PETROPHYSICAL ANALYSIS OF THE LOWER LANCE FORMATION, WASHAKIE BASIN, WYOMING

By

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TABLE OF CONTENTS

Chapter Page

I. INTRODUCTION 1

Abstract 1
Objectives 1
Literature Review 2
Methodology 4

II. GENERAL GEOGRAPHY AND GEOLOGY 6

Depositional Environment 6
Structural Geology 7
Stratigraphy 8
Ft. Union 8
Lance 9
Fox Hills 10

III. DATA 12

Well Data 12
Core Data 15
Barrel Springs 11-13-16-93 17
Jons #1 19
Aspirin Unit #1 19

IV. CALCULATIONS OF RESERVOIR PROPERTIES FROM DIGITAL WELL LOGS 22

Lithology 22
Shale Volume 24
Porosity 24
Core 24
Neutron-Density Cross Plot 26
Shale-Corrected Density Porosity 30
Neutron-Density Shale-Corrected Porosity 31

Formation Water Resistivity 33
Pickett Plot 34
Core 35
Produced Water..36
Formation Water Resistivity across the Study Area 38
Water Saturation 41
Gas-Bearing Sandstone 41

V. MAPS 43

Sandstone 43
Total Sandstone Thickness 43
Elimination of thin (<4 feet) sandstone bodies……………………………….48
Coal…………………………………………………………………………….52
Gas Potential Sandstone Reservoirs...56
Gas Producing Potential by Section...61

VI. DISSCUSSION……………………………………………………..……….63

VII. CONCLUSION 65

REFERENCES 66

APPENDICES A: PICKETT PLOTS...67

APPENDICES B: BARREL SPRINGS, LANCE FOMRATION
GAS PRODUCING ZONES COMPARED TO
CALCULATED PAY (FLAGS)..79

APPENDICES C: WELLS WITH POSSIBLE GAS-BEARING ZONES.
(POTENTIAL) IN THE LANCE FORMATION……………………………..…86

LIST OF TABLES

Table Page

1. Wells completed in the Lance Formation with production volume allocated to the Lance Formation sandstone reservoirs……………………………………………….…15

2. Porosity, permeability and water saturation measurements from a 9 feet thick interval of sandstone in the Lance Formation…………………………………….…..25

3. A comparison of wireline density log porosity (ρ_{matrix} = 2.68) with porosity measurements from core plugs………………………………………………..25

4. Density porosity (φ_D), neutron-density porosity ($\varphi_{N\text{-}D}$) and core porosity comparison……………………………………………………….…..27

5. Comparison of density porosity (D), Vsh corrected density porosity (Dcorr) and core porosity…………………………………………………….…...30

6. Schlumberger calculated porosities…………………………………………....31

7. Dewan calculated porosities…………………………………………..….32

8. Core calculated *Rw* values……………………………….……………35

9. M_{eq}/L and balance calculations ………………………………………………..37

10. *NaCl* dissolved solid equivalence data from Schlumberger Charts.....……………37

11. *Rw* results…………………………………………………….……38

12. Calculated *Sw* for the BSU 20-14-16-93………………………………………..42

13. Comparison of Lance production vs. Gross Sandstone in Barrel Springs………...47

14. Comparison of Lance production vs. 4' Sandstone in Barrel Springs……………..51

15. Comparison of Lance production vs. coal in Barrel Springs………………………57

16. Comparison of Lance production vs. pay in Barrel Springs………………………60

LIST OF FIGURES

Figure Page

1. Upper Cretaceous stratigraphy in the vicinity of Washakie Basin...................…..7

2. Structural contour map of the top of the Lance Formation, showing major tectonic features and the location of the study area ……………………….…………8

3. Type Log of the BSU 1-19-16-93 illustrating Formation boundaries…………...10

4. Distribution of oil and gas exploration wells within the study area……………..13

5. Study area with wells producing gas from the Lance Formation identified……..14

6. Barrel Springs 11-13-16-93 core lithology…..…..…………………………….…17

7. Sharp erosional contact between sandstone and underlying coal………………..18

8. Coarse grained with dark mica and carbonaceous material rich bedding structures. American Beryllium Oil Corp, Aspirin Unit 1, Depth 3045 ft….….21

9. Example of featureless (massive) coarse grained sandstone that makes up the Lance Formation in the American Beryllium Oil Corp, Aspirin Unit 1 Depth 3063-69 feet……………………………………………...21

10. Wireline logs calibrated with core for the Devon Energy Barrel Springs 11-13-16-93…………………………………………………………………..23

11. Neutron-density cross plot of the entire 300 foot zone of interest for the Barrel Springs 11-13-16-93………………………………………………….…27

12. Neutron-density cross plot of sandstones over the zone of interest…………….28

13. Pickett Plot of reservoir sandstones in the Lance Formation, Barrel Springs Unit 11-13-16-93………………………………………………34

14. Structure map of the study area contoured on the Fox Hills Formation……..…39

15. *Rw* and cementation value results by township……………………………..…40

16. The BSU 10-15-16-93 type log illustrating sandstone counts...……………....44

17. Gross sandstone map of the lower 300’ of the Lance Formation
in the Barrel Springs Township……………………………….………..45

18. Gross sandstone map across the study area……………………………………46

19. Gross sandstone vs. cumulative production….………………………………..47

20. Gross sandstone count, excluding sands less than 4’ thick……………………49

21. Gross sandstone count across the study area, excluding sands less
than 4’ thick……………………………………………………...……50

22. 4’ sandstones vs. cumulative production……………………………...……51

23. Coal count in the Barrel Springs Township……………………………...…53

24. Gross coal map across the study area……………………………………....54

25. Coal vs. production…………………………………………………....…55

26. Comparison of pay flag to actual pay in the BSU 9-14-16-93………………..57

27. Pay count contour map in the Barrel Springs Township……………………...58

28. Pay count contour map across the study area……………………………....59

29. Pay vs. production………………………………………………………….60

30. Lance potential by section…………………………………………………62

Chapter I

INTRODUCTION

Statement of Problem

The Upper Cretaceous Lance Formation in the Washakie Basin has the potential to be a high volume gas producer. Sandstones in the Lance Formation are currently secondary targets that produce gas within a small geographical area. A better understanding of the petrophysical parameters for the Lance Formation may permit the expansion of the limited productive area by improving wireline log interpretation of the Lance Formation.

Several problems are evident when petrophysical analysis of the Lance Formation is attempted. (1) There are no published values for the formation water resistivity (*Rw*) from the Lance Formation (2) values for the cementation factor (m), saturation exponent (n), and tortuosity factor (a) are not readily available (3) the characteristics (resistivity and porosity) of gas producing Lance sandstone and (4) 100% water saturated resistivity (*Ro*) is unknown.

To address the petrophysical problem, several hypothesis were proposed. (1) The *Rw* determined using log analysis can be confirmed by sampling Lance Formation water (2) the cementation exponent determined by Pickett Plot can be used in the Archie equation to facilitate the evaluation of potential gas-bearing areas in the basin and (3) The controls of Lance Formation gas production include thick sandstones, structure, faulting of anticlinal folding.

Methodology

The initial step toward completing this study is data acquisition, which involves acquiring well logs, digital log curves, and core data from as many wells as possible located in the study area. Most wells within the study area penetrated the Lance Formation, but not all wells have a full log suite run across the Lance interval. Most of this information pertaining to the subsurface is publicly available through the Wyoming Oil and Gas Conservation Commission and the United States Geological Survey.

The second step is correlation. The complicated intertonguing of Upper Cretaceous strata makes it very difficult to identify the top and the base of the Lance Formation and correlate beds across distances of more than a few miles. Establishing consistent correlations is an integral part of this study. Correlating individual coals, sandstones, and shales within the Lance Formation will be attempted within local areas to establish the distribution of productive trends. Only sandstones in the lower 300 feet were included in this study.

Once the interval sandstones were identified, Pickett Plots (Pickett, 1966) were constructed to determine R_w and m. Water samples were collected for chemical analysis and R_w determination. In addition R_w was calculated using water saturation (S_w) from core plug analyses. R_w values form three sources were compared to estimate validity.

Finally, an attempt was made to decipher the controls of oil and gas accumulations. Eight wells producing oil and gas from the Lance Formation in the Barrel Spring Township and another seven in the immediate study area will be examined to determine what makes them productive. There are probably a number of variables responsible for oil and gas accumulations in the Lance Formation. Variables that will be examined initially include: ratios of sandstone to coal and sandstone to shale, sandstone porosity, sandstone thickness, attitude of sandstone, water saturations of productive sandstone, depth below surface, reservoir architecture of individual sandstone bodies, TOC within adjacent shales, and proximity to coals.

Lance Formation core from a well in the Barrel Springs Township, will be examined and correlated to well logs to model depositional facies. The wells used for this study were logged by numerous logging companies and range in age from the 1970s to present. The logs will not be normalized, which may generate slight discrepancies in the calculations. However, these discrepancies are expected to be minor and should not alter the interpretation. Data of questionable validity will be excluded. The ultimate goal is to establish the footage of sandstone, shale, coal, and gas bearing rock for each well.

Study Area

The study area consists of 12 townships (T.15-18N, R.94-92W) and was chosen because of the proximity to eight Lance wells producing in the Barrel Springs Township (T.16N R.93W). Identifying areas with potential for oil and gas production neighboring the Barrel Springs Township will be the first step in evaluating the full production potential of the Lance Formation in the Washakie Basin.

Literature Review

The Lance Formation conformably overlies the Fox Hills Sandstone and represents the last recorded Cretaceous deposits in the Washakie Basin. Because of the importance of coal to the Union Pacific Railroad, the Lance has been studied since the

19th century: first by early territorial surveyors, then by miners, and finally by geologists. While the Lance Formation contains significant reserves of coal, it was not preferred by the railroad, which sought the thicker Mesaverde Group coal (Pearson et al, 1919).

Shultz (1907) was the first to study the stratigraphic relationships of the upper Cretaceous section in southwest Wyoming and included the sequence that lies beneath the Wasatch Formation and above the Lewis Shale into the "Black Butte coal group" (Lance, Fox Hills and Fort Union), which a year later was renamed the Laramie Formation. Dobbin et al (1929) addressed the problem of the Cretaceous-Tertiary boundary in the western interior of the United States and hypothesized three possible views. One view, which is now regarded as the current popular belief, is that the contact of the Fort Union and the Lance is the boundary between the Cretaceous and Tertiary. The Lance contains the last known fossils of dinosaurs and the invertebrates similar to those in other Cretaceous rocks Dobbin et al (1929). Hale (1950) proposed the term "Lance" Formation in favor of "Laramie" Formation in southwest Wyoming to better conform with popular terminology throughout the Rocky Mountain region. The Lance Formation was named for an area in which it outcrops in the vicinity of the Lance Creek, Niobrara County, Wyoming by J.G. Hatcher (1903).

