QUANTIFYING AND ANALYZING RELATIONSHIPS BETWEEN WELL LOG ATTRIBUTES AND PRODUCTION FOR THE MISSISSIPPIAN PLAY IN WOODS COUNTY, OK

By

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Title of Study: QUANTIFYING AND ANALYZING RELATIONSHIPS BETWEEN WELL LOG ATTRIBUTES AND PRODUCTION FOR THE MISSISSIPPIAN PLAY IN WOODS COUNTY, OK

Major Field: GEOLOGY

Abstract:

This case study outlines a workflow to use older vertical well data to better understand hydrocarbon plays and help guide modern horizontal drilling. The focus of the study is Woods County, Oklahoma which lies in the heart of the Mississippian play. This county has thousands of older vertical wells, for which hundreds of digital well log files are available. Woods County also has abundant horizontal wells.

The Mississippian play is a carbonate play producing at shallow depths. The relatively low horizontal drilling costs combined with existing infrastructure in place from older production make this play desirable for many operators.

Despite all of the positives for drilling Mississippian wells, there is currently a lack of understanding of what causes the relatively sporadic production compared to other plays. The multiple-porosity stacked systems in carbonate reservoirs create petrophysical variability. Although this variability can lead to frustration when trying to characterize a reservoir, it can also lead to opportunities to identify localized favorable trends.

The objective of this study is to quantify the relationships between well log attributes and production in the Mississippian play. By comparing older vertical well log relationships to current horizontal well log relationships, this study provides a workflow for using older well information to help guide current drilling.

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CHAPTER 1:
INTRODUCTION

1.1: Problem Statement

The Mississippian play, informally known as the “Mississippi lime” or the “Miss lime” play, in northern Oklahoma and southern Kansas is an expansive carbonate stratigraphic trap producing at shallow depths ranging from 4,500 - 7,500 ft (~1370 - 2290 m) (Pish *et al.*, 2011). With thousands of vertical wells drilled in the past 50 years, the Mississippian play is commercially proven. However, production remains somewhat sporadic for reasons that are not clear.

The objective of this research is to quantify and analyze how geological attributes derived from well logs relate to production for the Mississippian play. In the process of reaching this objective, five tasks are addressed: (1) define a workflow for building a project for the Mississippian play, (2) define a workflow for efficient quality control, (3) quantify correlations between vertical well log attributes and production, (4) determine whether horizontal well data correlations follow the same trends as those of the vertical data, (5) apply these results to the Mississippian play. Through achieving this objective, this research provides a blueprint for using older vertical well log data from a region to help optimize the return on investment (ROI) for modern horizontal drilling.

1.2: Study Area

The focus of this study is Woods County, Oklahoma. Woods County is located in the northwest part of Oklahoma and lies in the heart of the Mississippian play (Figure 1). Woods County is bordered by Kansas to the north and the Cimarron River to the west and south. To the east, Woods County is bordered by Alfalfa and Major Counties. Although the first well drilled in Woods County was completed in 1916, the first oil production did not occur until 1953 when the No. 1 Dyer was completed in the Simpson and Arbuckle groups in Yellowstone field (Bowles, 1959).

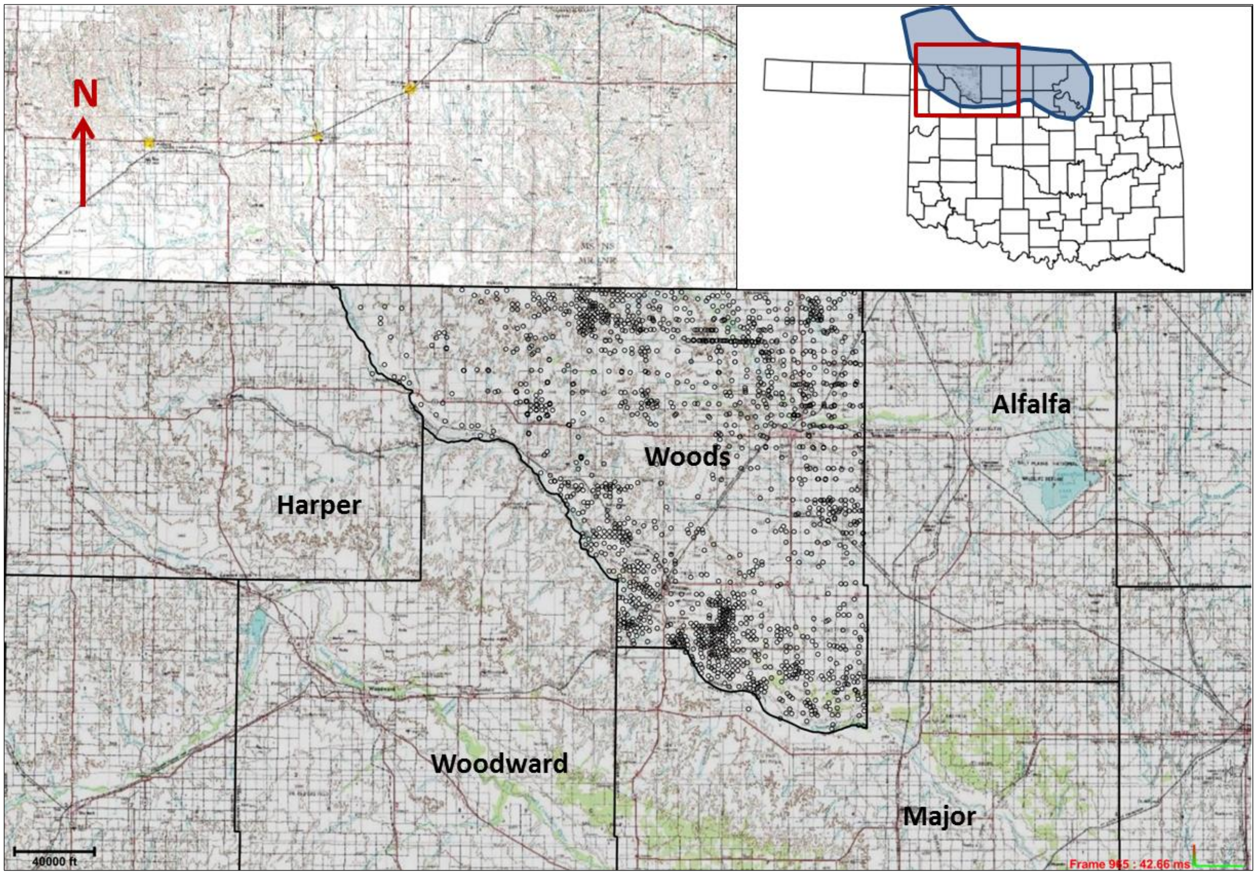


Figure 1: Well surface locations in Woods County. Inset displays approximate Mississippian play boundary (blue) and the map area (red box) relative to the Oklahoma county map.

The surface of Woods County consists of Permian strata that exhibit several local structural folds (Bowles, 1959). Although a major portion of these features result from dissolution of underlying Permian evaporites (Clifton, 1926), some of these features reflect deep-seated anticlinal folds (Bowles, 1959).

Woods County was chosen for study because well logs and production data for both vertical and horizontal wells are abundant. For this research, a project was created using Drillinginfo's Transform software (https://www.transformsw.com). Transform provides the ability to both interpret geology and run statistical analyses in the same platform using the geological data and production data imported from Drillinginfo.

1.3: Overview of the Mississippian Play

The Mississippian play is one of the newer horizontal plays in the United States (Darbonne, 2011), although reports vary regarding the first modern horizontal well. These range from a Spyglass Energy well in 2003 (Darbone, 2011) to a Chesapeake Energy well, the Howell 1-33H in northeast Woods County, in 2007 (Manger, 2013), which has produced more than 115,159 barrels of oil and 243,733 MCF of gas (Drillinginfo, 2013).

There are many reasons why this play has the interest of operators. Drilling the shallow horizontal wells is relatively inexpensive, some costing less than $2.5 million per well (Darbonne, 2011). Hydraulic fracturing (fracing) is usually done with fresh water, acid, and nearby sand from the Ottawa Formation. Lower horsepower rigs are adequate compared to those needed for deeper, tighter unconventional plays (Darbonne, 2011). Additionally, years of conventional drilling in the region resulted in development of infrastructure and compilation of abundant well log data for subsurface analysis. Most importantly, with West Texas Intermediate crude prices hovering near $100 per barrel as of this date, the play is economically rewarding.

Despite all the desirable attributes of the Mississippian play, there is still a lack of understanding regarding what is causing the production to be somewhat sporadic. Carbonate reservoir rocks are usually multiple-porosity systems creating petrophysical variability (Mazzullo and Chilingarian, 1992), such as lateral heterogeneity in the Mississippian play.

Woods County lies along the northern shelf of the Anadarko Basin (Figure 2). The Anadarko Basin is a deep sedimentary basin in the cratonic interior of the United States with sedimentary rocks as thick as 40,000 ft (~12,000 m) along the axis (Johnson, 1989). The basin is bounded on the east by the Nemaha uplift, on the southeast by the Arbuckle Mountains and Ardmore Basin, and on the south by the Wichita Mountains and Amarillo Uplift. The basin shoals onto a broad shelf to the west and north (Figure 2).

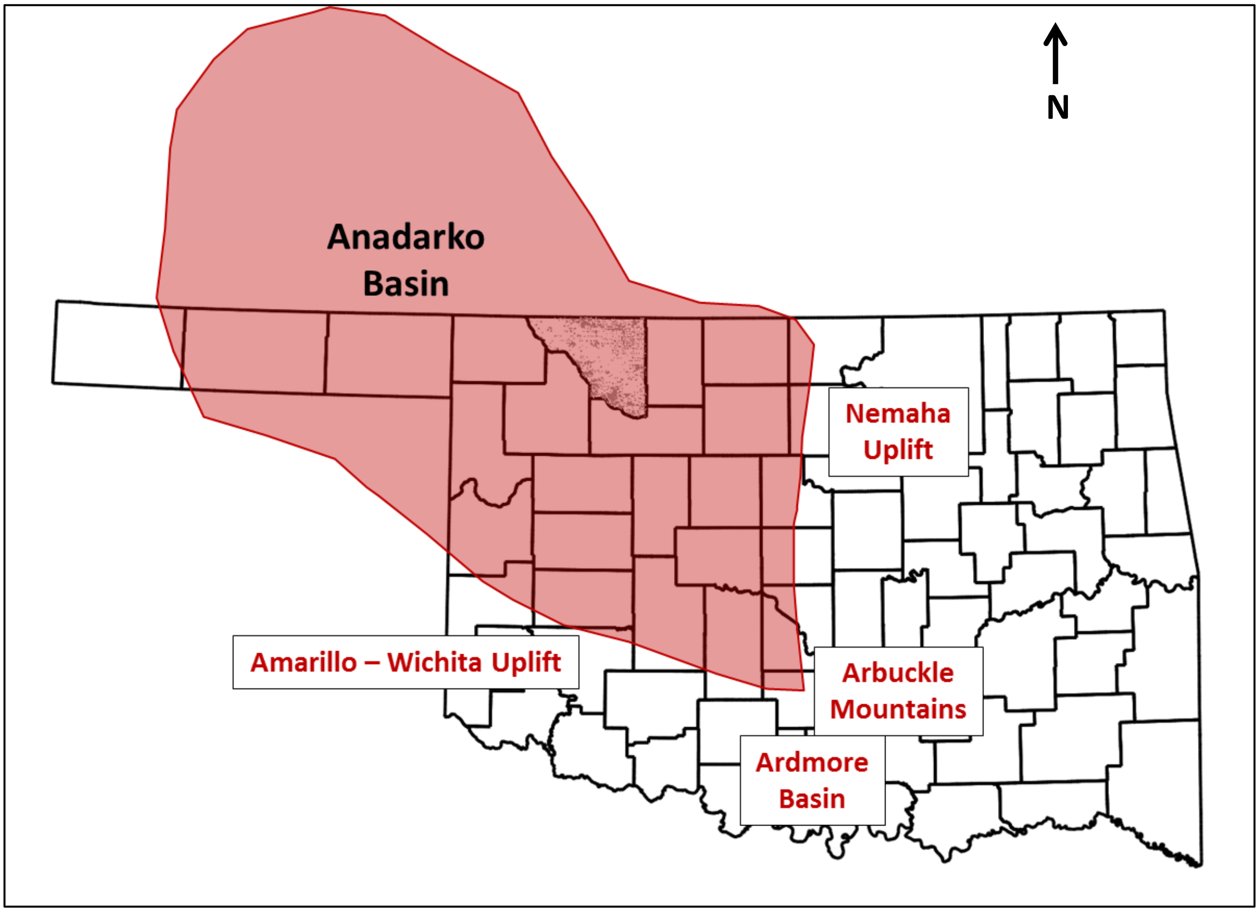
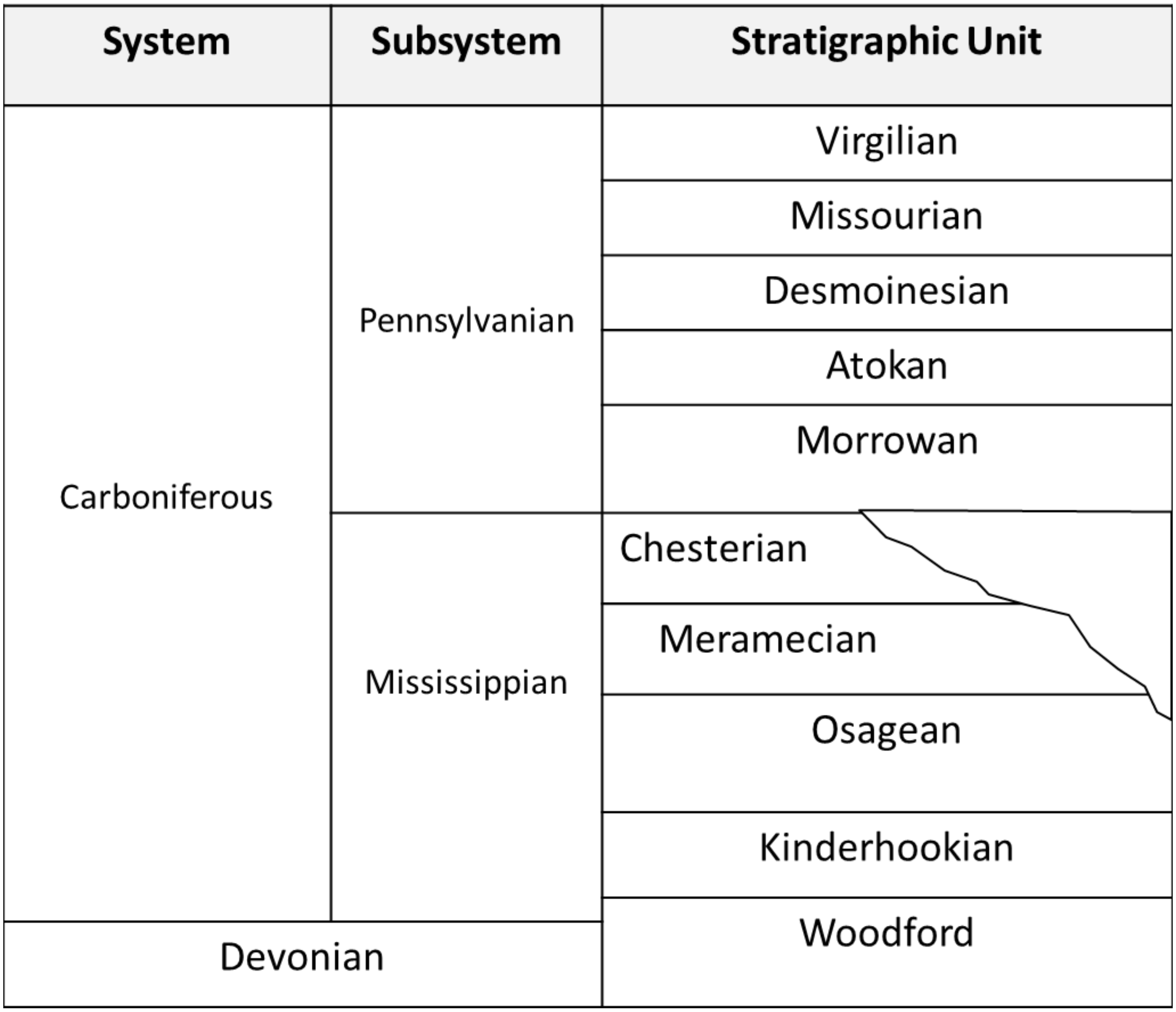


Figure 2: A generalized outline of the Anadarko Basin

Geochemical studies show that the source of the oil and gas in the Mississippian play is most likely the Woodford shale (Ball *et al.*, 1991). In northern Oklahoma, the Woodford entered the oil window in late Triassic time (Ball *et* al., 1991). The post-depositional erosion and diagenesis of the Mississippian along with Pennsylvanian deposition created the seal for the Mississippian play (Ball *et al.*, 1991). A generalized stratigraphic column for the northern shelf of the Anadarko Basin shows this petroleum system (Figure 3).



<table>
<tr><th>System</th><th>Subsystem</th><th>Stratigraphic Unit</th></tr>
<tr><td rowspan="9">Carboniferous</td><td rowspan="5">Pennsylvanian</td><td>Virgilian</td></tr>
<tr><td>Missourian</td></tr>
<tr><td>Desmoinesian</td></tr>
<tr><td>Atokan</td></tr>
<tr><td>Morrowan</td></tr>
<tr><td rowspan="4">Mississippian</td><td>Chesterian</td></tr>
<tr><td>Meramecian</td></tr>
<tr><td>Osagean</td></tr>
<tr><td>Kinderhookian</td></tr>
<tr><td colspan="2">Devonian</td><td>Woodford</td></tr>
</table>

Figure 3: Devonian to Carboniferous stratigraphic column on the northern shelf of the Anadarko Basin (modified after Smith, 1989). For purposes of this research, informal nomenclature is being used for the Mississippian stratigraphic units in order to be consistent with reported well data and to separate Chesterian production from the remaining Mississippian stratigraphic units.

1.4: Mississippian Geology of Northern Oklahoma

A solid understanding of the reservoir geology is necessary in order to guide statistical analysis. The informal nomenclature used in this section to define rocks in the Mississippian subsystem is not based on temporal boundaries. These units, consisting of the Chesterian, Meramecian, Osagean, and Kinderhookian, are not related to any temporal research such as biostratigraphy studies. In this county, the majority of production data is reported as producing from either the Chesterian or an aliased subzone containing the Meramacian, Osagean, and Kinderhookian. This nomenclature is being used in this study so that reported production reservoirs can be matched as closely as possible to well log zones. Also to preserve consistency with previous work, rock descriptions will be based on published descriptions and will not refer to any standardized rock color chart.

Rocks of the Chesterian are present in the southwest portion of the county, but are absent in the northeast portion of the county primarily due to post-Mississippian erosion (Bowles, 1959). The overall thickness of the Mississippian in Woods County ranges from approximately 1400 ft (~430 m) in the southwest to less than 400 (~120 m) feet in the northeast (Bowles, 1959). The cross-section in Figure 4 illustrates the thinning and disappearance of the Chesterian, the overall thinning of the Mississippian, and the decreasing depth from the southwest to the northeast.

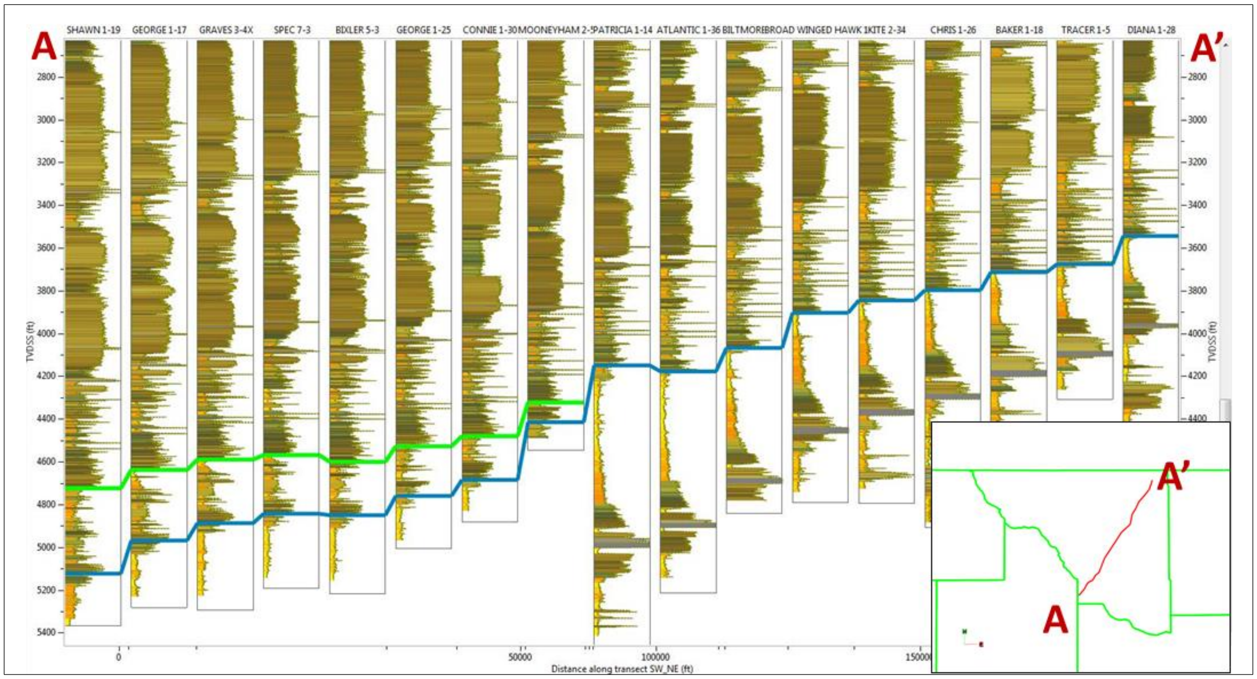


Figure 4: Cross-section built using Drillinginfo's Transform software. The Chesterian top is displayed in green, and the Meramecian/Osagean aliased top is displayed in blue. Cross-section illustrates that the structure shallows from SW to NE. The Chesterian thins out towards the center of Woods County.

Chesterian rocks may be divided into three lithologic subfacies (Bowles, 1959). The uppermost type contains buff to gray, medium-crystalline, oolitic, dolomitic, fossiliferous, porous limestones. These limestones are separated by varying shades of red, green, brown, and gray shales with thin beds of tan sandstone. The middle subfacies consists of gray, fine- to medium-crystalline, arenaceous, fragmental, oolitic, porous limestone with interbedded shale. The lower subfacies is mostly reddish-brown, gray, and greenish-gray shales. There is a basal section of off-white to gray siltstones and fine-grained sandstones. This lower most fine-grained unit is identified on a gamma log by a relatively high gamma ray signature. Northward thinning and eventual disappearance of the Chesterian is the result of erosion during Early Pennsylvanian time (Bowles, 1959).

The Meramecian series primarily consist of gray-white to tan, medium crystalline, fossiliferous limestones. These become dolomitic with interbedded light colored chert at the base (Bowles, 1959). Porosity of the Meramecian increases in the northwestern portion of Woods County (Bowles, 1959).

Osagean rocks are dolomitic and cherty limestones that are dark gray and brown. High density, rare glauconite grains, and gray to bluish-gray chert are characteristics of the Osagean series (Bowles, 1959).

The Kinderhookian is divided into two zones. The uppermost zone contains approximately 50 ft (~15 m) of dark gray, blocky, hard, calcareous shale underlain by a light gray to tan, fine crystalline, sucrosic limestone (Bowles, 1959). The lower part of the Kinderhookian contains dark brown, carbonaceous, blocky Woodford Shale with plant spores scattered throughout.

The Mississippi “chat” is an informal term used to define facies common in certain areas of the Mississippian play. This occurs at the unconformity between the Pennsylvanian and Mississippian subsytems and consists of a weathered and/or detrital interval of highly porous or hard, tight chert (Rogers, 2001).

CHAPTER 2:
METHODOLOGY

2.1: Well Location Data Import and Quality Control

A project was created in Transform software using data from Drillinginfo. 1,655 well locations in Woods County with completion dates since January, 2000 were imported into the project. Using more recent well locations helps minimize the effects of technological drilling advancements over time. Once the well location data were imported, the well locations were displayed over a live Bing web service map in Transform to verify wells were in reasonable locations and not in places such as roads or bodies of water; in many cases, drilling pads were visible in the map data (Figure 5). This provides confidence in the coordinate system conversion during import.

