	94.69	4.69	1.39	0.58	0.69	0.49	
73	9344.9	2.471	2.530	2.544	2.636	5.60	40.39	42.06	17.55	2.36	0.87	2.60	1.94	0.000116
75	9348.4	2.506	2.558	2.569	2.644	4.83	42.38	42.00	15.62	2.03	1.13	4.25	1.22	
77	9351.8	2.508	2.586	2.586	2.680	5.45	44.43	55.57	0.00	3.03	1.41	0.09	4.69	
79	9354.5	2.786	2.821	2.823	2.831	1.36	0.00	91.10	8.90	1.24	0.21	0.00	1.27	0.000063
81	9356.9	2.545	2.607	2.617	2.646	4.11	26.21	57.62	16.17	2.37	1.07	1.04	4.72	
83	9359.6	2.556	2.618	2.626	2.691	5.64	48.46	42.16	9.39	2.38	0.96	0.06	5.38	
85	9362.6	2.545	2.615	2.625	2.677	5.64	40.69	47.20	12.11	2.66	1.43	0.92	7.14	0.000120
87	9366.3	2.558	2.718	2.726	2.798	9.13	30.03	64.50	5.47	5.89	1.08	0.06	5.92	
89	9370.4	2.488	2.538	2.551	2.606	5.30	44.84	37.26	17.90	1.97	1.70	1.52	6.67	
91	9374.5	2.536	2.592	2.603	2.651	4.77	39.19	45.36	15.45	2.16	0.98	1.03	5.20	0.000118
93	9378.5	2.479	2.541	2.554	2.608	5.23	35.81	46.33	17.86	2.42	1.35	1.26	6.19	
95	9381.7	2.677	2.699	2.703	2.706	1.07	0.14	77.87	21.99	0.84	0.09	0.45	0.98	
97	9385.1	2.381	2.458	2.474	2.513	5.57	22.45	56.34	21.21	3.14	1.04	1.45	4.98	0.000238
99	9389.0	2.462	2.554	2.569	2.628	6.87	32.32	51.96	15.73	3.57	1.26	1.67	5.52	
101	9391.5	2.510	2.572	2.586	2.628	4.94	31.10	49.19	19.71	2.43	1.39	1.96	4.57	
103	9395.7	2.499	2.577	2.589	2.627	5.32	28.14	57.00	14.86	3.03	1.97	1.61	6.11	0.000101
105	9397.5	2.702	2.737	2.739	2.740	1.40	-1.82	92.74	9.08	1.30	0.07	0.59	0.23	
107	9400.6	2.510	2.560	2.572	2.619	4.80	42.29	40.93	16.78	1.97	1.70	1.13	5.83	
109	9404.9	2.515	2.560	2.570	2.609	4.20	40.82	42.19	16.99	1.77	1.77	0.79	5.38	0.000092
111	9407.1	2.494	2.526	2.538	2.568	3.42	36.56	36.26	27.19	1.24	1.11	2.03	4.23	
113	9411.5	2.545	2.597	2.605	2.662	5.15	50.22	38.68	11.10	1.99	1.79	0.54	6.40	
115	9415.1	2.485	2.541	2.554	2.607	5.60	44.61	39.47	15.92	2.21	1.63	1.96	6.28	0.000110
117	9419.4	2.558	2.611	2.615	2.703	6.57	64.61	31.23	4.17	2.05	1.53	0.16	6.88	
119	9423.3	2.547	2.594	2.599	2.677	5.80	63.55	30.98	5.48	1.80	1.39	0.32	6.10	
121	9426.8	2.500	2.560	2.567	2.638	5.74	49.93	40.39	9.68	2.32	1.85	0.42	6.22	0.000129
123	9430.6	2.547	2.588	2.591	2.696	7.25	75.72	21.72	2.56	1.58	1.27	0.13	6.61	
125	9433.3	2.481	2.567	2.568	2.647	7.82	56.30	42.96	0.75	3.36	1.69	0.00	2.54	

127	9435.4	2.763	2.856	2.856	2.856	2.869	3.86	15.08	84.41	0.51	3.26	0.53	0.08	0.59	0.000040
129	9437.5	2.793	2.874	2.876	2.887	3.45	15.18	81.39	3.43	2.81	0.39	0.16	0.39	0.39	
131	9439.7	2.732	2.830	2.842	2.857	4.50	7.73	76.78	15.48	3.46	1.32	0.23	1.40	1.40	

Appendix A: XRF Oxides (Normalized to sum to 100 wt%) - University 7-17B #4																			
Sample	Depth	SrO	ZnO	Fe2O3	FeO	Mn2O3	MnO	Cr2O3	TiO2	CaO	K2O	SO3	SO2	Al2O3	SiO2	MgO	P2O5		
336	8606	0.01	0.01	0.593	0.53	0	0	0	0.62	5.635	1.22	1.67	1.34	5.664	81.4	1.003	0.32		
335	8607	0.03	0	0.836	0.75	0	0	0	0.63	36.83	0.9	0.84	0.68	6.587	50.6	1.32	0		
334	8608	0.09	0	0.799	0.72	0.0419	0.04	0	0.45	8.148	1.12	1.57	1.25	5.412	79.47	0.894	0.2		
333	8609	0.05	0	1.327	1.19	0.0352	0.03	0.007	0.46	5.233	1.51	3.03	2.42	6.064	78.08	0.561	0.42		
332	8610	0.03	0	2.292	2.06	0.0473	0.04	0.013	0.47	12.07	1.4	2.91	2.33	7.05	68.09	1.199	0		
331	8611	0.04	0	2.123	1.91	0.0498	0.04	0.015	0.47	22.79	1.36	1.89	1.51	6.488	59.72	1.566	0		
330	8612	0.02	0	1.435	1.29	0.0214	0.02	0.011	0.49	0.541	1.76	2.03	1.62	7.365	82.82	0.573	0.19		
326	8613	0.02	0	1.493	1.34	0	0	0.012	0.52	14.09	1.42	2.33	1.87	6.991	68.1	1.812	0.17		
325	8614	0.01	0	1.297	1.17	0	0	0.018	0.73	21.69	1.65	2.91	2.33	9.085	57.69	1.42	0		
324	8615	0.02	0	2.226	2	0.0238	0.02	0.015	0.47	1.455	1.73	2.85	2.28	7.351	78.56	0.998	0.2		
323	8616	0.01	0.01	2.036	1.83	0	0	0.09	0.81	1.66	2.99	6.89	5.51	10.96	65.69	1.531	0.71		
322	8617	0.06	0	1.052	0.95	0.0172	0.02	0.045	0.27	52.66	0.54	1.84	1.47	3.865	33.23	3.988	0		
321	8618	0.1	0	0.826	0.74	0	0	0.02	0.27	48.22	0.34	2.33	1.86	3.264	39.4	2.61	0.98		
320	8619	0.09	0.01	0.707	0.64	0	0	0.024	0.32	30.8	0.8	4.86	3.89	4.019	53.84	0	0.54		
319	8620	0.03	0.02	1.95	1.75	0	0	0.094	0.86	16.12	2.44	7.01	5.61	9.589	52.83	1.691	0.74		
318	8621	0.02	0.01	3.947	3.55	0.0292	0.03	0.084	0.53	0.991	2.19	5.76	4.61	7.575	69.45	1.231	0		
317	8622	0.07	0	0.818	0.74	0	0	0.034	0.34	39.63	0.59	3.4	2.72	3.466	46.35	1.834	0.13		
316	8623	0.01	0	1.342	1.21	0	0	0.024	0.53	4.573	1.53	4.02	3.21	6.803	75.73	1.012	0.18		
315	8624	0.11	0.01	2.22	2	0.0513	0.05	0.035	0.37	39.22	1.05	3.88	3.1	4.488	42.1	1.312	0.53		
312	8625	0.01	0.03	2.345	2.11	0	0	0.097	0.98	2.21	3.24	6.71	5.37	11.64	64.05	1.23	0.12		
311	8626	0.01	0.05	1.598	1.44	0	0	0.07	0.97	1.612	3.3	5.62	4.5	14.56	65.07	1.201	0.34		
309	8627	0.05	0	0.949	0.85	0	0	0.047	0.41	63.52	0.48	2.22	1.78	3.811	25.87	0	0		
308	8628	0.06	0	1.993	1.79	0	0	0.039	0.45	18.13	1.45	4.52	3.62	5.454	61.27	1.21	0.67		
307	8629	0.04	0.01	2.769	2.49	0.0348	0.03	0.032	0.48	6.228	1.68	4.64	3.72	6.017	70.78	1.056	0.45		
306	8630	0.06	0	2.212	1.99	0.0285	0.03	0.026	0.42	12.64	1.33	3.76	3.01	5.074	68.14	1.278	0.51		
305	8631	0.01	0.01	3.167	2.85	0.0285	0.03	0.089	0.64	1.787	2.54	6.2	4.96	9.274	67.24	1.179	0.13		
304	8632	0.02	0.01	3.615	3.25	0.0286	0.03	0.07	0.52	1.938	2	6.02	4.82	7.682	68.94	1.065	0.1		
303	8633	0.12	0.02	2.021	1.82	0.0335	0.03	0.042	0.32	19.88	1.12	5.04	4.04	3.898	61.61	0	0.92		
302	8634	0.06	0	1.027	0.92	0	0	0.046	0.48	31.77	1.04	3.63	2.91	5.953	50.76	1.404	0.68		
301	8635	0.01	0	1.112	1	0	0	0.029	0.72	3.728	2.21	4.17	3.34	9.927	72.21	1.551	0.2		
300	8636	0.02	0	2.282	2.05	0.0309	0.03	0.018	0.42	2.168	1.44	4.05	3.24	5.579	78.14	0.525	0.22		
299	8637	0.02	0.01	4.195	3.77	0.0408	0.04	0.06	0.66	3.14	2.42	5.25	4.2	7.826	67.45	0.911	0.1		

298	8638	0.17	0.01	1.816	1.63	0.0734	0.07	0.023	0.2	60.91	0.46	1.72	1.38	2.418	27.52	1.608	0
297	8639	0.06	0.13	3.762	3.39	0.0376	0.03	0.053	0.59	7.928	2.08	5.95	4.76	8.087	61.99	1.157	3
296	8640	0.05	0	2.748	2.47	0.0364	0.03	0.032	0.49	8.835	1.82	3.86	3.09	6.771	68.86	0.909	0.45
295	8641	0.03	0.01	4.871	4.38	0.0397	0.04	0.044	0.58	4.03	2.12	7.36	5.89	7.768	61.38	1.463	0.97
294	8642	0.15	0.01	2.125	1.91	0.0349	0.03	0.027	0.3	22.57	1.07	4.23	3.39	4.541	57.62	1.987	0.63
293	8643	0.12	0.02	2.079	1.87	0.0392	0.04	0.025	0.34	15.76	1.15	5.5	4.4	4.345	63.31	1.011	0.66
292	8644	0.03	0	3.933	3.54	0.037	0.03	0.031	0.54	2.85	2.3	5.37	4.29	9.1	67	0.955	0.36
291	8645	0.02	0.01	4.554	4.1	0.0292	0.03	0.062	0.54	1.522	2.11	6.52	5.21	7.2	67.07	1.028	0.17
289	8646	0.2	0.01	0.914	0.82	0.0377	0.03	0.017	0.16	34.29	0.49	2.06	1.65	2.436	55.3	1.585	0.9
288	8647	0.01	0.02	1.755	1.58	0	0	0.055	0.85	2.456	3.22	7.74	6.19	11.67	63.4	1.046	0.17
286	8648	0.37	0	0.941	0.85	0.0357	0.03	0.024	0.17	31.85	0.56	2.46	1.97	2.268	57.26	1.212	0.59
285	8649	0.08	0	0.919	0.83	0	0	0.054	0.33	50.01	0.65	2.5	2	3.991	36.51	2.127	0.75
284	8650	0.03	0.01	4.553	4.1	0.0344	0.03	0.049	0.58	1.68	2.21	6.96	5.57	7.955	64.81	1.43	0.13
283	8651	0.04	0	1.516	1.36	0	0	0.04	0.53	42.28	1.4	3.63	2.91	7.479	38.8	0	0
281	8652	0.05	0	1.296	1.17	0	0	0.04	0.63	17.59	1.86	5.15	4.12	8.855	57.88	1.366	0.49
280	8653	0.02	0	1.462	1.32	0	0	0.076	0.66	2.341	2.34	5.51	4.41	8.434	71.82	1.611	0.22
279	8654	0.07	0	0.775	0.7	0	0	0.033	0.33	28.72	0.9	2.63	2.11	3.987	59.75	0	1.22
278	8655	0.06	0	0.674	0.61	0	0	0.018	0.24	36.12	0.47	3.41	2.73	3.382	51.1	1.182	0.67
275	8656	0.02	0.02	3.607	3.25	0.0375	0.03	0.068	0.53	3.003	2.28	6.13	4.91	7.646	67.89	0.578	0
274	8657	0.06	0	0.763	0.69	0.0445	0.04	0	0.37	29.67	1.3	1.3	1.04	3.972	59.93	0.815	0
273	8658	0.02	0.01	2.691	2.42	0.0279	0.03	0.029	0.49	2.466	1.85	4.03	3.23	7.102	74.98	0.626	0.08
272	8659	0.09	0	1.237	1.11	0.047	0.04	0	0.23	28.35	0.75	3.6	2.88	3.394	57.5	0.758	0
271	8660	0.05	0	1.693	1.52	0.0304	0.03	0.023	0.32	16.54	1.13	2.28	1.82	5.364	68.13	1.07	0.2
270	8661	0.04	0	1.313	1.18	0.0234	0.02	0.005	0.3	3.81	1.21	1.75	1.4	5.055	83.09	0.8	0.14
269	8662	0.08	0	0.89	0.8	0.0297	0.03	0	0.37	13.96	0.83	1.11	0.89	4.197	75.96	0.858	0
268	8663	0.03	0.01	2.195	1.97	0.03	0.03	0.02	0.48	2.087	1.66	3.64	2.91	6.896	76.82	1.215	0
267	8664	0.16	0	5.834	5.25	0.1688	0.15	0.024	0	60.28	0.32	1.22	0.98	1.808	14.21	9.587	0
266	8665	0.08	0	1.775	1.6	0.0416	0.04	0.013	0.3	26.24	1.05	2.19	1.75	4.772	60.16	0	0
265	8666	0.01	0	1.154	1.04	0	0	0.045	0.7	1.861	2.28	5.42	4.33	10.31	71.08	1.755	0
264	8667	0.06	0	0.946	0.85	0.0499	0.04	0.009	0.26	30.55	0.85	1.99	1.59	4.415	57.22	1.167	0
263	8668	0.07	0	0.734	0.66	0.0463	0.04	0	0.19	31.54	0.77	1.17	0.93	3.772	59.38	0.708	0
259	8672	0.13	0.01	1.944	1.75	0.0706	0.06	0.024	0.1	50.32	0.63	2.13	1.7	2.89	35.9	2.338	0
258	8673	0.05	0.01	2.268	2.04	0.039	0.04	0.028	0.41	19.98	1.47	2.83	2.27	6.508	61.07	0.991	0.23
257	8674	0.04	0	2.131	1.92	0.0327	0.03	0.026	0.44	8.25	1.63	3.28	2.62	6.674	71.63	1.303	0.69