Weimer (1960) described the Upper Cretaceous rocks within the Rocky Mountain region as intertonguing marine, transitional, and non-marine sediments. Weimer (1960) noted that the Upper Cretaceous sediments were deposited in a nonmarine environment in the western Rockies and a marine environment in the eastern plains of the Rockies, with a transitional area between. In the Washakie Basin, all three of these environments are represented by intertonguing deposits, which is the result of a long period of regression that was punctuated by sharp transgressions that resulted in a constantly changing shoreline position. The Lance represents the nonmarine sequence composed of carbonaceous shale, sandstone, siltstone, and coal formed from sediments deposited in a lagoonal environment. The Fox Hills Sandstone represents the Upper Cretaceous transitional sequence and a barrier island facies, where the Lewis Shale represents the marine sequence (Weimer, 1960).

Roehler's (1993) findings supported Weimer's depositional model. Roehler (1993) described the Lance Formation as a continental deposit consisting of bay or lagoonal origin that overlies and intertongues the barrier shoreface deposits of the Fox Hills Formation. Roehler (1993) further described the Lance with the term "bay cycle" to explain the fresh-water and brackish-water cyclical deposits. According to Roehler (1993) the Lance Formation contains fourteen cycles, which could be related to Milankovitch cyclicity.

Chapter II

GENERAL GEOLOGY AND GEOGRAPHY

Depositional Environment

Before Laramide uplift, the present site of the Washakie Basin was positioned on the western edge of the Cretaceous Interior Seaway. The seaway was a large, shallow inland sea extending from the Arctic Ocean across North America into the Gulf of Mexico. Large amounts of sediments were deposited on the western edge of the seaway, sourced from the Sevier Orogeny to the west. The Sevier Orogeny is a large uplift formed as a result of the Farallon and Kula Plate collision approximately 140 million years ago (Gary et al., 1972).

During the Late Cretaceous, the Cretaceous Interior Seaway repeatedly transgressed and regressed until the time of deposition of the Fox Hills Formation, when the Seaway made its final retreat. Sevier sediments continued to be deposited along the western edge of the Seaway while it continued its retreat as a result of Laramide uplift. Once Laramide uplift interrupted the Sevier sediment source, the Cretaceous-Tertiary unconformity formed. The stratigraphic nomenclature for this interval is illustrated in Figure 1.

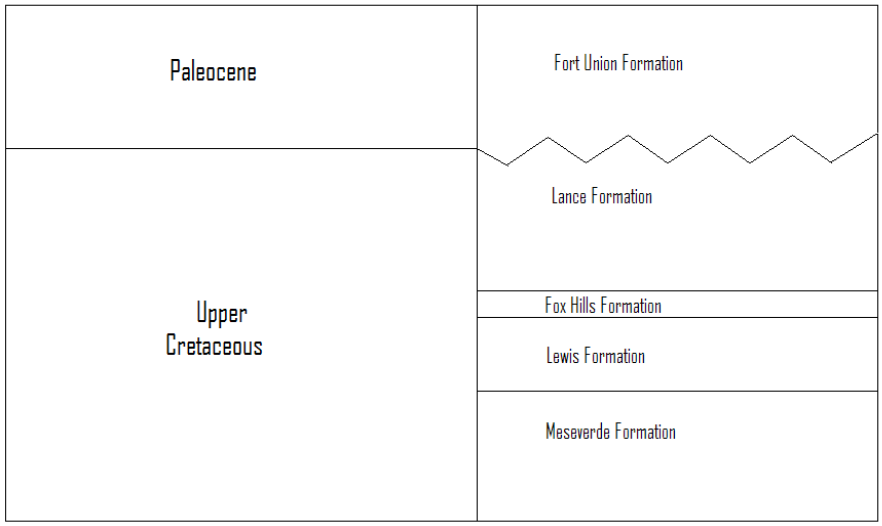


Figure 1. Upper Cretaceous stratigraphy in the vicinity of Washakie Basin

Structural Geology

The Washakie Basin is a relatively symmetrical basin with an 8º dip along the eastern flank and a 15º dip along the western flank, encompassing approximately 2500 square miles in south-central Wyoming (Love, 1970). The basin is separated from the Great Divide Basin to the north by the Wamsutter Arch, the Sand Wash Basin to the south by the Cherokee Ridge, the Green River Basin to the west by the Rock Springs Uplift, and the Laramie Basin to the East by the Sierra Madre Mountains (Figure 1). To date, no wells have penetrated the entire Phanerozoic section within the deeper portion of the basin. Hale (1961) reported the Washakie Basin contains over 32,000 feet of post-Cambrian sedimentary rock. The topographic basin floor is generally flat and covered with unconsolidated, Tertiary-age alluvial fill sourced from the Sierra Madre Mountains to the east, the Rock Springs Uplift to the West, and the Wind River Mountains to the north. The surface elevation ranges from 6000 to 9000 feet with primary drainage being the Bitter Creek. The Washakie Basin formed during the Laramide Oregeny in late

Cretaceous time. The Laramide Orogeny was a time of deformation in the eastern Rocky Mountains and was preceded by several phases that began in late Cretaceous and extended into the end of the Paleocene (Gary et al, 1972). Laramide deformation produced great compression structures, thrust faults and folds. Most thrust faults are low angle and have been thrust horizontally great distances (Eardley, 1951).

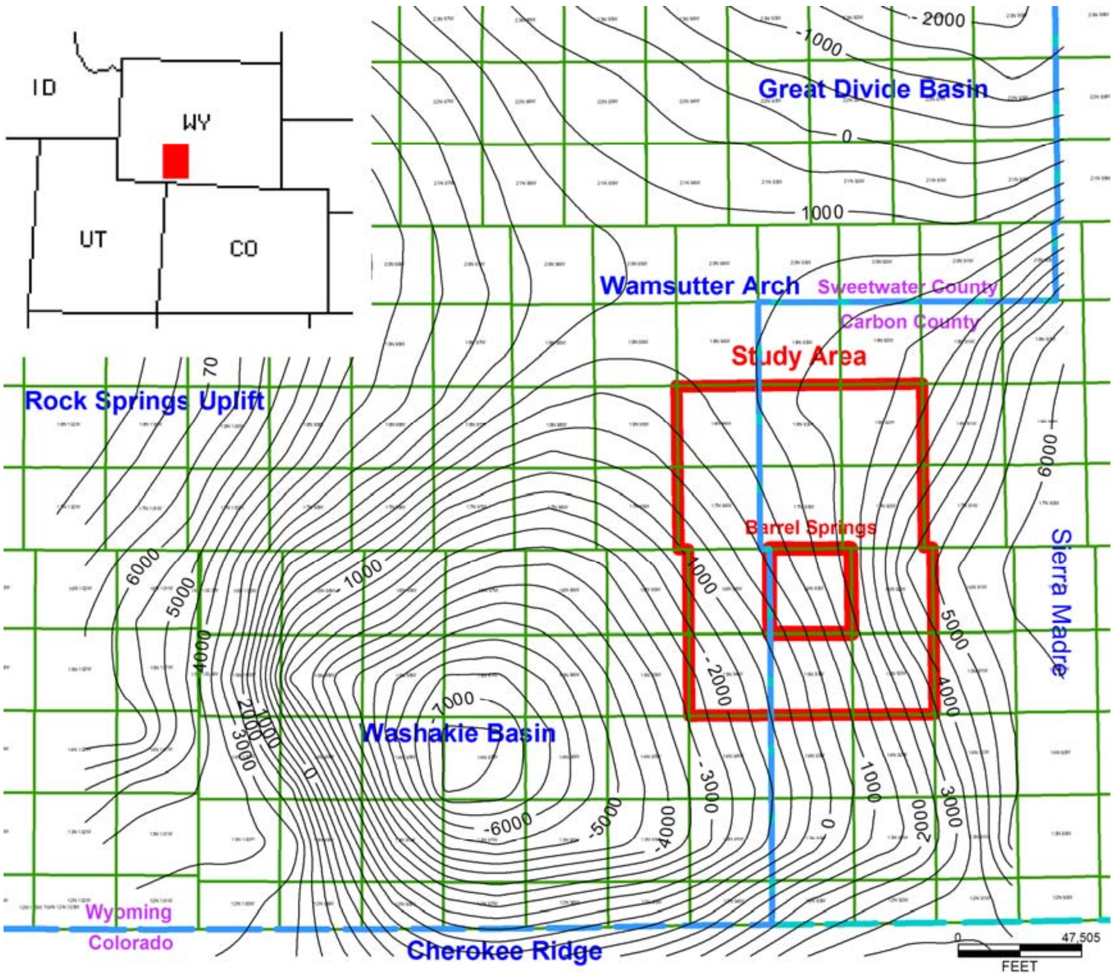


Figure 2. Structural contour map of the top of the Lance Formation, showing major tectonic features and the location of the study area. Contour interval = 500 feet

Stratigraphy

Ft. Union Formation

The Ft. Union is present throughout Wyoming and is most known for its large coal deposits. In the Washakie Basin, the Ft. Union Formation is composed of gray-green carbonaceous shales, coals, white to gray, fine to conglomeratic sandstones, gray-green siltstones and brown nodular limestones (Colson, 1969). The Sierra Madre complex to the east sourced the Ft. Union with coarse, arkosic clastic material (Colson, 1969).

Cretaceous - Tertiary Contact

The top of the Lance Formation marks the regional, Cretaceous-Tertiary unconformity. This unconformity is marked in outcrop by a conglomerate or palesol horizon at the base of the Fort Union (Hettinger et al, 1991). In the subsurface the Cretaceous-Tertiary unconformity is placed at the base of the Red Rim Coal (Figure 3). The Fort Union can be distinguished from the Lance by the Red Rim Coal as well as a decrease in deep resistivity on the well logs.

Lance Formation

The Lance Formation is divided into an upper and lower section based on an increased abundance of shales and coals towards the bottom. Like the rest of the Upper Cretaceous stratigraphy, the upper zone of the Lance Formation intertongues the lower zone making it difficult to laterally map the contact. While the upper part of the Lance Formation is composed of clean, thick, highly porous sandstones, they tend to be wet. It is the lower part of the Formation where the coals are thick and laterally extensive and the sandstones are thin and channelized, that is the interest and the focus for this paper.