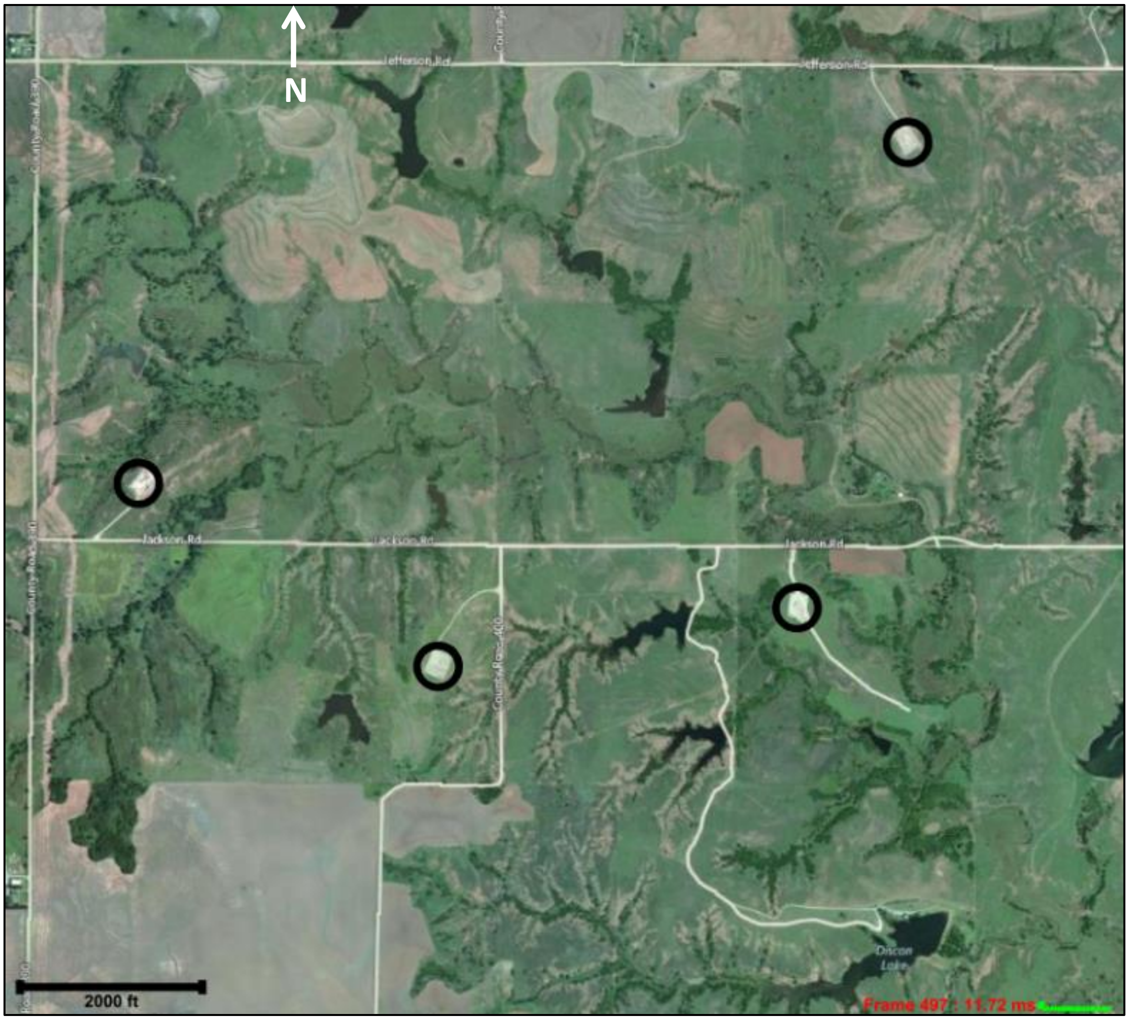


Figure 5: Well surface locations represented by black circles are displayed over a live Bing map using Transform software. Drilling pads, still visible from the live map, confirm that the well locations are in the correct place from a map view perspective.

Next a digital elevation model (DEM) from the USGS National Map website (http://www.nationalmap.gov/) was imported. The DEM was rendered in a 3D scene using kelly bushing (KB) elevations. This provides a visual check of the well location accuracy from a vertical perspective (Figure 6). Erroneously reported KB values were identified and updated to the KB values from the well log headers using this procedure. Because well log depths are referenced from KB elevation values in this project, this quality control step helps to more accurately define the geological structure of Woods County.

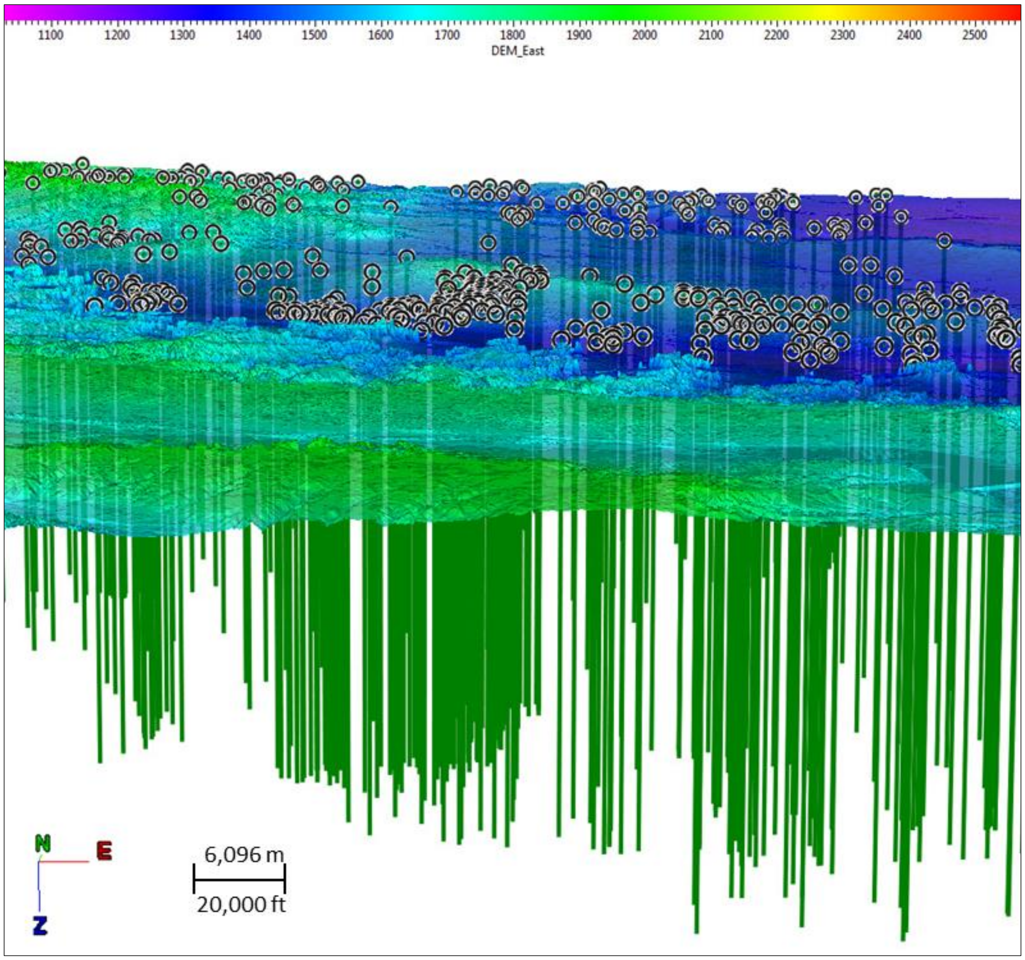


Figure 6: Well surface locations and wellbores in a 3D view with the digital elevation model. The surfaces locations, referenced as kelly bushing elevation values, are in reasonable locations when compared to the digital elevation model. The image has been vertically exaggerated by a ratio of 9:1.

2.2: Well Log Import and Picking Tops

Vertical well log LAS files for Woods County were imported for 518 wells based on availability from Drillinginfo as of September, 2013. The imported wireline log curves include gamma ray, caliper, resistivity, density, density porosity, and neutron porosity. These curves were used to identify (pick) the depth of the uppermost portion (top) of the formations. For purposes of matching production to the correct stratigraphic units on the well logs, the Meramecian, Osagean, and areas of Mississippi “chat” are aliased together under the informal Mississippi “lime” nomenclature. Chesterian units, where present, were picked separately.

This resulted in 244 Chesterian tops, 479 Mississippi “lime” tops, and 137 Woodford tops (e.g., Figure 7, Appendix A, Appendix B). Picking formation tops allows for definition of zones for more detailed geological analysis and consistency for deriving data used in the correlations.

This study focuses on the lithology and production from Mississippi “lime” units along with the Mississippi “chat” where it exists near the Pennsylvanian unconformity. In most areas of the county the Meramecian is present. Where the Meramecian is absent the Osagean or the Mississippi “chat” represents the uppermost portion of the study area. This grouped zone appears to be the focus of most past and current drilling activity. However, where the Chesterian is present, the Mississippi “lime” was picked below the lower most, fine-grained sequence of the Chesterian.

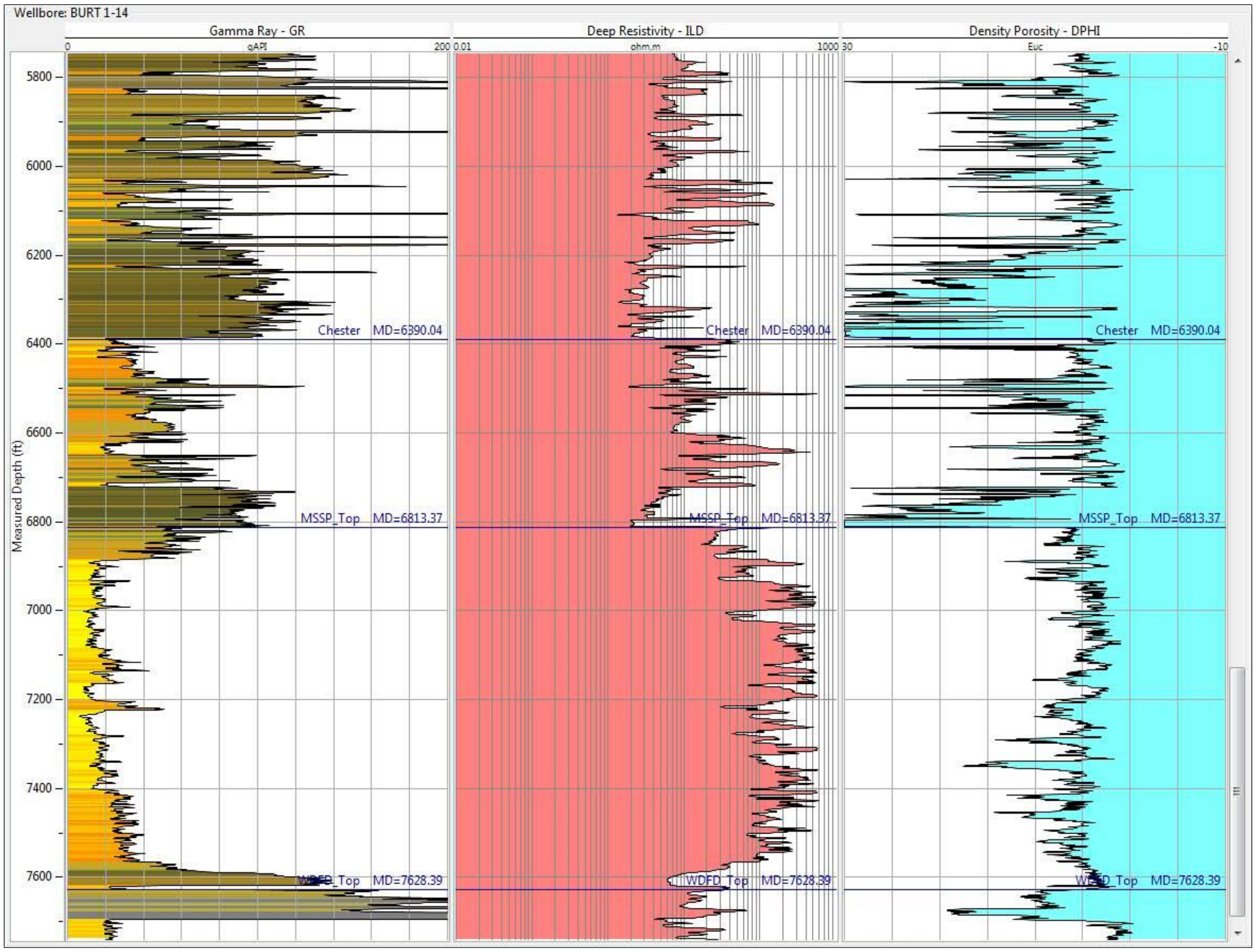


Figure 7: Tops picked from the imported LAS files. Late Mississippian Chesterian tops were picked where available. For purpose of this study, the Meramecian, Osagean and areas of "chat" near the Pennsylvanian-Mississippian unconformity are grouped under an informal Mississippi "lime" alias. This is represented in the image as lithology below the MSSP top and above the WDFD top. Where the Chesterian is present, the MSSP top was picked under the lower most fine-grained sequence of the Chesterian, which is identified from the relatively high gamma ray signature as seen in the image above the MSSP pick.

The large discrepancy between the number of picked Mississippian and Woodford tops results from a majority of the vertical wells not drilled or logged beyond the Mississippian subsystem. Well log images known as raster images (rasters) do not contain high resolution digital data points, but they provide a visual representation of the well logs for analysis. To obtain better coverage of Woodford tops and thickness, the Woodford top and base was picked on 32 rasters (e.g., Appendix C) throughout the county (Figure 8). For some portions of the county, rasters containing the Woodford zone were also sparse, but the rasters did help fill in the gaps of poor coverage areas. The main purpose of picking the Woodford top and base is to create a Woodford isopach across Woods County. For this reason, two well logs located outside of Woods County were included to help create a more accurate isopach.

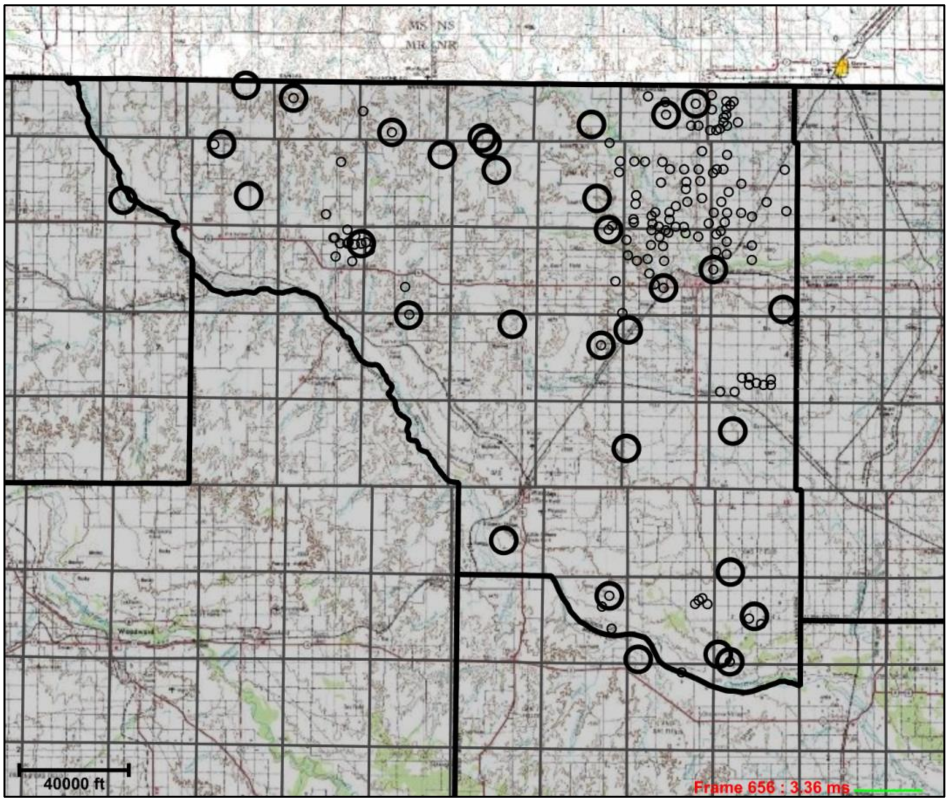


Figure 8: Small well location surface symbol sizes represent locations where a Woodford top and base were picked from LAS files. Large symbols represent locations where raster images were used to help fill in areas of poor coverage. Some of the raster images are for wells outside the county to assist in creating a Woodford isopach.

2.3: Well Zone Creation and Quality Control

For this study the zone of interest is defined as the upper 200 ft (~60 m) of the Mississippian, not including the Chesterian series. By doing so, the Mississippian lithology directly under the seal created from the Pennsylvanian or the fine-grained unit of the Chesterian can be compared to production. As stated earlier, it is within this zone that well log attributes were extracted. These extractions include porosity measurements, average gamma ray, and average deep resistivity. Where available on well logs, the thickness of the Woodford was extracted as this is the prominent source rock in the region.

Although the upper 100 ft (~30 m) produced well log and production relationships that resembled those of the upper 200 ft, the upper 200 ft interval seemed to define the relationships best. As seen from the cross-section in Figure 9, there is a thickness change of approximately 500 ft (~150 m) from the Mississippi "lime" aliased top to the Woodford top throughout Woods County. Based on the thickness variations and the limited number of samples available with well log information down to the Woodford, it was not considered appropriate to use the entire interval for well log extractions.

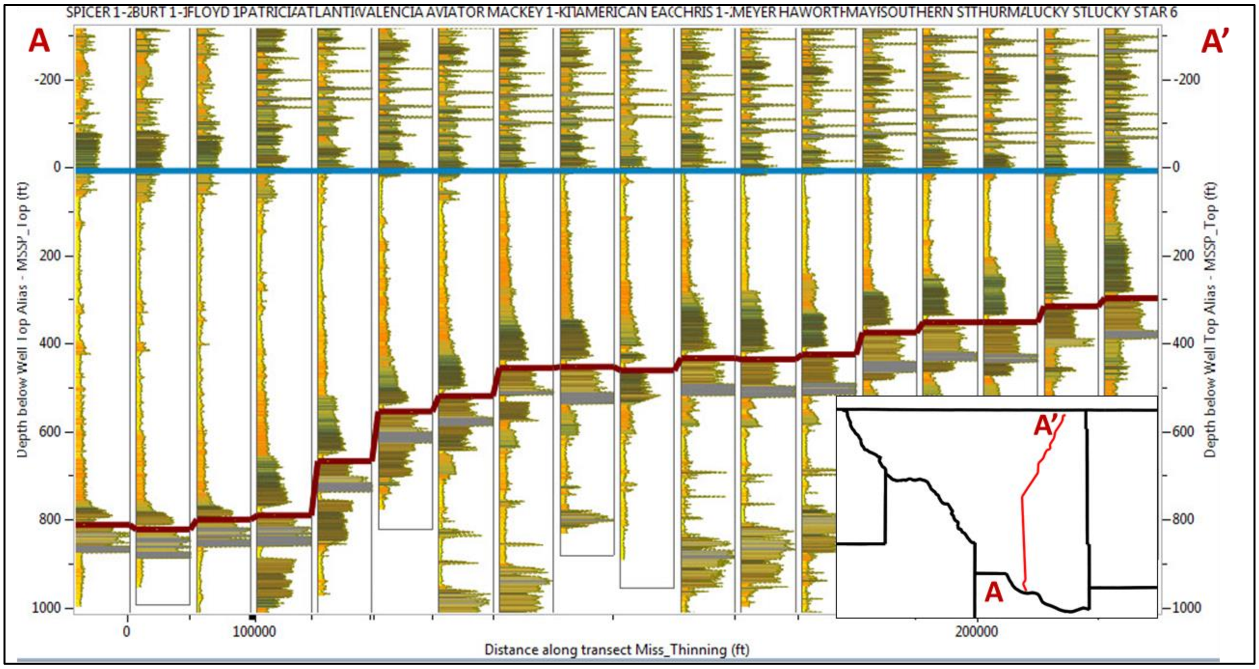


Figure 9: Cross-section is flattened on the Mississippi “lime” top (blue). The Woodford top is in red. The thinning of the Mississippian interval from the south to the north can be seen.

The digital well logs in the project are sampled at every 0.5 ft (0.15 m). Because the well logs are being compared to production, the individual values contained within the upper 200 ft of the Mississippi “lime” zone were cross-plotted to check for outliers. Two examples of these well log cross-plots are given (Figures 10-11).

Figure 10 shows a cross-plot of all wells with density porosity and deep resistivity curves in the interval of interest. Each well is represented by a different color. The density porosity values are on the x-axis and the deep resistivity values are on the y-axis. From the highlighted polygon we see that only one well, the Rex 1-16, contains deep resistivity readings above 2,500 ohm-meters. With readings topping out near 15,000 ohm-meters, this well is treated as a statistical outlier with regards to deep resistivity. These values of more than 6 times the readings in any other well appear to be the result of faulty measurement readings or tool calibration.

Figure 11 shows the neutron porosity curve on the x-axis and the caliper curve on the y-axis. This reveals a range of porosity values near 30 percent that appear related to a washout zone from the corresponding caliper readings showing a borehole diameter of greater than 12 inches. Based on the results of this cross-plot, the Benn Smith Trusts 1-34 well was not included for statistical analyses that involve porosity.

The use of well log cross-plots in the zone of interest provides a quick way to check for values that could adversely affect the statistical analysis. In the case of the caliper cross-plotted against the neutron porosity, insight to the origin of the erroneous values, borehole washout, is identified.

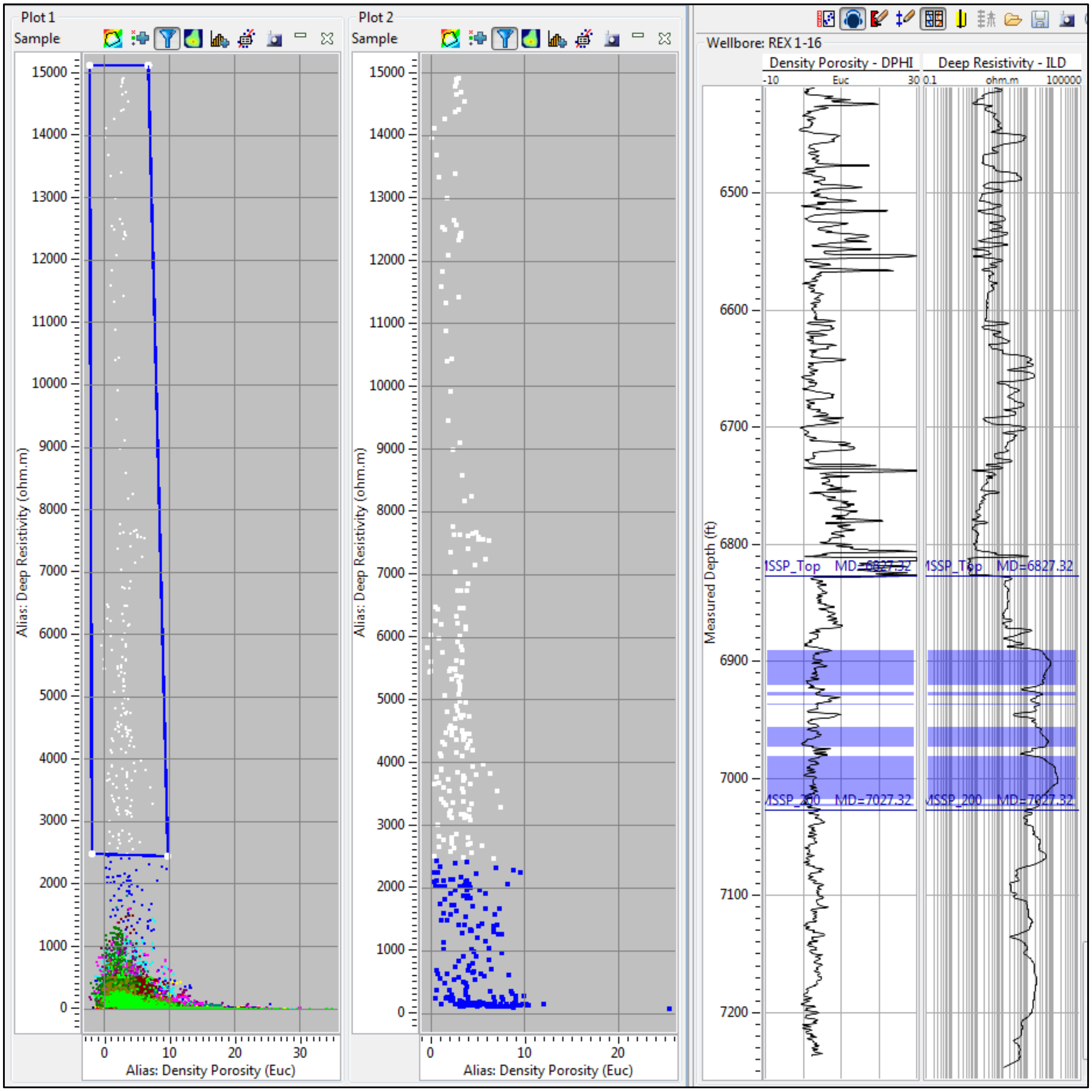


Figure 10: The cross-plot on the left shows all values of density porosity (x-axis) and deep resistivity (y-axis) within the upper 200 ft (~60 m) of the Mississippi “lime”. The cross-plot in the middle of the image shows how only the Rex 1-16 had the outlying resistivity readings. The curves on the right portion of the image highlight the outlier resistivity readings for the Rex 1-16. Each color represents data for a single well.