256	8675	0.05	0.01	2.998	2.7	0.0388	0.03	0.044	0.49	13.51	1.89	8.14	6.51	7.166	55.29	1.151	1.18
255	8676	0.04	0.01	2.555	2.3	0.0331	0.03	0.039	0.43	9.874	1.7	4.02	3.22	6.931	67.44	1.376	1.75
254	8677	0.02	0	1.597	1.44	0.0242	0.02	0.012	0.4	7.351	1.21	2.17	1.73	4.464	79.07	0.482	0
253	8678	0.03	0	4.085	3.68	0.0314	0.03	0.035	0.73	5.295	2.95	7.53	6.03	9.795	59.78	0	0.73
252	8679	0.01	0.01	3.096	2.79	0.0266	0.02	0.04	0.61	2.139	2.27	7.55	6.04	8.386	66.3	0.725	0.55
251	8680	0.06	0	1.764	1.59	0.228	0.2	0.012	0.04	64.29	0.49	2.71	2.17	2.449	22.09	1.906	0
250	8681	0.01	0	0.384	0.35	0	0	0	0.49	3.357	1.36	1.47	1.17	6.254	84.2	0.97	0.47
249	8682	0.01	0.01	1.342	1.21	0	0	0.034	0.81	2.366	2.61	6.21	4.97	11.94	66.95	1.547	0
246	8683	0.02	0	1.93	1.74	0.0387	0.03	0	0.31	6.743	0.87	0.86	0.69	4.148	81.23	1.395	0.11
245	8684	0.01	0.01	1.843	1.66	0.0233	0.02	0.015	0.57	1.418	1.84	2.04	1.63	7.634	80.34	0.954	0.14
244	8685	0.02	0	1.818	1.64	0.0281	0.03	0.006	0.38	2.83	1.37	2.08	1.67	5.921	81.5	0.714	0
243	8686	0.02	0.01	1.77	1.59	0	0	0.027	0.73	5.248	2.13	4.43	3.54	7.918	72.59	0	0
242	8687	0.01	0.02	0.561	0.5	0	0	0	0.55	1.495	1.71	2.63	2.1	6.058	83.28	1.075	0
241	8688	0.01	0	1.445	1.3	0	0	0.018	0.8	2.443	2.95	3.59	2.87	11.38	72.11	1.09	0
239	8689	0.03	0.01	3.024	2.72	0.0322	0.03	0.024	0.6	2.051	2.48	4.04	3.23	10.01	70.96	0.757	0.42
238	8690	0.01	0	2.894	2.6	0	0	0.082	0.53	3.295	2.17	5.67	4.54	8.684	68.33	1.187	0
237	8691	0.03	0	1.783	1.6	0	0	0	0.65	15.42	1.47	1.42	1.14	6.767	69.72	0	0
235	8692	0.02	0	2.798	2.52	0.0342	0.03	0.015	0.62	3.101	2.41	4.01	3.21	10.5	69.34	1.405	0.16
234	8693	0.04	0	2.316	2.08	0.0344	0.03	0.012	0.57	3.845	1.78	2.64	2.12	8.29	74.74	1.493	0.34
233	8694	0.19	0	4.122	3.71	0.1362	0.12	0.02	0.16	44.52	1.12	3.35	2.68	4.205	23.42	12.26	0
232	8695	0.09	0	3.014	2.71	0.0816	0.07	0.009	0.28	7.385	1.1	1.64	1.31	4.881	77.42	0	0
231	8696	0.06	0	2.766	2.49	0.0591	0.05	0.007	0.31	9.03	1.11	1.67	1.33	5.123	74.39	1.598	0.1
230	8697	0.04	0	2.469	2.22	0.0466	0.04	0.01	0.53	5.926	1.55	2.77	2.21	6.975	74.12	1.091	0.38
229	8698	0.04	0	2.01	1.81	0.0211	0.02	0.012	0.76	4.065	1.98	5.31	4.25	6.972	72.74	0	0
228	8699	0.07	0	7.174	6.46	0.182	0.16	0.027	0.21	31.88	1.04	1.56	1.25	4.967	39.06	5.959	0
226	8700	0.01	0	1.051	0.95	0	0	0.022	0.89	1.495	3.04	3.44	2.76	13.17	72.1	1.07	0.19
225	8701	0.01	0	0.622	0.56	0	0	0	0.66	2.296	1.99	1.71	1.37	9.026	80.54	1.216	0
224	8702	0.01	0	1.523	1.37	0	0	0.023	0.91	1.676	3.25	3.68	2.95	12.34	70.58	1.685	0
223	8703	0.02	0	1.923	1.73	0	0	0.009	0.49	12.11	1.39	1.51	1.21	7.465	69.06	3.085	0
222	8704	0.03	0	1.511	1.36	0	0	0	0.53	12.75	1.3	2.4	1.92	6.96	69.33	1.902	0.11
221	8705	0.01	0	1.634	1.47	0	0	0.02	0.83	3.928	2.8	4	3.2	12.82	68.06	1.225	0.37
218	8706	0.01	0	0.983	0.88	0	0	0.013	0.79	4.85	2.44	2.94	2.35	11.88	71.47	1.396	0.21
217	8707	0.01	0	0.968	0.87	0	0	0.01	0.67	5.701	2.08	2.35	1.88	10.65	73.34	1.459	0
216	8708	0.02	0	1.781	1.6	0	0	0.013	0.49	14.19	1.31	1.32	1.05	7.206	67.53	3.485	0.7
215	8709	0.02	0	1.392	1.25	0.0086	0.01	0.016	0.57	6.037	1.79	2.61	2.09	8.275	74.58	1.361	0

214	8710	0.01	0.01	2.28	2.05	0.0242	0.02	0.019	0.54	2.537	1.94	2.79	2.24	8.094	76.71	0.73	0.75
213	8711	0.03	0.01	3.089	2.78	0.0305	0.03	0.035	0.68	4.376	2.45	4.62	3.69	9.664	67.09	1.432	0
212	8712	0.03	0	1.508	1.36	0.0211	0.02	0.01	0.4	1.229	1.41	2.11	1.69	5.746	83.76	0.704	0
211	8713	0.01	0.01	2.773	2.5	0.0286	0.03	0.021	0.54	2.918	1.83	5.01	4.01	7.747	71.67	0.914	0.29
210	8714	0.08	0.06	2.261	2.03	0.0536	0.05	0.016	0.45	26.63	1.45	3.08	2.47	6.064	54.56	0.754	0.33
209	8715	0.07	0	2.348	2.11	0.0581	0.05	0.024	0.39	28.77	2.08	2.3	1.84	5.392	53.7	0.869	0
208	8716	0.01	0.01	2.252	2.03	0.0211	0.02	0.02	0.48	1.963	1.72	3.11	2.49	7.354	77.03	1.495	0
207	8717	0.08	0.01	2.105	1.89	0.0493	0.04	0.024	0.35	29.16	1.18	2.82	2.26	5.214	54.08	0.744	0
206	8718	0.01	0	1.589	1.43	0	0	0.03	1.03	1.343	3.5	4.09	3.27	13.5	68.91	1.296	0
201	8719	0.02	0	2.146	1.93	0.0223	0.02	0.023	0.61	0.912	2.13	3.94	3.15	8.542	75.72	0.826	0.13
200	8720	0.03	0	2.202	1.98	0.0297	0.03	0.016	0.49	2.234	1.81	2.77	2.22	7.756	77.36	1.071	0
199	8721	0.04	0	2.559	2.3	0.0532	0.05	0.019	0.49	15.4	1.55	8.55	6.84	6.002	55.04	1.115	0.89
198	8722	0.05	0	3.624	3.26	0.0393	0.04	0.035	0.55	11.46	2.44	5.35	4.28	9.561	57.76	1.547	0.34
197	8723	0.04	0	3.281	2.95	0.0532	0.05	0.026	0.46	15.68	1.67	2.78	2.23	6.249	63.26	1.269	1.19
196	8724	0.02	0	3.683	3.31	0.0246	0.02	0.031	0.71	0.528	3.14	4.46	3.57	11.07	68.72	0.7	0.26
195	8725	0.02	0	2.607	2.35	0.0397	0.04	0.017	0.5	4.433	1.91	2.66	2.13	7.149	75.48	0.657	0
194	8726	0.02	0	2.588	2.33	0.0296	0.03	0.023	0.51	1.329	1.88	3.2	2.56	7.832	76.37	1.299	0
193	8727	0.12	0	0.949	0.85	0.0655	0.06	0.023	0.08	49.59	0.3	1.54	1.24	2.112	43.06	0	0
192	8728	0.15	0.01	1.122	1.01	0.0757	0.07	0.017	0	60.57	0.24	1.24	1	1.398	31.91	1.198	2.02
191	8729	0.05	0.01	2.573	2.32	0.0204	0.02	0.047	0.5	2.085	1.99	3.31	2.65	7.432	75.95	1.055	0.11
190	8730	0.06	0	3.29	2.96	0.0273	0.02	0.029	0.49	1.252	2.04	4.64	3.72	9.107	71.46	0.902	0.43
189	8731	0.09	0.01	1.943	1.75	0.0276	0.02	0.028	0.36	7.153	1.4	3.32	2.65	5.858	74.46	0.93	0
188	8732	0.13	0	1.575	1.42	0.0631	0.06	0.015	0.07	58.65	0.27	1.29	1.03	1.784	33.64	0	0
187	8733	0.13	0.01	1.206	1.08	0.0876	0.08	0.015	0	64.78	0.16	1.13	0.91	1.367	27.86	1.186	0.18
186	8734	0.02	0.02	3.164	2.85	0.034	0.03	0.023	0.52	1.456	2.01	4.43	3.55	8.88	71.81	1.203	0
185	8735	0.02	0	4.945	4.45	0.0416	0.04	0.044	0.6	2.862	2.32	6.32	5.06	6.739	65.37	1.179	0
184	8736	0.13	0	1.885	1.7	0.0798	0.07	0	0.04	66.36	0.27	1.25	1	1.697	25.51	0	0
183	8737	0.02	0.01	3.493	3.14	0.0369	0.03	0.019	0.53	6.089	1.98	3.79	3.03	7.555	69.54	0.739	0
182	8738	0.09	0	0.646	0.58	0	0	0.024	0.08	52.21	0.25	1.39	1.11	1.922	39.5	2.199	0
181	9568.00	0.022	0.004	1.576	1.418	0.077	0.069	0.028	0.000	72.213	0.154	1.096	0.877	2.955	11.877	7.640	0.000
180	9570.00	0.006	0.002	1.515	1.363	0.000	0.000	0.066	1.005	4.596	3.062	4.931	3.946	13.534	63.514	2.251	0.236
179	9572.00	0.012	0.003	2.353	2.118	0.031	0.028	0.015	0.643	2.362	2.089	2.675	2.141	8.647	75.480	1.287	0.118
178	9574.00	0.011	0.047	2.726	2.453	0.036	0.032	0.016	0.657	2.346	2.189	3.433	2.747	8.726	73.432	1.024	0.125
177	9576.00	0.008	0.001	1.432	1.289	0.000	0.000	0.021	0.791	3.520	2.491	3.900	3.120	11.582	70.067	1.631	0.154

176	9578.00	0.007	0.002	1.160	1.044	0.000	0.000	0.037	0.922	3.634	2.741	3.573	2.859	12.371	69.483	2.052	0.133
175	9580.00	0.007	0.002	1.192	1.073	0.000	0.000	0.021	0.886	4.569	2.636	2.665	2.133	12.566	69.668	2.475	0.116
174	9582.00	0.008	0.000	1.723	1.551	0.000	0.000	0.073	1.025	3.374	3.268	4.613	3.691	14.641	63.550	2.283	0.232
173	9584.00	0.018	0.003	2.255	2.029	0.037	0.033	0.012	0.589	3.482	1.778	2.488	1.991	7.327	76.644	1.197	0.117
172	9586.00	0.014	0.001	1.767	1.590	0.000	0.000	0.024	0.695	4.086	2.284	2.901	2.322	10.009	72.520	1.661	0.132
171	9588.00	0.008	0.000	1.471	1.323	0.000	0.000	0.029	0.896	4.191	2.764	2.653	2.123	12.441	69.726	2.235	0.152
170	9590.00	0.007	0.000	1.591	1.431	0.000	0.000	0.052	0.889	2.592	2.786	3.410	2.729	11.345	71.327	1.635	0.226
167	9592.00	0.016	0.038	2.429	2.186	0.036	0.033	0.011	0.605	2.206	1.983	1.883	1.507	7.976	77.357	1.514	0.221
165	9594.00	0.015	0.002	2.333	2.099	0.032	0.029	0.014	0.605	2.771	1.799	2.710	2.168	8.113	75.430	1.624	0.258
164	9596.00	0.019	0.009	2.974	2.676	0.043	0.038	0.016	0.668	2.775	2.375	2.554	2.044	9.475	72.605	1.554	0.177
162	9598.00	0.021	0.003	4.770	4.292	0.090	0.080	0.019	0.583	11.235	1.822	2.167	1.734	8.263	62.314	2.607	0.000
161	9600.00	0.017	0.004	2.864	2.577	0.040	0.036	0.014	0.609	2.756	1.840	2.801	2.241	7.621	75.007	1.366	0.206
158	9602.00	0.017	0.006	3.234	2.910	0.039	0.035	0.030	0.660	2.266	2.282	3.867	3.095	9.277	70.563	1.516	0.203
157	9604.00	0.016	0.005	2.451	2.206	0.032	0.029	0.029	0.820	2.674	2.716	3.066	2.454	10.757	71.108	1.405	0.238
156	9606.00	0.025	0.002	2.587	2.328	0.038	0.035	0.016	0.617	2.747	1.780	2.141	1.713	7.310	77.261	1.215	0.186
155	9608.00	0.017	0.002	2.294	2.064	0.039	0.035	0.010	0.583	2.828	1.755	1.491	1.193	7.424	78.529	1.563	0.174
154	9610.00	0.020	0.002	2.191	1.972	0.040	0.036	0.010	0.610	2.407	1.803	1.637	1.310	7.400	78.991	1.369	0.203
151	9612.00	0.018	0.002	2.050	1.845	0.033	0.030	0.008	0.597	2.158	1.760	1.806	1.445	7.456	79.571	0.970	0.253
153	9614.00	0.019	0.003	2.520	2.267	0.039	0.035	0.011	0.598	2.916	1.859	2.038	1.631	7.893	76.627	1.400	0.145
152	9616.00	0.071	0.003	4.336	3.902	0.124	0.112	0.009	0.399	27.546	1.127	1.117	0.894	4.941	47.313	8.105	0.000
149	9618.00	0.022	0.002	2.686	2.416	0.037	0.033	0.012	0.658	2.879	1.825	2.645	2.117	7.740	75.433	1.274	0.221
148	9620.00	0.019	0.002	2.369	2.132	0.036	0.032	0.010	0.589	2.875	1.637	1.970	1.576	7.050	78.277	1.212	0.213
147	9622.00	0.021	0.002	2.546	2.291	0.041	0.037	0.013	0.585	2.978	1.762	2.115	1.692	7.561	76.514	1.599	0.243
146	9624.00	0.016	0.017	2.845	2.560	0.033	0.030	0.015	0.622	2.153	2.299	2.816	2.254	9.472	73.528	1.099	0.240
144	9626.00	0.013	0.004	2.524	2.271	0.041	0.037	0.011	0.601	2.331	1.916	2.170	1.737	7.872	76.994	1.220	0.259
143	9628.00	0.016	0.005	2.722	2.449	0.028	0.025	0.027	0.668	2.392	2.288	3.175	2.541	9.301	72.445	1.315	0.606
142	9630.00	0.014	0.007	3.256	2.930	0.039	0.035	0.027	0.699	2.283	2.491	3.100	2.481	10.337	70.429	1.681	0.193
141	9632.00	0.015	0.009	2.986	2.687	0.045	0.040	0.018	0.632	2.609	2.195	2.958	2.367	9.392	72.461	1.385	0.201
140	9634.00	0.019	0.004	2.846	2.561	0.049	0.044	0.013	0.693	2.639	2.399	2.050	1.641	9.761	73.813	1.322	0.144
139	9636.00	0.022	0.008	3.204	2.883	0.034	0.031	0.022	0.873	2.673	2.618	2.805	2.245	10.948	69.773	1.659	0.202
138	9638.00	0.017	0.006	2.558	2.302	0.031	0.028	0.021	0.638	2.347	2.188	2.839	2.271	9.704	73.545	1.277	0.231
137	9640.00	0.013	0.039	1.995	1.795	0.033	0.030	0.004	0.439	2.328	1.635	1.773	1.419	7.275	79.991	1.058	0.172
136	9642.00	0.022	0.006	2.991	2.691	0.045	0.041	0.009	0.882	2.364	2.554	2.542	2.034	10.956	70.727	1.907	0.228
135	9644.00	0.016	0.004	3.011	2.709	0.046	0.041	0.013	0.653	2.793	2.046	2.826	2.262	8.568	73.478	1.373	0.160