Lance – Fox Hills Contact

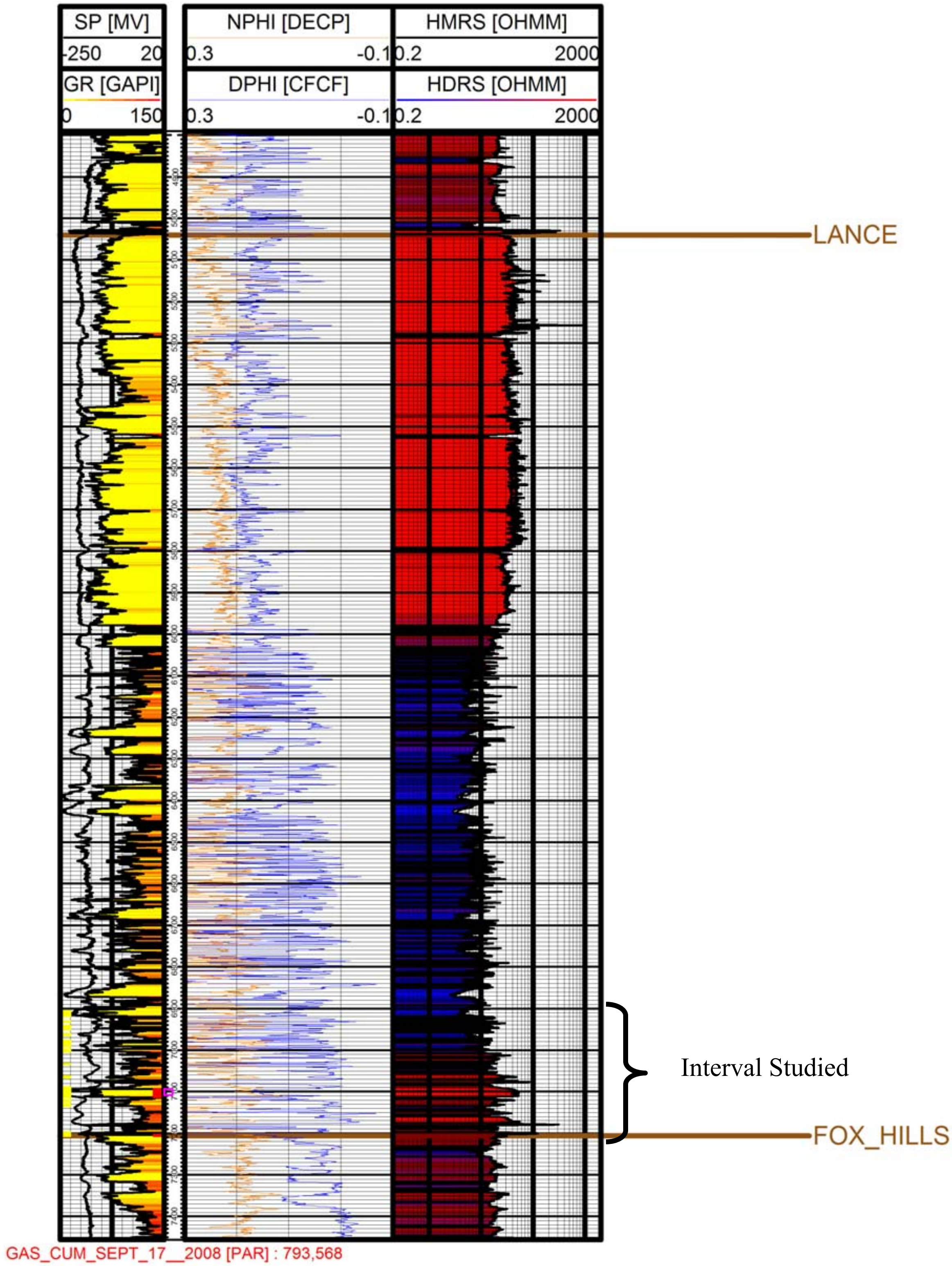


Figure 3. Type Log of the BSU 1-19-16-93 illustrating formation boundaries

The contact between the Lance Formation and the Fox Hills Formation can be very difficult to correlate over large areas. Intertonguing of strata and possible unconformities can make for very inconsistent picks. The bottommost coal in the Lance Formation can be correlated with consistency and is used as the pick for the base of the Lance Formation.

Fox Hills Formation

The Fox Hills Formation is approximately 15-60 feet thick and represents the short period of time when nearshore-marine and marginal-marine environment existed as the Seaway retreated (Roehler, 1993). Fox Hills sandstones are thick, blocky, barrier-island deposits (Roehler, 1993).

Chapter III

DATA

Well Data

Within the study there are 1,315 well bores; 1243 currently producing, 59 dry holes, 9 plugged and abandoned and 4 injection wells (Figure 4). The primary oil and gas exploration target in this area is the Mesaverde Formation, with secondary exploration targets in the Lance, and Lewis Formations. Well density increases in the northern portion of the study area where a thick bar sandstone at the top of the Mesaverde Formation is extensively drilled. All of these wells penetrated the Lance and range in age from ones drilled in the early 1970s to present day. Of the 1,315 wellbores, 1,195 have some sort of wireline log data associated with them. Four-hundred forty eight (448) wells have the digital log ascii standard (LAS) data required for this project. The required digital LAS curves consist of neutron porosity, density porosity, deep resistivity, shallow resistivity, and gamma ray. Furthermore, to be useful the curves must be run at least 300 feet into the Lance Formation.

The most important well data will come from the 18 Lance Formation producing wells in the Washakie area (Figure 5). The densest and most prolific production occurs in the Barrel Springs Township. Evaluating the volume of production from the Lance