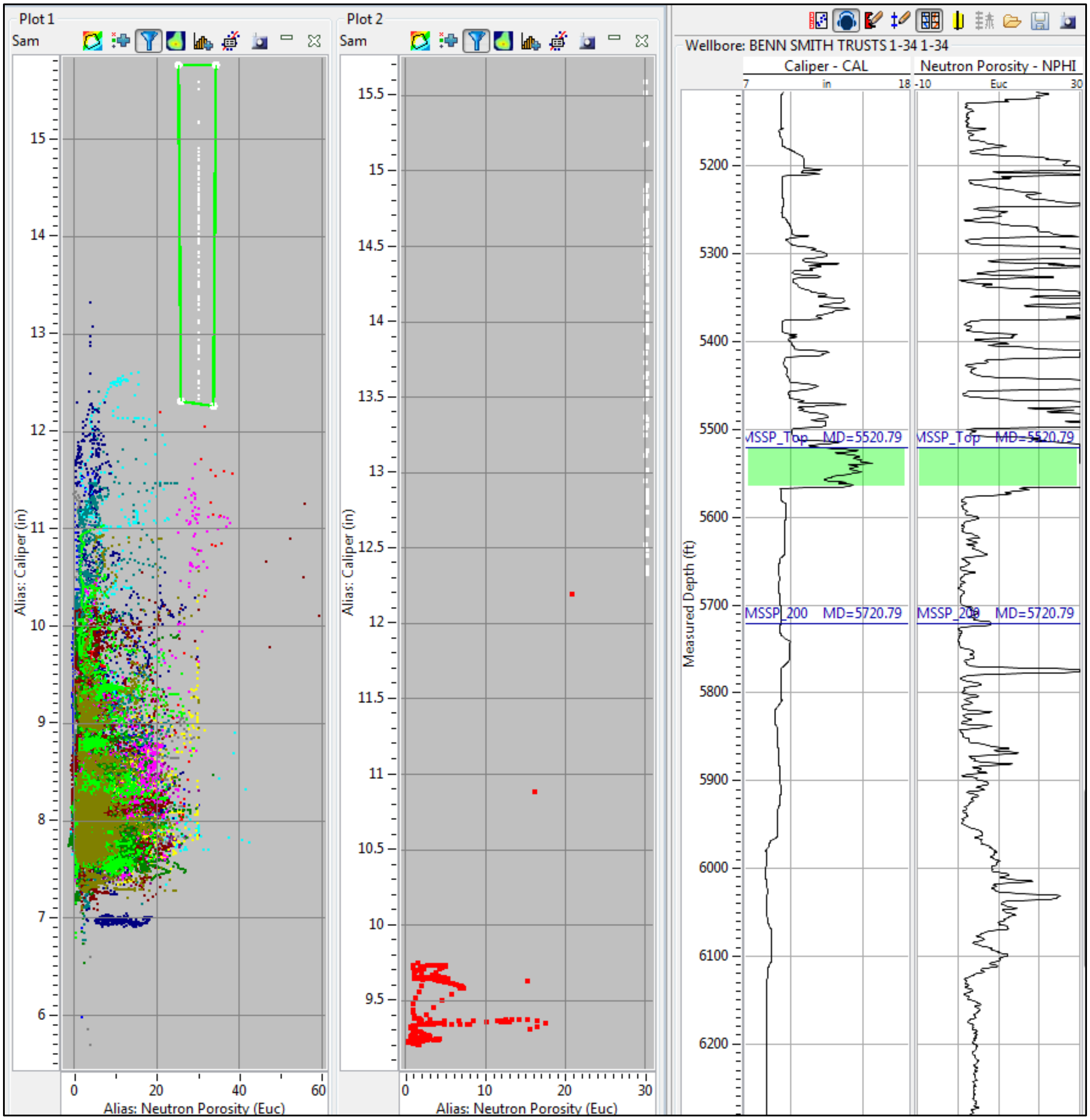


Figure 11: The cross-plots show values of neutron porosity (x-axis) and the caliper (y-axis) within the upper 200 ft (~60 m) of the Mississippi "lime". The middle cross-plot and the curves on the right highlight the erroneous values that were present in the Benn Smith Trusts 1-34 well. Each color represents data for a single well.

2.4: Production Import and Quality Control

Production data attributes were imported based on availability from Drillinginfo for 1,085 Mississippian wells. These include total oil accumulations (cums), gas cums, and barrels of oil equivalent (BOE). These attributes were duplicated for intervals of initial 6 month, 12 month, and 2 year values. The well type from Drillinginfo was imported as horizontal or vertical. Further, wells producing from the Chesterian according to Drillinginfo were separated from wells producing from zones defined in the Mississippi “lime” alias. Grouping production data by lithology helps ensure consistency in comparing the production values to the correct zone on the well logs.

When comparing log attributes to production values, there is a balance between using more stable long term production metrics versus losing sample size. Due to inherent differences between well types, it is not reasonable to compare production from vertical wells to production from horizontal wells. For this study, vertical wells and horizontal wells are treated as separate populations. Being that the most recent wells drilled in Woods County are horizontal wells, significantly more samples with shorter term initial production for the horizontal wells are expected. Inversely, the lack of recent vertically drilled wells should allow for the use of longer term production metrics without significantly reducing the vertical well sample size.

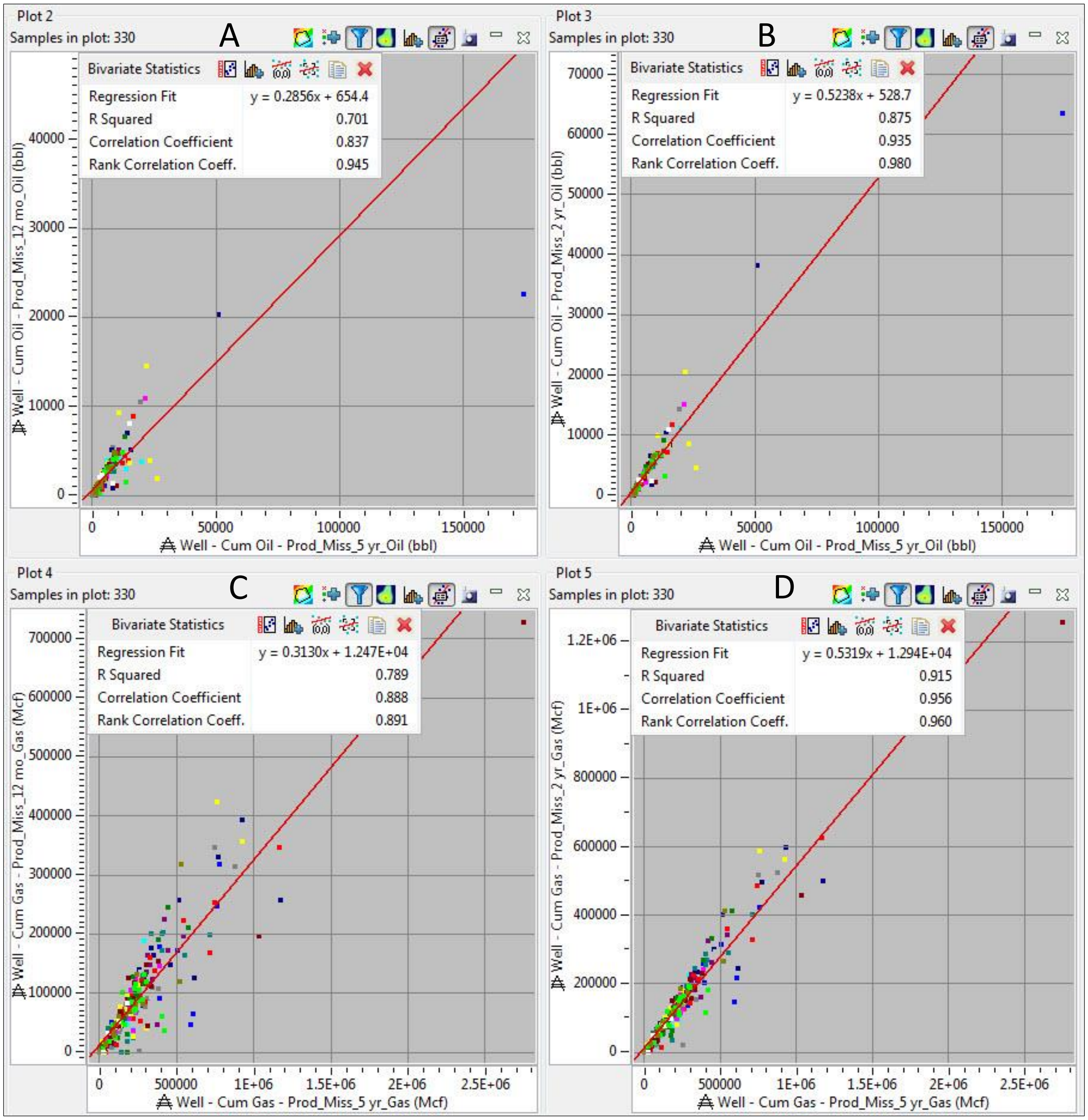
It is important to be as diligent as possible when comparing production attributes to the proper zones on the well logs. For this study, there were some wells that produced from the Chesterian which is present only in the southwest portion of the county. However there are not enough useable Chesterian samples to yield statistical correlations. For this reason, production defined by regulatory filings as Chesterian is excluded from the analysis in this study. There were also wells containing duplicate production values. These wells most likely represent a shared pipeline when reporting production and have been removed from the analysis. Even though some imperfections in the reported data could still be present, taking these quality control steps should help reduce much of the potential for skewed results.

CHAPTER 3:
ANALYSIS AND RESULTS

3.1: Production Variables Analysis

Figures 12 and 13 show a series of cross-plots to help choose the optimal production variables when analyzing well log attributes. These cross-plots have been separated into vertical and horizontal well populations.

Based on the values present in Figure 12, there are 330 vertical wells with initial 5 year production values in the interval of interest. When comparing the initial year and the initial 2 years of oil production to initial 5-year oil production, the correlation coefficient increases from 0.837 to 0.935. Using the same intervals for gas production, the correlation increases from 0.888 to 0.956. There are 466 eligible samples with initial 2-year production and 472 eligible samples with initial 1-year production. It is important for the production metric to be as representative as possible to long-term production because it is the baseline to which well log attributes are compared. Based on the correlations, the initial 2-year production values are used for comparisons to well log attributes for vertical wells. This allows for increasing the production data sample size from 330 to 466 while maintaining confidence that the values are consistent with long term production.



A

Bivariate Statistics	
Regression Fit	y = 0.2856x + 654.4
R Squared	0.701
Correlation Coefficient	0.837
Rank Correlation Coeff.	0.945

B

Bivariate Statistics	
Regression Fit	y = 0.5238x + 528.7
R Squared	0.875
Correlation Coefficient	0.935
Rank Correlation Coeff.	0.980

C

Bivariate Statistics	
Regression Fit	y = 0.3130x + 1.247E+04
R Squared	0.789
Correlation Coefficient	0.888
Rank Correlation Coeff.	0.891

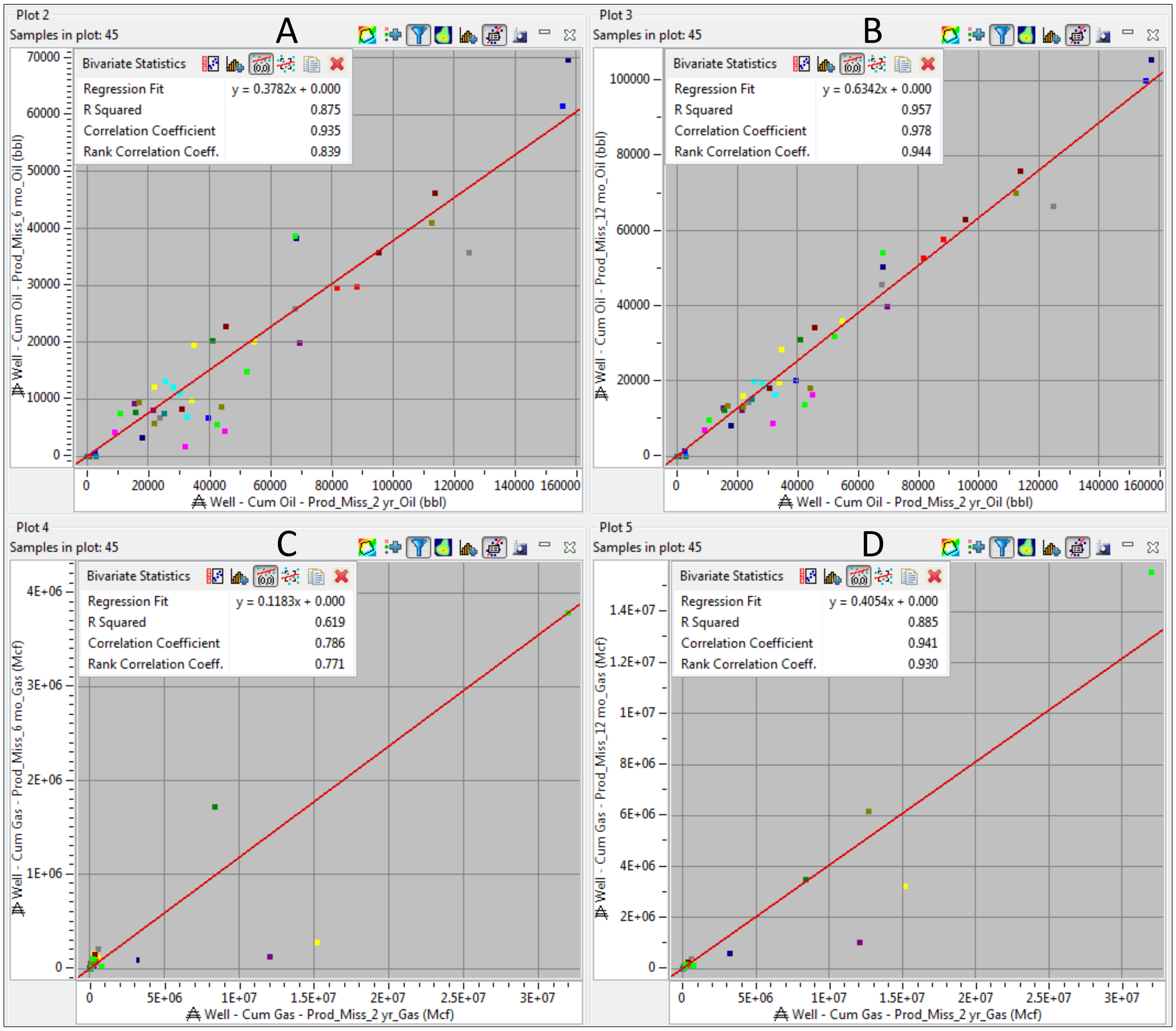
D

Bivariate Statistics	
Regression Fit	y = 0.5319x + 1.294E+04
R Squared	0.915
Correlation Coefficient	0.956
Rank Correlation Coeff.	0.960

Figure 12: Short term initial vertical well production values (y-axis) relative to 5-year values (x-axis). A) Initial 1-year oil. B) Initial 2 year oil. C) Initial 1-year gas. D) Initial 2-year gas.

For horizontal wells a different approach is taken. For eligible samples, there is only 1 well with 5-year production. There are 45 wells with initial 2-year production, 101 wells with initial 1-year production, and 158 wells with initial 6-month production. In Figure 13, cross-plots comparing initial 6-month and initial 1-year production values to initial 2-year values are displayed. For oil, the increase in correlation coefficient is from 0.935 to 0.978. For gas, the increase is from 0.786 to 0.941.

For this study, it is optimal to use initial 1-year production for horizontal wells. The sample size decreases by 57 when compared to 6-month production but there are 56 more samples than horizontal wells with initial 2-year production. The initial 1-year production values provide more than 100 samples while still maintaining confidence that the values are consistent with longer term production.



A

Bivariate Statistics	
Regression Fit	y = 0.3782x + 0.000
R Squared	0.875
Correlation Coefficient	0.935
Rank Correlation Coeff.	0.839

B

Bivariate Statistics	
Regression Fit	y = 0.6342x + 0.000
R Squared	0.957
Correlation Coefficient	0.978
Rank Correlation Coeff.	0.944

C

Bivariate Statistics	
Regression Fit	y = 0.1183x + 0.000
R Squared	0.619
Correlation Coefficient	0.786
Rank Correlation Coeff.	0.771

D

Bivariate Statistics	
Regression Fit	y = 0.4054x + 0.000
R Squared	0.885
Correlation Coefficient	0.941
Rank Correlation Coeff.	0.930

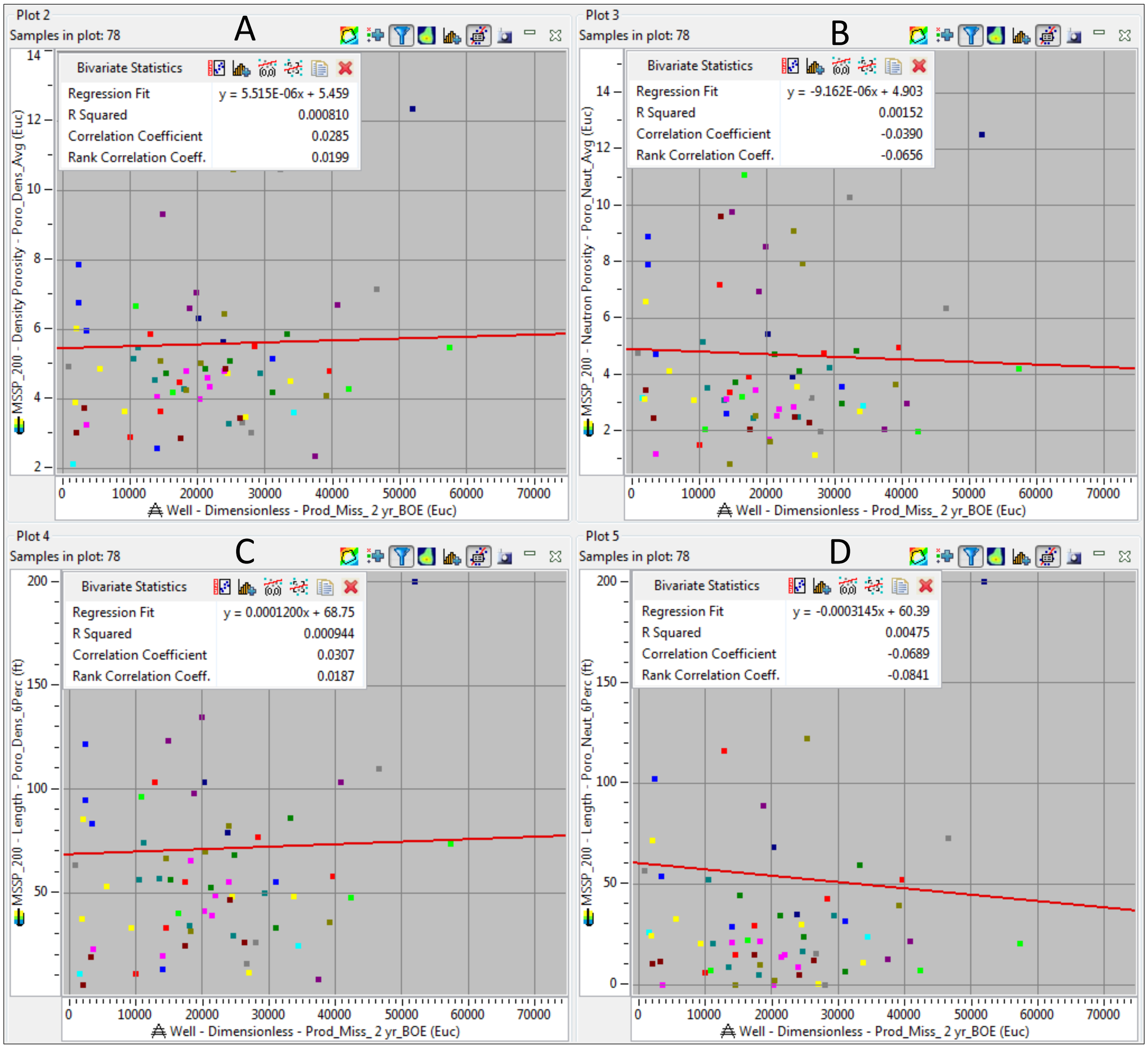
Figure 13: Short term initial horizontal well production values (y-axis) relative to 2-year values (x-axis). A) Initial 6-month oil. B) Initial 1-year oil. C) Initial 6-month gas. D) Initial 1-year gas.

3.2: Porosity Analysis on Vertical Wells

Attributes were extracted from the vertical well log data. The first sets of attributes are derived from the density porosity and neutron porosity curves. From these curves, average porosity values were extracted. Based on discussions with operators active in the Mississippian, a net thickness value of rock with greater than 6 percent porosity is commonly used during evaluation. These net thickness values were also extracted from the porosity logs. Although there are 466 wells in the county with eligible production values, only 78 of these contain porosity logs. These 78 samples will be used when comparing porosity to production.

The porosity analysis provides some interesting results. Although correlations between porosity and BOE are minimal (Figure 14), the correlations with oil (Figure 15) and gas (Figure 16) production provide some insight. There are positive correlations between porosity and oil production ranging from 0.560 to 0.569; there is a moderate inverse correlation between porosity and gas production ranging from -0.210 to -0.319.

When compared to sandstone porosity, carbonate pore shapes and sizes can be much more varied (Choquette and Pray, 1970). Although porosity can be measured from well logs, permeability can only be measured from cores or from magnetic resonance logs (Lonoy, 2006). Because this data is not available for this project, pore types cannot be identified.



Plot 2

Samples in plot: 78

Bivariate Statistics

Regression Fit	y = 5.515E-06x + 5.459
R Squared	0.000810
Correlation Coefficient	0.0285
Rank Correlation Coeff.	0.0199

Plot 3

Samples in plot: 78

Bivariate Statistics

Regression Fit	y = -9.162E-06x + 4.903
R Squared	0.00152
Correlation Coefficient	-0.0390
Rank Correlation Coeff.	-0.0656

Plot 4

Samples in plot: 78

Bivariate Statistics

Regression Fit	y = 0.0001200x + 68.75
R Squared	0.000944
Correlation Coefficient	0.0307
Rank Correlation Coeff.	0.0187

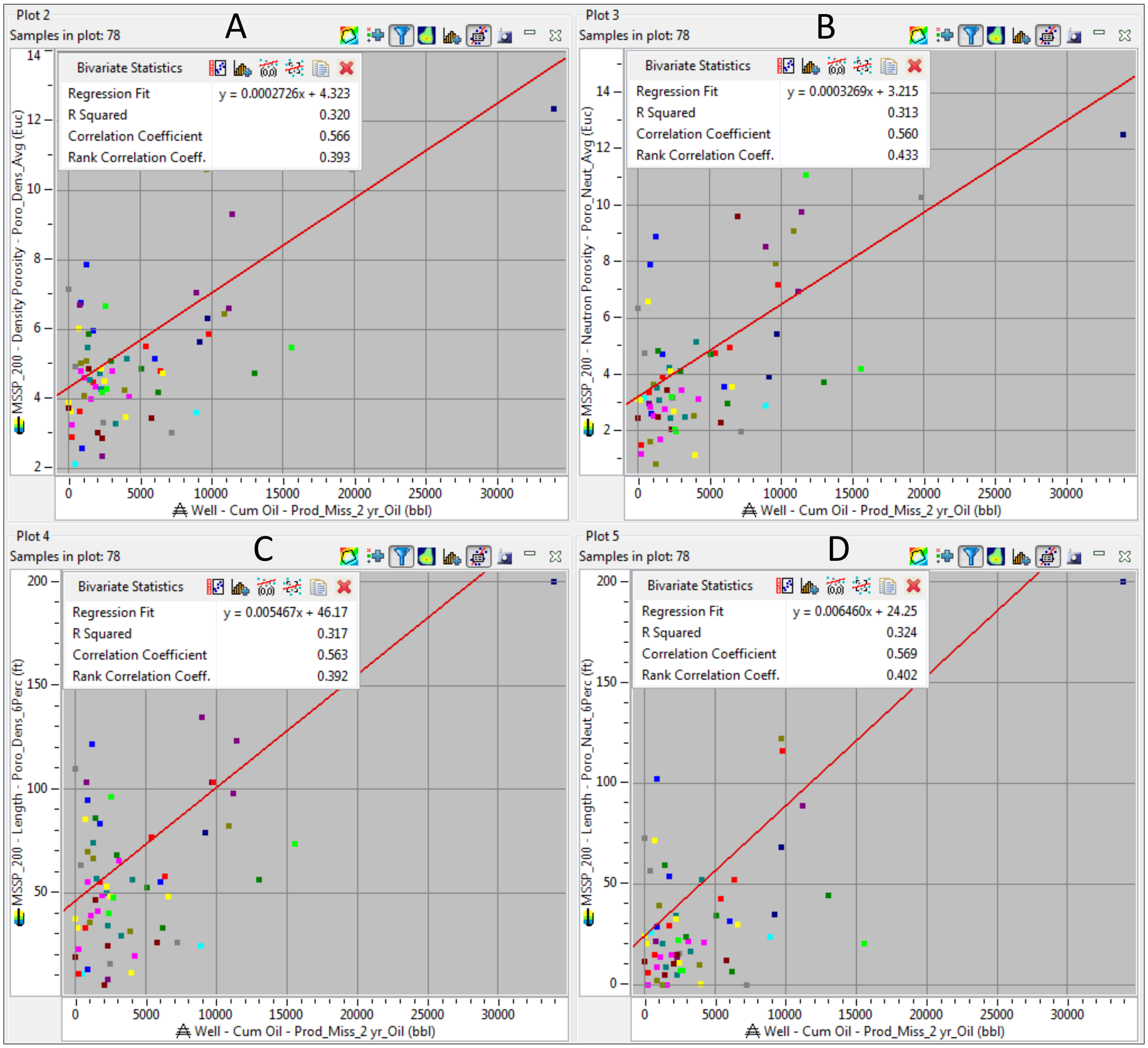
Plot 5

Samples in plot: 78

Bivariate Statistics

Regression Fit	y = -0.0003145x + 60.39
R Squared	0.00475
Correlation Coefficient	-0.0689
Rank Correlation Coeff.	-0.0841

Figure 14: Porosity relative to initial 2 year BOE production for vertical wells over the upper 200 ft (~60 m) of the Mississippi “lime”. A) Average density porosity. B) Average neutron porosity. C) Net thickness of density porosity greater than 6 percent. D) Net thickness of neutron porosity greater than 6 percent.