134	9646.00	0.021	0.004	2.703	2.432	0.037	0.033	0.008	0.787	2.739	2.002	2.652	2.122	8.737	73.789	1.642	0.292
133	9648.00	0.014	0.003	2.843	2.559	0.036	0.032	0.015	0.673	2.441	2.178	4.115	3.293	9.312	70.973	1.322	0.192
132	9650.00	0.018	0.002	2.600	2.339	0.038	0.034	0.020	0.679	2.331	2.162	2.333	1.867	9.319	74.689	1.294	0.277
131	9652.00	0.021	0.003	2.449	2.204	0.042	0.038	0.008	0.650	2.661	2.044	1.717	1.374	9.231	75.553	1.601	0.402
130	9654.00	0.020	0.053	3.115	2.803	0.039	0.035	0.016	0.732	2.558	2.452	2.594	2.076	10.255	71.583	1.508	0.162
129	9656.00	0.016	0.014	2.805	2.524	0.047	0.042	0.010	0.605	2.962	1.879	2.855	2.284	8.616	73.668	1.453	0.222
128	9658.00	0.015	0.003	2.642	2.378	0.035	0.031	0.015	0.676	2.493	2.109	2.955	2.365	9.658	73.247	1.144	0.233
127	9660.00	0.025	0.003	2.889	2.600	0.039	0.035	0.013	0.691	2.875	2.048	2.697	2.158	8.791	74.059	0.864	0.211
126	9662.00	0.025	0.003	2.907	2.615	0.041	0.037	0.014	0.675	2.524	2.041	2.894	2.315	8.993	73.344	1.405	0.165
125	9664.00	0.064	0.002	5.465	4.918	0.155	0.139	0.014	0.388	27.192	1.189	1.758	1.407	5.531	44.648	7.127	0.000
124	9666.00	0.021	0.003	3.077	2.769	0.047	0.042	0.021	0.695	2.862	2.505	2.701	2.161	10.528	70.573	1.769	0.228
123	9668.00	0.014	0.002	2.773	2.496	0.039	0.035	0.014	0.670	2.377	2.361	2.208	1.767	10.249	73.229	1.562	0.203
121	9670.00	0.019	0.035	2.641	2.377	0.050	0.045	0.012	0.634	2.480	2.209	2.522	2.018	9.710	73.823	1.249	0.177
120	9672.00	0.018	0.002	2.578	2.320	0.039	0.035	0.012	0.762	2.497	2.124	2.259	1.807	9.097	74.695	1.519	0.237
119	9674.00	0.021	0.003	2.979	2.681	0.042	0.038	0.021	0.881	2.698	2.435	2.398	1.919	10.126	71.575	1.844	0.337
118	9676.00	0.041	0.003	6.314	5.681	0.167	0.150	0.022	0.387	25.375	1.187	1.812	1.450	6.147	44.270	6.992	0.000
117	9678.00	0.019	0.003	2.672	2.404	0.042	0.038	0.015	0.688	2.570	2.512	1.694	1.356	10.268	74.090	1.474	0.155
116	9680.00	0.023	0.003	3.096	2.786	0.045	0.040	0.014	0.863	2.861	2.515	2.464	1.972	10.286	71.200	1.664	0.168
115	9682.00	0.018	0.002	2.738	2.464	0.039	0.035	0.016	0.641	2.333	2.043	2.931	2.346	8.934	73.842	1.397	0.221
114	9684.00	0.020	0.006	2.711	2.439	0.044	0.039	0.014	0.636	2.958	2.095	2.612	2.090	8.786	73.251	1.799	0.501
113	9686.00	0.018	0.003	2.369	2.131	0.042	0.038	0.013	0.673	2.660	2.231	2.241	1.793	9.593	74.072	1.801	0.325
112	9688.00	0.008	0.002	1.575	1.417	0.000	0.000	0.054	1.043	3.528	3.321	3.382	2.706	15.170	65.590	1.761	0.469
111	9690.00	0.017	0.002	4.285	3.855	0.101	0.090	0.029	0.596	16.818	1.648	2.094	1.676	8.154	56.594	3.518	0.528
110	9692.00	0.021	0.002	2.805	2.524	0.044	0.039	0.007	0.722	3.139	2.007	2.988	2.391	8.565	72.454	1.889	0.405
109	9694.00	0.013	0.003	2.787	2.508	0.036	0.033	0.018	0.694	2.304	2.283	3.285	2.628	9.753	71.460	2.008	0.186
107	9697.00	0.049	0.002	2.648	2.383	0.077	0.069	0.022	0.499	28.560	1.344	1.355	1.085	7.477	45.260	9.174	0.000
106	9699.00	0.020	0.002	2.432	2.189	0.048	0.044	0.009	0.651	2.723	2.047	1.903	1.523	8.363	76.248	1.530	0.268
105	9701.00	0.014	0.002	3.021	2.719	0.049	0.044	0.014	0.727	2.384	2.427	3.000	2.401	9.611	71.749	1.427	0.410
104	9703.00	0.017	0.002	2.950	2.654	0.046	0.042	0.012	0.654	3.645	2.079	2.344	1.876	8.986	73.089	1.414	0.189
103	9705.00	0.064	0.003	7.113	6.401	0.215	0.194	0.023	0.377	28.839	1.106	1.493	1.195	5.172	41.594	6.208	0.000
102	9707.00	0.016	0.002	2.686	2.416	0.042	0.038	0.011	0.640	2.695	2.003	2.741	2.193	8.432	74.473	1.220	0.393
101	9709.00	0.016	0.003	2.684	2.415	0.035	0.031	0.016	0.635	2.428	2.025	2.945	2.357	8.525	74.091	1.494	0.300
100	9711.00	0.020	0.005	3.046	2.740	0.042	0.037	0.025	0.703	2.521	2.447	3.387	2.710	10.040	70.320	1.779	0.179
99	9713.00	0.018	0.004	2.304	2.073	0.039	0.035	0.008	0.839	2.345	2.135	1.678	1.342	8.701	76.765	1.507	0.206

96	9715.00	0.022	0.002	2.555	2.299	0.051	0.046	0.006	0.808	2.780	2.075	2.029	1.623	8.945	74.747	1.841	0.171
95	9717.00	0.017	0.002	2.879	2.591	0.050	0.045	0.013	0.778	2.662	2.364	2.302	1.842	9.614	73.290	1.358	0.193
94	9719.00	0.030	0.002	2.437	2.193	0.042	0.038	0.011	0.593	2.951	1.848	2.165	1.732	8.018	76.565	1.171	0.204
93	9721.00	0.023	0.003	3.067	2.760	0.055	0.049	0.008	0.811	4.829	1.971	2.358	1.887	8.558	71.903	1.470	0.250
91	9723.00	0.344	0.003	3.398	3.058	0.107	0.096	0.008	0.303	34.695	1.125	1.642	1.314	4.854	38.162	10.889	0.000
90	9725.00	0.029	0.002	2.702	2.432	0.038	0.034	0.013	0.639	2.756	2.054	2.709	2.167	8.552	74.514	1.195	0.166
89	9727.00	0.021	0.002	2.484	2.235	0.038	0.035	0.015	0.673	2.897	2.014	3.306	2.645	8.309	73.848	1.279	0.198
88	9729.00	0.017	0.003	2.471	2.223	0.045	0.040	0.013	0.670	3.158	2.012	2.607	2.086	8.338	75.043	1.075	0.198
87	9731.00	0.021	0.002	2.760	2.484	0.036	0.033	0.007	0.754	3.513	1.857	4.294	3.436	7.542	71.853	1.254	0.155
86	9733.00	0.019	0.003	2.597	2.336	0.035	0.032	0.014	0.839	2.949	2.217	2.262	1.810	8.516	74.744	1.320	0.308
80	9735.00	0.019	0.009	2.548	2.292	0.041	0.037	0.014	0.640	2.990	2.043	2.182	1.746	8.323	75.278	1.359	0.480
75	9737.00	0.020	0.015	3.049	2.743	0.037	0.033	0.023	0.677	2.409	2.293	4.602	3.683	9.305	69.349	1.270	0.492
71	9739.00	0.015	0.003	1.854	1.668	0.022	0.019	0.023	0.721	3.099	2.134	3.684	2.948	8.714	73.242	1.153	0.708
67	9741.00	0.021	0.003	3.005	2.704	0.035	0.031	0.025	0.673	2.823	2.201	4.247	3.398	9.366	69.336	1.755	0.378
61	9743.00	0.021	0.002	2.335	2.101	0.045	0.041	0.013	0.602	3.580	1.814	2.035	1.629	7.790	76.409	1.375	0.209
57	9745.00	0.015	0.003	2.537	2.283	0.044	0.040	0.009	0.661	2.979	1.955	2.588	2.071	8.445	74.686	1.223	0.460
53	9747.00	0.072	0.004	6.576	5.918	0.216	0.194	0.021	0.373	30.816	1.461	2.273	1.819	5.788	38.673	5.350	0.440
49	9749.00	0.023	0.002	2.703	2.432	0.042	0.038	0.011	0.673	3.570	1.954	2.693	2.155	8.203	74.014	1.383	0.102
45	9751.00	0.016	0.002	2.430	2.187	0.021	0.019	0.016	0.803	3.958	2.384	3.798	3.039	9.442	69.888	1.866	0.129
41	9753.00	0.020	0.003	3.470	3.123	0.060	0.054	0.014	0.717	5.461	2.153	3.246	2.598	8.137	69.308	1.629	0.000
35	9755.00	0.023	0.002	2.318	2.086	0.043	0.039	0.013	0.683	3.128	2.098	2.501	2.001	8.720	74.855	1.313	0.177
31	9757.00	0.024	0.003	2.985	2.686	0.050	0.045	0.013	0.669	3.414	2.070	3.571	2.857	8.293	71.679	1.537	0.100
27	9759.00	0.024	0.002	3.075	2.767	0.041	0.037	0.015	0.629	3.033	2.179	4.624	3.700	8.802	68.948	1.965	0.156
23	9761.00	0.019	0.003	3.605	3.244	0.049	0.044	0.020	0.679	4.897	2.181	4.607	3.686	9.014	66.208	1.584	0.161
19	9763.00	0.019	0.002	3.248	2.923	0.056	0.051	0.014	0.582	6.918	1.846	2.998	2.399	7.482	69.773	1.689	0.000
13	9765.00	0.019	0.001	2.209	1.988	0.038	0.034	0.010	0.470	6.549	1.206	2.259	1.808	5.632	76.279	1.385	0.114
9	9767.00	0.013	0.002	3.341	3.006	0.054	0.049	0.016	0.553	7.061	1.794	3.229	2.584	7.662	68.549	2.087	0.000
6	9768.50	0.010	0.062	4.047	3.642	0.032	0.028	0.070	0.703	0.763	2.822	6.584	5.268	10.725	63.775	1.115	0.359

APPENDIX B

FLUID MODULE INPUTS

Zone	Water	Gas	H2S	N2	CO2	Cond Liquid	Condensate	Oil	Oil
#	Salinity	Gravity	Conc	Conc	Conc	Loading	Gravity	Gravity	SolGas
1	85000	0.556	0	0	0	0	0.8	40	3000
2	85000	0.556	0	0	0	0	0.8	40	3000
3	85000	0.556	0	0	0	0	0.8	40	3000
4	85000	0.556	0	0	0	0	0.8	40	3000

Zone	Dspth	Temp	Pressure	Water Salinity	Gas Gravity	H2S	N2	CO2	Liquid Loading	Cond Gravity	Oil Gravity	Oil SolGas	Report
#	Units	Units	Units	Units	Unit	Unit	Unit	Unit	Unit	Unit	Unit	Unit	Units
1	ft	F	psia	ppm	fraction	fraction	fraction	fraction	bb/MMft3	API	API	scf/stb	imperial
2	ft	F	psia	ppm	fraction	fraction	fraction	fraction	bb/MMft3	API	API	scf/stb	imperial
3	ft	F	psia	ppm	fraction	fraction	fraction	fraction	bb/MMft3	API	API	scf/stb	imperial
4	ft	F	psia	ppm	fraction	fraction	fraction	fraction	bb/MMft3	API	API	scf/stb	imperial

Fluid module endpoints

APPENDIX C

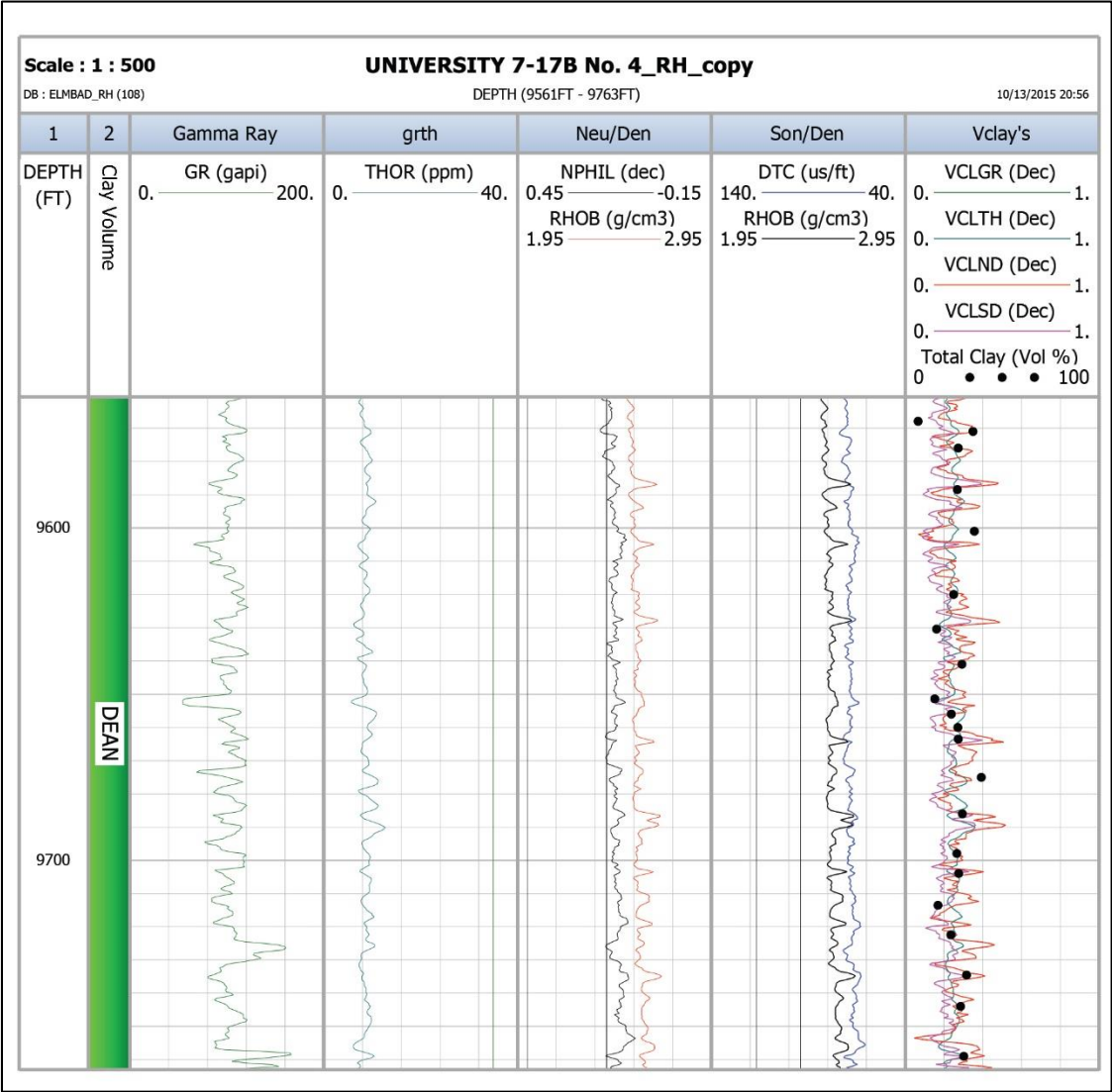
CLAY VOLUME CALIBRATION

Zone	ND	ND Neu	ND Den	ND Den	ND Den	ND Den	ND Neu	ND Neu
#	Use	Clay	Clay	Clean1	Clean2	Clean1	Clean1	Clean2
1	✓	0.42	2.41	2.71	1.03	0	0	1.03
2	✓	0.42	2.41	2.71	1.03	0	0	1.03
3	✓	0.42	2.41	2.71	1.03	0	0	1.03
4	✓	0.42	2.41	2.71	1.03	0	0	1.03