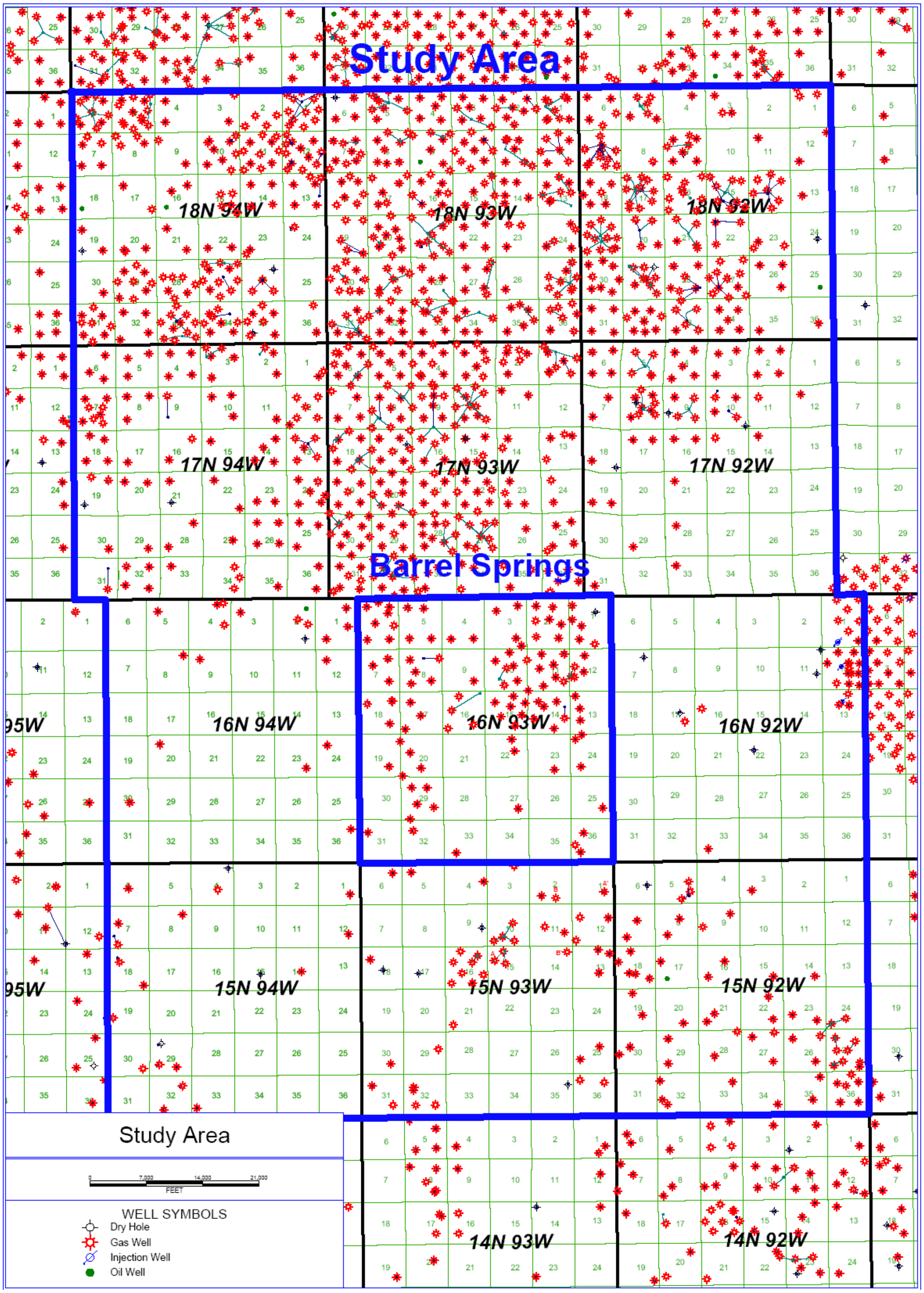


Figure 4: Distribution of oil and gas exploration wells within the Study Area

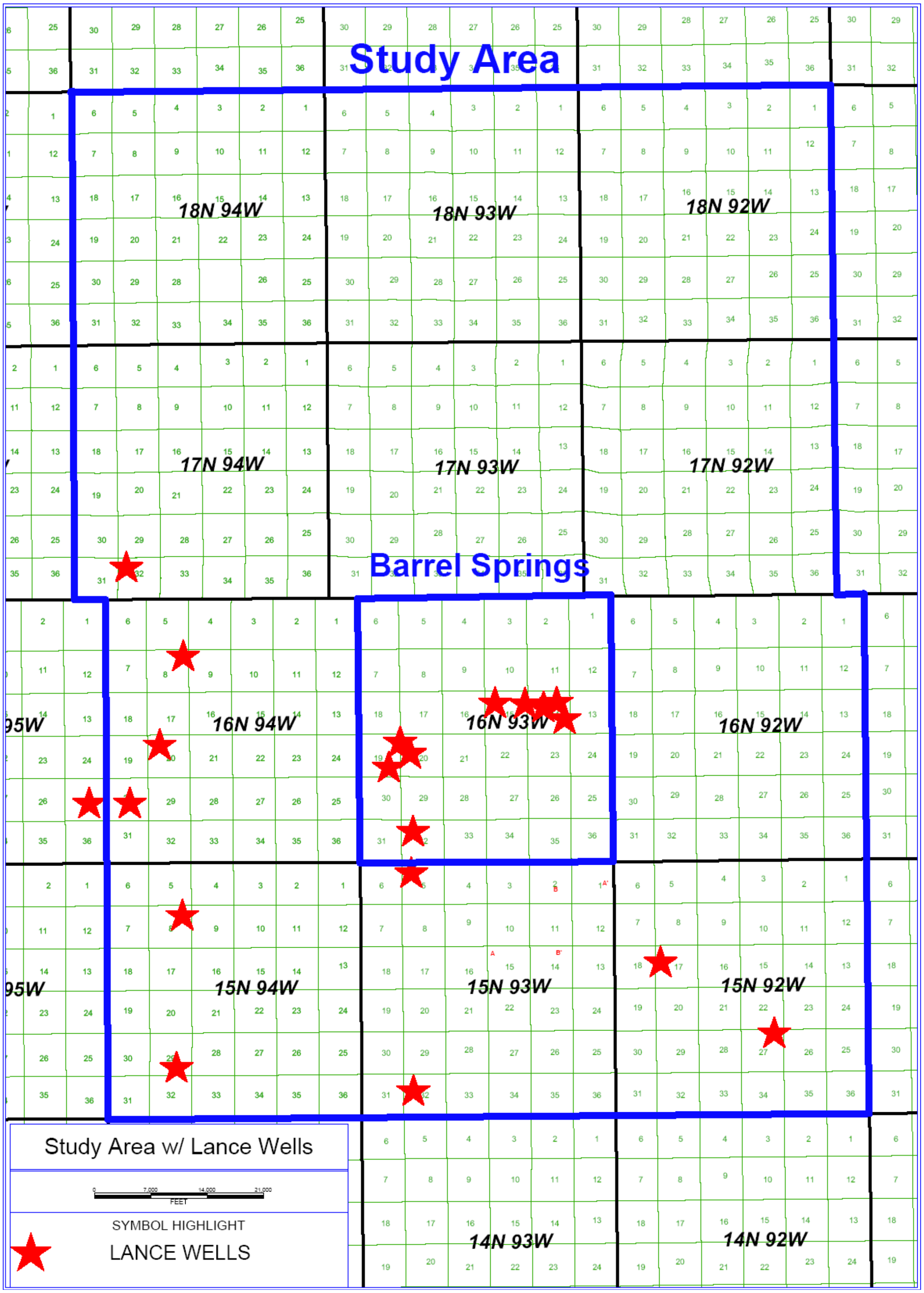


Figure 5: Study area with wells producing gas from the Lance Formation ientified

Formation can be very difficult because it is usually comingled with production from the Mesaverde Formation. In comingled wells, production logs and flow tests were used to distinguish Lance production from Mesaverde. The volume of Lance Formation oil and gas production varies significantly, as seen in Table 1.

Well	Cumulative Gas (MCF)	Lance Completion Date	Lance Production (MCF)	Lance Cumulative Water (bbl)
Barrel Springs Unit 9-14-16-93	903,331	8/25/1998	599,073	34,080
Barrel Springs Unit 20-14-16-93	1,219,673	1/27/2005	43,934	3,082
Barrel Springs 14-2	1,902,696	5/22/2002	669,699	2,041
Barrel Springs Unit 20-15-16-93	2,057,778	7/8/2002	601,144	9,957
Barrel Springs II 10-15-16-93	2,085,083	11/16/1983	2,085,083	5,884
Barrel Springs Unit 1-19-16-93	1,049,136	10/9/2002	671,296	10,672
Barrel Springs 10-20-16-93	1,082,418	12/30/2002	149,606	15,460
Barrel Springs 10-32-16-93	1,134,504	4/4/2003	231,263	52,143
Federal 40-19-16-93	577,888	9/19/1989	422,615	1,757
Flat Top 4-5	214,213	11/15/2003	214,213	8,402
Federal 1-8	74,909	12/18/1974	74,909	1,575
DiMaggio Unit 2	114,168	3/24/2004	114,168	26,094
Shallow Creek 1	187,672	5/29/1980	187,672	18,154
DiMaggio 11-8	33,145	1/28/2004	33,145	6,293
North Ruger Unit 34-29	213,371	7/23/1994	213,371	162
Mexican Flats 5-17-15-92	873,751	8/18/1999	719,973	5,703
Mexican Flats 2-27-15-92	684,135	11/26/2003	356,739	2,440

Table 1: Wells completed in the Lance Formation with production volume allocated to the Lance Formation sandstone reservoirs.

Core Data

Three wells were located that cored the Lance Formation. One, the Barrel Springs 11-13-16-93 was located within the boundaries of the study area, and therefore only core that could be used to calibrate the wireline data. The other two cores (Jons #1 and Asprin

Unit 1) were examined to help improve the interpretation of the depositional setting and environments.

Barrel Springs 11-13-16-93

The Barrel Springs 11-13-16-93 was drilled and cored in 2002 by Devon SFS Operating. This well offset existing Lance production in the Barrel Springs Township and recovered 110 feet core from the Lance Formation. Due to its proximity to existing Lance production, this core was studied extensively. The Barrel Springs 11-13-16-93 was never completed in the Lance Formation because of a lack of sandstone and the presence of high water saturation in the sandstones that were present. The cored rock is very consolidated and consists of sandstones, carbonaceous shale and coal. The shales are rich in mollusks (oyster), which are indicators of a marginal marine environment. A schematic diagram of the Barrel Springs 11-13-16-93 core is shown in Figure 6. The coals are dark, crumbly, and have abundant cleating (Figure 7). These coals are believed to be a source of the natural gas in the Lance Formation and are potential reservoirs. The water associated with these coals is not understood and they could be water charged.

The channel sandstones are fine grained and contain limited amounts of visible feldspars and micas. These sandstone are sourced from the distal Sevier Uplift to the west.