Bivariate Statistics (A)

Regression Fit	y = 0.0002726x + 4.323
R Squared	0.320
Correlation Coefficient	0.566
Rank Correlation Coeff.	0.393

Bivariate Statistics (B)

Regression Fit	y = 0.0003269x + 3.215
R Squared	0.313
Correlation Coefficient	0.560
Rank Correlation Coeff.	0.433

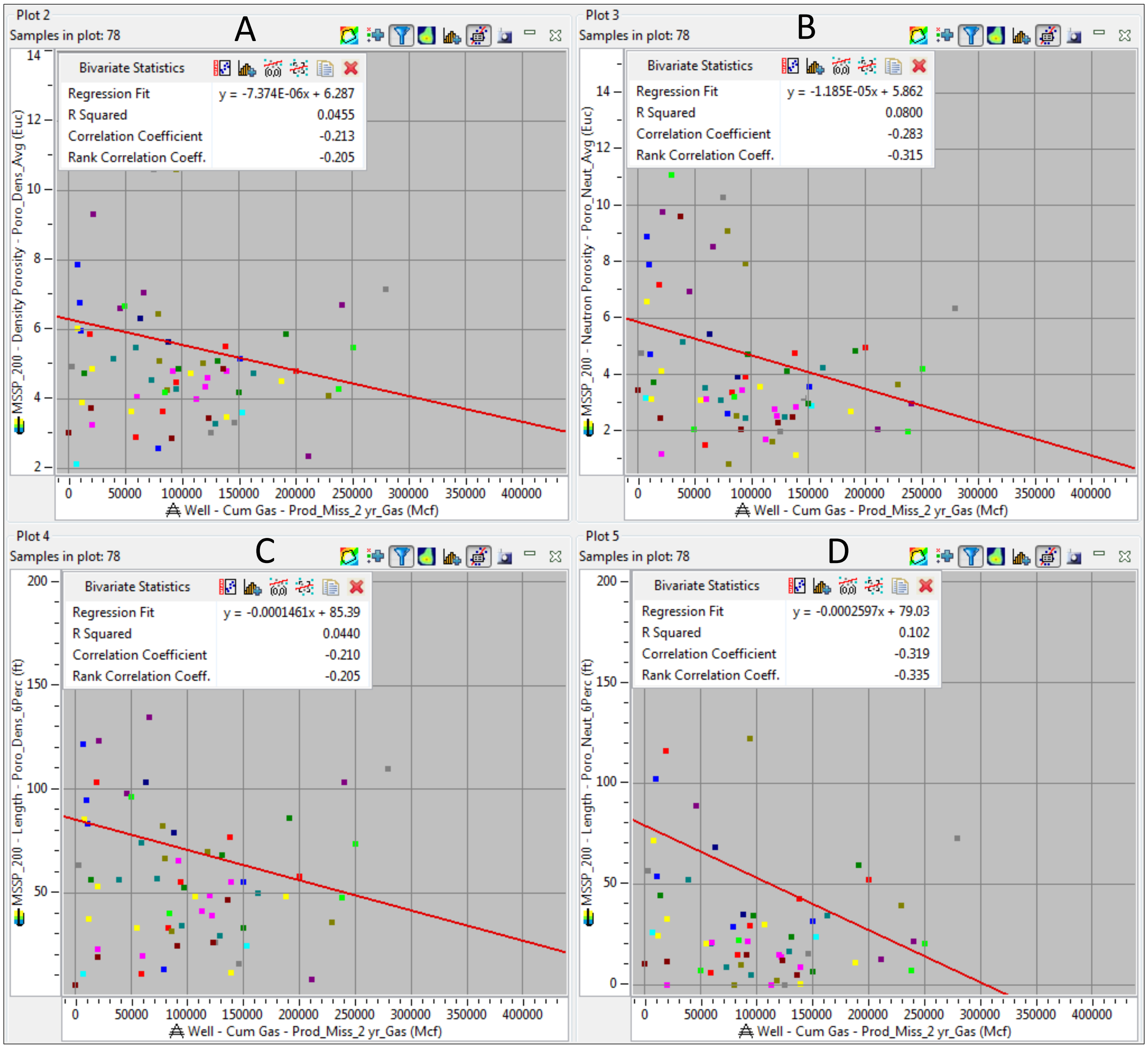
Bivariate Statistics (C)

Regression Fit	y = 0.005467x + 46.17
R Squared	0.317
Correlation Coefficient	0.563
Rank Correlation Coeff.	0.392

Bivariate Statistics (D)

Regression Fit	y = 0.006460x + 24.25
R Squared	0.324
Correlation Coefficient	0.569
Rank Correlation Coeff.	0.402

Figure 15: Porosity relative to initial 2 year oil production for vertical wells over the upper 200 ft (~60 m) of the Mississippi “lime”. A) Average density porosity. B) Average neutron porosity. C) Net thickness of density porosity greater than 6 percent. D) Net thickness of neutron porosity greater than 6 percent.



A

Bivariate Statistics	
Regression Fit	y = -7.374E-06x + 6.287
R Squared	0.0455
Correlation Coefficient	-0.213
Rank Correlation Coeff.	-0.205

B

Bivariate Statistics	
Regression Fit	y = -1.185E-05x + 5.862
R Squared	0.0800
Correlation Coefficient	-0.283
Rank Correlation Coeff.	-0.315

C

Bivariate Statistics	
Regression Fit	y = -0.0001461x + 85.39
R Squared	0.0440
Correlation Coefficient	-0.210
Rank Correlation Coeff.	-0.205

D

Bivariate Statistics	
Regression Fit	y = -0.0002597x + 79.03
R Squared	0.102
Correlation Coefficient	-0.319
Rank Correlation Coeff.	-0.335

Figure 16: Porosity relative to initial 2 year gas production for vertical wells over the upper 200 ft (~60 m) of the Mississippi “lime”. A) Average density porosity. B) Average neutron porosity. C) Net thickness of density porosity greater than 6 percent. D) Net thickness of neutron porosity greater than 6 percent.

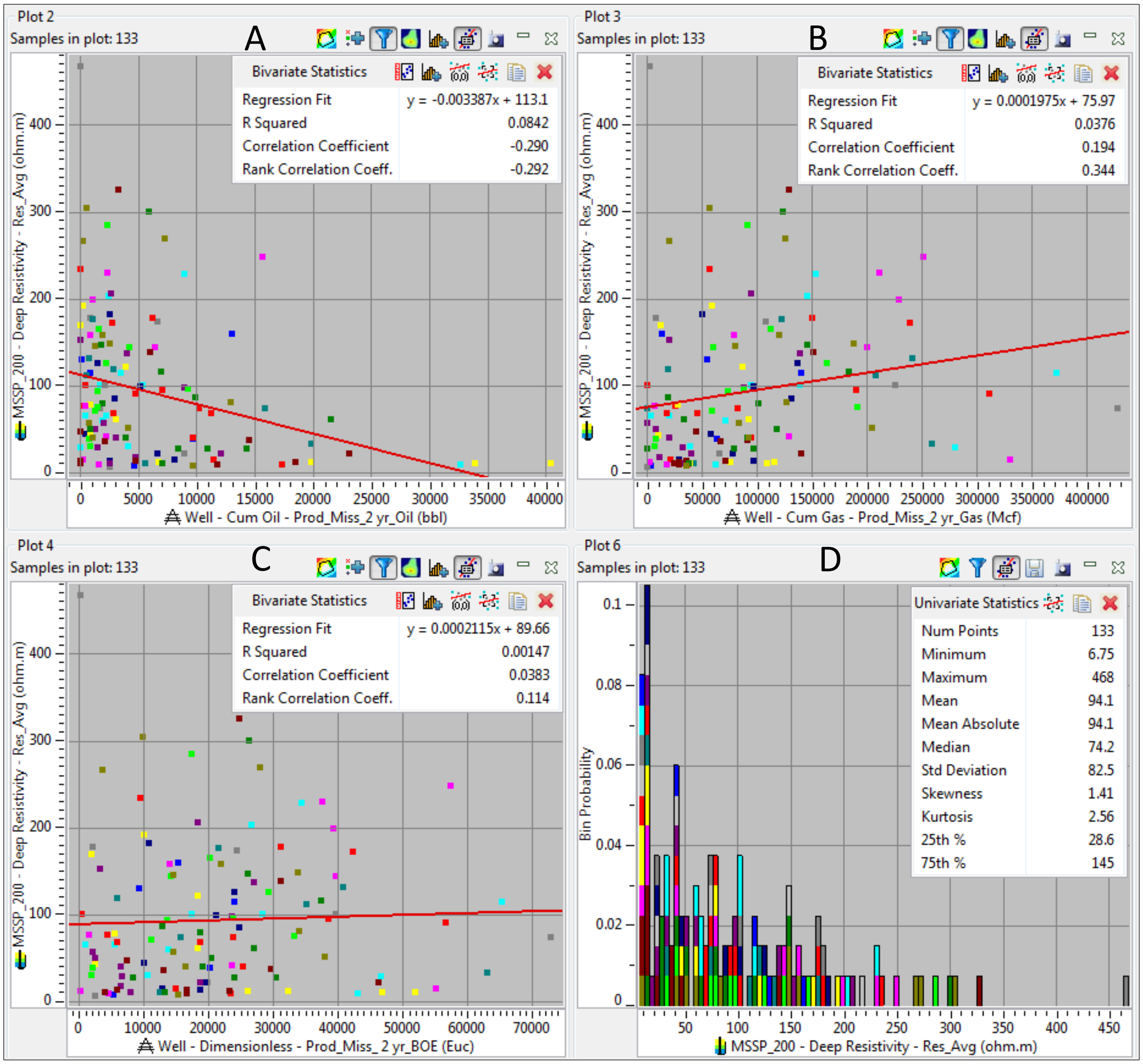
3.3: Deep Resistivity Analysis on Vertical Wells

The next attribute extracted was deep resistivity. There are 133 vertical wells with deep resistivity logs through the upper 200 ft (~60 m) of the Mississippi “lime” with eligible production values. The average deep resistivity extracted values range from 6.75 ohm-meters to 468 ohm-meters as seen in the histogram in Figure 17D. The mean value is 94.1 ohm-meters and the median value is 74.2 ohm-meters.

The cross-plots in Figure 17 do not show much correlation between deep resistivity and BOE. However there is a correlation of -0.290 between deep resistivity and oil showing an inverse relationship between these variables. There is also a correlation of 0.194 with gas showing a positive relationship between gas and deep resistivity.

Being that oil is more resistive than salt water, a positive relationship between oil and resistivity might be expected. Neutron porosity is affected by the hydrogen content of fluid in rocks (Asquith and Krygowski, 2004) and should reveal higher porosity readings than density porosity in the presence of bounded water. As stated in the porosity analysis section, pore types cannot be defined due to the absence of core data or magnetic resonance logs. However, cross-plotting average density porosity and average neutron porosity against deep resistivity not only reveals how porosity relates to deep resistivity, but provides insight to the presence of immovable bound water.

These plots show high correlations between porosity and deep resistivity (Figure 18). Further, average neutron porosity has only a slightly higher correlation of 0.025 to deep resistivity than average density porosity. Immovable bound water does not appear significant based on these results. The porosity types in this zone seem to be conducive for permeability for both oil and salt water with the salt water masking the true relationship of deep resistivity to oil.



Bivariate Statistics (A)

Regression Fit	y = -0.003387x + 113.1
R Squared	0.0842
Correlation Coefficient	-0.290
Rank Correlation Coeff.	-0.292

Bivariate Statistics (B)

Regression Fit	y = 0.0001975x + 75.97
R Squared	0.0376
Correlation Coefficient	0.194
Rank Correlation Coeff.	0.344

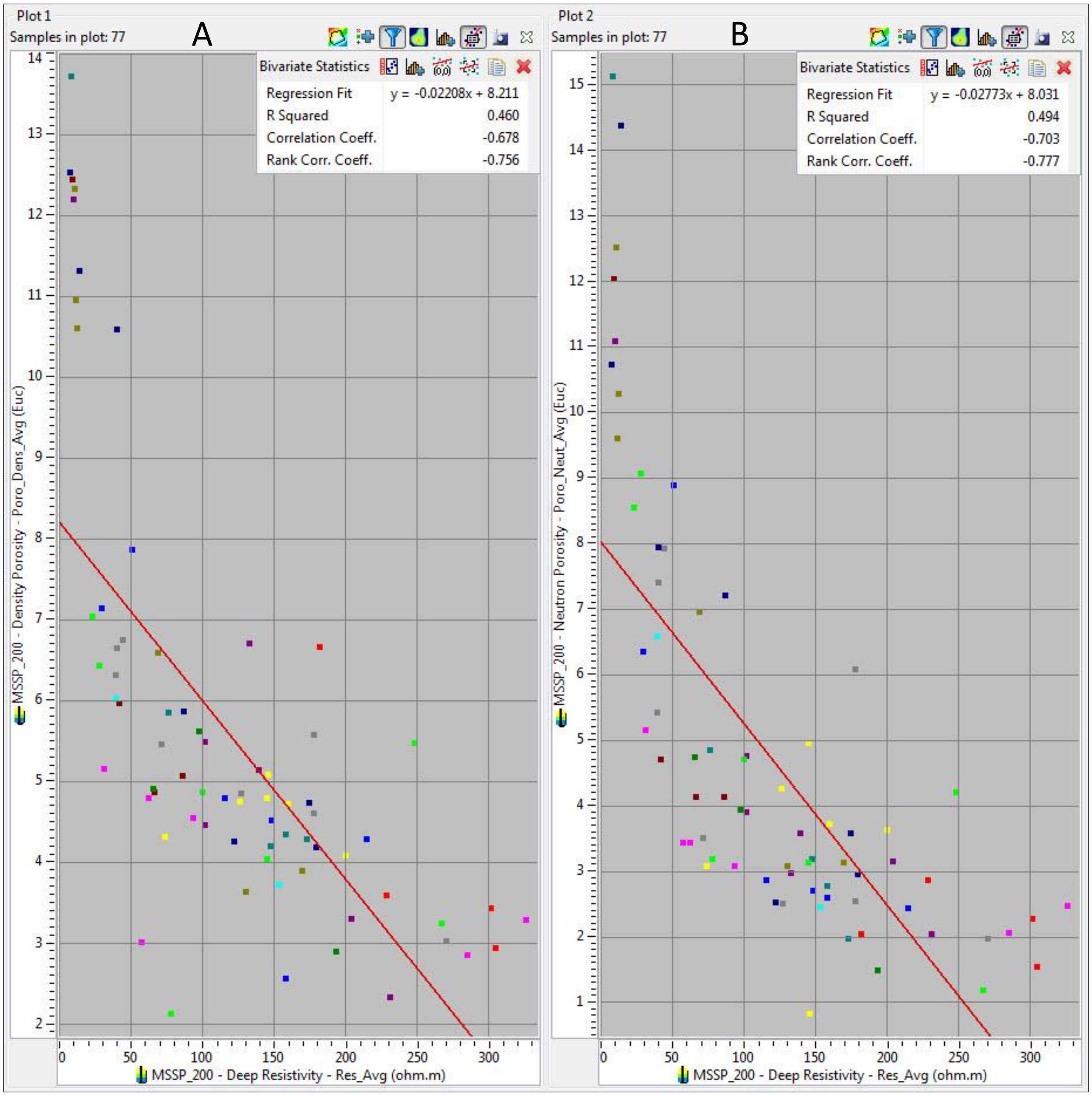
Bivariate Statistics (C)

Regression Fit	y = 0.0002115x + 89.66
R Squared	0.00147
Correlation Coefficient	0.0383
Rank Correlation Coeff.	0.114

Univariate Statistics

Num Points	133
Minimum	6.75
Maximum	468
Mean	94.1
Mean Absolute	94.1
Median	74.2
Std Deviation	82.5
Skewness	1.41
Kurtosis	2.56
25th %	28.6
75th %	145

Figure 17: Average deep resistivity plots for vertical wells. A) Deep resistivity relative to initial 2-year oil. B) Deep resistivity relative to initial 2-year gas. C) Deep resistivity relative to initial 2-year BOE. D) Histogram of average deep resistivity values.



A

Bivariate Statistics	
Regression Fit	y = -0.02208x + 8.211
R Squared	0.460
Correlation Coeff.	-0.678
Rank Corr. Coeff.	-0.756

B

Bivariate Statistics	
Regression Fit	y = -0.02773x + 8.031
R Squared	0.494
Correlation Coeff.	-0.703
Rank Corr. Coeff.	-0.777

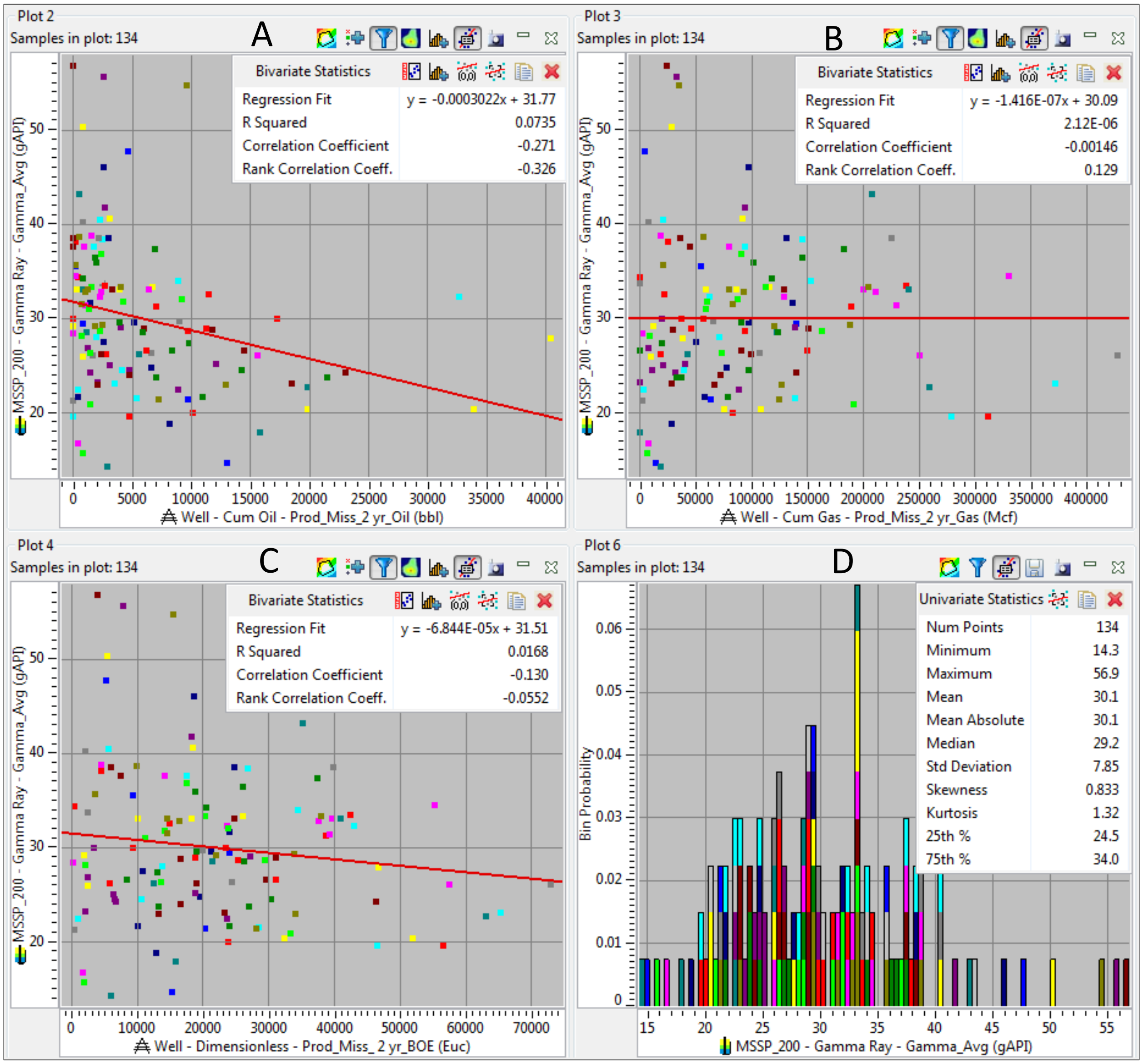
Figure 18: Similar results are displayed when comparing average density porosity and average neutron porosity to deep resistivity. A) Average density porosity. B) Average neutron porosity.

3.4: Gamma Ray Analysis on Vertical Wells

The average gamma ray was extracted over the upper 200 ft (~60 m) of the Mississippi “lime”. There are 134 samples with gamma ray curves through the interval that also have eligible production values. The average extracted gamma ray values for this interval range from 14.3 API to 56.9 API (Figure 19D). The mean value is 30.1 API and the median value is 29.2 API.

As seen from the cross-plots in Figure 19, there is a correlation of -0.130 between average gamma ray and BOE showing a slight inverse relationship between the two variables. There is a moderate inverse relationship of -0.271 between oil production and average gamma ray. For gas production, there does not appear to be a relationship with average gamma ray.

In general, increasing shale composition of rock leads to higher concentrations of radioactive material and higher gamma ray readings (Asquith and Krygowski, 2004). It is reasonable that carbonate zones with less shale content would have higher oil production as these zones are likely to contain more porosity.



A

Bivariate Statistics	
Regression Fit	y = -0.0003022x + 31.77
R Squared	0.0735
Correlation Coefficient	-0.271
Rank Correlation Coeff.	-0.326

B

Bivariate Statistics	
Regression Fit	y = -1.416E-07x + 30.09
R Squared	2.12E-06
Correlation Coefficient	-0.00146
Rank Correlation Coeff.	0.129

C

Bivariate Statistics	
Regression Fit	y = -6.844E-05x + 31.51
R Squared	0.0168
Correlation Coefficient	-0.130
Rank Correlation Coeff.	-0.0552

D

Univariate Statistics	
Num Points	134
Minimum	14.3
Maximum	56.9
Mean	30.1
Mean Absolute	30.1
Median	29.2
Std Deviation	7.85
Skewness	0.833
Kurtosis	1.32
25th %	24.5
75th %	34.0

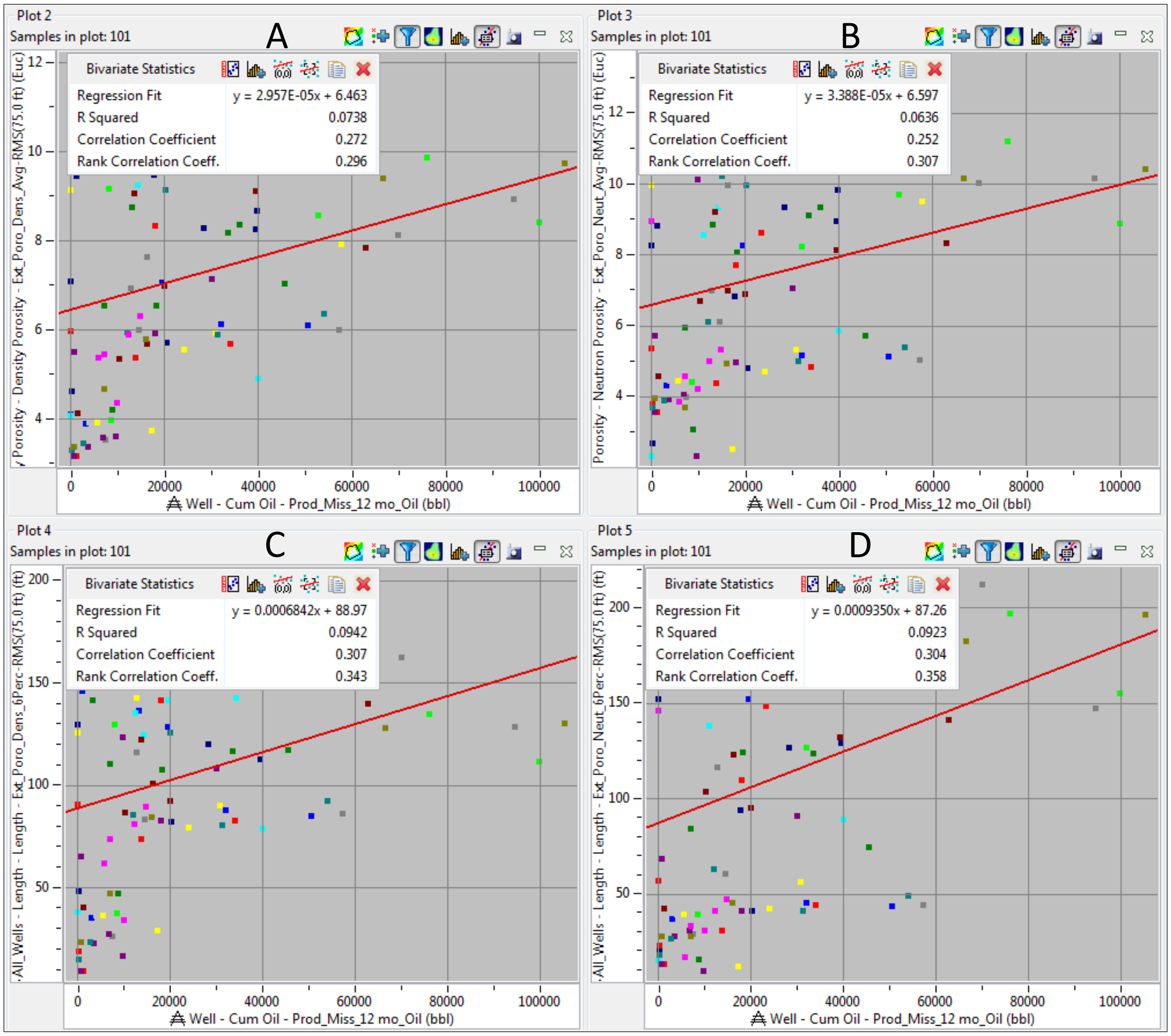
Figure 19: Average gamma ray plots for vertical wells. A) Gamma ray relative to initial 2 year oil. B) Gamma ray relative to initial 2 year gas. C) Gamma ray relative to initial 2 year BOE. D) Histogram of average gamma ray values.