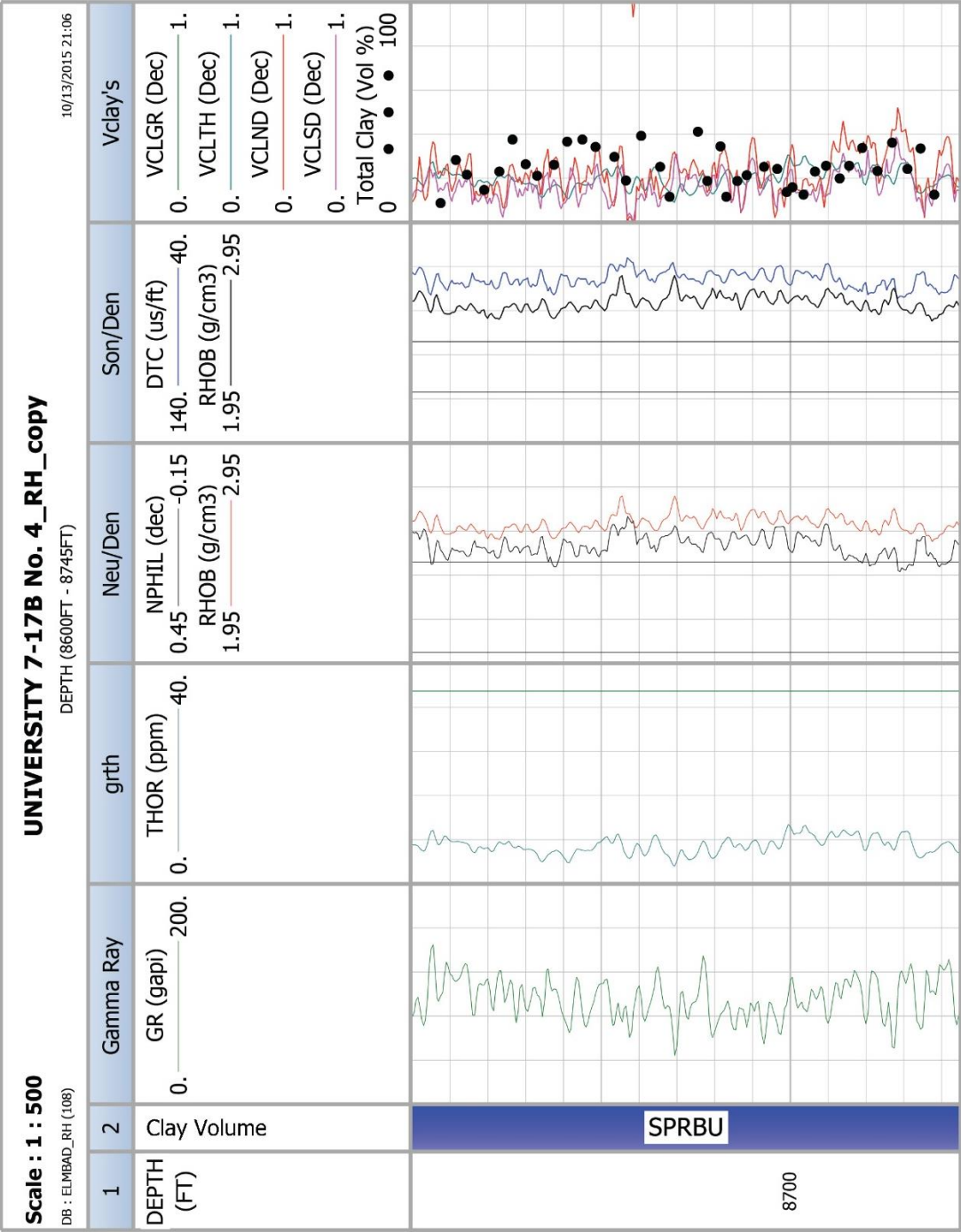
Zone	SD	SD Son	SD Den	SD Den	SD Den	SD Son	SD Son
#	Use	Clay	Clay	Clean1	Clean2	Clean1	Clean2
1	✓	115	2.41	2.71	1.03	48	189
2	✓	115	2.41	2.71	1.03	48	189
3	✓	115	2.41	2.71	1.03	48	189
4	✓	115	2.41	2.71	1.03	48	189

Zone	Oth	Oth	Oth	Oth
#	Use	Clean	Clean	Clay
1	✓	0	0	40
2	✓	0	0	40
3	✓	0	0	35
4	✓	0	0	40

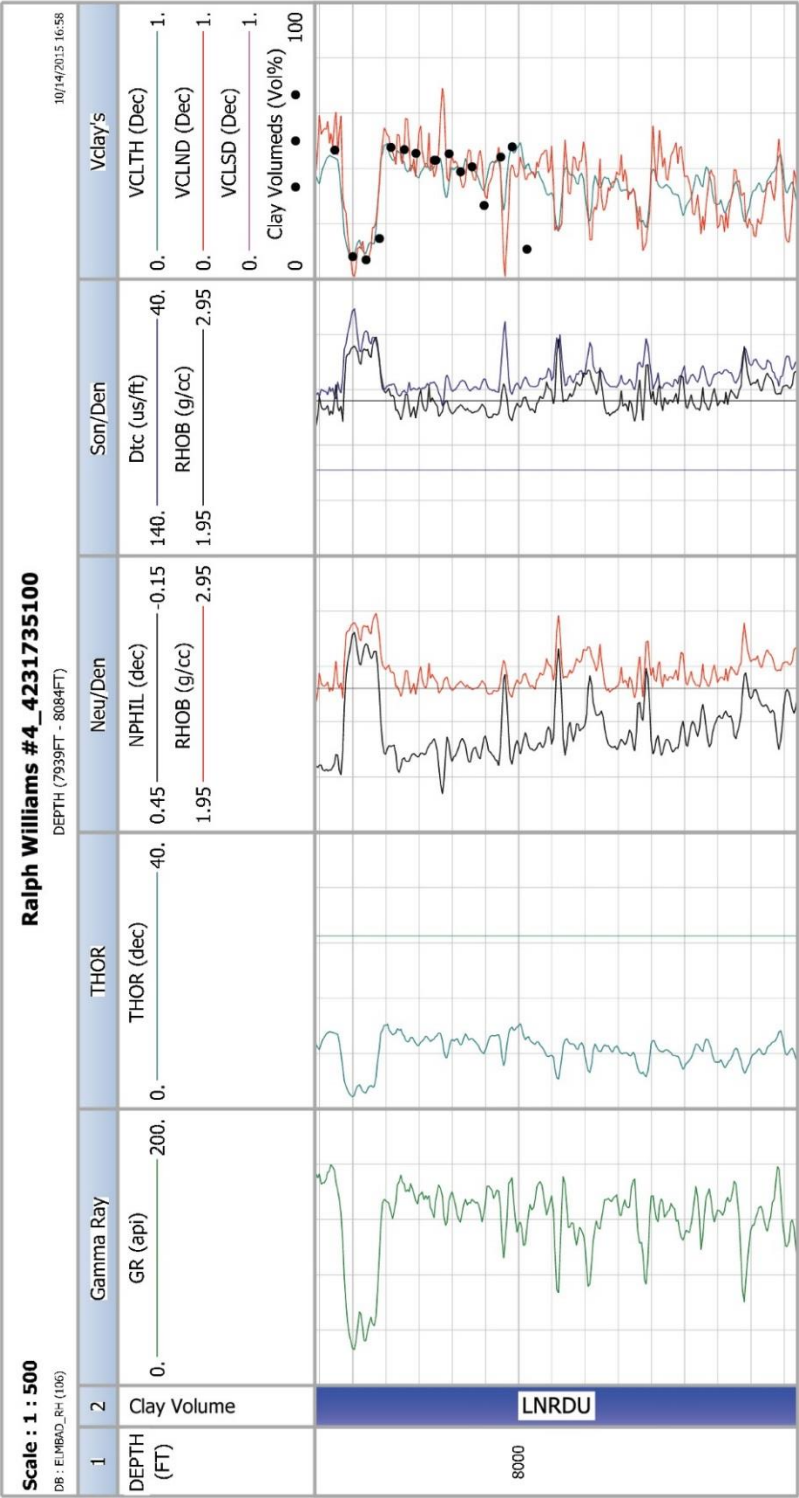
Clay volume endpoints



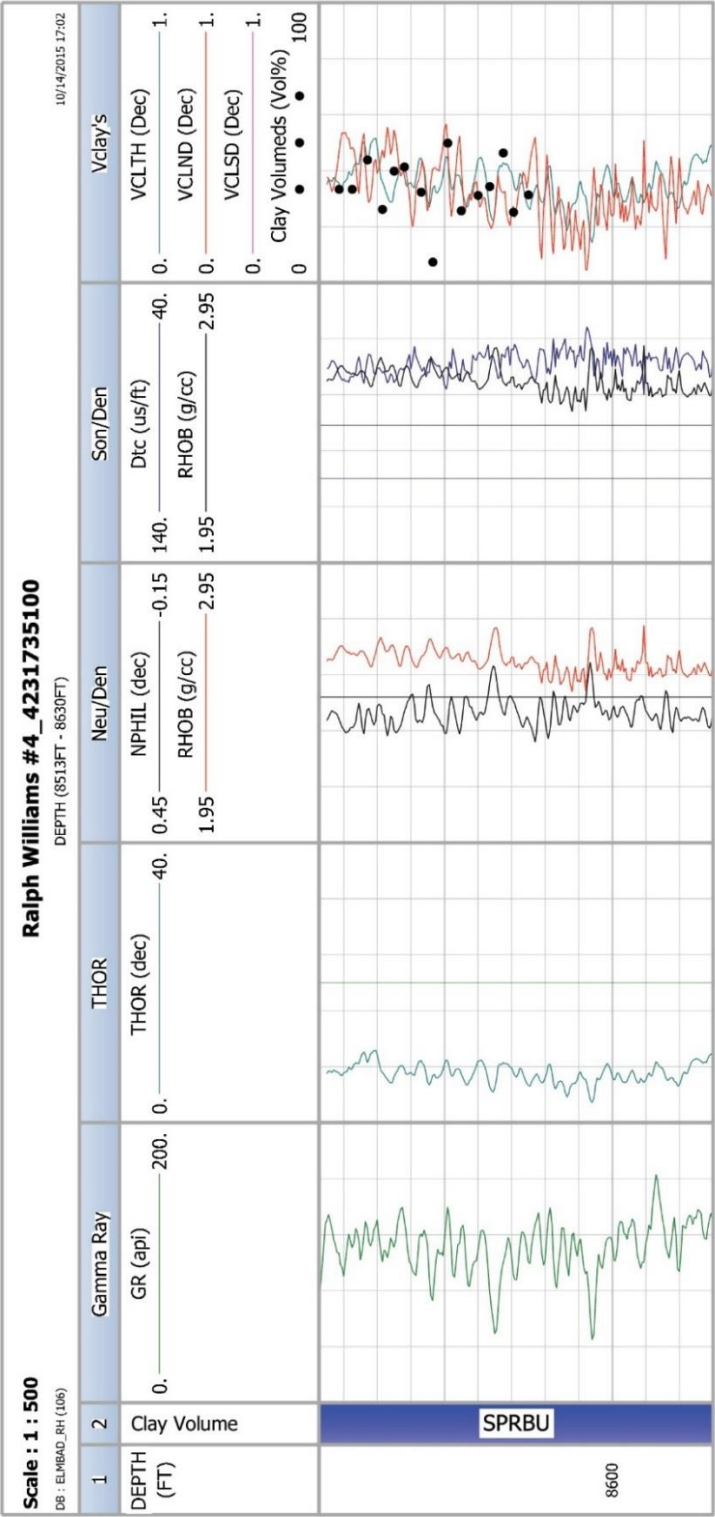
Dean Formation calibration



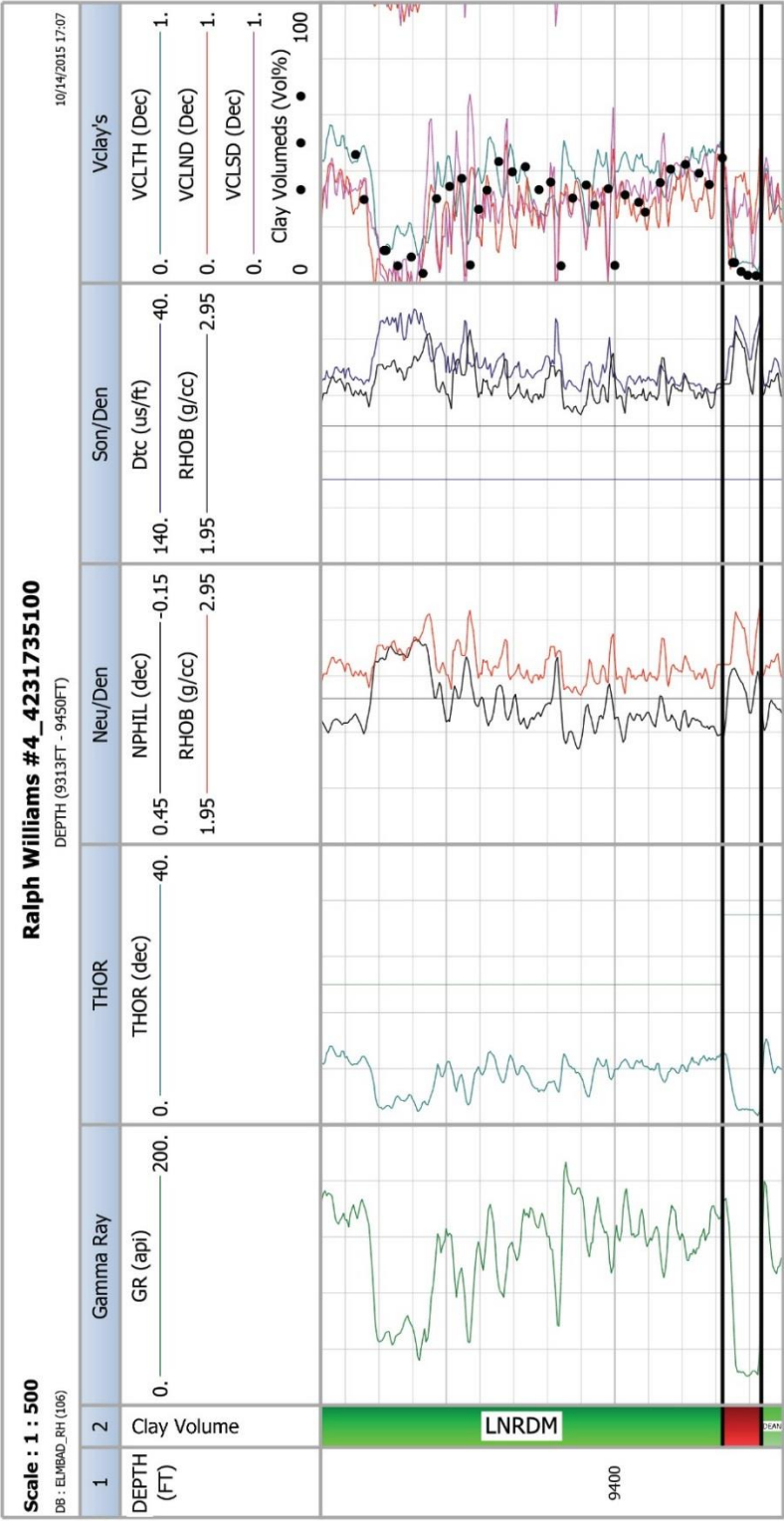
Upper Spraberry Formation calibration.



Middle Leonard interval calibration.



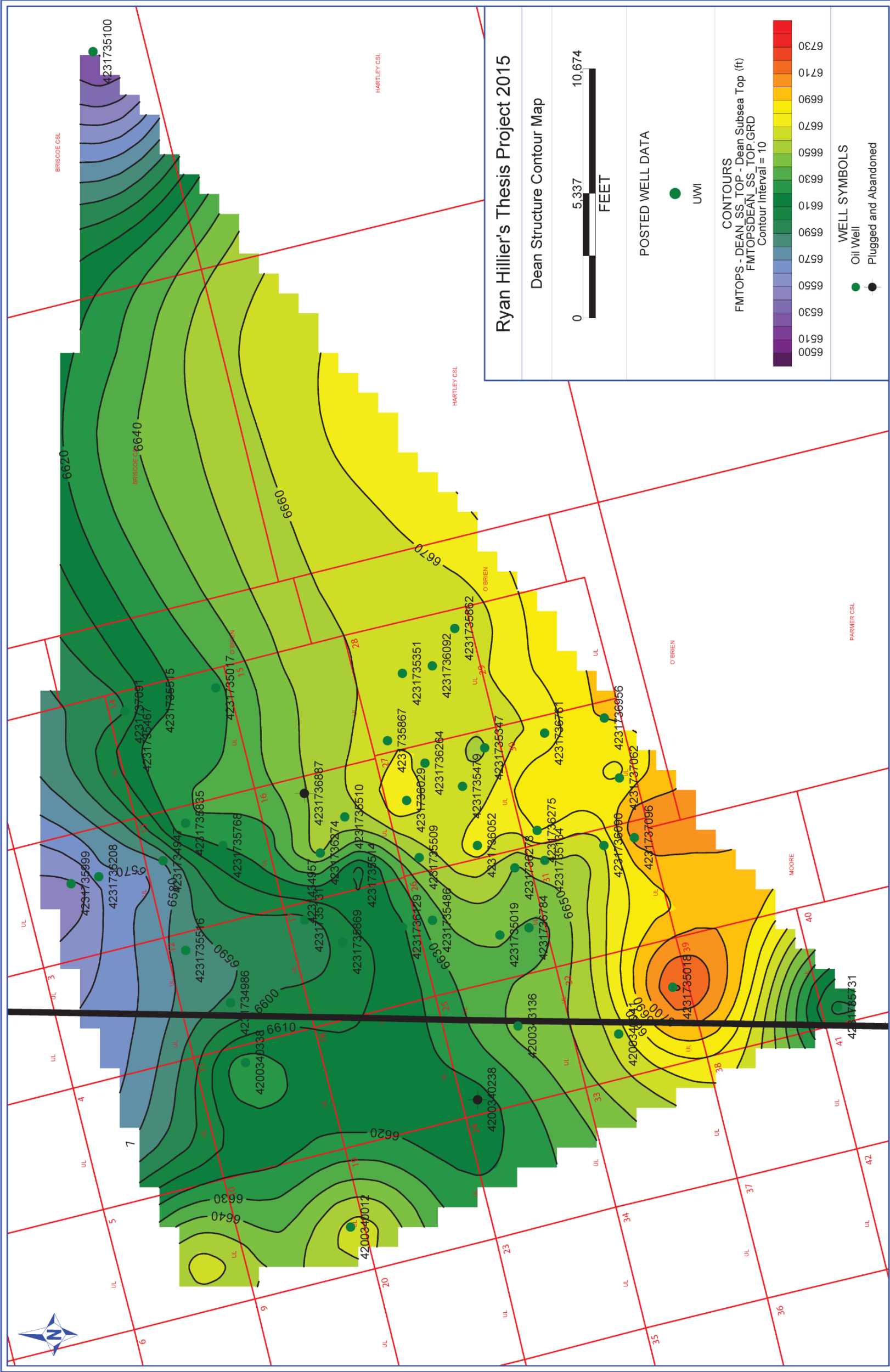
Upper Spraberry Formation calibration.