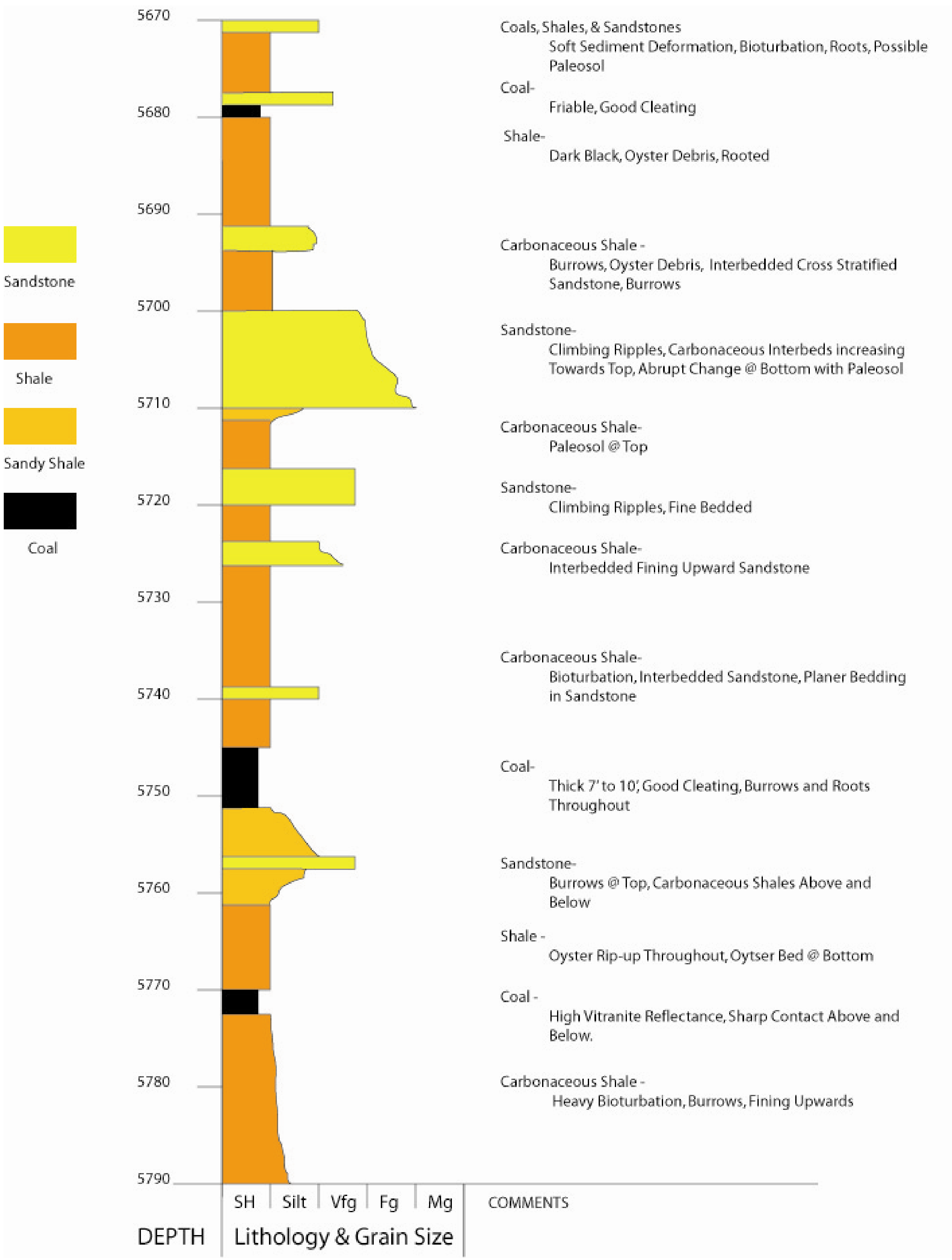


Figure 6: Barrel Springs 11-13-19-93 core lithology

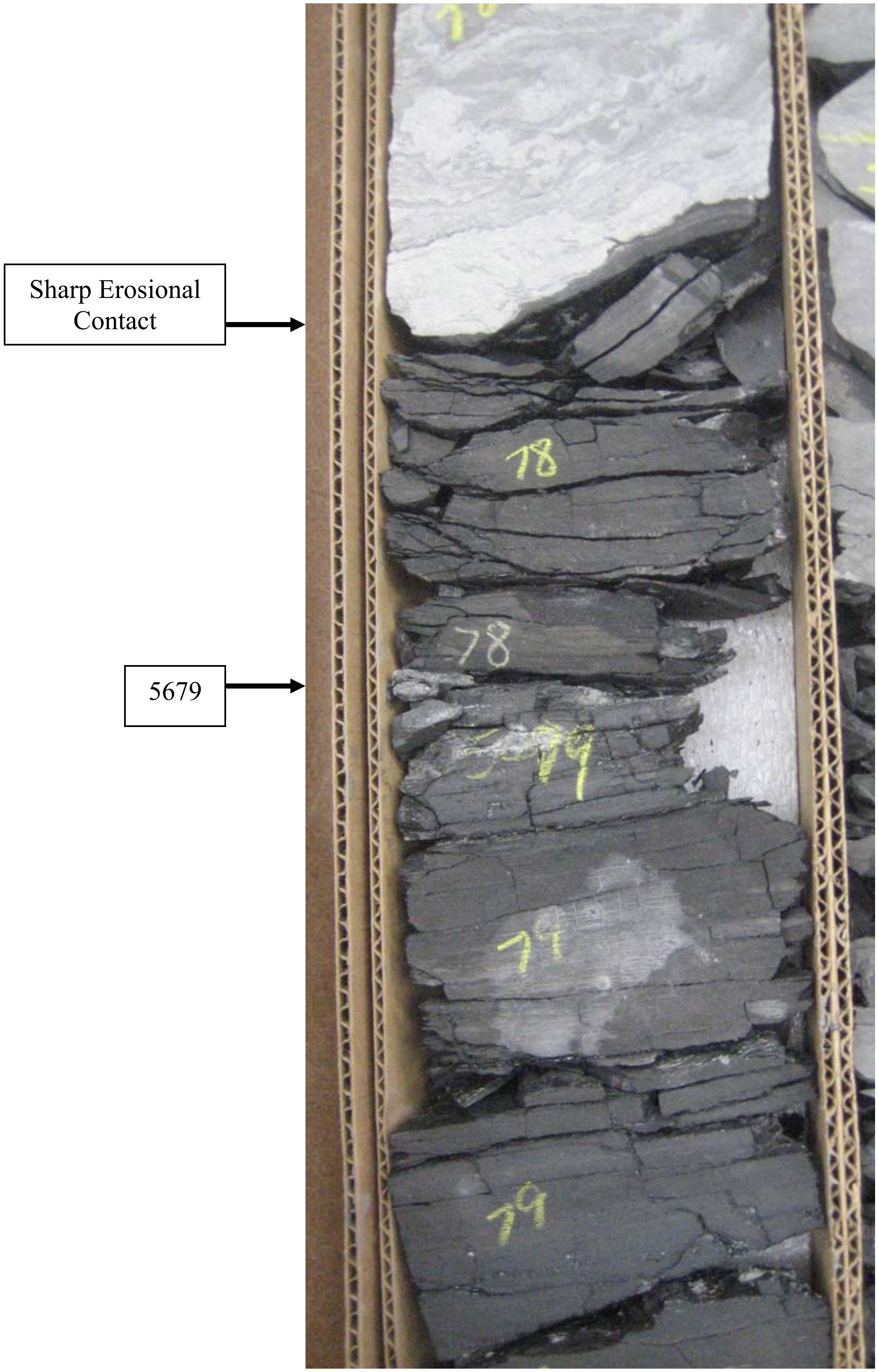


Figure 7: Sharp erosional contact between sandstone (light color) and underlying coal. Depth 5678 -5679 feet. Devon, BSU 11-13-19-63

Jons #1

The Superior Oil Company Jons #1 well is located in the West Side Canal Field approximately 32 miles to the south of the study area. The well was drilled in 1966 and 48 feet of core were recovered from the Lance Formation. The sandstone is coarser grained than the sandstones in Barrel Springs and contain more mica and feldspars. The coarser grain size is interpreted as indicating a closer source. These Lance sandstones were likely sourced from a highland to the south that was generated by the early stages of the Laramide uplift.

The West Side Canal Field has produced 168 BCF primarily out of the Lance (WOGCC, 2009). The West Side Canal Field provides confirmation that substantial volumes of gas exist in the Washakie Basin. However, the Lance Formation at West Side Canal is quite different from the sandstones in the study area based on the two cores examined for this project. At West Side Canal Field the reservoir quality of the Lance Formation is much better, probably as a result of grain size and shallower burial history. The West Side Canal Field also lies along the crest of the Cherokee Ridge Arch and is bounded to the north by a left lateral shear fault zone (Parker, 2001).

Aspirin Unit 1

The American Beryllium Oil Corp Aspirin Unit 1 is a Wildcat well drilled in 1980, 6 miles south of Jonah Field and 115 miles northwest of the study area. The Jonah Field is a giant oil and gas field with a current cumulative production in excess of 2.27 MMBOE from the Lance (WOGCC, 2009). This well was analyzed to understand how the Lance in the Washakie Basin varies from the Lance Formation in the Jonah Field.

The Aspirin Unit 1 shows evidence of being deposited much closer to the source than that of the Lance in the Barrel Springs area. The core is composed largely of coarse-grained, massive to cross-bedded sandstones (Figure 8). The interpreted braided stream deposits seen here are quite different from the other two samples. This braided stream environment deposited hundreds of feet of sandstone (Figure 9). Mica and conglomerate clasts are common, indicating deposition close to the source. It is believed these braided streams fed the Lance deposits further downstream in the Washakie Basin. From the core of the Aspirin Unit 1, it is quickly understood how the Jonah and associated Lance Fields in the northern Green River Basin are very different from the Washakie Basin Fields. The Lance Formation in the Washakie Basin consists of irregular channel sands that are very difficult to predict, while the Lance Formation in the northern Green River Basin contains a thick (up to 1,500 ft) accumulation of sandstones. Thus, Barrel Springs cannot be expected to have results similar to that of the Jonah Field due to the overall lack of Lance reservoir.

Figure 8: Coarse grained sandstone with dark mica and abundant carbonaceous material illustrating bedding structures. American Beryllium Oil Corp, Aspirin Unit 1, Depth 3045 feet.

Figure 9: Example of featureless (massive) coarse grained sandstone that makes up the Lance Formation in the American Beryllium Oil Corp, Aspirin Unit 1 Depth 3063-69 feet.

Chapter IV

CALCULATIONS OF RESERVOIR PROPERTIES FROM DIGITAL WELL LOGS

Lithology

The amount of reservoir fluid and saturation data available for the Lance Formation in the study area is minimal. In order to obtain the most accurate, consistent results, reservoir data derived from wireline logs was calculated from digital log curves rather than interpreted from raster logs. The consistent identification of sandstone, coal, and shale from the digital curves was completely dependent on using suitable petrophysical models and a number of log curves.

Figure 10 illustrates the correlation of the wireline logs with the core. Furthermore, this figure illustrates the lithologic correlation between the calculations from the logs and the core description in Figure 6. The shaded gamma-ray curve represents the calculated wireline lithology using the gamma-ray and density-porosity curves. The following parameters were determined to best represent the actual lithology:

- Sandstone = Gamma Ray < 85 American Petroleum Institute (A.P.I.) and Density Porosity < 30%
- Coal = Density Porosity > 30%
- Shale = Gamma Ray >= 105 A.P.I. units
- Sandy Shale = Gamma Ray > 85 < 105 A.P.I. units

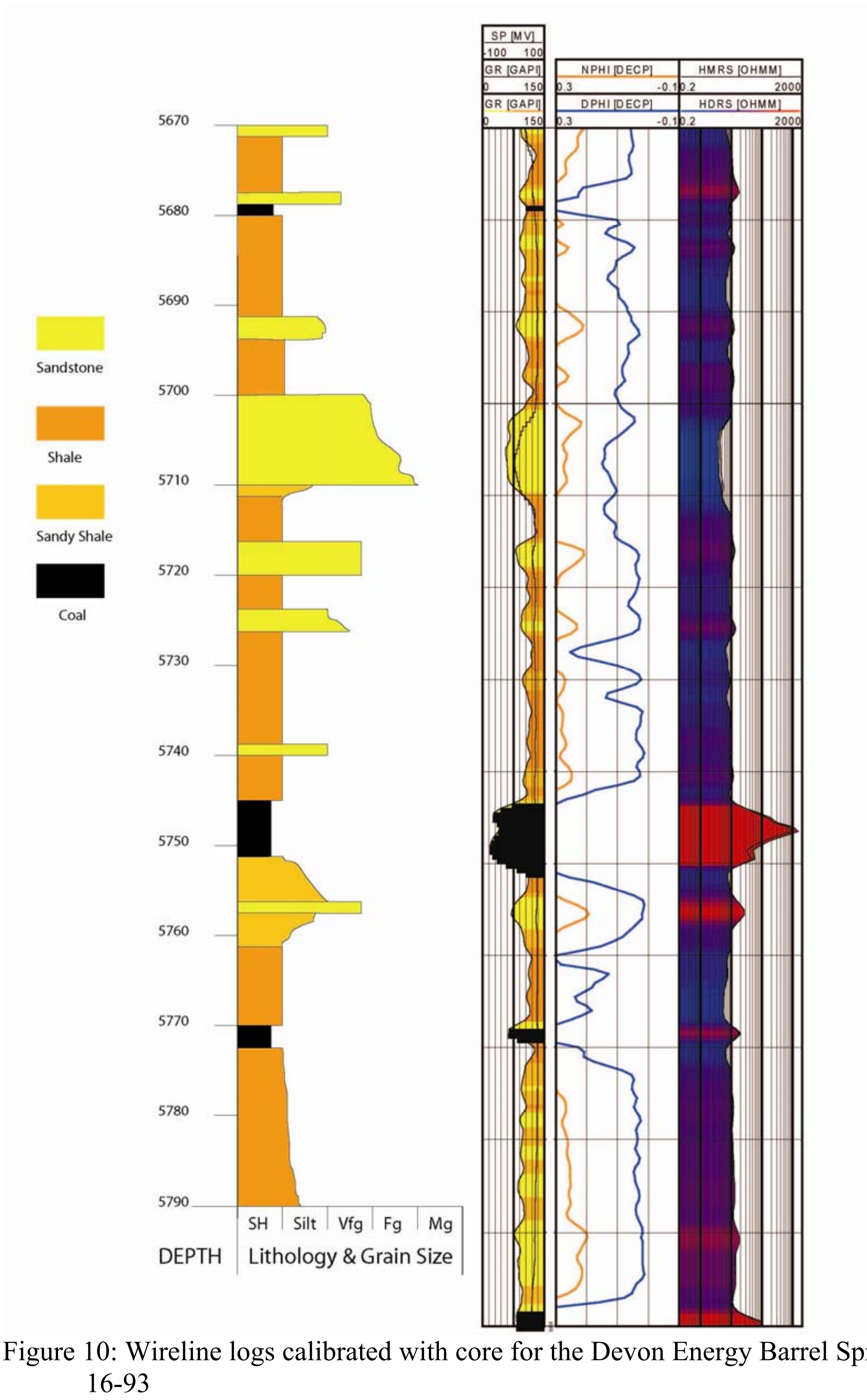


Figure 10: Wireline logs calibrated with core for the Devon Energy Barrel Springs 11-13-16-93