3.5: Porosity Analysis on Horizontal Wells

The relationships between porosity attributes and oil production for horizontal wells were also analyzed. In Woods County, horizontal wells with LAS files were not available. However grids were created from vertical well log extractions in the upper 200 ft (~60 m) of the Mississippi “lime” (Appendix D) using a minimum curvature algorithm. The grids created include average density porosity, average neutron porosity, thickness of density porosity greater than 6 percent, and thickness of neutron porosity greater than 6 percent. Because horizontal surveys are also unavailable, grids values were extracted relative to the surface locations for the horizontal wells. Based on the analysis illustrated in Figure 13, initial 1-year production values were used for comparison to extracted log attribute values for horizontal wells.

Cross-plots for the horizontal well production versus porosity values were created (Figures 20-22). Correlations are similar to the vertical production, just not as strong. Oil production has a positive correlation with the extracted porosity values ranging from 0.252 to 0.307 (Figure 20). Gas production and BOE both have weak negative correlations with porosity (Figures 21 and 22).

The weaker correlations are to be expected. Ideally, porosity logs in the horizontal wells would be used for comparison. However these horizontal well logs are not as common as in vertical wells. Also, by using surface location extractions as opposed to the entire horizontal portion of the wellbore, lateral error is introduced in a reservoir that contains small scale heterogeneity. However, it is significant that the correlation trends follow those of the vertical well porosity analysis.



A — Bivariate Statistics

Regression Fit	y = 2.957E-05x + 6.463
R Squared	0.0738
Correlation Coefficient	0.272
Rank Correlation Coeff.	0.296

B — Bivariate Statistics

Regression Fit	y = 3.388E-05x + 6.597
R Squared	0.0636
Correlation Coefficient	0.252
Rank Correlation Coeff.	0.307

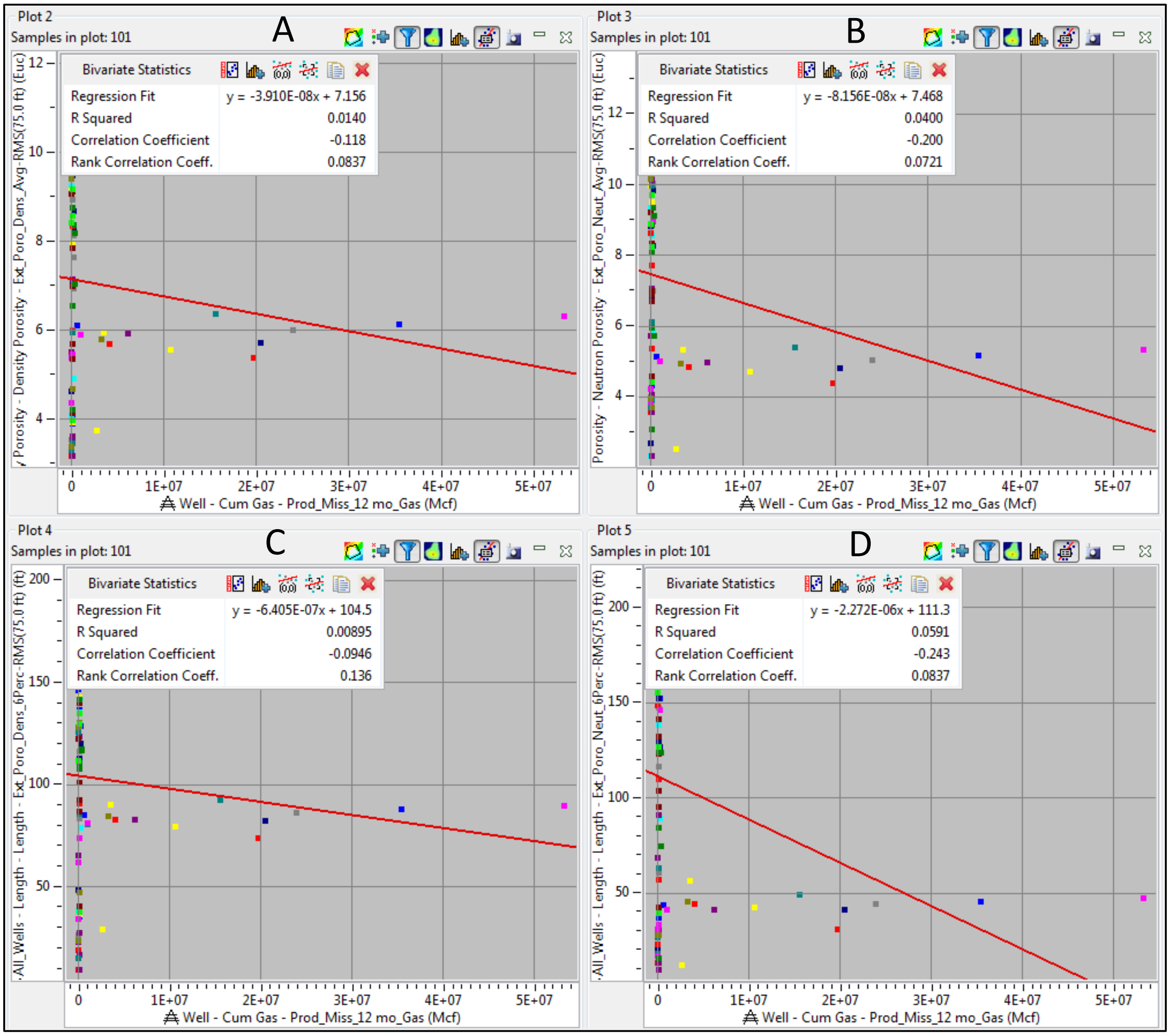
C — Bivariate Statistics

Regression Fit	y = 0.0006842x + 88.97
R Squared	0.0942
Correlation Coefficient	0.307
Rank Correlation Coeff.	0.343

D — Bivariate Statistics

Regression Fit	y = 0.0009350x + 87.26
R Squared	0.0923
Correlation Coefficient	0.304
Rank Correlation Coeff.	0.358

Figure 20: Porosity relative to 1-year oil production for horizontal wells. A) Average density porosity. B) Average neutron porosity. C) Net thickness of density porosity greater than 6 percent. D) Net thickness of neutron porosity greater than 6 percent.



A

Bivariate Statistics	
Regression Fit	y = -3.910E-08x + 7.156
R Squared	0.0140
Correlation Coefficient	-0.118
Rank Correlation Coeff.	0.0837

B

Bivariate Statistics	
Regression Fit	y = -8.156E-08x + 7.468
R Squared	0.0400
Correlation Coefficient	-0.200
Rank Correlation Coeff.	0.0721

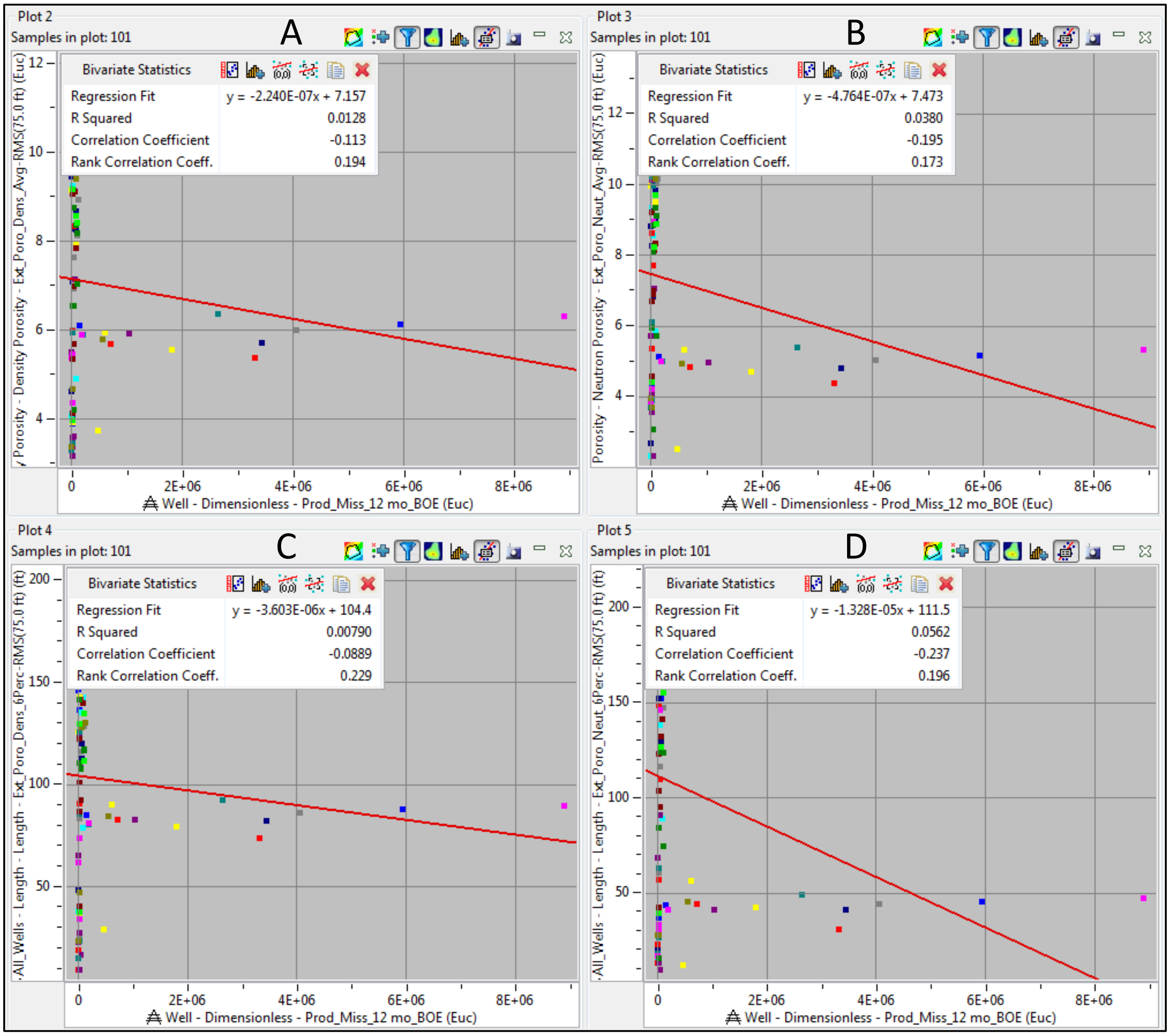
C

Bivariate Statistics	
Regression Fit	y = -6.405E-07x + 104.5
R Squared	0.00895
Correlation Coefficient	-0.0946
Rank Correlation Coeff.	0.136

D

Bivariate Statistics	
Regression Fit	y = -2.272E-06x + 111.3
R Squared	0.0591
Correlation Coefficient	-0.243
Rank Correlation Coeff.	0.0837

Figure 21: Porosity relative to initial 1-year gas production for horizontal wells. A) Average density porosity. B) Average neutron porosity. C) Net thickness of density porosity greater than 6 percent. D) Net thickness of neutron porosity greater than 6 percent.



A) Bivariate Statistics

Regression Fit	y = -2.240E-07x + 7.157
R Squared	0.0128
Correlation Coefficient	-0.113
Rank Correlation Coeff.	0.194

B) Bivariate Statistics

Regression Fit	y = -4.764E-07x + 7.473
R Squared	0.0380
Correlation Coefficient	-0.195
Rank Correlation Coeff.	0.173

C) Bivariate Statistics

Regression Fit	y = -3.603E-06x + 104.4
R Squared	0.00790
Correlation Coefficient	-0.0889
Rank Correlation Coeff.	0.229

D) Bivariate Statistics

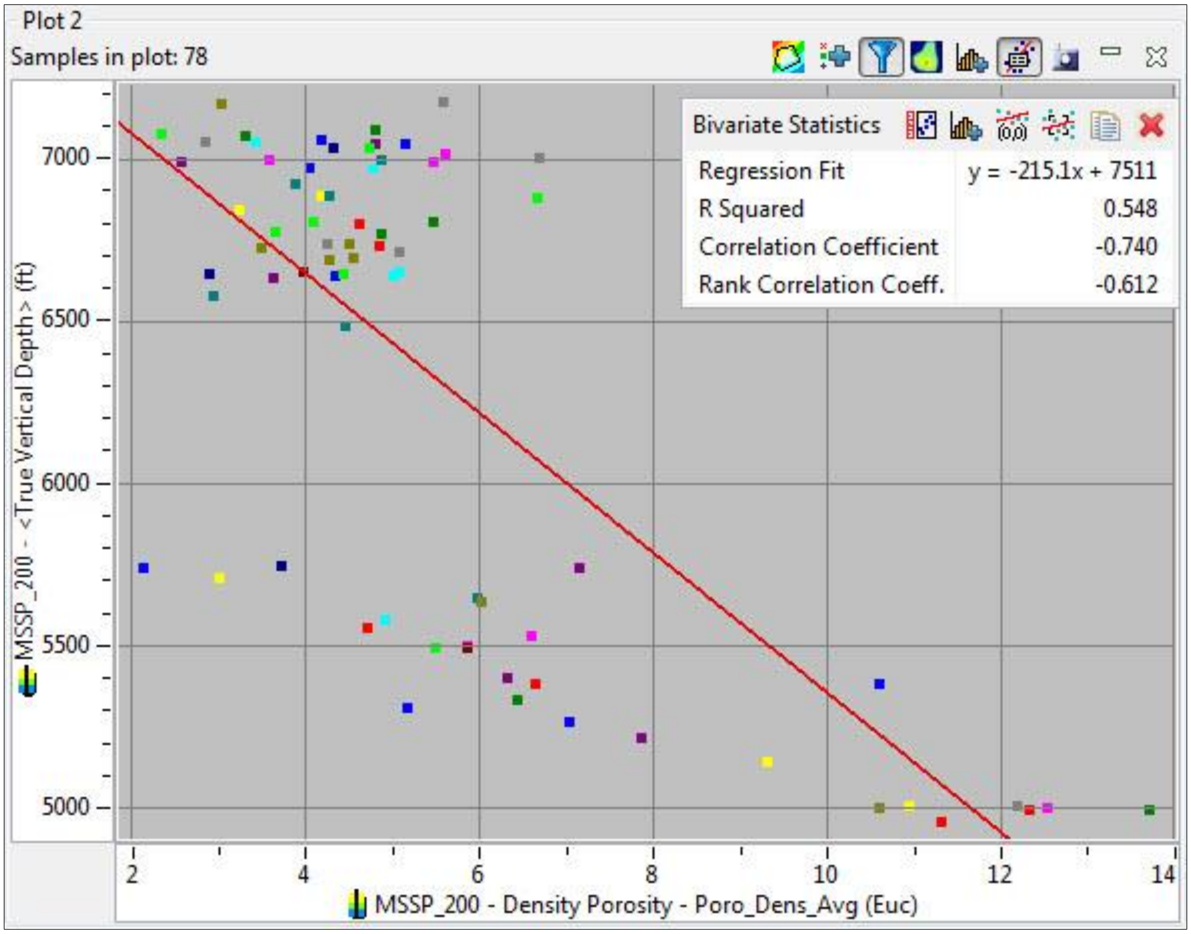
Regression Fit	y = -1.328E-05x + 111.5
R Squared	0.0562
Correlation Coefficient	-0.237
Rank Correlation Coeff.	0.196

Figure 22: Porosity relative to initial 1-year BOE production for horizontal wells. A) Average density porosity. B) Average neutron porosity. C) Net thickness of density porosity greater than 6 percent. D) Net thickness of neutron porosity greater than 6 percent.

3.6: Analysis of True Vertical Depth

The analysis of cross-plots involving true vertical depth (TVD) from this study reveals that some caution must be taken regarding conclusions of the porosity analysis. The Mississippi “chat” is more commonly found in the northeast portion of Woods County (Bowles, 1959). This “chat” often consists of porous rock at the boundary between the Pennsylvanian and Mississippian systems. The northeast portion of Woods County is also structurally shallow for the Mississippian as seen in the Figure 4 cross-section.

A cross-plot was created relating TVD to average density porosity (Figure 23). This reveals a high negative correlation, -0.740, between the two variables. A well filter was also created for the wells containing higher than 6 percent average density porosity. Figure 24 shows that most of the wells with greater than 6 percent average density porosity are in the northeast portion of the county.



Regression Fit	y = -215.1x + 7511
R Squared	0.548
Correlation Coefficient	-0.740
Rank Correlation Coeff.	-0.612

Figure 23: True Vertical Depth of the Upper Mississippi “lime” zone relative to average density porosity.

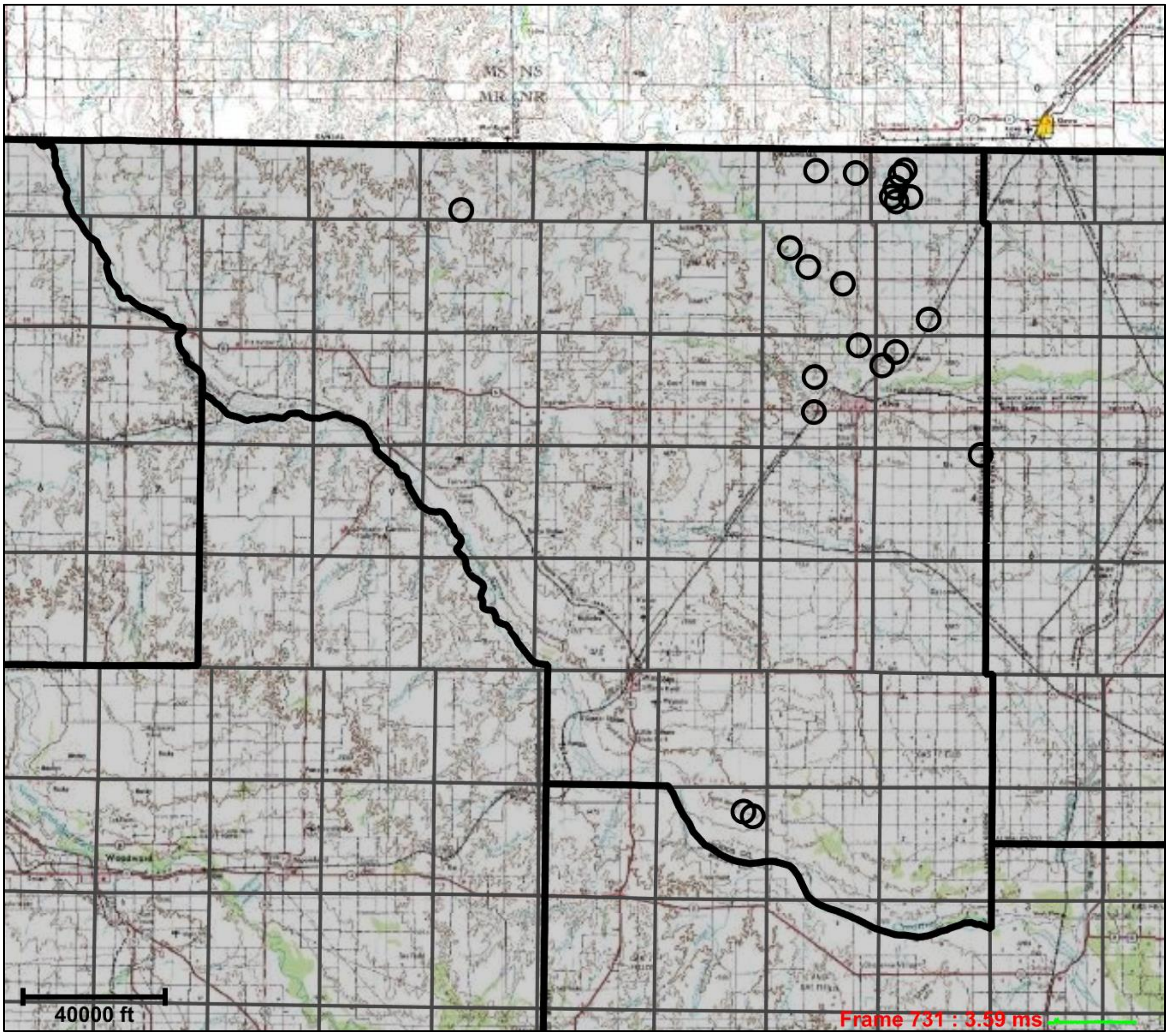
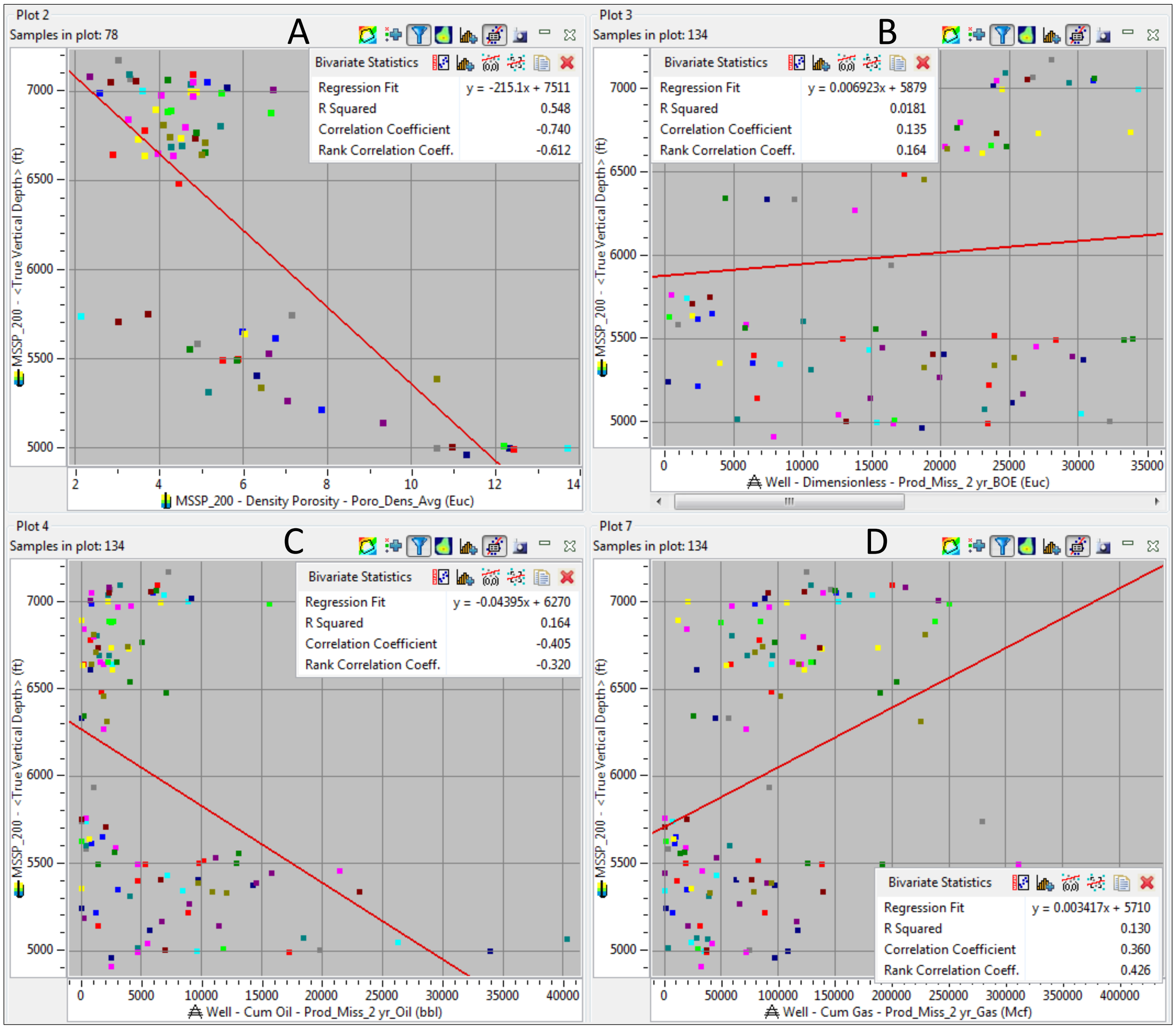


Figure 24: Location of wells with higher than 6 percent average density porosity.

Earlier, strong correlations between the porosity attributes and oil were revealed. Negative correlations between porosity attributes and gas were found. Figure 25 shows TVD versus oil, gas, and BOE production. This shows a strong negative correlation with oil, a positive correlation to gas, and a slightly positive correlation to BOE.