Middle Leonard interval calibration.

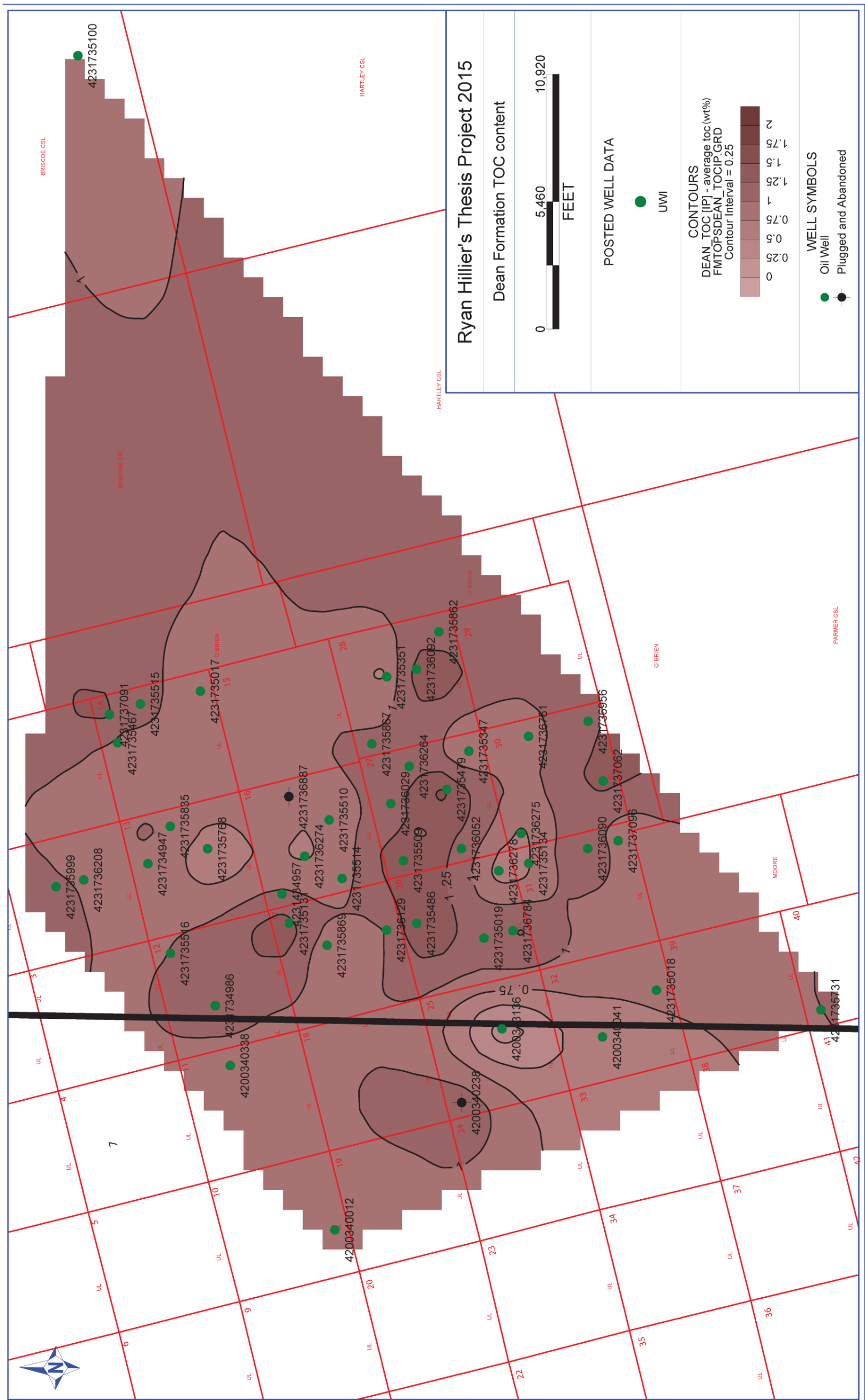
APPENDIX D

SUPPLEMENTAL ATTRIBUTE MAPS

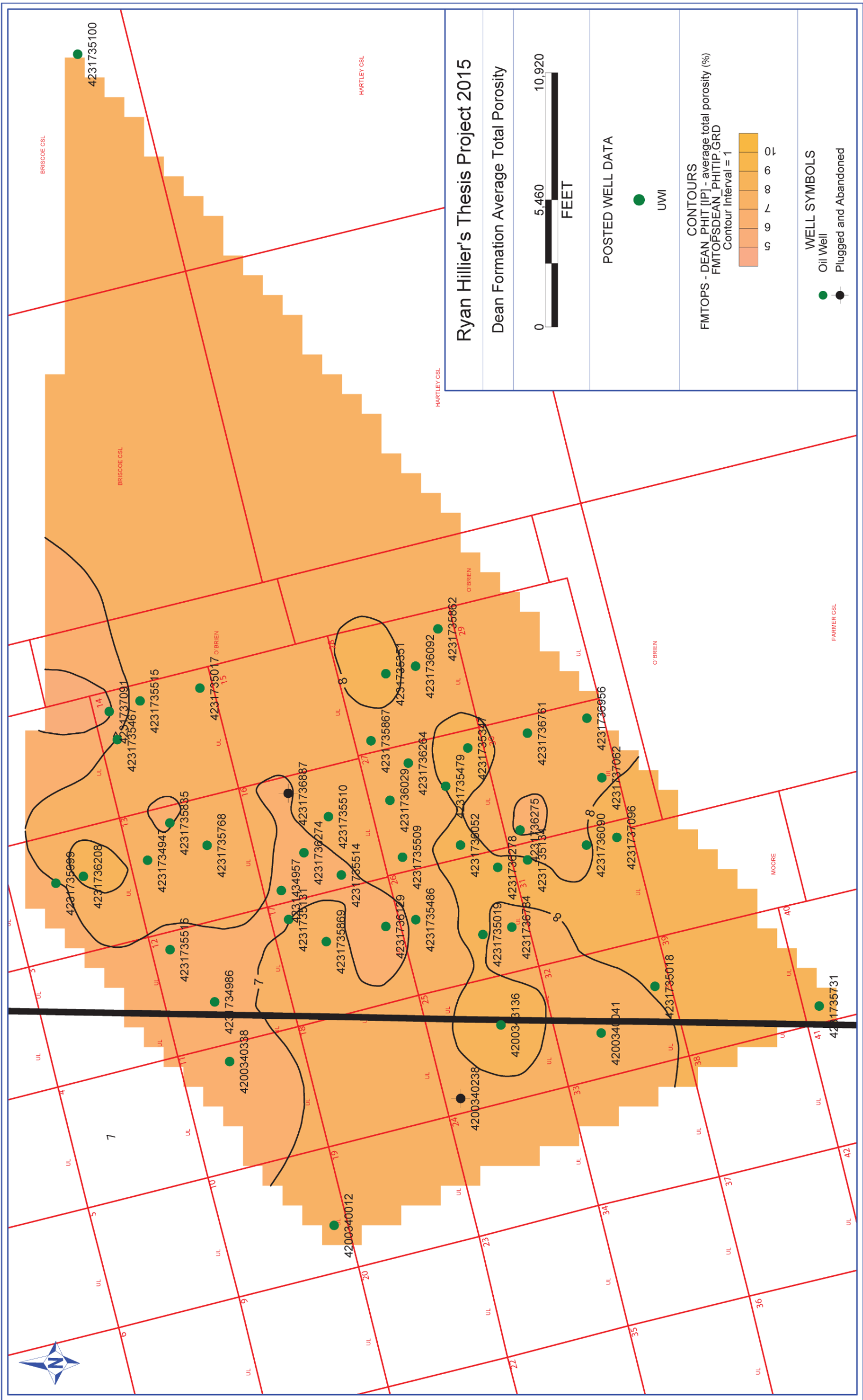


Dean Formation structure contour map.

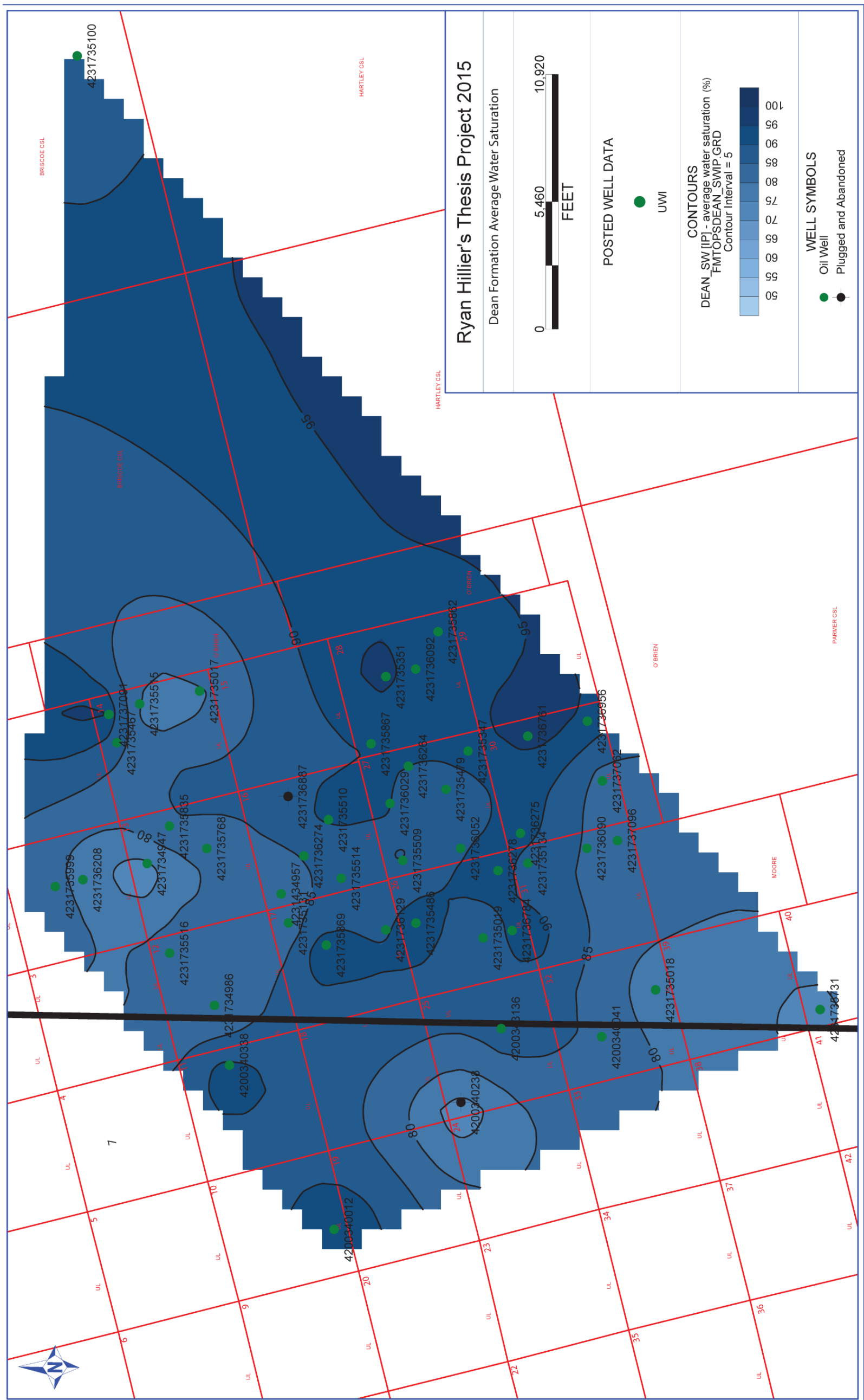
Dean Formation clay volume map.



Dean Formation TOC map.

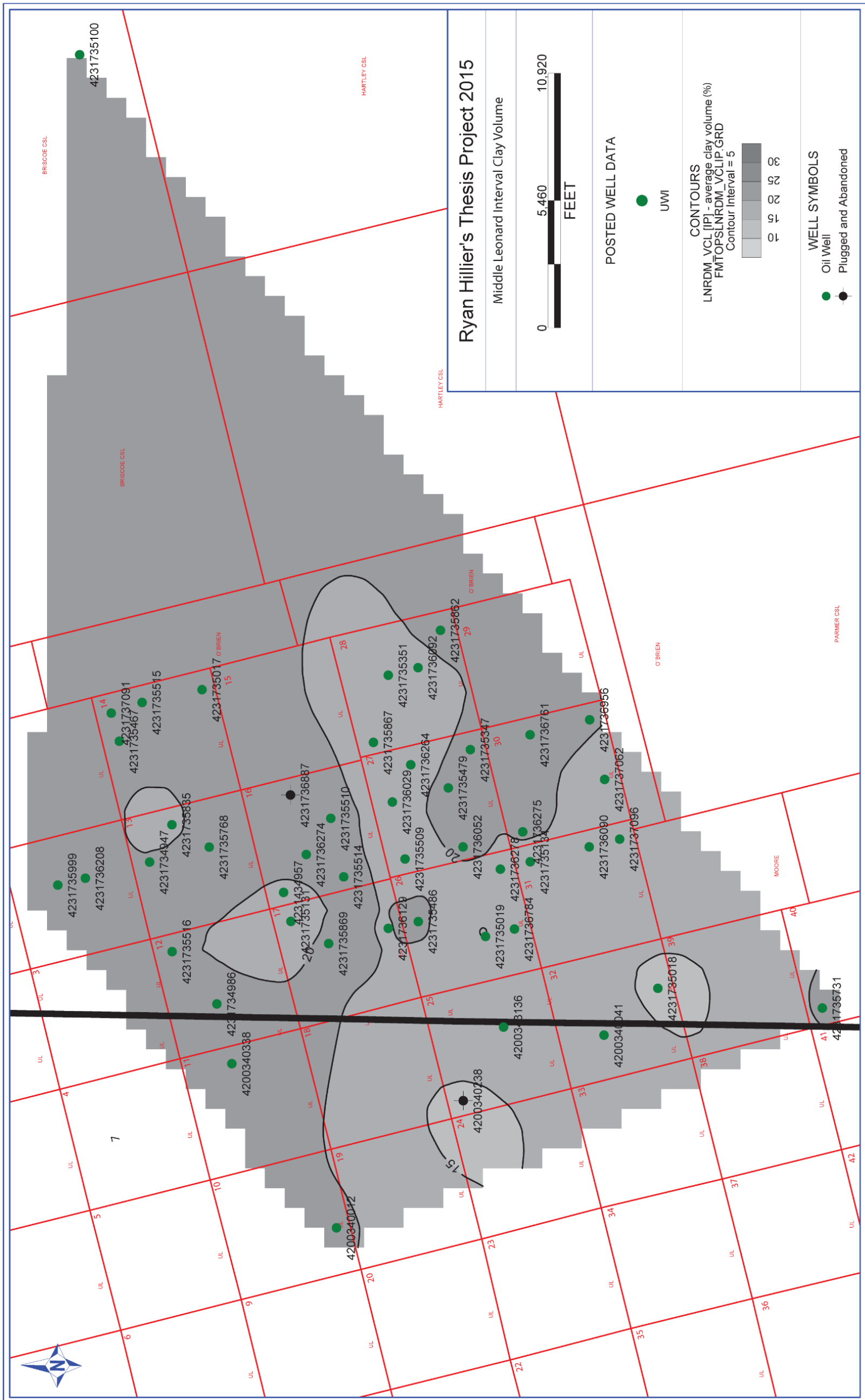


Dean Formation porosity map.