Shale Volume

The Lance Formation contains interbedded sandstones, shales and claystones. The interbedded shales contain bound water and can reduce the resistivity reading and cause erroneous porosity readings. To compensate for these effects, the volume of shale (V_{sh}) must be calculated. Larionov (1969) recommended V_{sh} for consolidated rocks:

$$V_{sh} = 0.33\left[2^{(2I_{GR})} - 1.0\right]$$

$$I_{GR} = \frac{GR_{\log} - GR_{\min}}{GR_{\max} - Gr_{\min}}$$

Where:
I_{Gr} = gamma ray index
GR_{max} = gamma ray maximum (shale zone)
GR_{min} = gamma ray minimum (clean sand)
$GRlog$ = gamma ray log (shaly sand)

Porosity

Permeability and porosity lab tests were conducted on plugs taken from sandstones throughout the core. Several techniques were used to develop a method to best calibrate wireline porosity to core porosity. It was assumed that the core porosity is the most accurate. Therefore, all methods were evaluated relative to calibration with the core data

Core Analyses

Nine plugs, one for every foot, were taken from the thickest sandstone cored. These plugs were analyzed for porosity, permeability and water saturation (Table 2). Density porosity (**$ø_D$**) from the wireline log (ρ_{matrix} = 2.68) and the porosity from the core were compared to establish a correlation coefficient (Table 3).

Sample Number	Depth (feet)	Porosity (%)	Permeability (md)	Water Saturation (%)
1	5702	8.52	0.028	72.83
2	5703	9.25	0.082	67.65
3	5704	12.63	2.581	76.14
4	5705	11.97	0.157	75.05
5	5706	14.81	0.791	75.88
6	5707	15.59	1.394	70.66
7	5708	15.76	1.605	73.58
8	5709	14.38	0.672	75.49
9	5710	12.50	0.462	77.72

Table 2: Porosity, permeability and water saturation measurements from a 9 foot thick interval of sandstone in the Lance Formation.

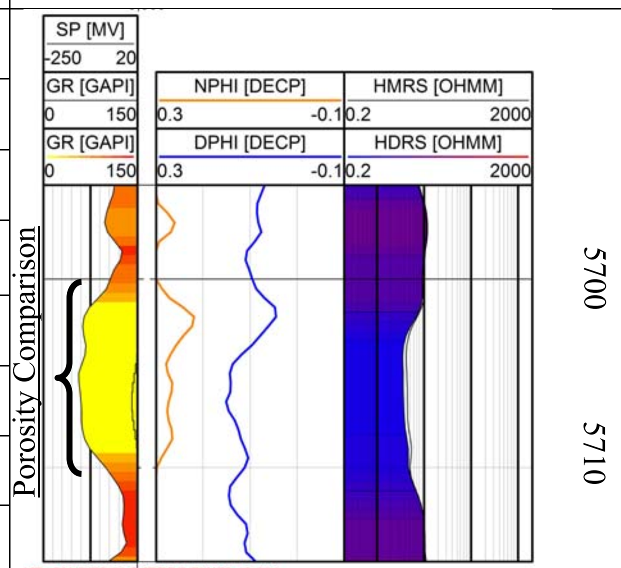
Depth	**Wireline Porosity ($\varnothing_D$)**	**Core Porosity ($\varnothing_{Core}$)**	**Area of Comparison**
5702	4.53	8.52	
5703	7.84	9.25	
5704	11.81	12.63	
5705	14.33	11.97	
5706	14.24	14.81	
5707	14.60	15.59	
5708	12.51	15.76	
5709	11.1	14.38	
5710	11.1	12.50	

Table 3: A comparison of wireline density log porosity ($\rho_{matrix} = 2.68$) with porosity measurements from core plugs.

a

Neutron-Density Cross Plot

By cross plotting bulk density (RHOB) amd neutron density (NPHI), neutron-density porosity can be estimated. The 300 feet thick zone immediately above the Fox Hills Formation was analyzed by cross plotting bulk density and neutron density to give a scattered data or "shot-gun" appearance (Figure 11). The scattering of data in this plot is believed to be the result of including all lithologies with large density variances. When data form only sandstones were plotted the results were much less scattered (Figure 12). The area within the red circle indicates data points from the cored. Using the sandstone lithology curve, it is possible to see that these points intersect around 20% porosity.

Neutron-density porosity can also be calculated mathematically using the root mean square formula (Asquith et all, 1982). Using this formula, the neutron-density porosity can be compared with the core porosity (Table 4). The neutron-density porosity consistently calculated much higher than the core porosity. Density porosity from wireline log correlates better to the core porosity than the porosity calculated using the neutron-density root mean square method.

$$\phi_{N-D} = \sqrt{\frac{\phi_N^{\;2} + \phi_D^{\;2}}{2}}$$

Where:

$ø_N$ = neutron porosity
$ø_D$ = density porosity
$ø_{N-D}$ = neutron-density porosity

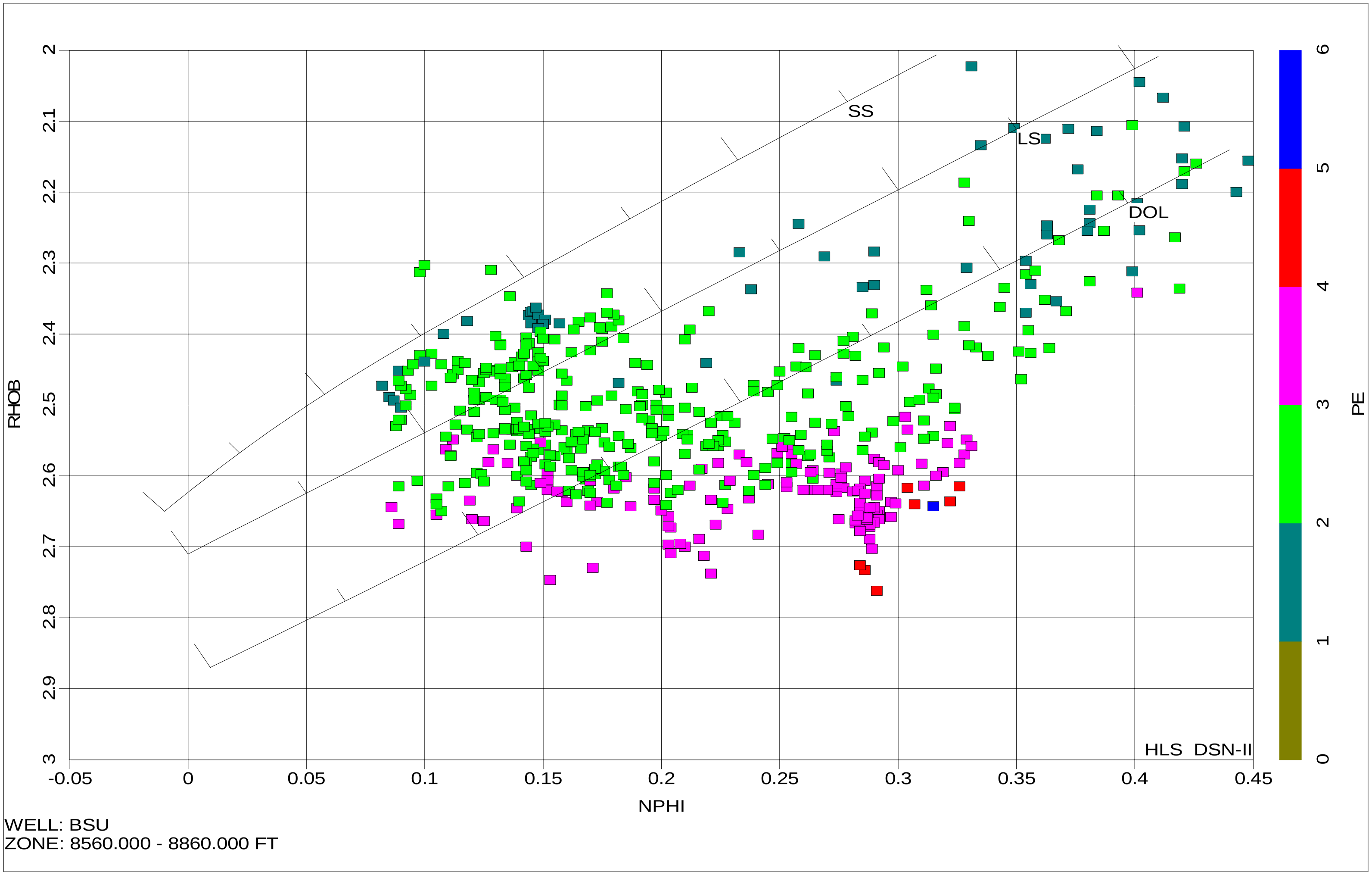


Figure 11: Neutron-density cross plot of the entire 300 foot zone of interest for the Barrel Springs 11-13-16-93