A

Bivariate Statistics	
Regression Fit	y = -215.1x + 7511
R Squared	0.548
Correlation Coefficient	-0.740
Rank Correlation Coeff.	-0.612

B

Bivariate Statistics	
Regression Fit	y = 0.006923x + 5879
R Squared	0.0181
Correlation Coefficient	0.135
Rank Correlation Coeff.	0.164

C

Bivariate Statistics	
Regression Fit	y = -0.04395x + 6270
R Squared	0.164
Correlation Coefficient	-0.405
Rank Correlation Coeff.	-0.320

D

Bivariate Statistics	
Regression Fit	y = 0.003417x + 5710
R Squared	0.130
Correlation Coefficient	0.360
Rank Correlation Coeff.	0.426

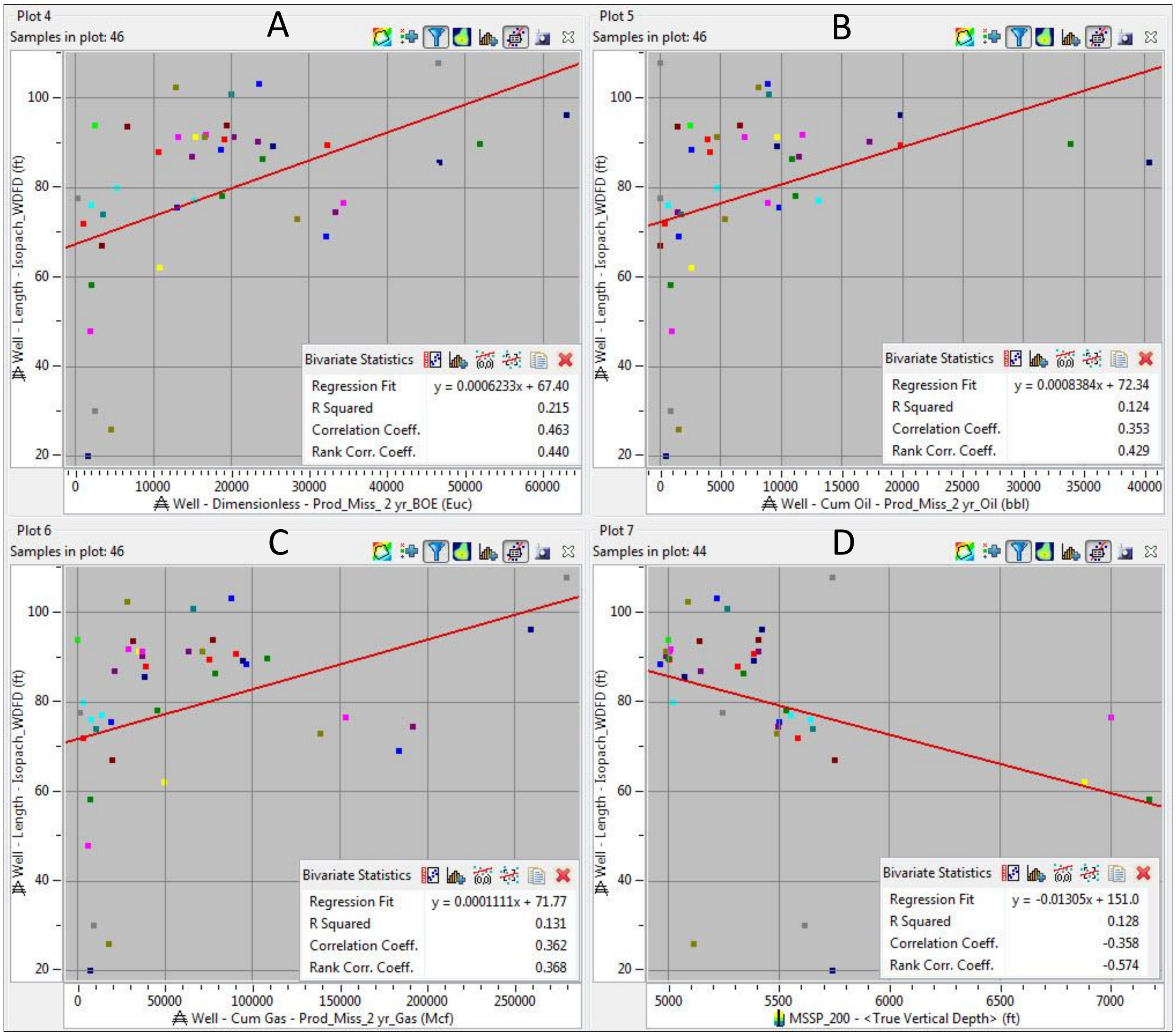
Figure 25: TVD (y-axis) verses porosity and production for vertical wells. A) Average density porosity. B) Initial 2-year BOE. C) Initial 2-year oil. D) Initial 2-year gas.

3.7: Woodford Analysis

Most oil and gas accumulations are the result of both vertical and lateral migration (Pratsch, 1991). The oil and gas industry started with the recognition of naturally occurring seepages resulting from vertical migration of oil and gas (Pratsch, 1991). The Woodford shale is a predominant source rock for the Mississippian play (Ball *et al.*, 1991). By quantifying the relationship between Woodford thickness and Mississippian production, the importance of vertical migration and source rock proximity in the play can be analyzed.

As seen in Figure 6, there are some regions of the study area that lack sufficient coverage of LAS files containing the entire Woodford zone. Because of this, the Woodford top and base was extracted from 32 raster logs to help provide more coverage. This yielded a total of 152 vertical well samples with Woodford thickness. From these samples, 47 have production in the Mississippian. The Erickson 1 well was removed from the analysis because with more than 4 times the initial 2-year gas production than the nearest well, this sample was treated as a statistical outlier. Using the remaining 46 samples, positive correlations were found between all production values and Woodford thickness (Figure 26).

It must also be noted that the Woodford thickness is greater in the northeast portion of the county (Figure 27) where porosity is greatest and the structure is the shallowest. The analysis of porosity and TVD revealed positive correlations with oil and negative correlations with gas. The overlap of greater Woodford thickness with porosity and TVD could help explain the positive correlation between Woodford thickness and oil, but does not explain a positive correlation between Woodford thickness and gas.



Bivariate Statistics

Regression Fit	y = 0.0006233x + 67.40
R Squared	0.215
Correlation Coeff.	0.463
Rank Corr. Coeff.	0.440

Bivariate Statistics

Regression Fit	y = 0.0008384x + 72.34
R Squared	0.124
Correlation Coeff.	0.353
Rank Corr. Coeff.	0.429

Bivariate Statistics

Regression Fit	y = 0.0001111x + 71.77
R Squared	0.131
Correlation Coeff.	0.362
Rank Corr. Coeff.	0.368

Bivariate Statistics

Regression Fit	y = -0.01305x + 151.0
R Squared	0.128
Correlation Coeff.	-0.358
Rank Corr. Coeff.	-0.574

Figure 26: Woodford thickness (y-axis) relative to production and TVD for vertical wells. A) Initial 2 year oil. B) Initial 2 year gas. C) Initial 2 year BOE. D) TVD.

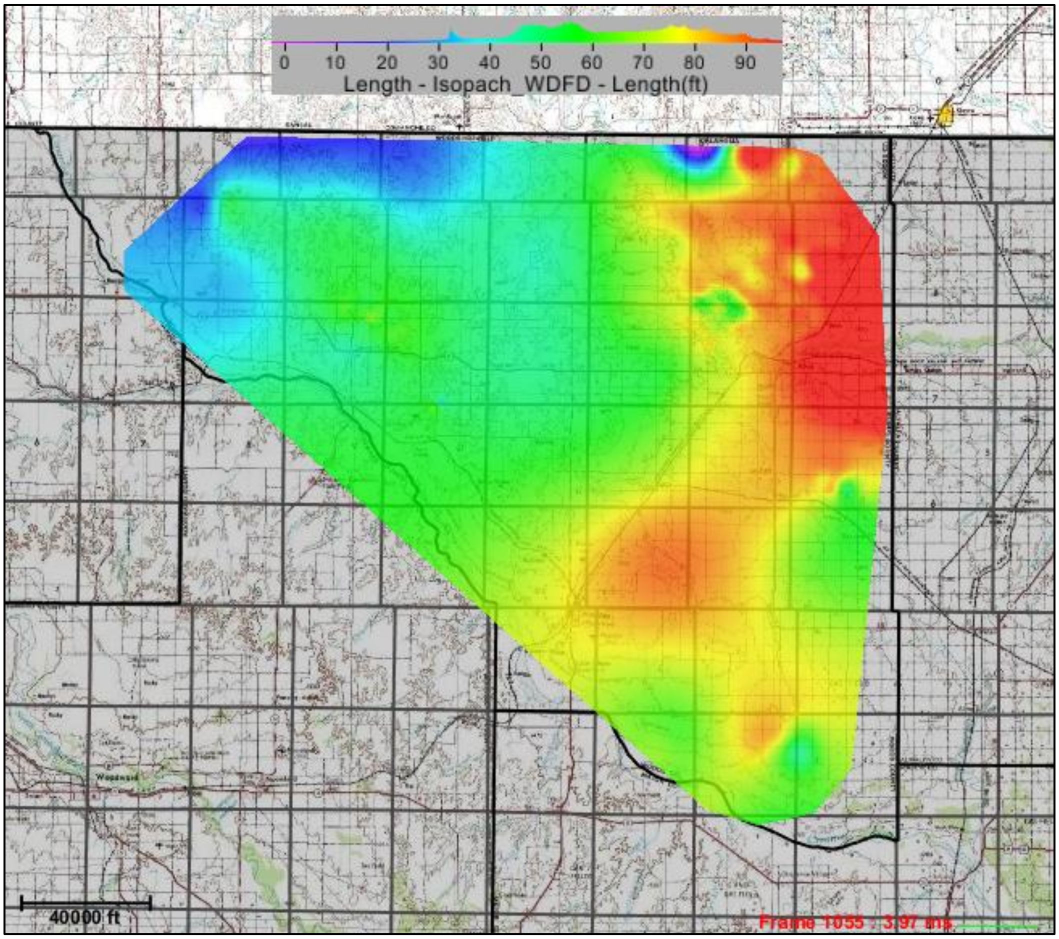
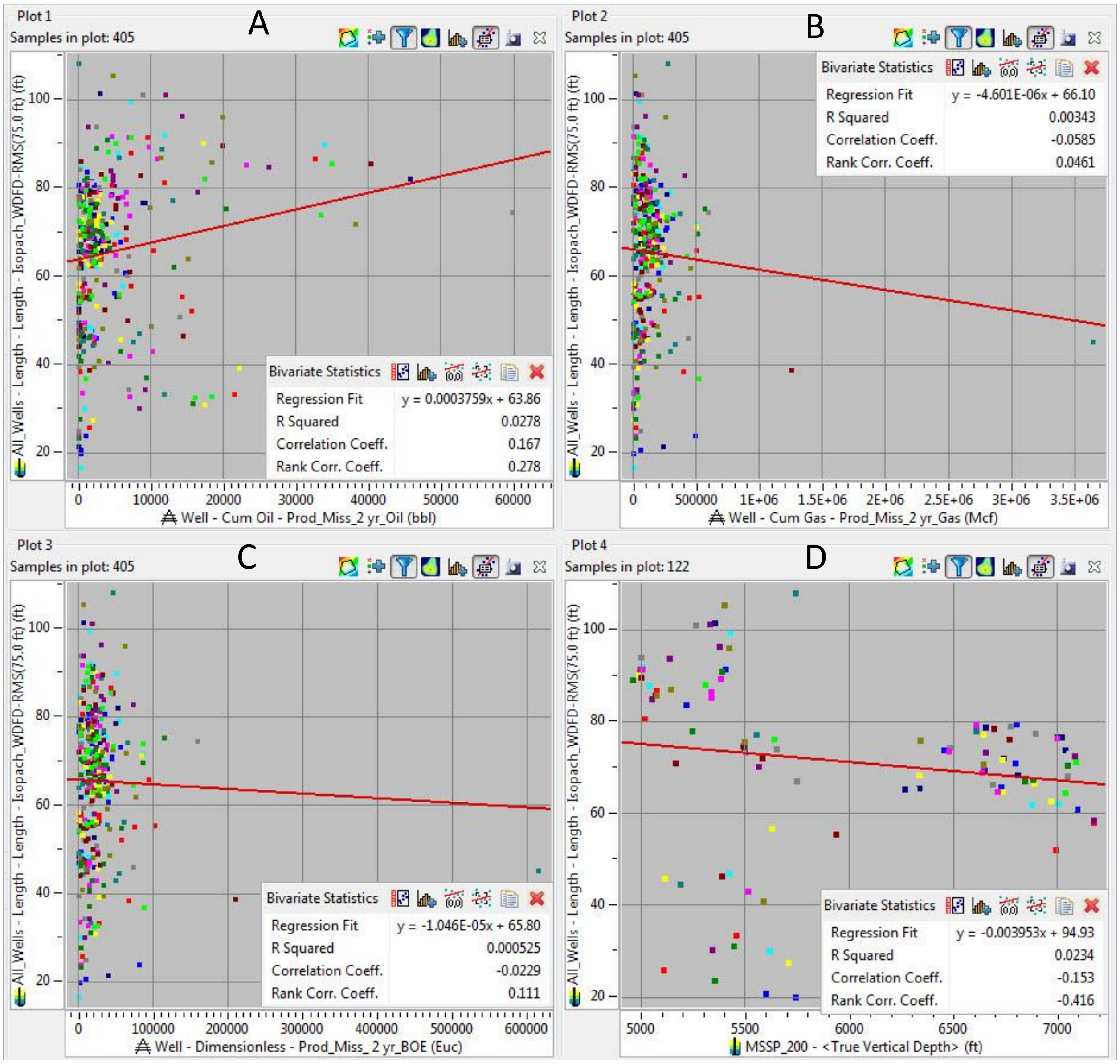


Figure 27: Woodford isopach created from LAS files and raster images

For further analysis the Woodford isopach grid was used to extract Woodford thickness values relative to the surface locations for all wells within the grid. This provides a Woodford thickness value for each well within the Woodford isopach grid. Using the extracted values, there is less correlation with the vertical wells (Figure 28). A positive correlation between Woodford thickness and oil still exists, but there is no significant correlation with gas and BOE. There is also a weak negative correlation between Woodford thickness and TVD. Comparison of the Woodford thickness to horizontal Mississippian production reveals similar results as the vertical wells, only with slightly higher correlation for both oil and TVD (Figure 29). Again it is important to note that the horizontal well correlations follow the same trends as the vertical well correlations with regards to oil production.



A) Bivariate Statistics

Regression Fit	y = 0.0003759x + 63.86
R Squared	0.0278
Correlation Coeff.	0.167
Rank Corr. Coeff.	0.278

B) Bivariate Statistics

Regression Fit	y = -4.601E-06x + 66.10
R Squared	0.00343
Correlation Coeff.	-0.0585
Rank Corr. Coeff.	0.0461

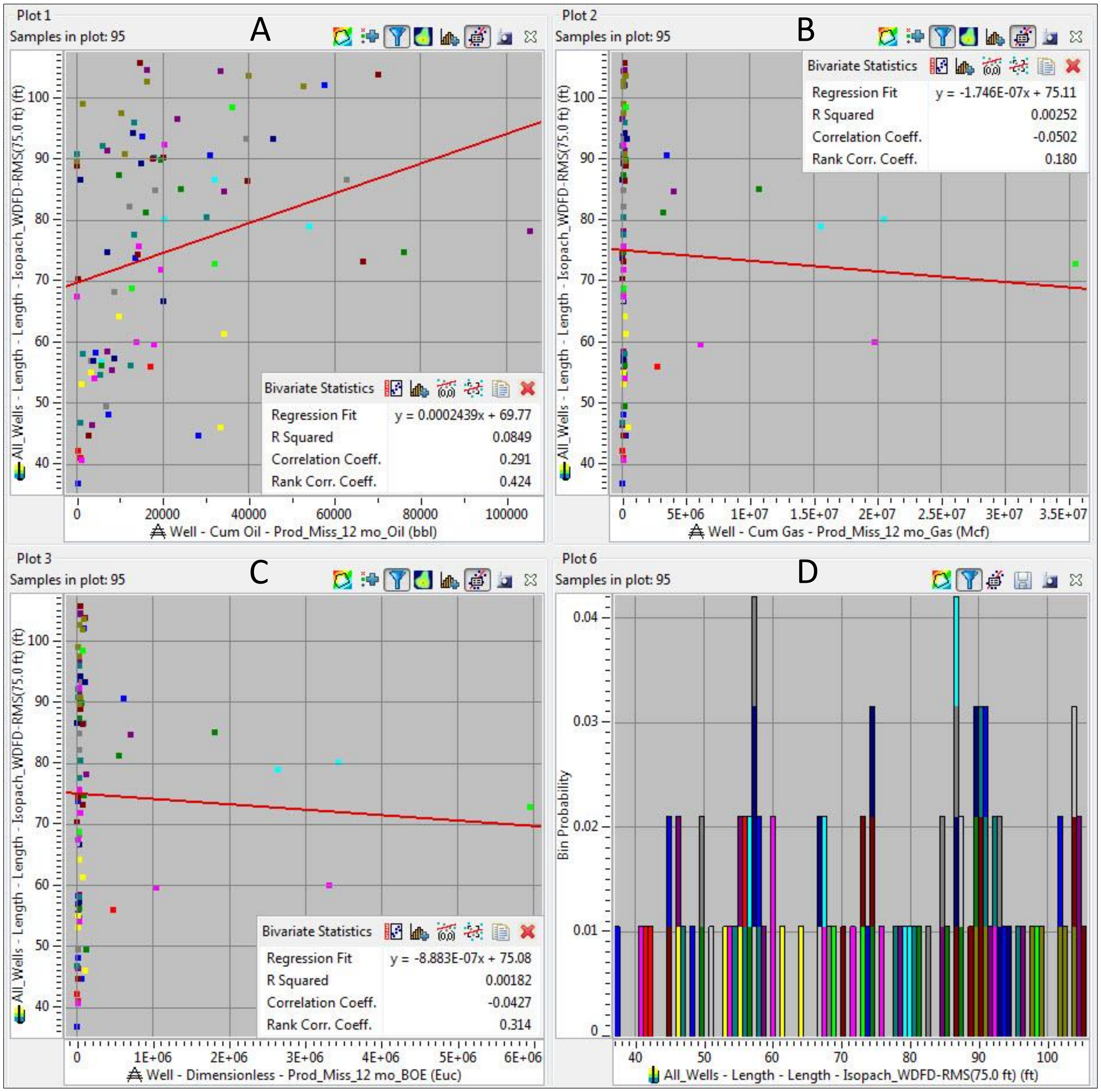
C) Bivariate Statistics

Regression Fit	y = -1.046E-05x + 65.80
R Squared	0.000525
Correlation Coeff.	-0.0229
Rank Corr. Coeff.	0.111

D) Bivariate Statistics

Regression Fit	y = -0.003953x + 94.93
R Squared	0.0234
Correlation Coeff.	-0.153
Rank Corr. Coeff.	-0.416

Figure 28: Woodford extracted thickness values (y-axis) relative to production and TVD for vertical wells. A) Initial 2-year oil. B) Initial 2-year gas. C) Initial 2-year BOE. D) TVD.



A

Bivariate Statistics	
Regression Fit	y = 0.0002439x + 69.77
R Squared	0.0849
Correlation Coeff.	0.291
Rank Corr. Coeff.	0.424

B

Bivariate Statistics	
Regression Fit	y = -1.746E-07x + 75.11
R Squared	0.00252
Correlation Coeff.	-0.0502
Rank Corr. Coeff.	0.180

C

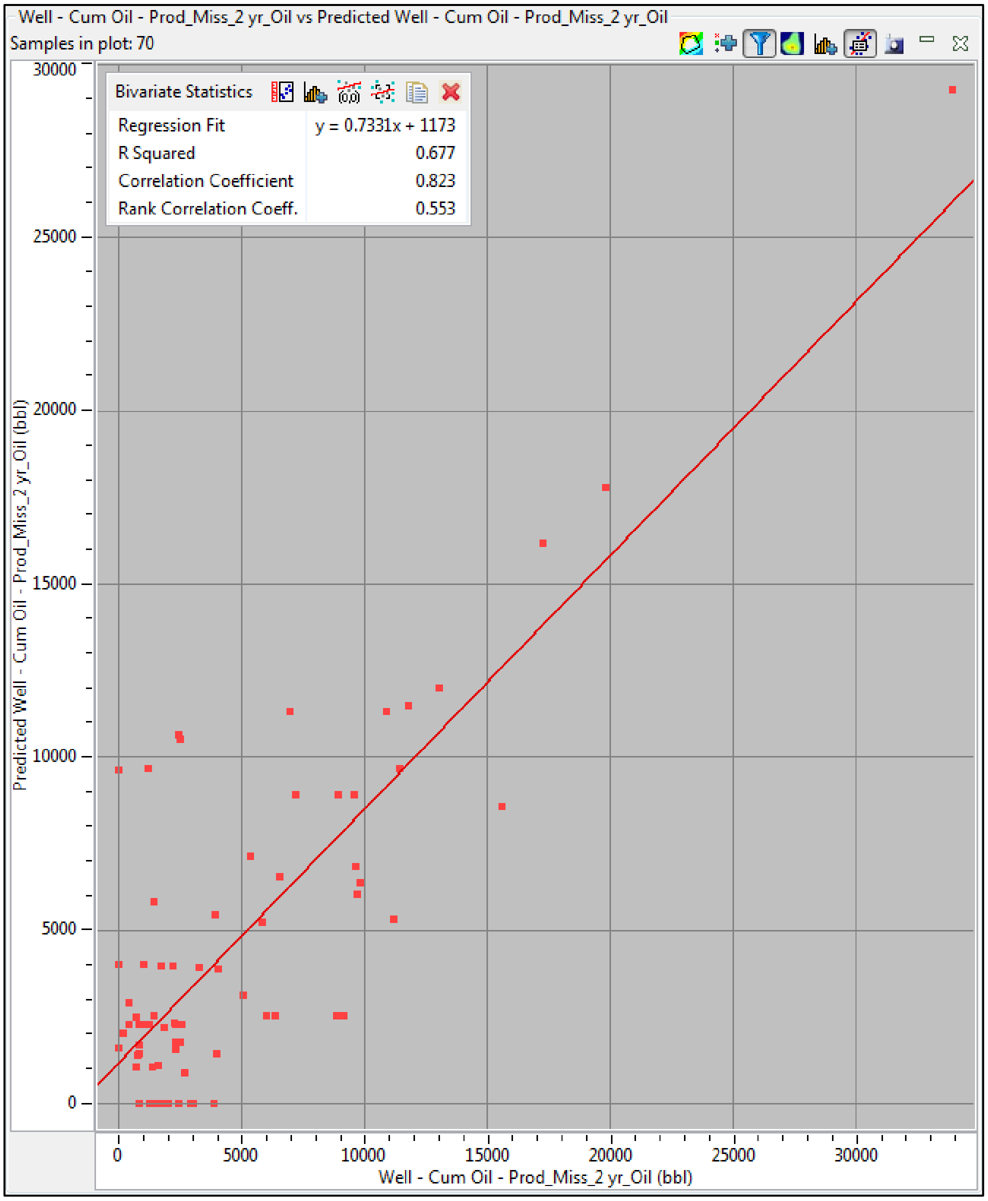
Bivariate Statistics	
Regression Fit	y = -8.883E-07x + 75.08
R Squared	0.00182
Correlation Coeff.	-0.0427
Rank Corr. Coeff.	0.314

Figure 29: Woodford extracted thickness values (y-axis) relative to production and TVD for horizontal wells. A) Initial 2-year oil. B) Initial 2-year gas. C) Initial 2-year BOE. D) Histogram.

3.8: Multi-variate Analysis

Using the extracted vertical well log attributes, a predicted oil production grid was created. To accomplish this, a multi-variate statistical approach was implemented using a combination of variables. Initial 2-year oil is the response variable (i.e., the variable to be predicted). The variables used to predict oil production are average neutron porosity, average gamma ray, average deep resistivity, and thickness of the Woodford shale relative to the surface locations.

When running a model using all of these variables a 0.823 correlation with production (Figure 30) was obtained. In the analysis section, the bi-variate plot of deep resistivity versus oil production revealed an unexpected inverse relationship. In a multi-variate model, each variable is forced to contribute uniquely. When looking at the contribution of deep resistivity in the multi-variate model, a positive correlation with predicted oil production is revealed (Figure 31). Furthermore, average gamma ray, average neutron porosity, and extracted Woodford thickness followed their expected bi-variate relationships. This not only gives more confidence in the model, but also reveals that the higher porosity rocks not only relate to more oil, but also provide a more conductive path for the salt water. With increased confidence in the model, a production prediction map was created for Woods County based on these log attributes (Figure 32).



Regression Fit	y = 0.7331x + 1173
R Squared	0.677
Correlation Coefficient	0.823
Rank Correlation Coeff.	0.553

Figure 30: Predicted initial 2-year oil production (y-axis) using multiple attributes relative to actual 2-year oil production.