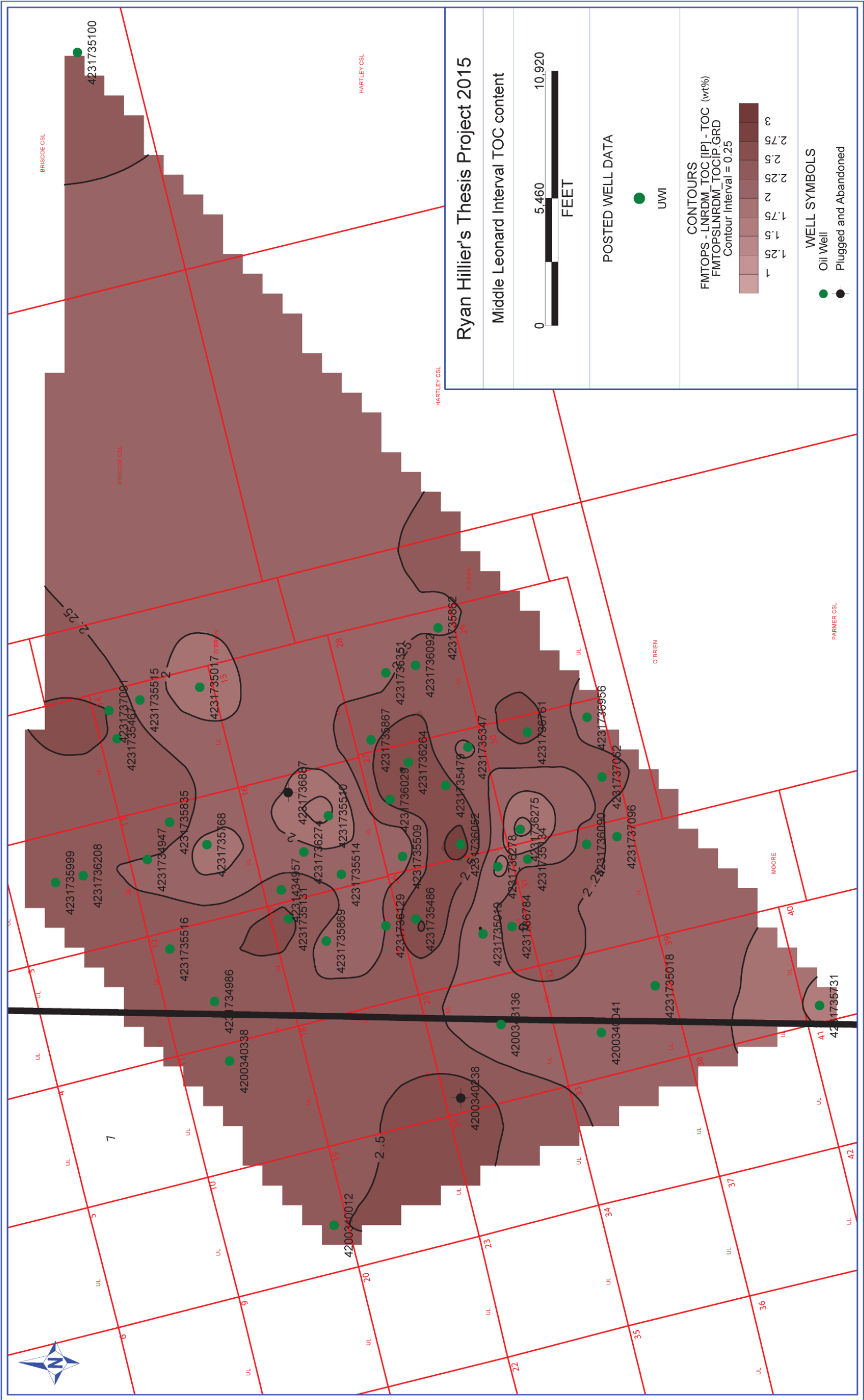


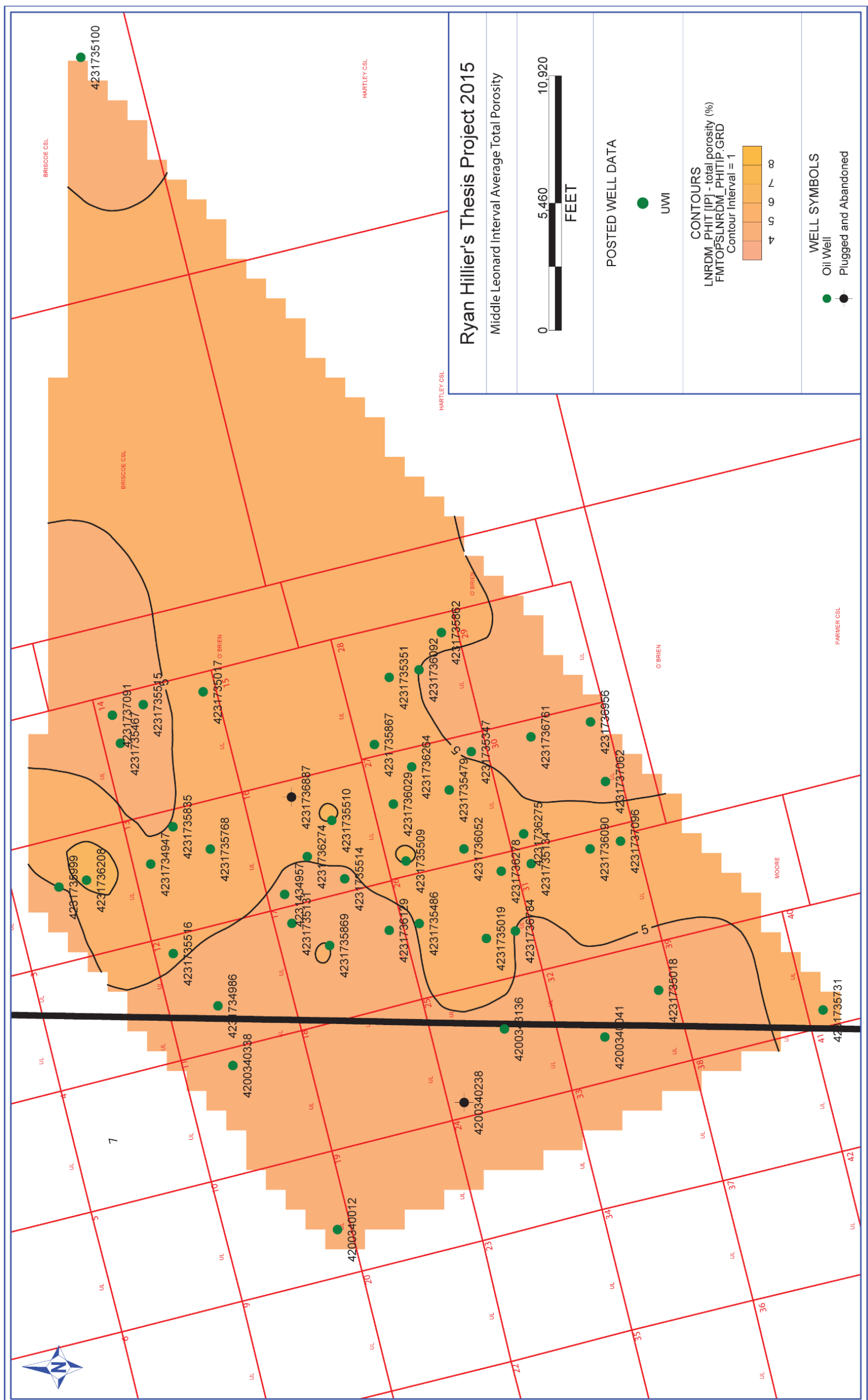
Dean Formation water saturation map.

Middle Leonard interval structure contour map.

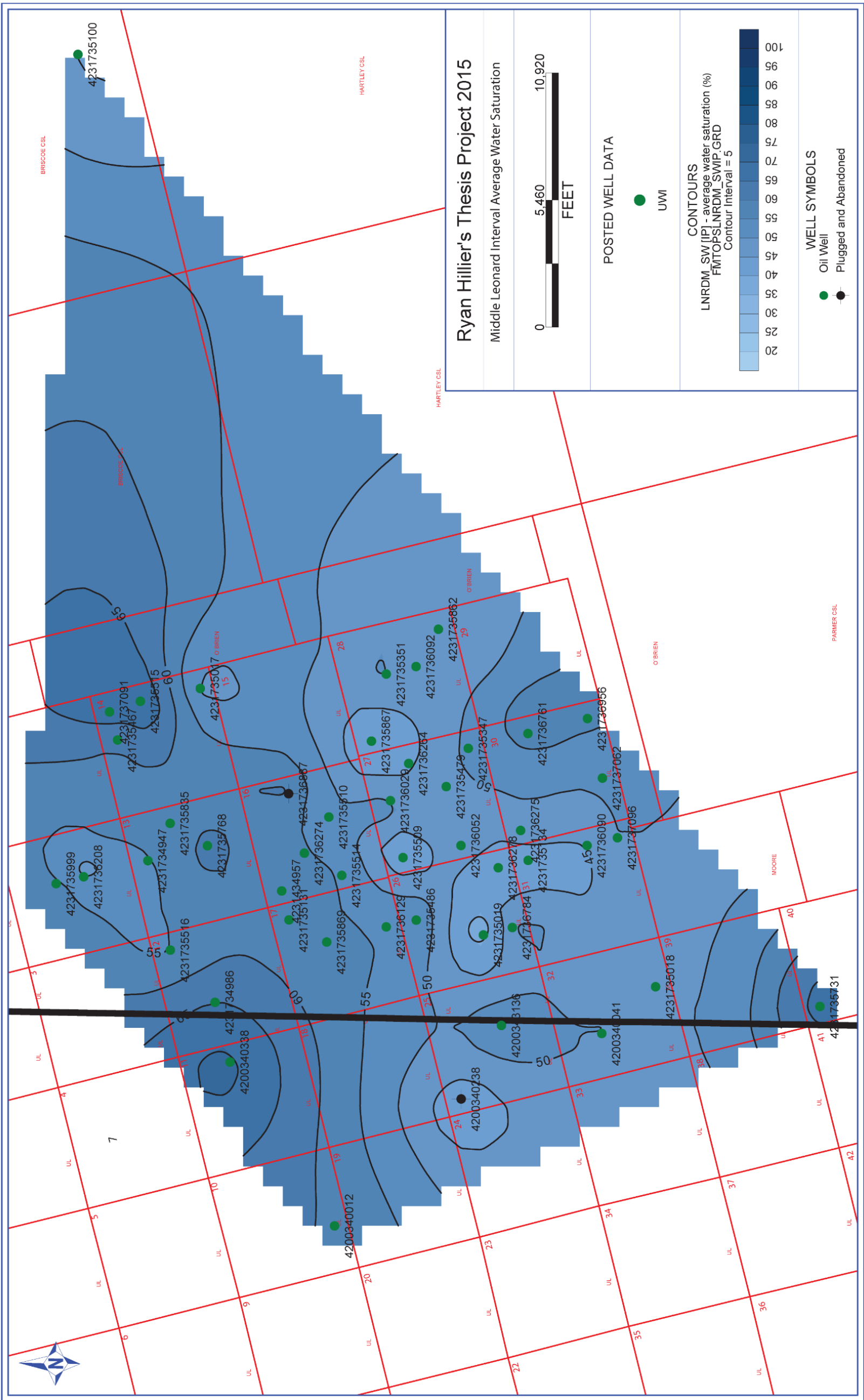


Middle Leonard interval clay volume map.