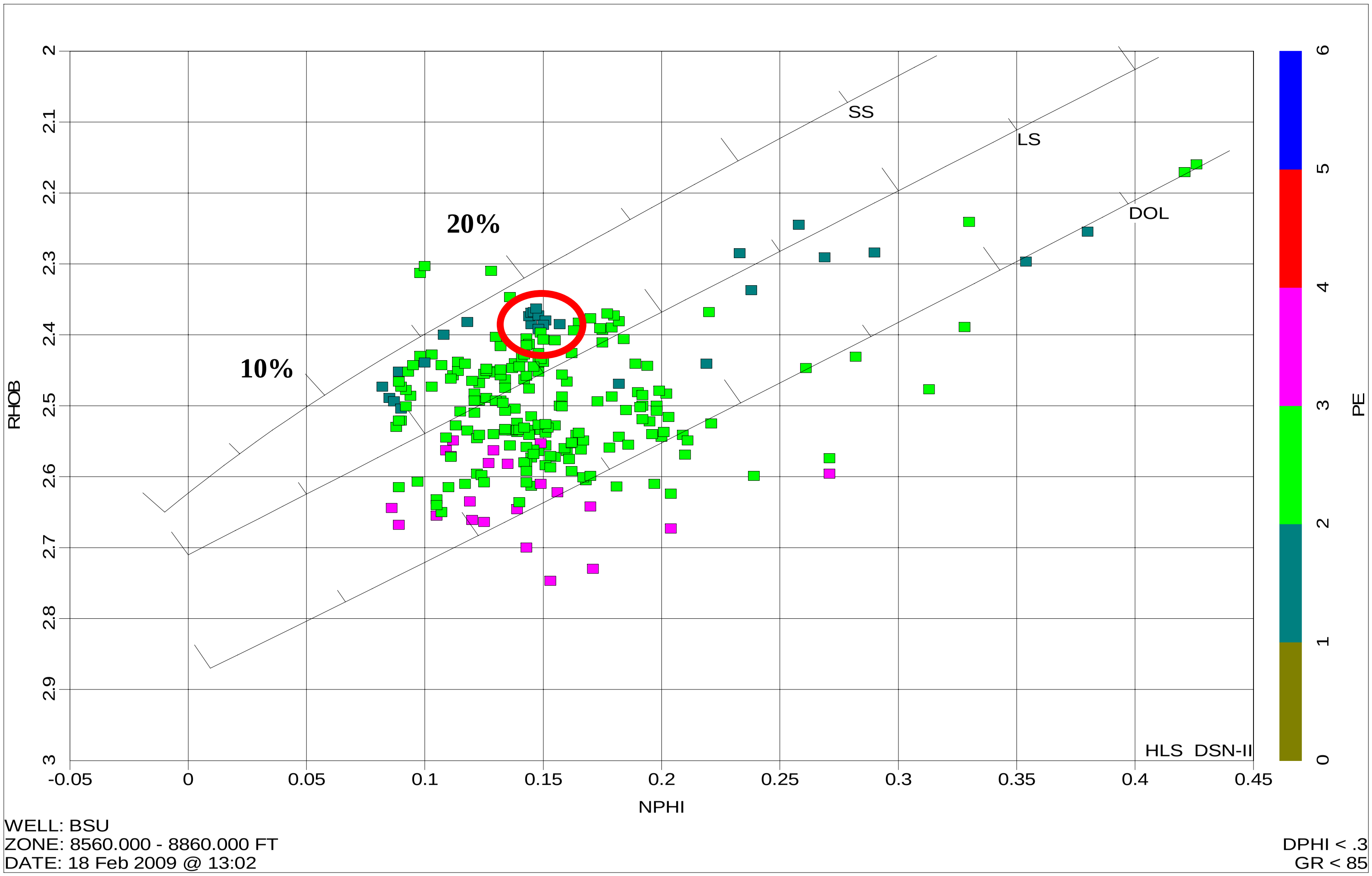


Figure 12: Neutron-density cross plot of sandstones over the zone of interest.

Depth Feet	$ø_D$	$ø_{N-D}$	$ø_{Core}$	$ø_{Core}$ & $ø_{N-D}$ Variance	Core & $ø_D$ Variance
5702	4.50%	12.91%	8.52%	4.39%	4.02%
5703	7.80%	14.52%	9.25%	5.27%	1.45%
5704	11.80%	18.03%	12.63%	5.40%	0.83%
5705	14.30%	19.27%	11.97%	7.30%	2.33%
5706	14.20%	18.75%	14.81%	3.94%	0.61%
5707	14.60%	19.44%	15.59%	3.85%	0.99%
5708	12.50%	18.14%	15.76%	2.38%	3.26%
5709	11.10%	18.31%	14.38%	3.93%	3.28%
5710	11.20%	19.76%	12.50%	7.26%	1.30%
			Average	4.86%	2.01%

Table 4: Density porosity ($ø_D$), neutron-density porosity ($ø_{N-D}$) and core porosity comparison

Shale-Corrected Density Porosity ($ø_{Dcorr}$)

The shale effect on the density porosity measurement of the Lance sandstone in the Barrel Springs Township is unknown. Therefore, using the Vsh calculation and the equation for Vsh corrected density porosity (Schlumberger, 1975), a corrected density porosity was calculated. This method consistently slightly underestimated the porosity compared with core porosity. It appears that this method overcompensates for the shale. This is probably due to the shale having a similar matrix density compared to sandstone or small sample size. When shale corrected density porosity and core porosity are compared, core porosity correlated best to density porosity (Table 5).

$$\phi_{Dcorr} = \phi_D - \left[\left(\frac{\phi_{Nclay}}{0.45} \right) \times 0.13 \times V_{sh} \right]$$

Where:
$ø_{Dcorr}$ = density porosity corrected for shale
$ø_{Nclay}$ = neutron porosity of adjacent shale
$ø_N$ = neutron porosity uncorrected for shale
$ø_D$ = density porosity uncorrected for shale

Depth Feet	$ø_D$ Porosity	$ø_{Dcorr}$ Porosity	Core Porosity	Core & $ø_{Dcorr}$ Variance	Core & $ø_D$ Variance
5702	4.50%	3.11%	8.52%	5.41%	4.02%
5703	7.80%	6.45%	9.25%	2.80%	1.45%
5704	11.80%	10.28%	12.63%	2.35%	0.83%
5705	14.30%	13.58%	11.97%	1.61%	2.33%
5706	14.20%	13.32%	14.81%	1.49%	0.61%
5707	14.60%	13.53%	15.59%	2.06%	0.99%
5708	12.50%	11.33%	15.76%	4.43%	3.26%
5709	11.10%	8.87%	14.38%	5.51%	3.28%
5710	11.20%	5.66%	12.50%	6.84%	1.30%
			Average	3.61%	2.01%

Table 5: Comparison of density porosity ($ø_D$), Vsh corrected density porosity ($ø_{Dcorr}$) and core porosity

Shale-Corrected Neutron-Density Porosity ($ø_{N\text{-}D}$)

Shale corrected neutron porosity was incorporated into the shale corrected neutron-density porosity to mitigate the over-compensated *Vsh* problem evident in the shale corrected density porosity. Two methods were chosen to incorporate both corrected neutron and density porosities. The results of these comparisons are shown in tables 6 and 7.

$$\phi_{Ncorr} = \phi_N - \left[\left(\frac{\phi_{Nclay}}{0.45}\right) \times 0.03 \times V_{sh}\right]$$

$$\phi_{Dcorr} = \phi_D - \left[\left(\frac{\phi_{Nclay}}{0.45}\right) \times 0.13 \times V_{sh}\right]$$

$$\phi_{Ncorr-Dcorr} = \sqrt{\frac{\phi_{Ncorr}{}^2 - \phi_{Dcorr}{}^2}{2}}$$

Schlumberger (1989)

Where:
$ø_{Ncorr}$ = neutron porosity corrected for shale
$ø_{Dcorr}$ = density porosity corrected for shale
$ø_{Nclay}$ = neutron porosity of adjacent shale
$ø_{N}$ = neutron porosity uncorrected for shale
$ø_{D}$ = density porosity uncorrected for shale
$ø_{Ncorr-Dcorr}$ = neutron-density porosity corrected for shale

Depth Feet	$ø_D$ Porosity	$ø_{Ncorr}$ - $ø_{Dcorr}$ Porosity (Schlumberger)	Core Porosity	Core & $ø_{Ncorr}$ - $ø_{Dcorr}$ Variance (Schlumberger)	Core & $ø_D$ Variance
5702	4.50%	12.48%	8.52%	3.96%	4.02%
5703	7.80%	13.98%	9.25%	4.73%	1.45%
5704	11.80%	17.33%	12.63%	4.70%	0.83%
5705	14.30%	18.91%	11.97%	6.94%	2.33%
5706	14.20%	18.31%	14.81%	3.50%	0.61%
5707	14.60%	18.90%	15.59%	3.31%	0.99%
5708	12.50%	17.58%	15.76%	1.82%	3.26%
5709	11.10%	17.36%	14.38%	2.98%	3.28%
5710	11.20%	17.66%	12.50%	5.16%	1.30%
			Average	4.12%	2.01%

Table 6: Schlumberger (1989) calculated porosities

$$\phi_{Ncorr} = \phi_N - V_{sh} \times \phi N_{Clay}$$

$$\phi_{Dcorr} = \phi_D - V_{sh} \times \phi D_{Clay}$$

$$\phi_{Ncorr-Dcorr} = \sqrt{\frac{{\phi_{Ncorr}}^2 - {\phi_{Dcorr}}^2}{2}}$$

Dewan (1983)

Where:
$ø_{Ncorr}$ = neutron porosity corrected for shale
$ø_{Dcorr}$ = density porosity corrected for shale
$ø_{Nclay}$ = neutron porosity of adjacent shale
$ø_{N}$ = neutron porosity uncorrected for shale
$ø_{D}$ = density porosity uncorrected for shale
$ø_{Ncorr-Dcorr}$ = neutron-density porosity corrected for shale

Depth Feet	$\varnothing_D$ Porosity	$\varnothing_{Ncorr}$ - $\varnothing_{Dcorr}$ Porosity (Dewan)	Core Porosity	Core & $\varnothing_{Ncorr}$ - $\varnothing_{Dcorr}$ Variance (Dewan)	Core & $\varnothing_D$ Variance
5702	4.50%	12.50%	8.52%	3.98%	4.02%
5703	7.80%	14.09%	9.25%	4.84%	1.45%
5704	11.80%	17.53%	12.63%	4.90%	0.83%
5705	14.30%	19.03%	11.97%	7.06%	2.33%
5706	14.20%	18.46%	14.81%	3.65%	0.61%
5707	14.60%	19.08%	15.59%	3.49%	0.99%
5708	12.50%	17.75%	15.76%	1.99%	3.26%
5709	11.10%	17.59%	14.38%	3.21%	3.28%
5710	11.20%	17.99%	12.50%	5.49%	1.30%
			Average	4.29%	2.01%

Table 7: Dewan (1983) calculated porosities

A third method for correcting $\varnothing_{Ncorr\text{-}Dcorr}$ was tested. This method from Dewan (1983) removed the coefficient evident in the Schlumberger (1989) equation. The Dewan (1983) method also overestimated porosity related to measured porosity from core (Table 7). Both the Schlumberger (1989) and Dewan (1983) methods calculated higher porosity than measured porosity from core. As in previous comparisons the wireline density porosity values are the closest approximation of core porosity. As a result of the comparative analyses of the various wireline log porosity measurements, corrections, and core porosity values, it was decided to use density porosity values in future analyses.

Formation Water Resistivity

One of the key parameters necessary for the petrophysical determination of pore fluids is formation water resistivity (*Rw*). A search for *Rw* measurements for Lance reservoir revealed that formation water resistivity is unknown in this area. To alleviate this problem *Rw* was calculated using several different methods to establish a reasonable value to use in water saturation (*Sw*) calculations.