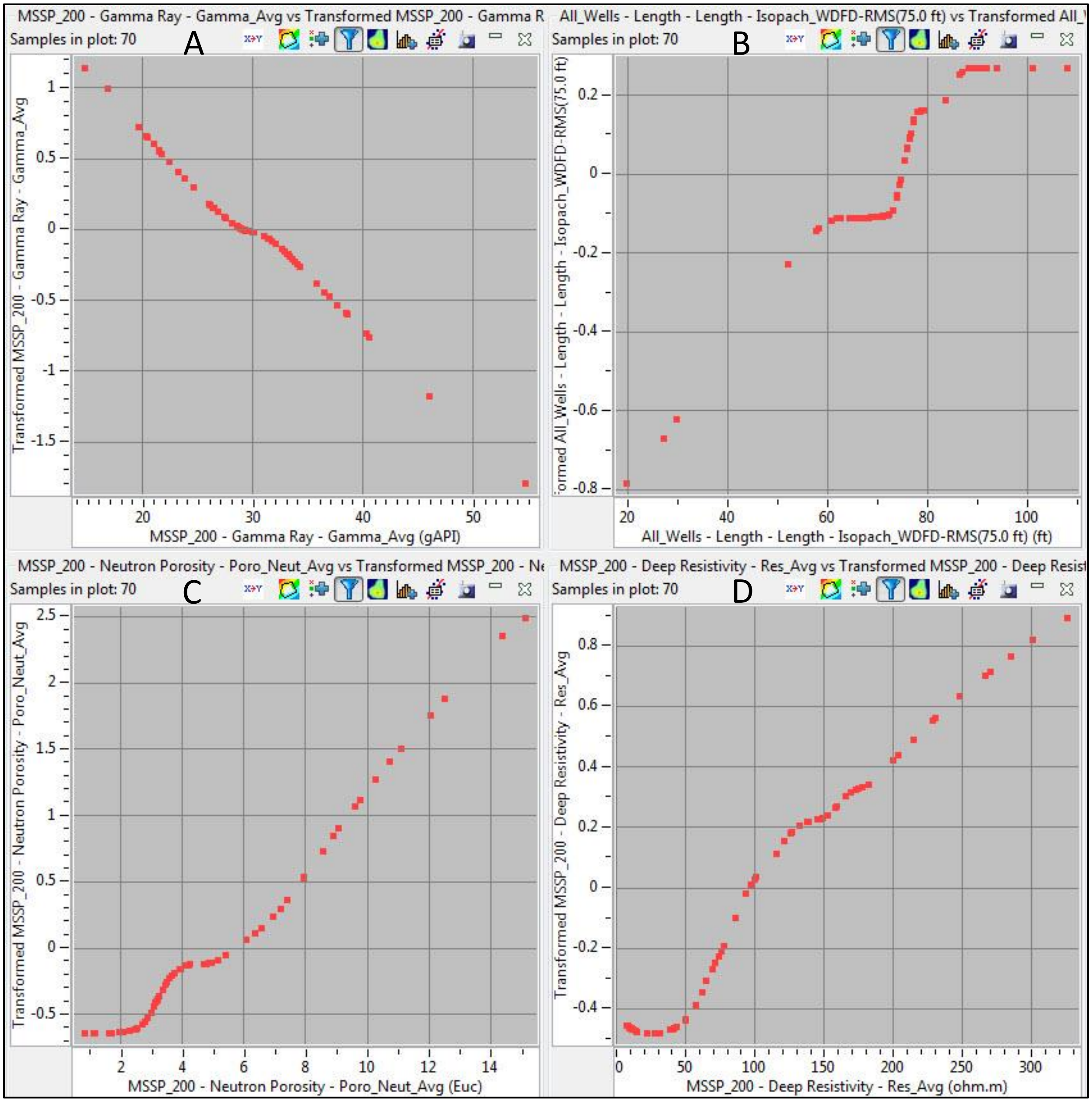


Figure 31: Relative contributions to predicted production for individual variables in the multi-variate statistical model. A) Gamma ray. B) Extracted Woodford thickness. C) Average neutron porosity. D) Deep resistivity

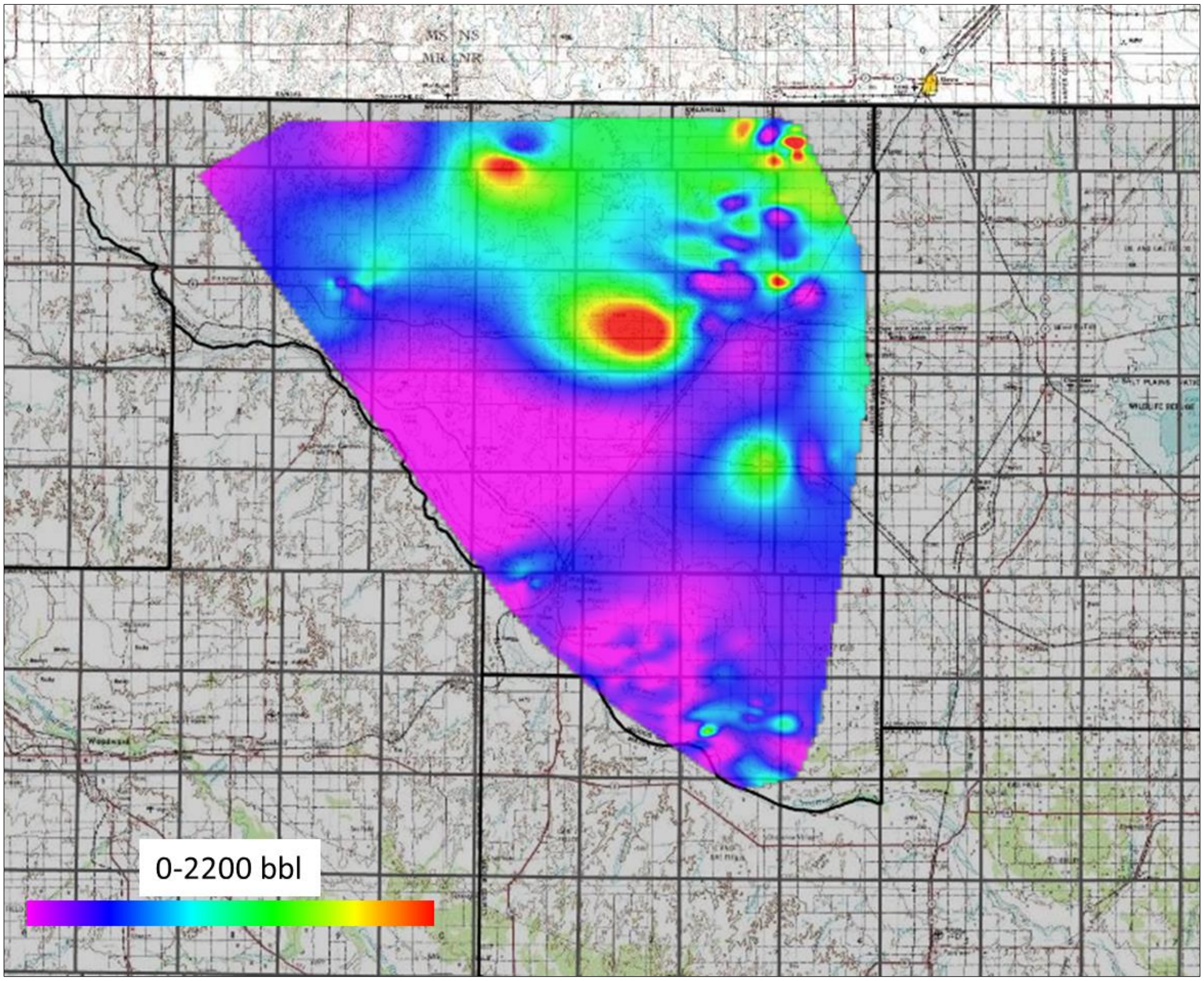


Figure 32: Oil production prediction map derived from well log attributes in Woods County.

CHAPTER 4:
DISCUSSION

Through the analyses described in Chapter 3, the first four tasks have been accomplished: (1) a workflow was developed for building a project using Drillinginfo's Transform software, (2) efficient quality control checks were developed and implemented, (3) relationships between vertical well log attributes and production values were quantified, and (4) relationships between available horizontal well data and production were found to follow the same trends as the vertical relationships. The final task was achieved through applying the results to the Mississippian play.

There are some clear observations from the study. The cross-sections confirm that the Mississippian thickens and deepens to the Southwest in Woods County. As the analyses presented herein demonstrate, porosity has a strong positive correlation with oil production in Woods County, and TVD has a strong negative correlation with oil production. The Woodford thickness, which has a positive correlation with oil, is greatest in the east/northeast portion of the county. Finally, a multi-variate analysis using average neutron porosity, average gamma ray, average resistivity, and extracted Woodford thickness provided a predictive production model that correlates well with actual production.

The most highly correlated set of individual attributes extracted from well logs were porosity attributes. Each porosity attribute had similar, positive correlations to oil production, ranging from 0.560 to 0.569. There are numerous variables across multiple disciplines that affect production in the Mississippian play. These include the geological variables examined in this study; geophysical variables such as curvature, fracture intensity, and distance to faults; and engineering variables such as well length, proppant, and number of stages. Considering the number of variables involved, having such a strong correlation for the individual porosity variables is important.

The porosity analysis does not reveal an overall increase in hydrocarbons with increased porosity. This could be explained by the larger hydrocarbon oil molecules filling the high porosity rock first, followed by the smaller hydrocarbon gas molecules charging the tighter rock afterwards.

Although the porosity analysis does not reveal an overall increase in hydrocarbon production with increased porosity, it does show that higher porosity wells in this study produce more oil and less gas. For example, the correlation line for neutron porosity in Figure 15(B) reveals that initial 2-year oil production for a well with 7% average neutron porosity is approximately 5 times more than a well with a 4% average. This is a significant difference, especially considering current commodity prices.

It must be noted that the areas of highest porosity are located where the Mississippian play is the shallowest in the county. This brings into question the true controls on oil production, which could be a combination of both high porosity and TVD.

The thickness of the Woodford shale relative to Mississippian production was also evaluated as this is a prominent source rock for the play. For both vertical and horizontal wells, increased Woodford thickness revealed positive correlations to oil production. However no significant correlations were found with gas or BOE. Comparing the source rock thickness to reservoir production suggests that primary vertical migration is likely significant, but that the role of lateral migration along the northeastward shallowing contact between the Woodford and Mississippi "lime" may also be important. Detailed geochemical analyses of Woodford source rock and oil produced in Woods County may help to elucidate oil migration.

Perhaps the most interesting attribute was deep resistivity. Deep resistivity had a negative relationship to oil production in a bi-variate comparison. This relationship reversed when analyzing the contribution of deep resistivity to a predicted production model that used multiple well log variables (including average neutron porosity, average density porosity, and average gamma ray). The relative contributions to the model for all variables other than average deep resistivity remained the same as revealed in the bi-variate plots. This indicates that when all other variables are normalized to their statistical averages, deep resistivity has a positive relationship to oil production.

Without core samples or magnetic resonance logs, the porosity types within the carbonate rocks and their associated permeability cannot be determined. As indicated in the deep resistivity analysis section (3.3) the average density porosity displays a -0.678 correlation with average deep resistivity and the average neutron porosity has a -0.703 correlation with average deep resistivity. Being that the neutron porosity can help reveal immovable bound water present in lithology containing micro porosity, this similar relationship with average density porosity strengthens the argument that the higher conductivity related to oil production is the result of increased permeability instead of immovable bound water.

Oil is more resistive than salt water. This study shows how relying on bi-variate plots might not give true relationships due to multiple correlations between parameters. For deep resistivity, it appears as though free moving salt water along with oil in the high porosity rock masked the true relationship between deep resistivity and oil. When forced to contribute uniquely to a multi-variate model, deep resistivity had a positive relationship with oil, as expected.

CHAPTER 5:
CONCLUSIONS

In this study well log attributes were extracted, compared to production, and evaluated. Comparisons of porosity to production revealed a strong correlation between porosity and oil. Comparisons between Woodford thickness and oil revealed a moderate positive relationship. Gamma ray and deep resistivity had moderate negative relationships to oil production.

Although deep resistivity had a negative relationship to oil production in a bi-variate comparison, this relationship reversed when analyzing the contribution of deep resistivity to a predicted production model that used multiple well log variables. The relative contributions to the model for all variables other than average deep resistivity remained the same as revealed in the bi-variate plots. This indicates that when all other variables in the model are normalized to their statistical averages, deep resistivity has a positive relationship to oil production. There are multiple variables to consider during oil and gas exploration. The deep resistivity analysis shows that relying on bi-variate plots might not show the true relationships between variables. Using a multi-variate statistical analysis can help reveal how variables truly contribute to production.

If analyzing recent vertical well data (as well as older data if properly normalized to account for changes in well log technology) is to be significant, the horizontal well results should follow the same trends as the vertical data. By creating grids from the vertical well data and extracting the grids relative to the horizontal locations, analysis can be implemented to see if the horizontal well activity follows the trends of the vertical well data, as is the case in Woods County. Knowledge that the horizontal well analysis follows the same trends revealed in the vertical well analysis makes the vertical well analysis applicable for modern horizontal drilling activity in the Mississippian play.

This workflow can be implemented in other plays. There are many other areas, such as the Cretaceous sands of the Powder River Basin in Wyoming, where modern horizontal drilling techniques are being implemented in areas containing older vertical well data. Implementing the workflows described in this research that include a project build with efficient quality control, identifying long term production indicators, and comparing extracted well log attributes to production, can help guide and optimize prospective mapping.

CHAPTER 6:
FUTURE WORK

Expanding the study area could help differentiate which individual variables contribute most to oil production. Expanding into areas without an overlap between high porosity and shallow structure would help differentiate between how each variable correlates with oil production.

Analyzing well logs is just one portion of the Mississippian analysis. Adding seismic data and engineering completions data would be helpful for performing a more thorough analysis. Extracting attributes such as curvature and distance to faults could add to the model. It would also be helpful to have completions data including well length, proppant amount, proppant type, and volume of water pumped. Geochemical analysis could help determine relationships between the source rock and the reservoir, including migration pathways.

If seismic and engineering variables were available to compliment the geological well log attributes, the multi-variate model should improve. Also by adding the seismic variables and normalizing engineering variables, an improved geological sweet spot map could be created. Further, an attempt to tie well log attributes, specifically porosity, to seismic response could help interpolate the model in areas between well log locations.

When compared to the time of data import for this project (September, 2013), there are now many more horizontal well samples available that could be used to help correlate how well horizontal activity relates to the vertical well analysis. Importing horizontal surveys would also allow for extracting grid values relative to the horizontal portions of the wellbore instead of the surface locations. Extracting along the horizontal portion of the wellbores would provide more accurate data in a heterogeneous play such as the Mississippian play.

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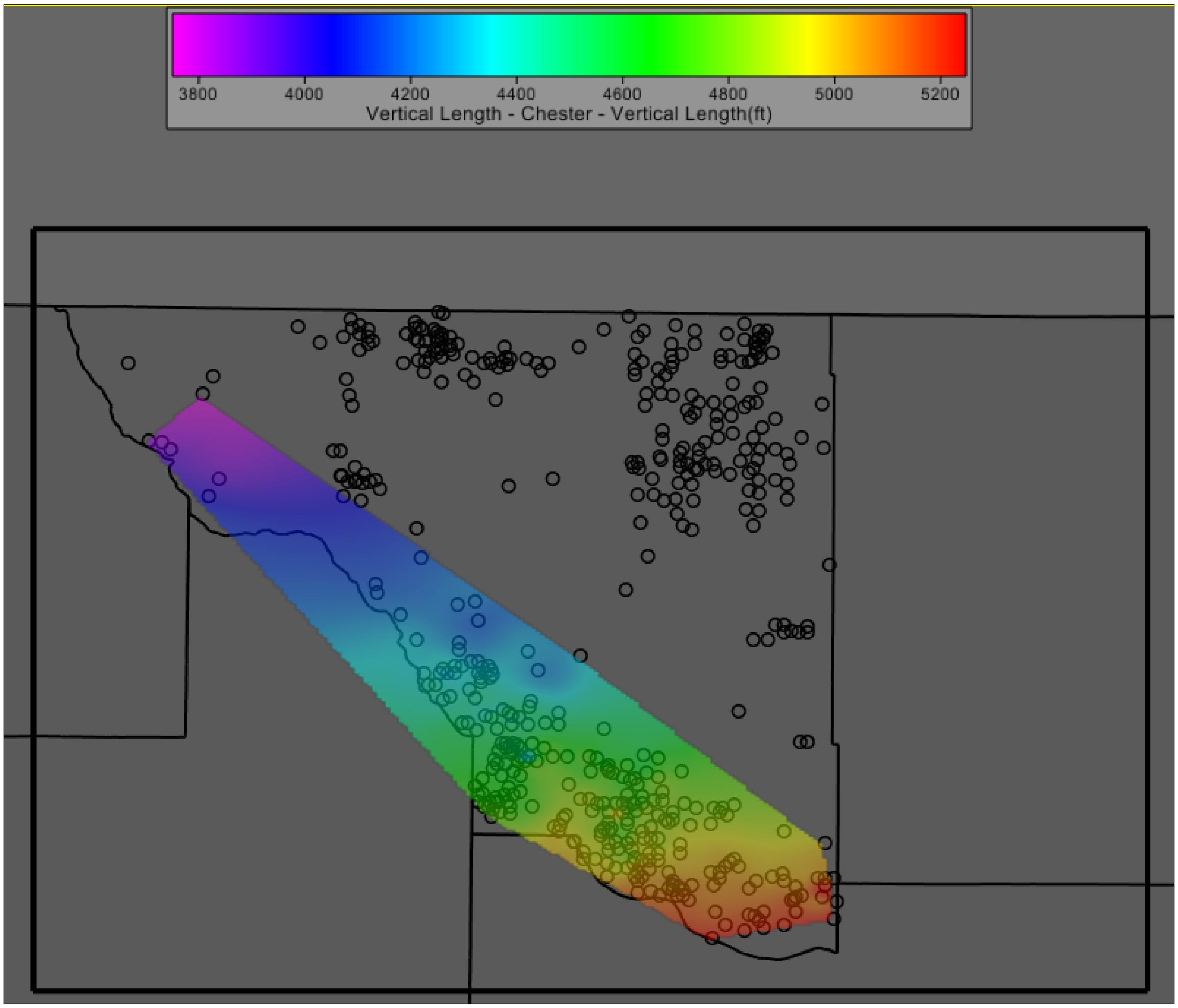
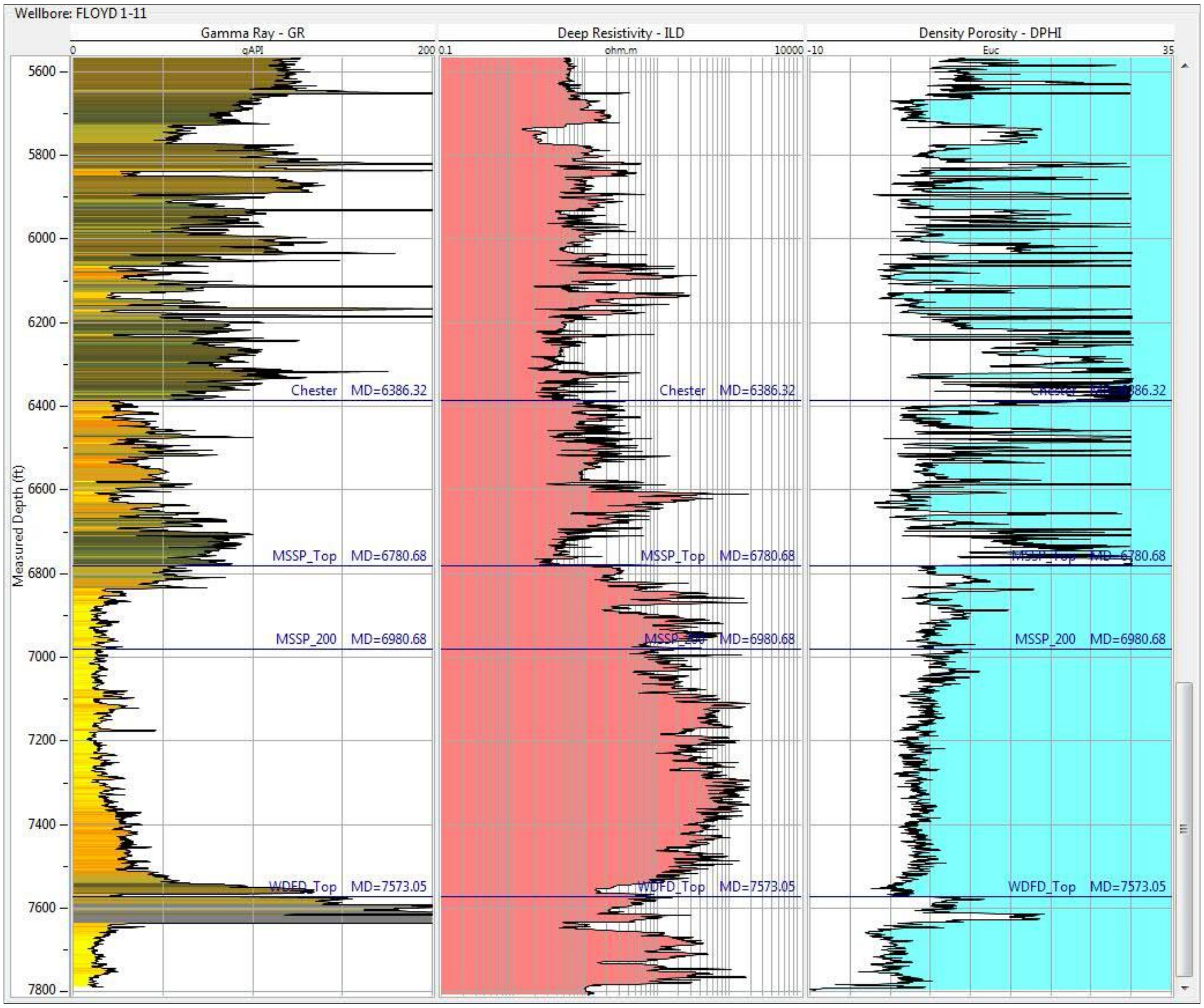
APPENDIX A: Example of well log picks for the Chesterian

Chesterian Structure Map Created from Picks

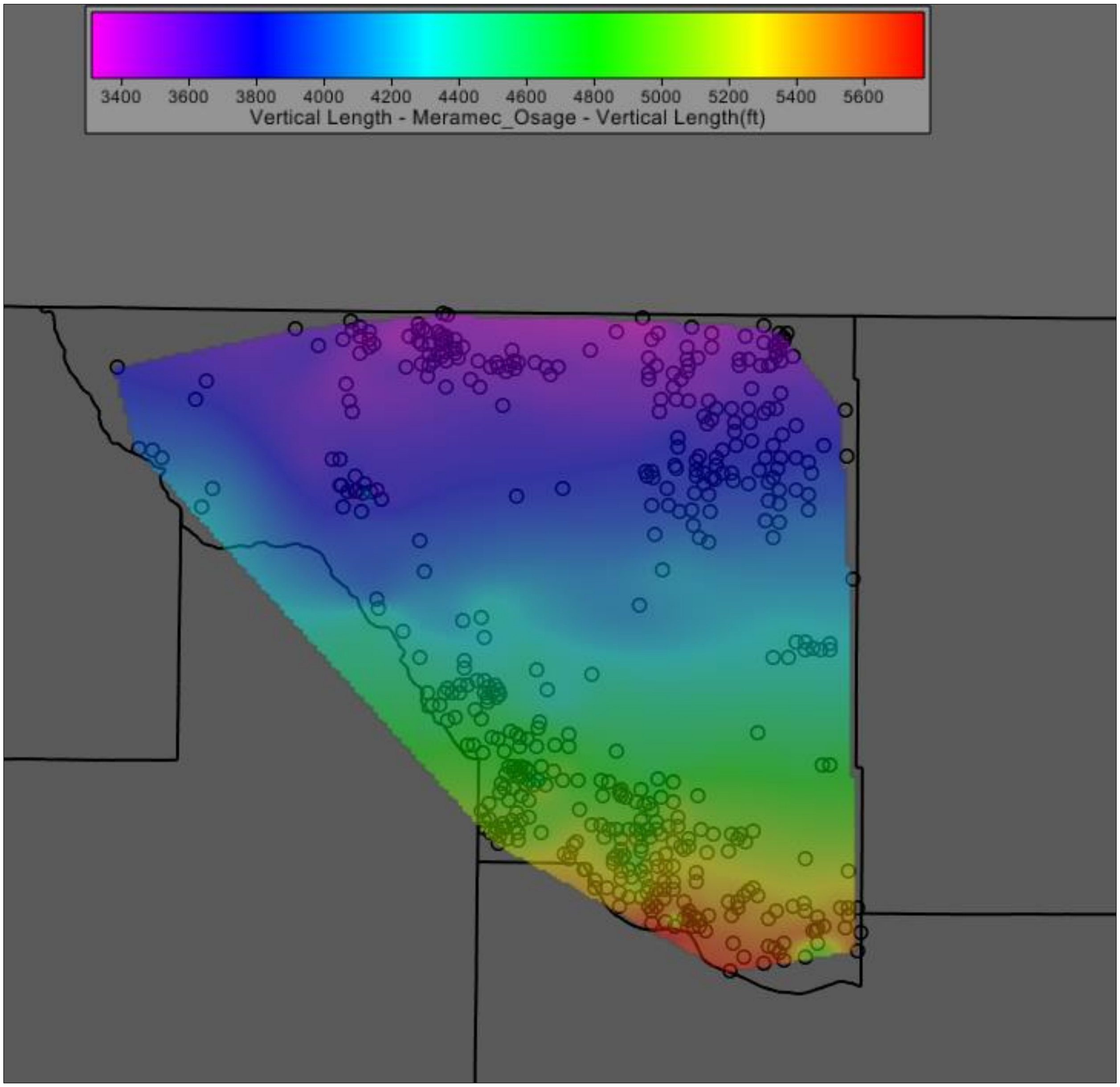


Floyd 1-11: This image shows where the Chesterian top is picked and where the Mississippi "lime" aliased top is picked when the Chesterian is present.