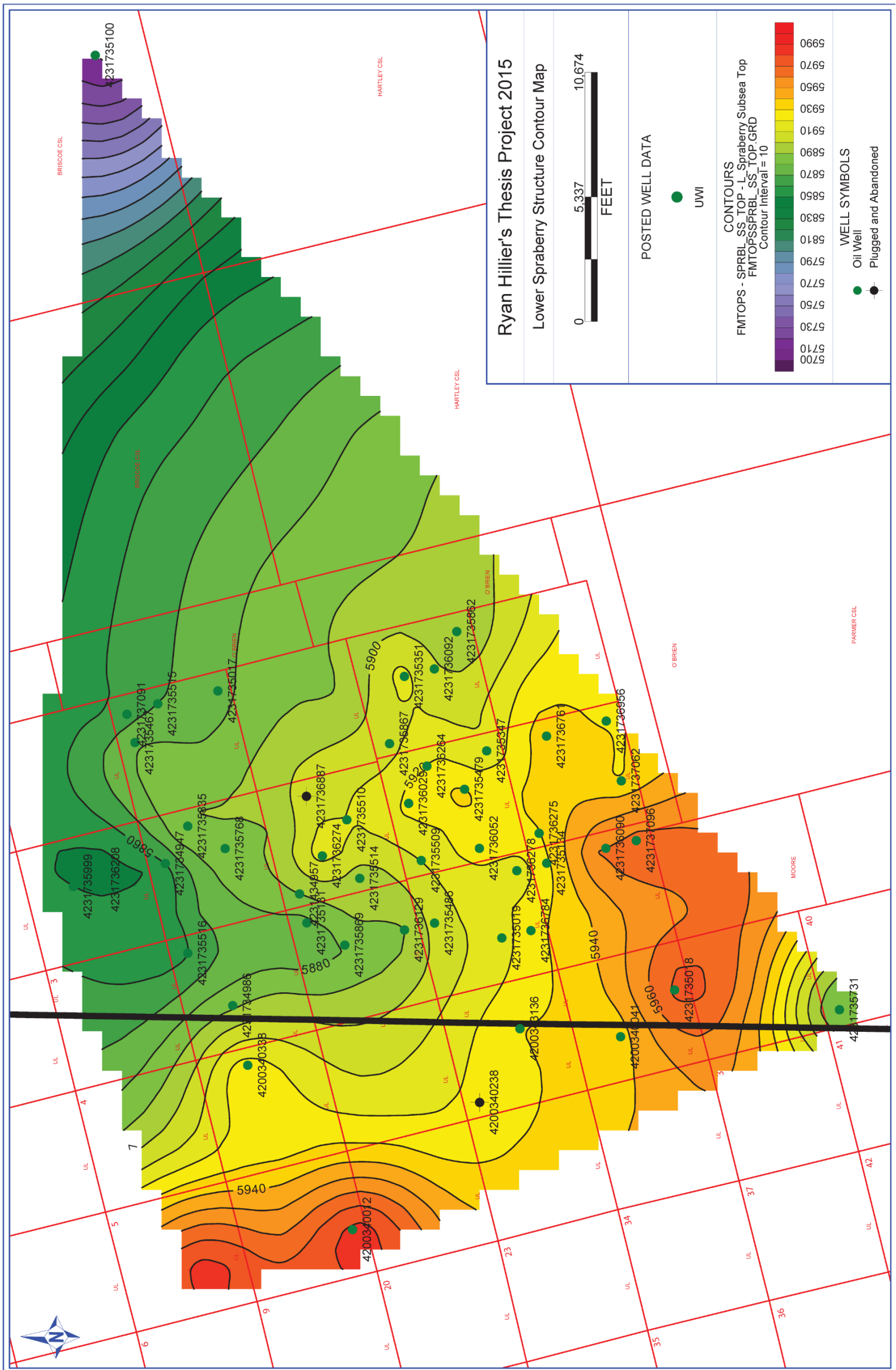




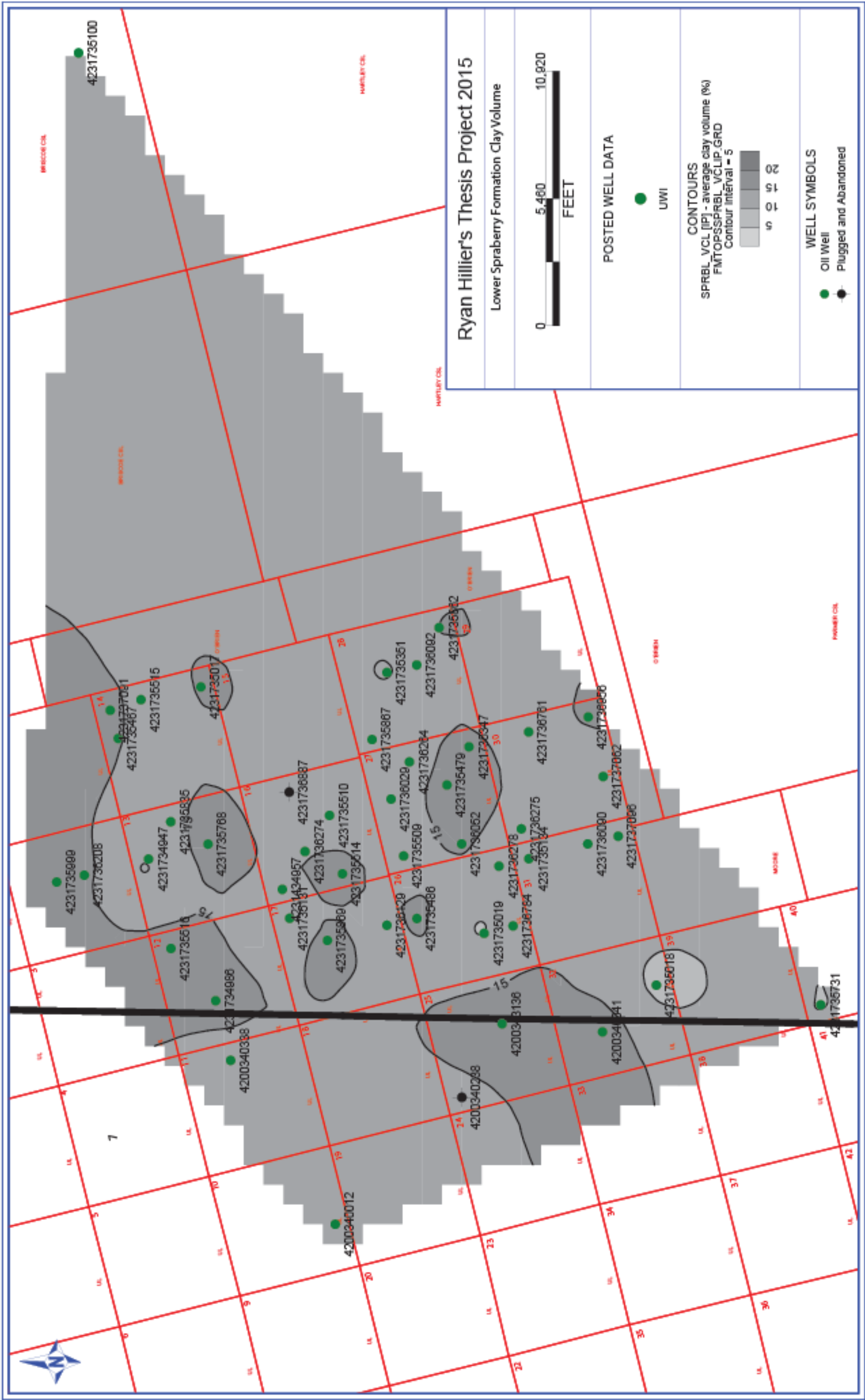
Middle Leonard interval total porosity map.



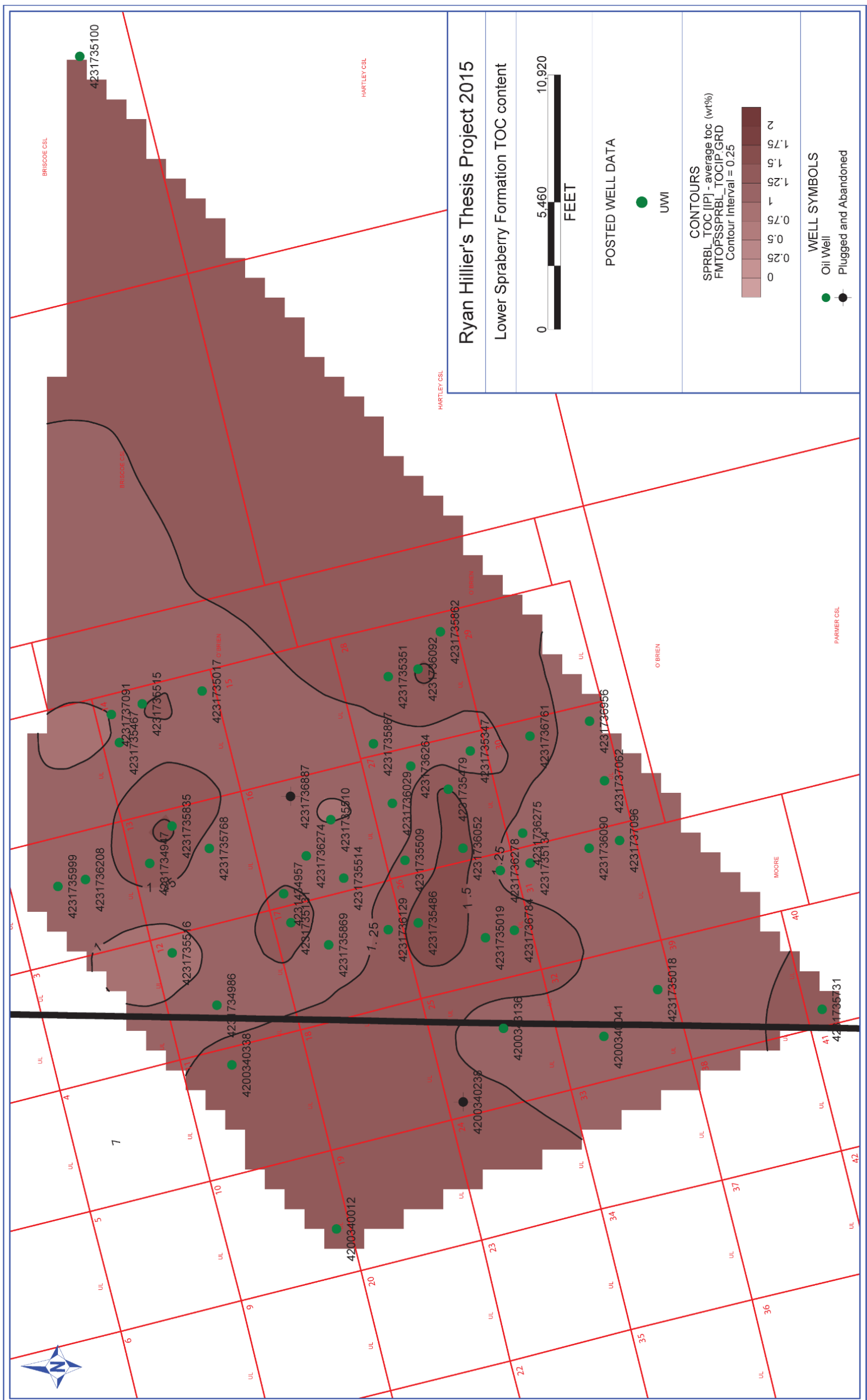
Middle Leonard interval water saturation map.



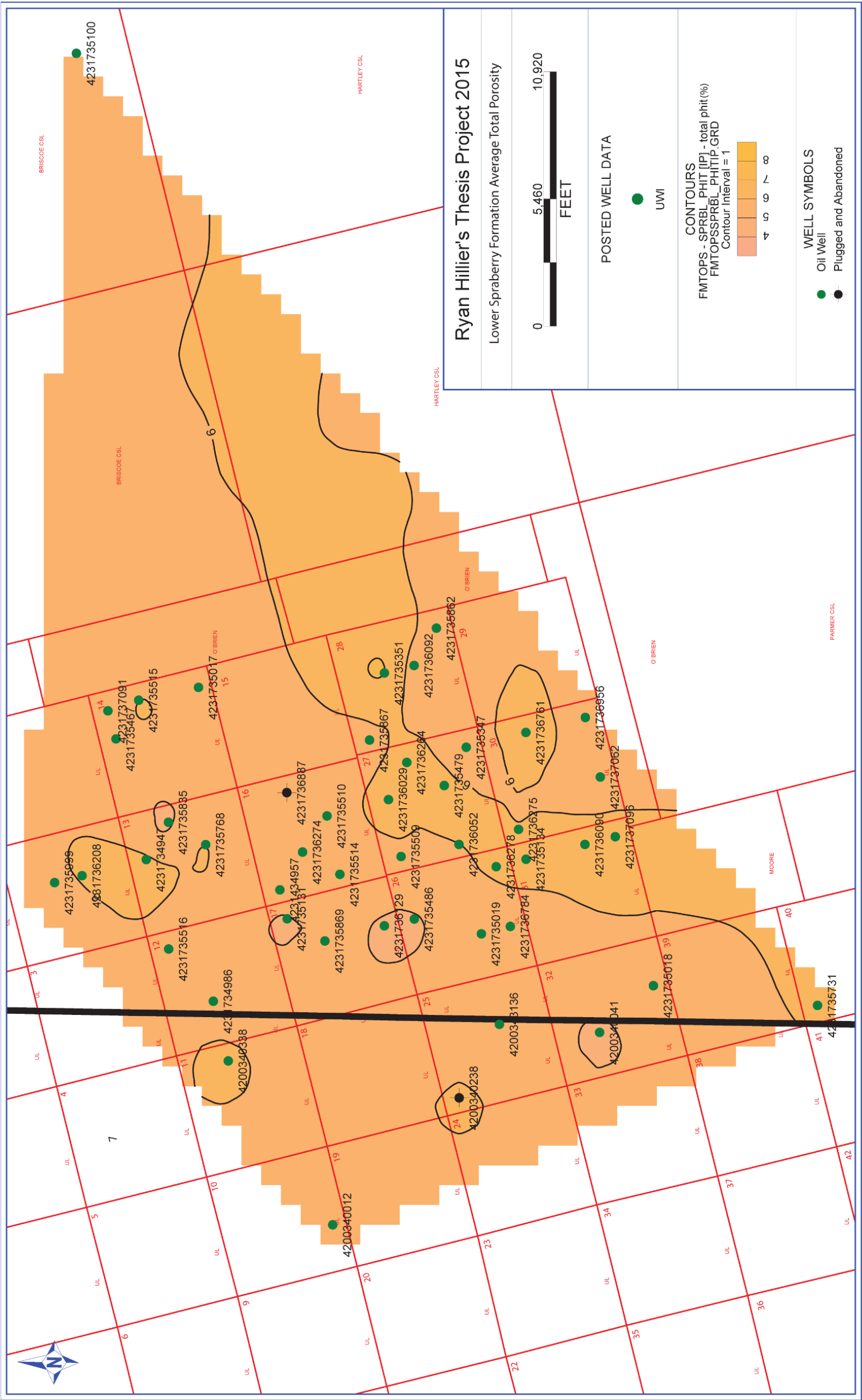
Lower Spraberry Formation structure contour map.



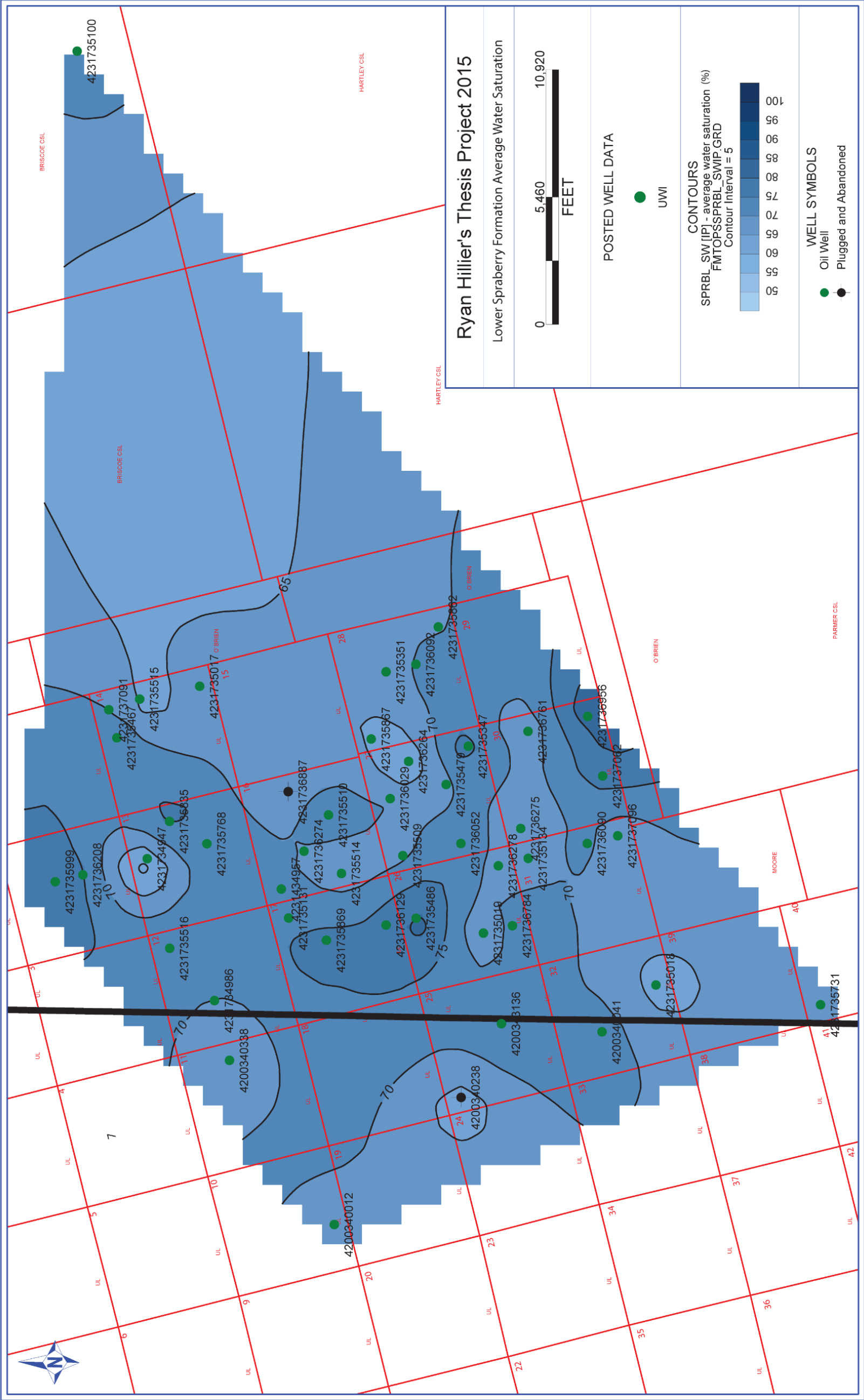
Lower Spraberry Formation clay volume map.



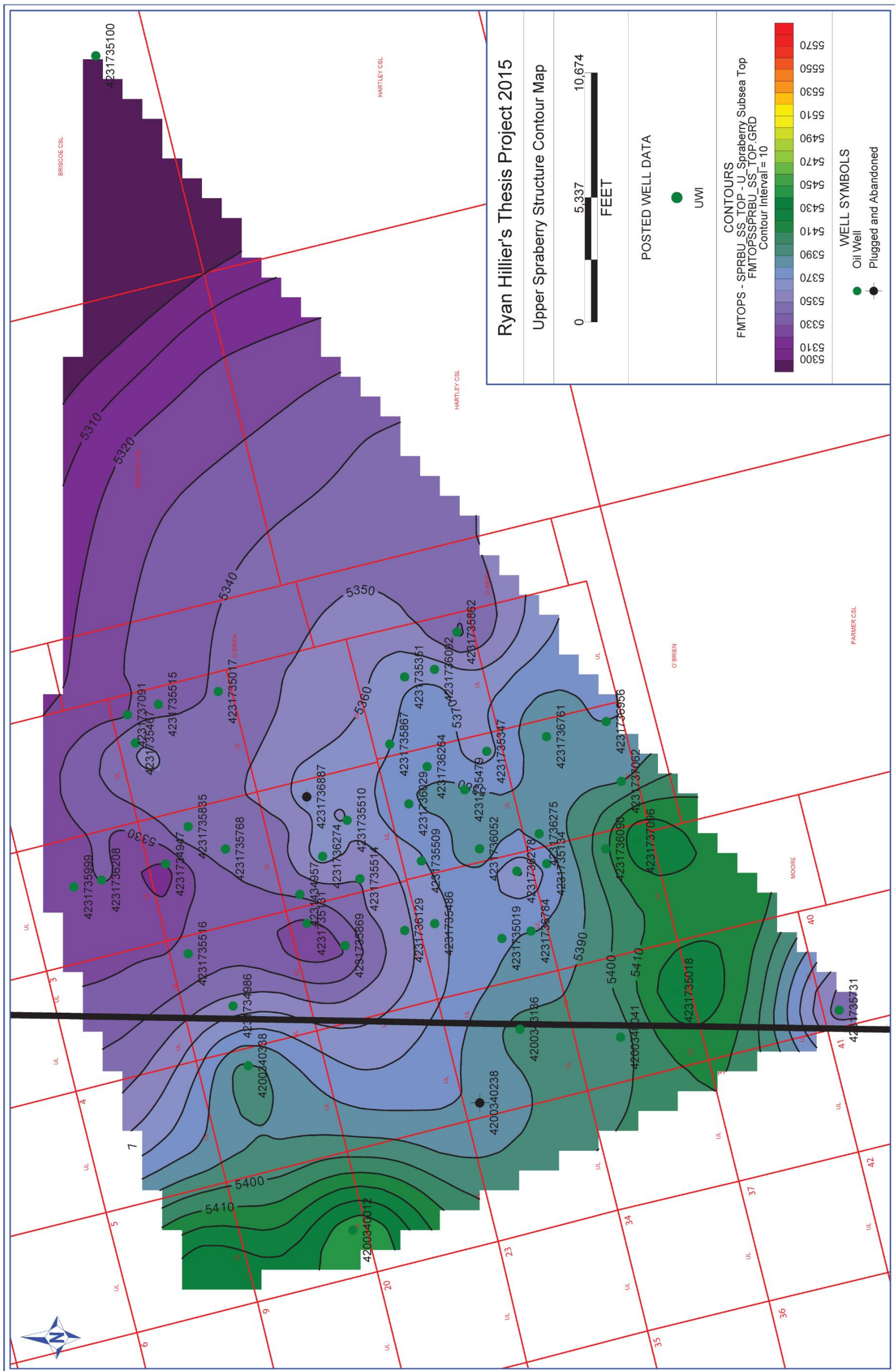
Lower Spraberry Formation TOC map.



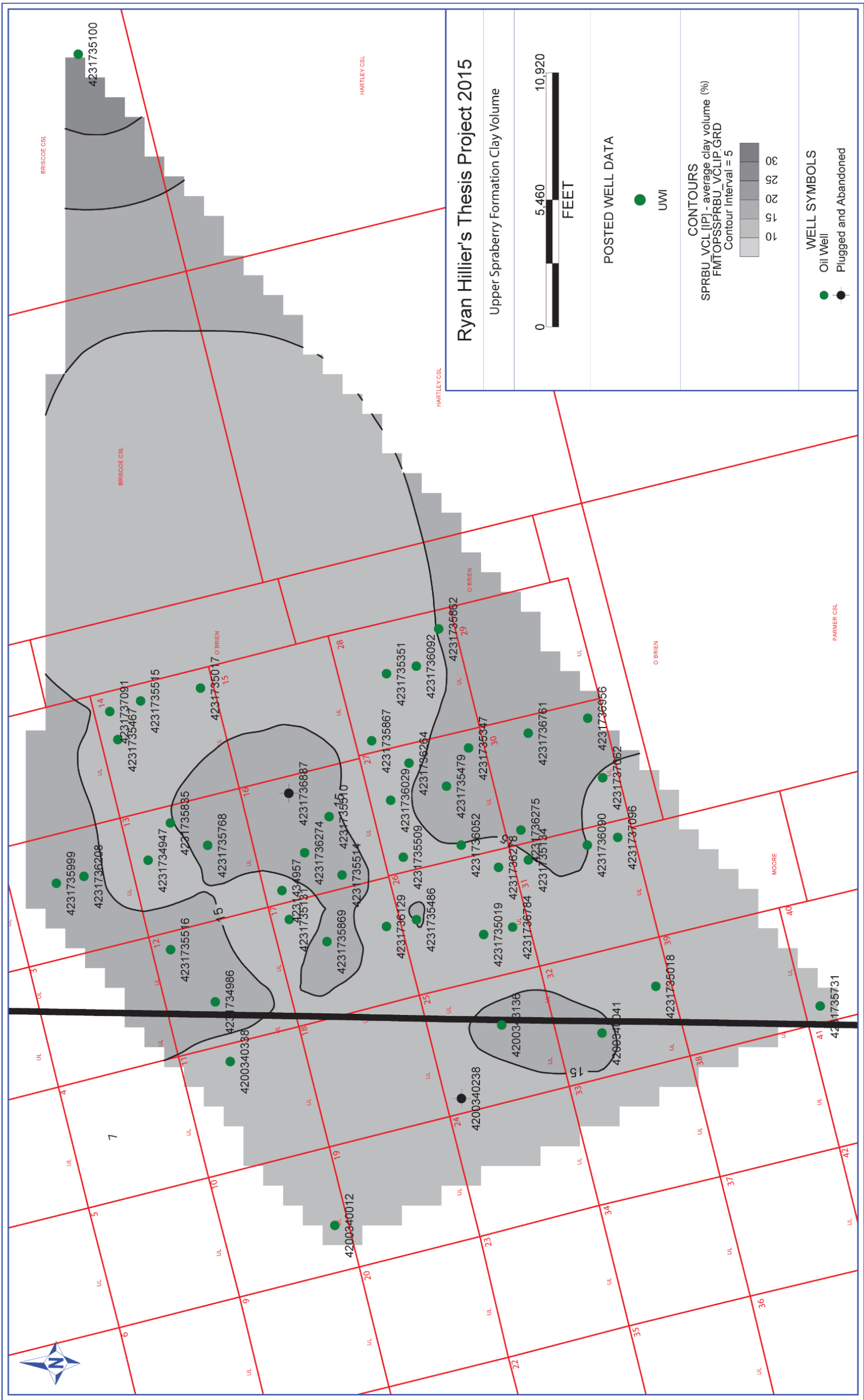
Lower Spraberry Formation total porosity map.



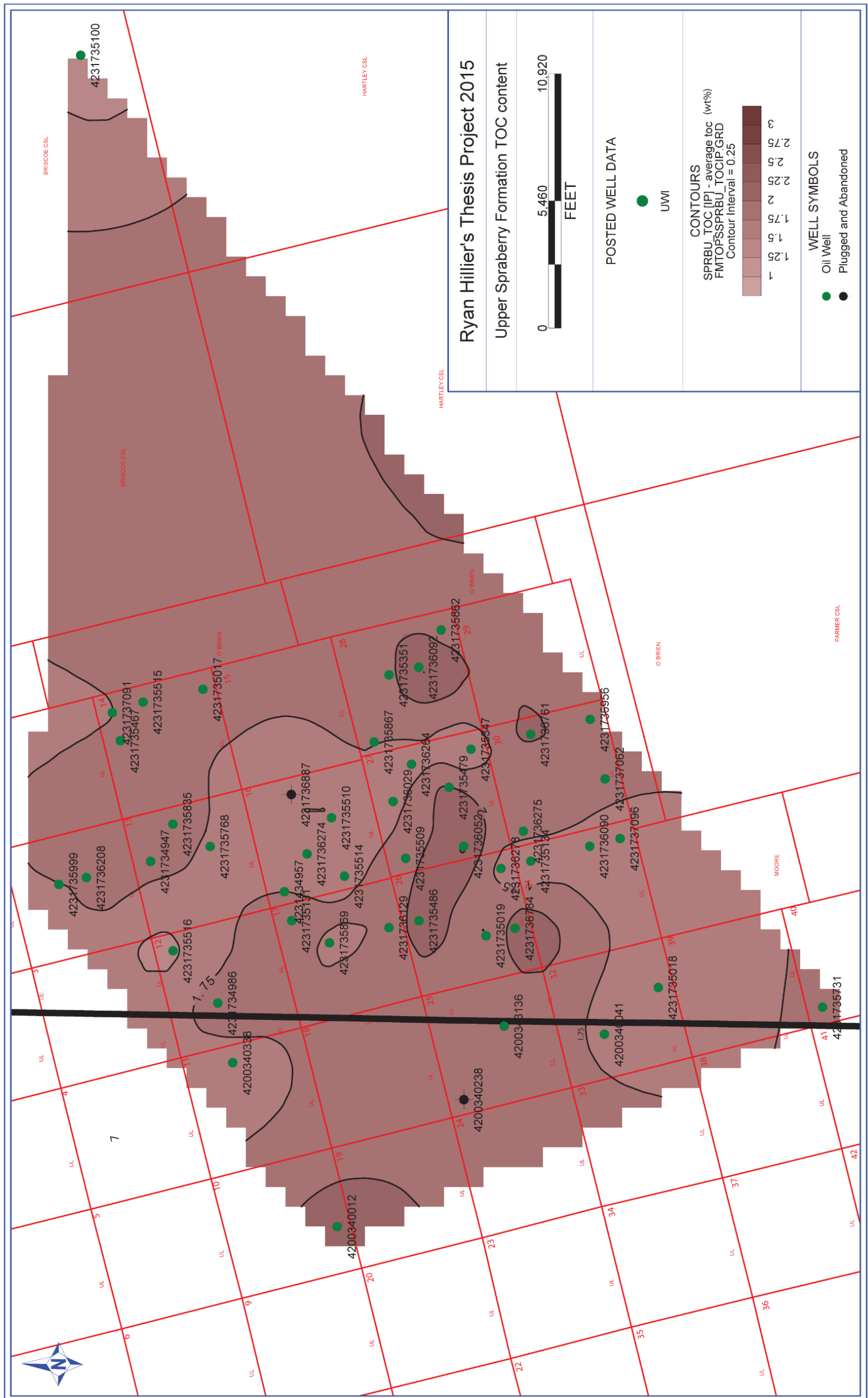
Lower Spraberry Formation water saturation map.



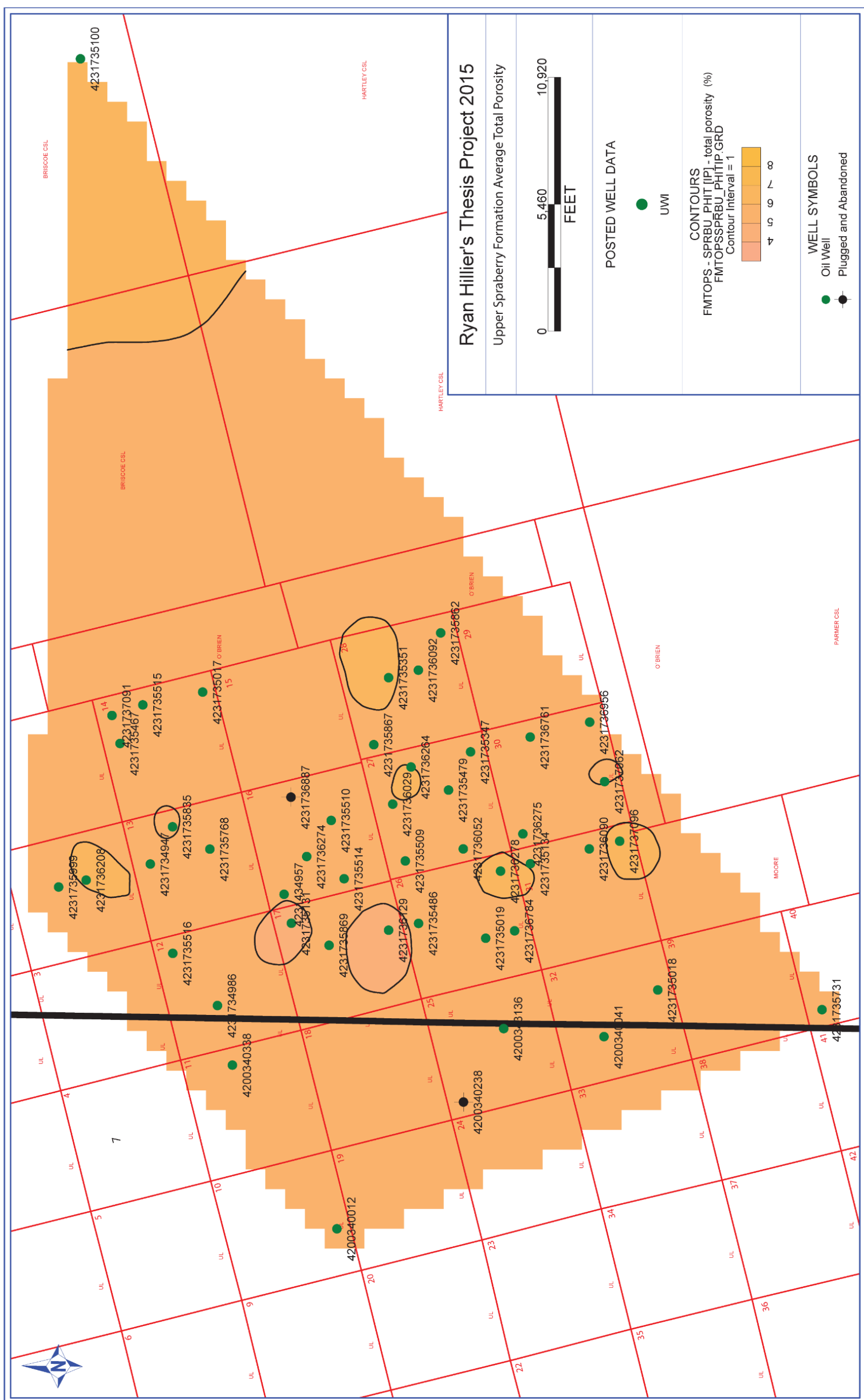
Upper Spraberry Formation structure contour map.



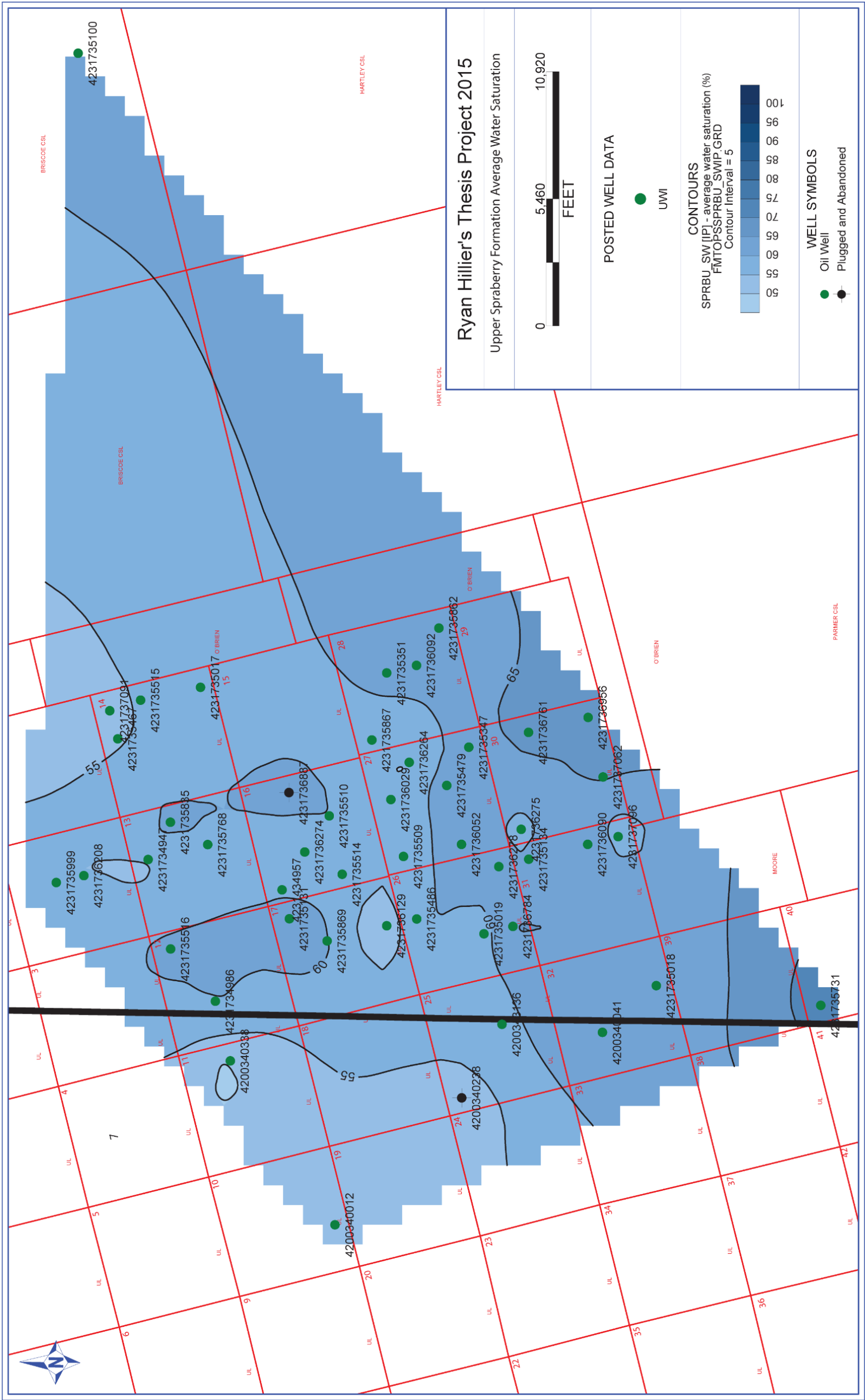
Upper Spraberry Formation clay volume map.



Upper Spraberry Formation TOC map.



Upper Spraberry Formation total porosity map.



Upper Spraberry Formation water saturation map.