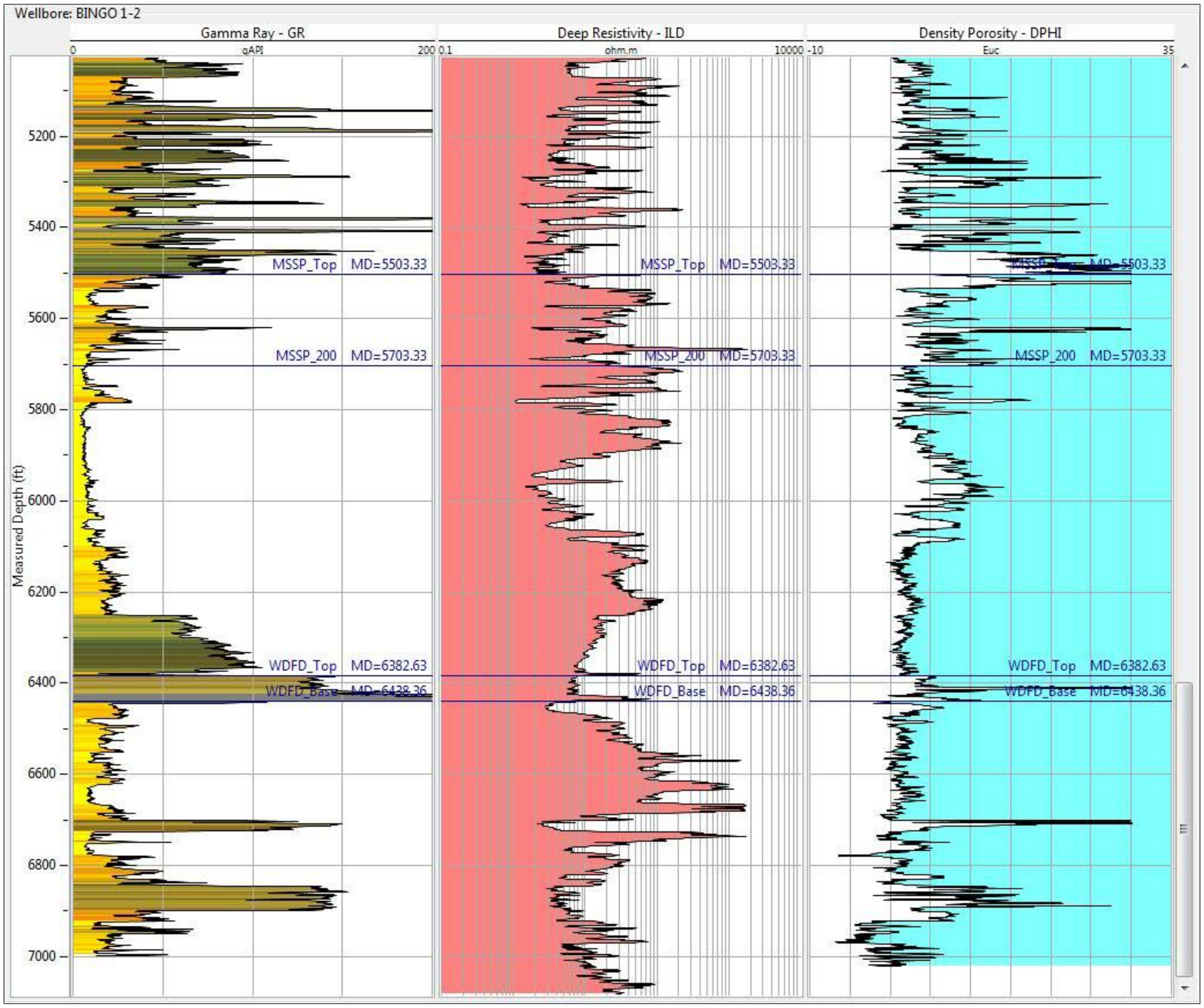


APPENDIX B: Examples of picks in wells that do not contain the Chesterian

Structure map illustrating depth to the top of the Mississippi "lime" aliased from picks



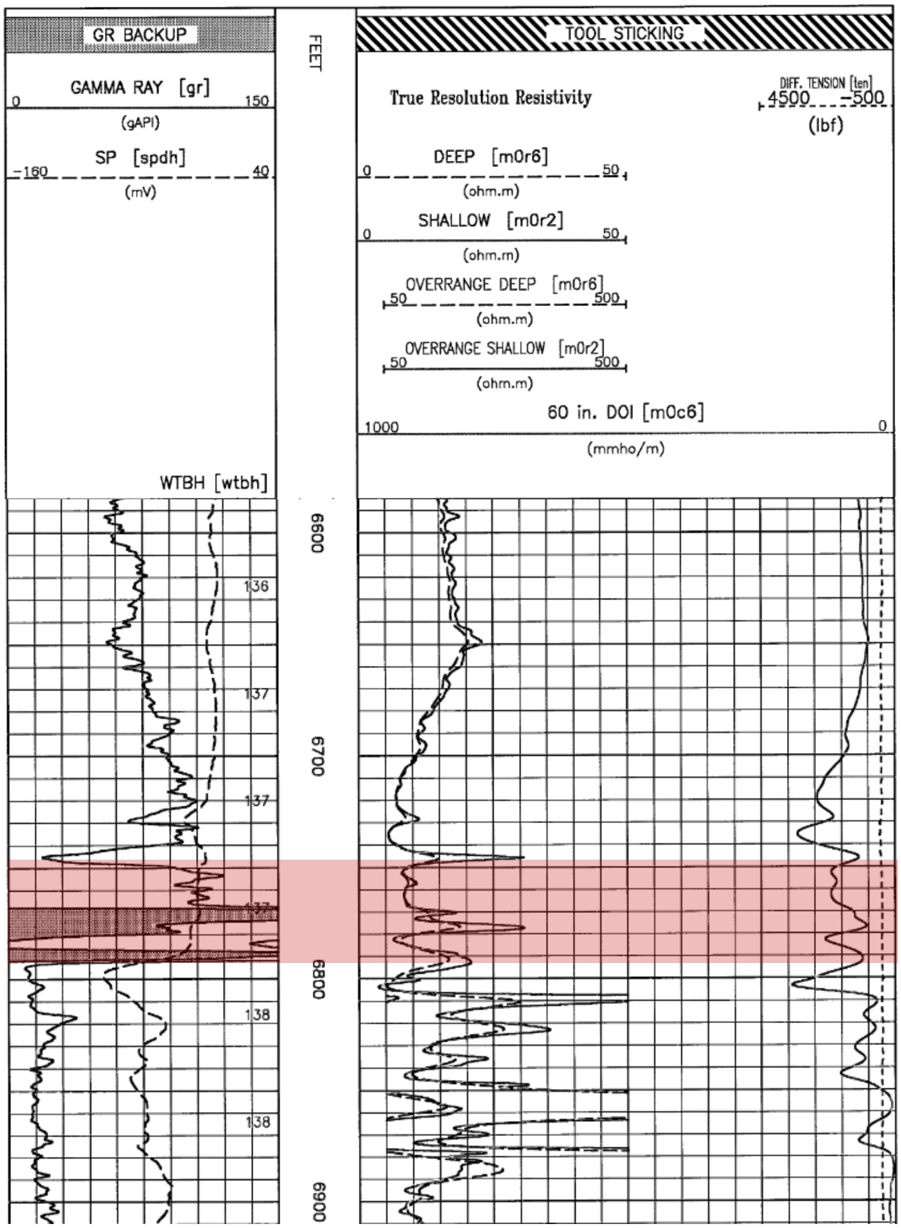
Bingo 1-2: Example showing how the Mississippi "lime" aliased tops were picked under the Pennsylvanian unconformity when the Chesterian is absent.



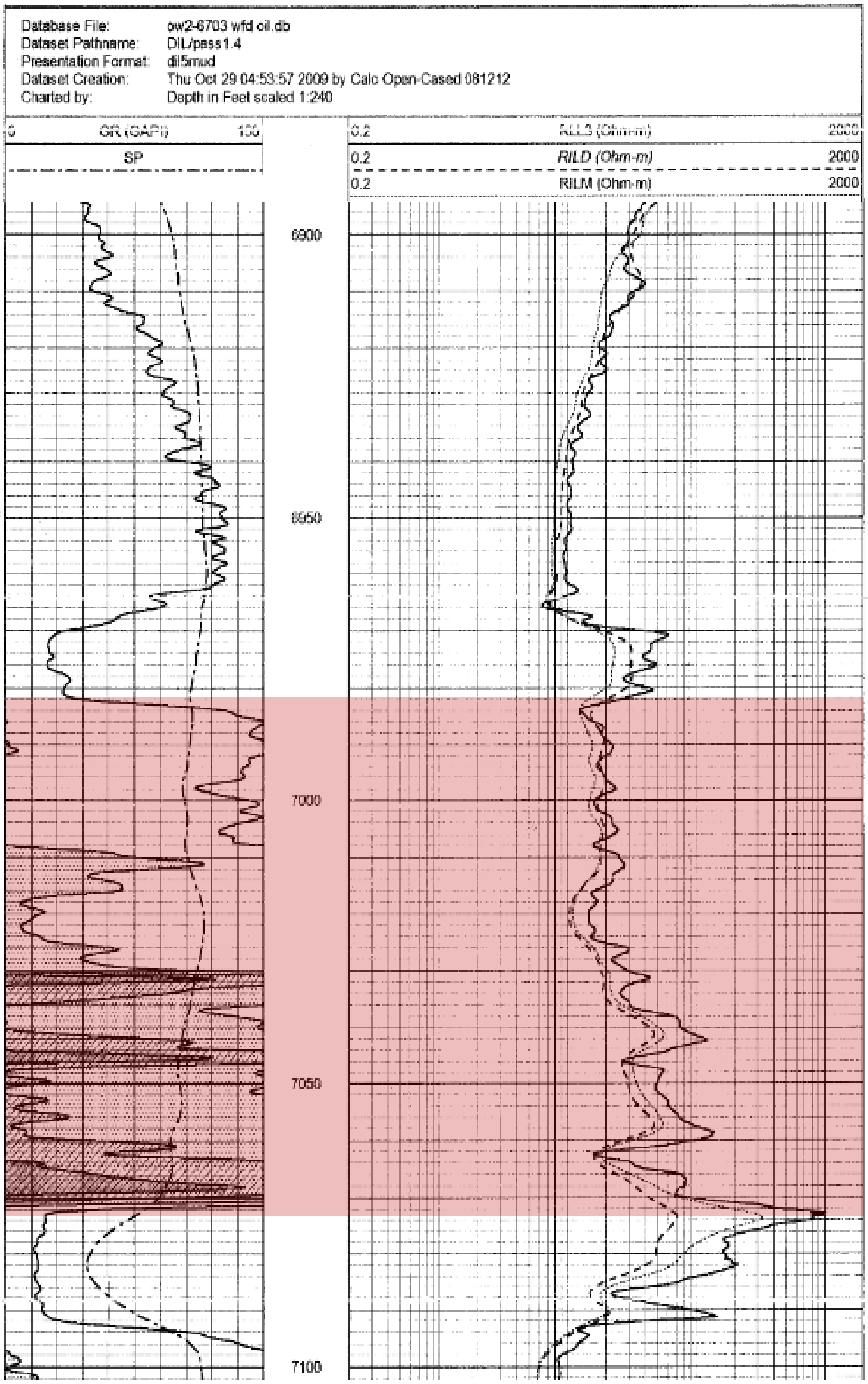
APPENDIX C: Examples of Woodford zones picked from raster images

This appendix is included to show how the Woodford top and base were picked from each raster logs. Such raster logs were used to help create the Woodford isopach.

Landry SWD 1-5: The Woodford zone is highlighted in red



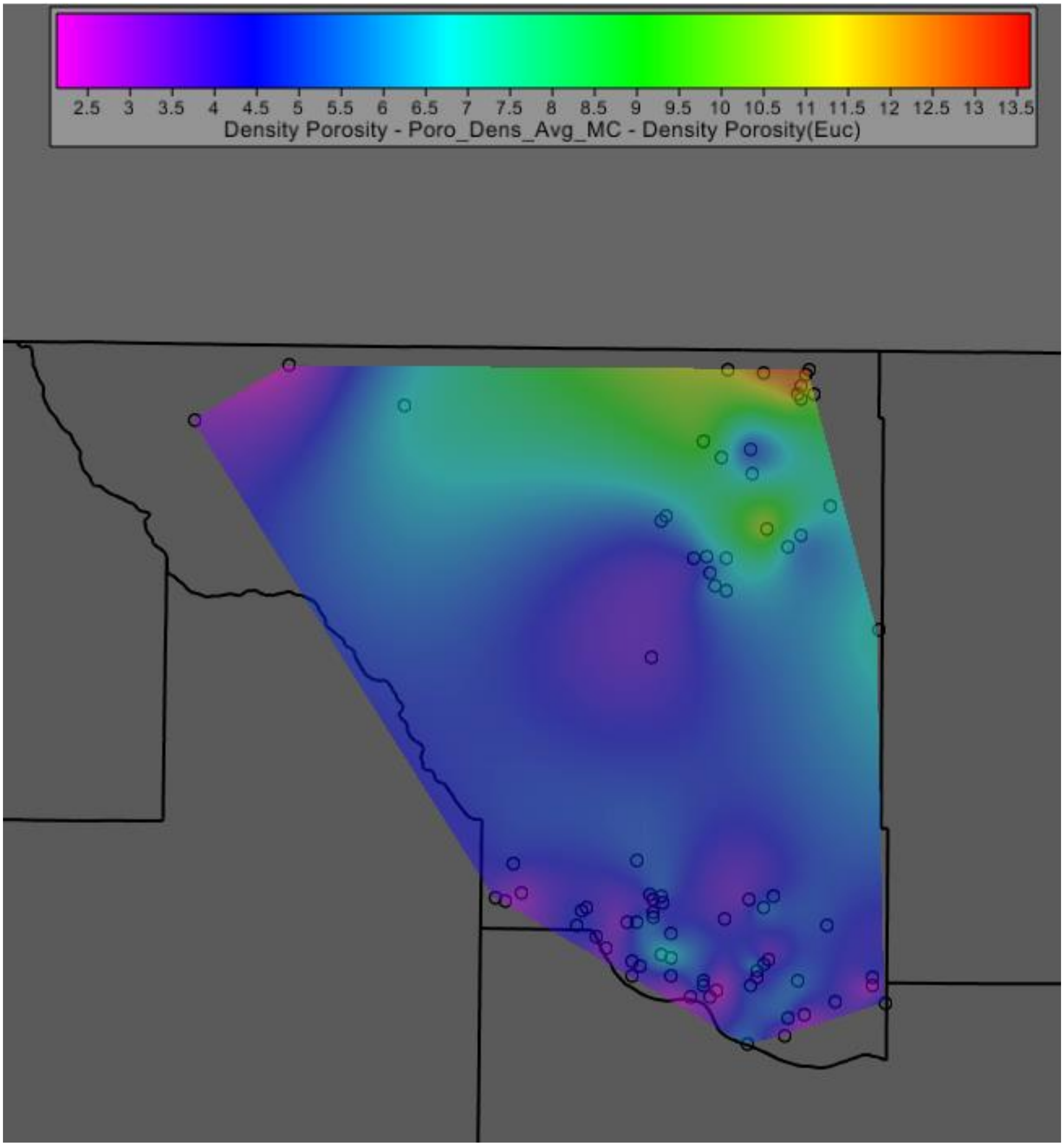
Goucher 1-19: The Woodford zone is highlighted in red



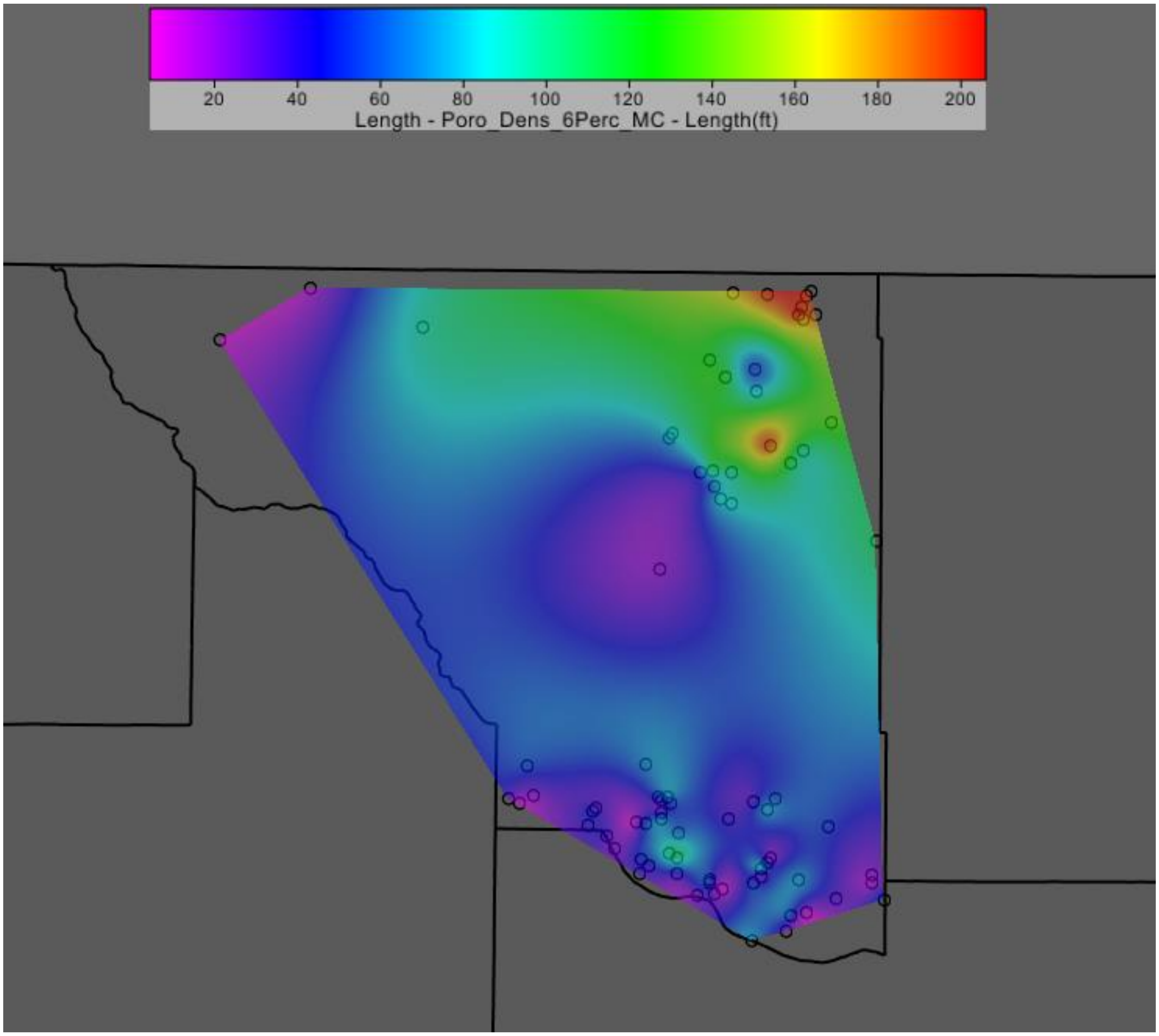
Database File: ow2-6703 wfd oil.db
Dataset Pathname: DIL/pass1.4
Presentation Format: dil5mud
Dataset Creation: Thu Oct 29 04:53:57 2009 by Calc Open-Cased 081212
Charted by: Depth in Feet scaled 1:240

APPENDIX D: Porosity grids used for extraction to horizontal wells

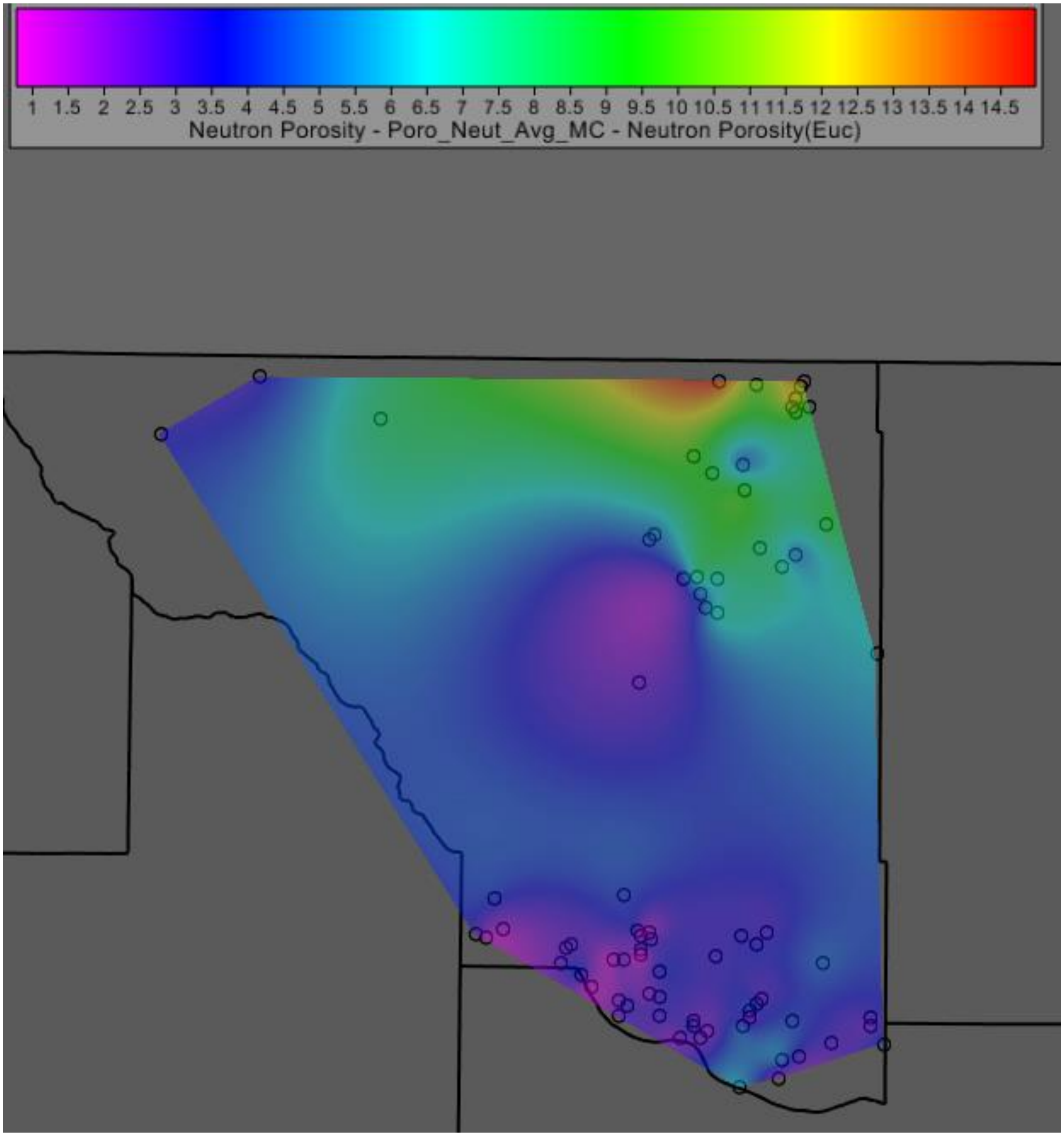
Average density porosity grid created from vertical well logs



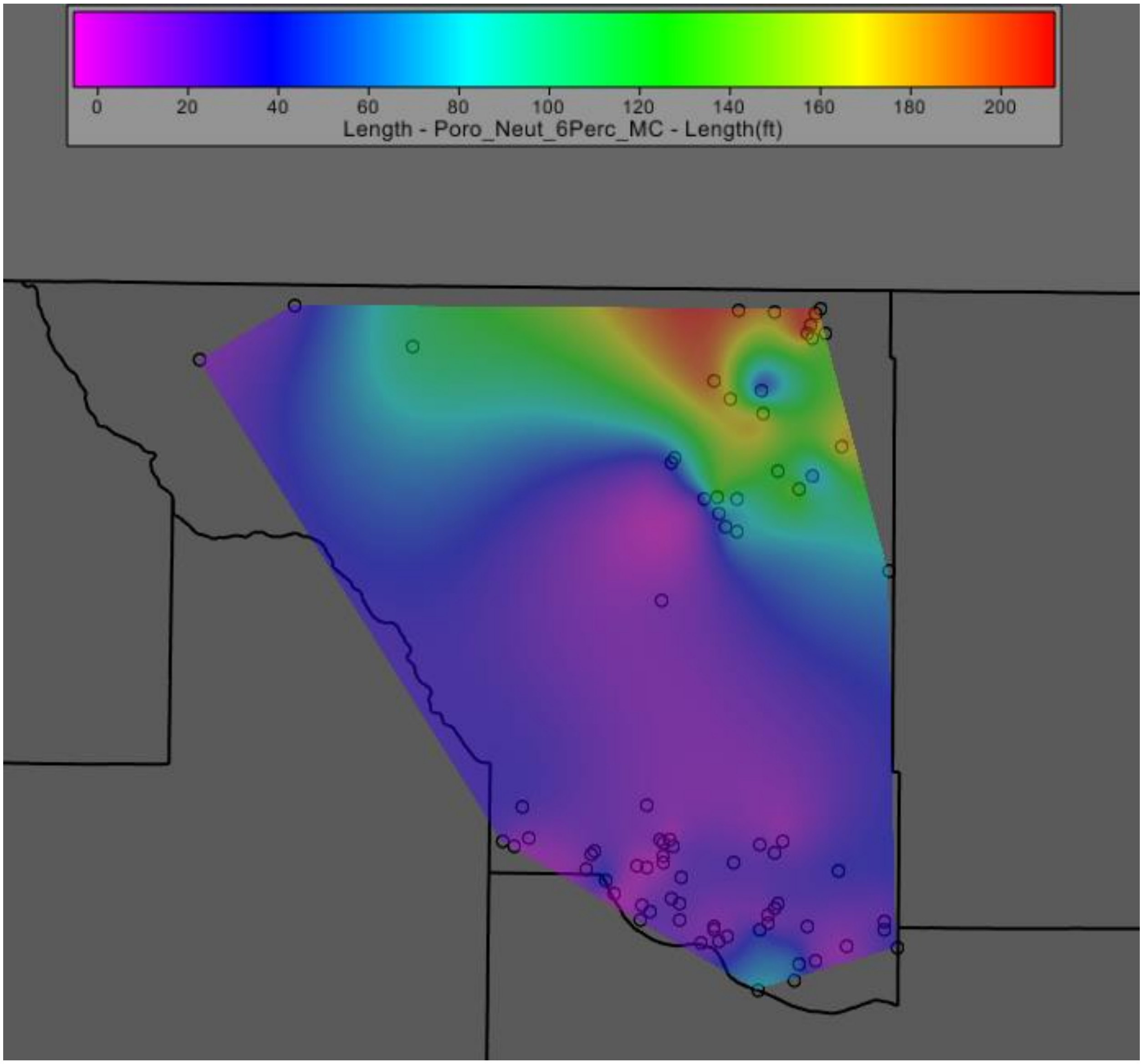
Grid showing thickness of density porosity greater than 6 percent



Average neutron porosity grid created from vertical well logs



Grid showing thickness of neutron porosity greater than 6 percent



VITA

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