Pickett Plot

One procedure to estimate *Rw* from *Sw* calculations is the Pickett Plot (Pickett, 1966). The Pickett Plot is a simple cross plotting method and is based on the observation that true resistivity is a function of porosity *ø*, water saturation *Sw* and cementation factor (m) (Asquith, 1970). To create a Pickett Plot, the porosity and deep resistivity values for the Lance Formation taken from the wireline logs in the Barrel Springs Unit 11-13-16-93 were cross plotted (Figure 13). *Rw* is calculated from the Pickett Plot using the equation:

$$R_w = \frac{R_o \times \phi^m}{a}$$

Where:
a = Tortuosity, in this case = 1.0
m = Cementation factor
R_0 = Resistivity of the undisturbed water-bearing zone
ø= Porosity at R_0 reading on the Pickett Plot

Using this equation, an *Rw* of .08 ohms was calculated for the Lance Formation in the Barrel Springs 11-13-16-93 at reservoir conditions. The slope of the 100% water saturation line (*Ro*) is equal to the cementation factor (m). For the Barrel Springs 11-13-16-93, a cementation factor value of 1.73 was calculated from the Pickett Plot.

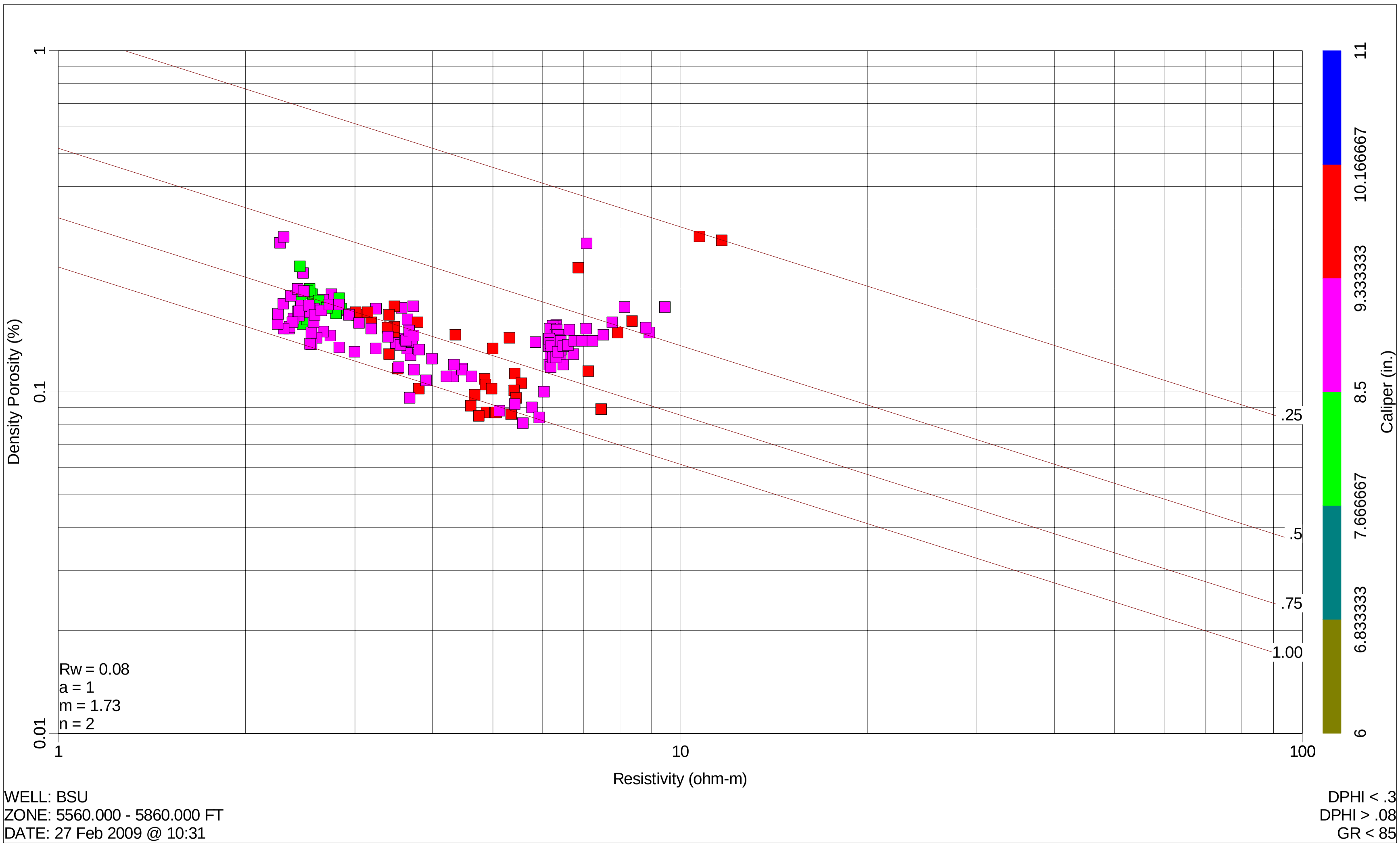


Figure 13: Pickett Plot of reservoir sandstone in the Lance Formation, of the Barrel Springs Unit 11-13-16-93

Core

The water saturations and porosities from the core analyses (Table 8) were used to calculate *Rw*. Using the cementation value calculated from the Pickett Plot (m=1.73) and a tortousity factor recommended by Asquith (1982) for consolidated sands (a=.81), it was possible to calculate *Rw*. Using Archie's equation (Equation A), it is possible to solve for *Rw* (Equation B). The *Rw* values ranged from 0.036 to 0.107 ohm-m using this process. The Average *Rw* was 0.08, which was lower than expected because samples were not 100% water saturated.

Archie equation

Equation A:

$$S_w = \left(\frac{a}{\phi^m} \times \frac{R_w}{R_t} \right)^{\frac{1}{n}}$$

Equation B:

$$R_w = \frac{S_w{}^n \phi^m R_t}{a}$$

(Archie, 1942)

Depth	Porosity	Water Saturation	Rt (ohm-m)	*Rw* (ohm-m)
5702	8.52%	72.83%	6.8	0.06
5703	9.25%	67.65%	4.15	0.04
5704	12.63%	76.14%	3.53	0.07
5705	11.97%	75.05%	3.61	0.06
5706	14.81%	75.88%	3.63	0.09
5707	15.59%	70.66%	3.73	0.09
5708	15.76%	73.58%	3.99	0.11
5709	14.38%	75.49%	4.57	0.11
5710	12.50%	77.72%	5.12	0.10
			Average	**0.08**

Table 8: Core calculated *Rw* values

Produced Water

Two wells producing formation water from the Lance sandstones in Barrel Springs Township were sampled and analyzed to determine composition. Using formation temperatures and Schlumberger log interpretation charts (Schlumberger, 1979), *Rw* can be calculated if solute concentrations are known. The first step is to determine the quality of the water analysis. The accuracy of water analyzed can be easily checked by determining the electrical neutrality by anion-cation balance (Hounslow, 1995). If a water analysis is accurate, the sum of cations in milliquivalents per liter (M_{eq}/L) should equal the sum of the anions in M_{eq}/L. The charge balance is calculated as follows and expanded as a percentage.

$$\frac{M_{eq}}{l} = \frac{\frac{mg}{l} * valence}{formula \quad wt}$$

$$Balance = \frac{\sum C - \sum A}{\sum C + \sum A} * 100$$

Where:
$\sum C =$ Sum of Cations
$\sum A =$ Sum of Anions
Calculation Balance < 5% is considered good

The second step is to determine the NaCl resistivity equivalent from the total dissolved solids (TDS) reported in the water analysis. The quality of a water sample is related to the balance of anions and cations. The two water samples used for this study to calculate *Rw* balanced exceptionally well, as shown in Table 9.

	BSU 20-15-16-93	**BSU 20-14-16-93**
	Meq/l	**Meq/l**
Cation $\sum C$		
Na	758.04	708
K	3.23	2.8
Ca	78	54
Mg	22	15.1
Fe	1.07	3.75
Total	**862.34**	**783.35**
Anion $\sum A$		
SO	1.77	1.56
Cl	848.81	767.8
HCO	14	16
Total	**864.58**	**785.36**
Balance	**0.1297%**	**0.1281%**

Table 9: M_{eq}/L and balance calculations.

	BSU 20-15-16-93		BSU 20-14-16-93	
	Dissolved Solids (ppm)	NaCl Equivalent (ppm)	Dissolved Solids (ppm)	NaCl Equivalent (ppm)
Sodium	17,435.00	**17,435.00**	16,283.00	**16,283.00**
Potassium	126.00	**126.00**	98.00	**98**
Calcium	1,560.00	**1,248.00**	1,080.00	**864**
Magnesium	268.00	**241.00**	183.00	**165**
Iron	30.00	**30.00**	105.00	**105.00**
Sulfate	85.00	**26.00**	75.00	**23**
Chloride	30,048.00	**30,048.00**	27,180.00	**27,180.00**
Bicarbonate	854	**214**	976.00	**244**
Dissolved Solids	50,406.00	**49,368.00**	45,980.00	**44,962.00**

Table 10: NaCl dissolved solid equivalence data from Schlumberger Charts

Once the NaCl dissolved solid equivalence is established, it is possible to calculate the *Rw*. The BSU 20-15-16-93 calculated an *Rw* of 0.08 ohm-m at a formation temperature of 117°F and the Barrel Springs 20-14-16-93 calculated an *Rw* of 0.09 at formation temperature of 125°F.

The water analysis also contained direct *Rw* values computed be inducing a current in the sample and calculating the resistivity. Using the Schlumberger, 1972 chart, the *Rw* was calculated at a temperature of 68°F. The BSU 20-15-16-93 had an *Rw* of 0.15 ohm-m at 68°F; this value computes to 0.09 ohm-m at a bottom hole temperature of 125°F. The BSU 20-14-16-93 calculated *Rw* of 0.162 ohm-m at 68°F computed an *Rw* of 0.095 at a bottom hole temperature of 117°F. The three methods resulted in very similar *Rw* values (Table 11).

Core	**Pickett Plot**	**Produced Water**	**Average**
0.08 ohm-m	0.08 ohm-m	0.09 ohm-m	0.083 ohm-m

Table 11: *Rw* results

Formation Water Resistivity Across the Study Area

Due to the large study area and the structural variability, it would be unsuitable to use the same *Rw* and cementation exponent over the entire area. The structural position of the Fox Hills Formation ranges from < 2,000 feet above sea level to > 3,000 feet below sea level within the study area (Figure 14). To compensate for changing *Rw* and cementation values, Pickett Plots were constructed to calculate these values for each township. One well from each township was chosen randomly to represent each township (Appendix A). From the Pickett Plots, each township was assigned an *Rw* and a cementation value to be used for subsequent water saturations calculations (Figure 15).

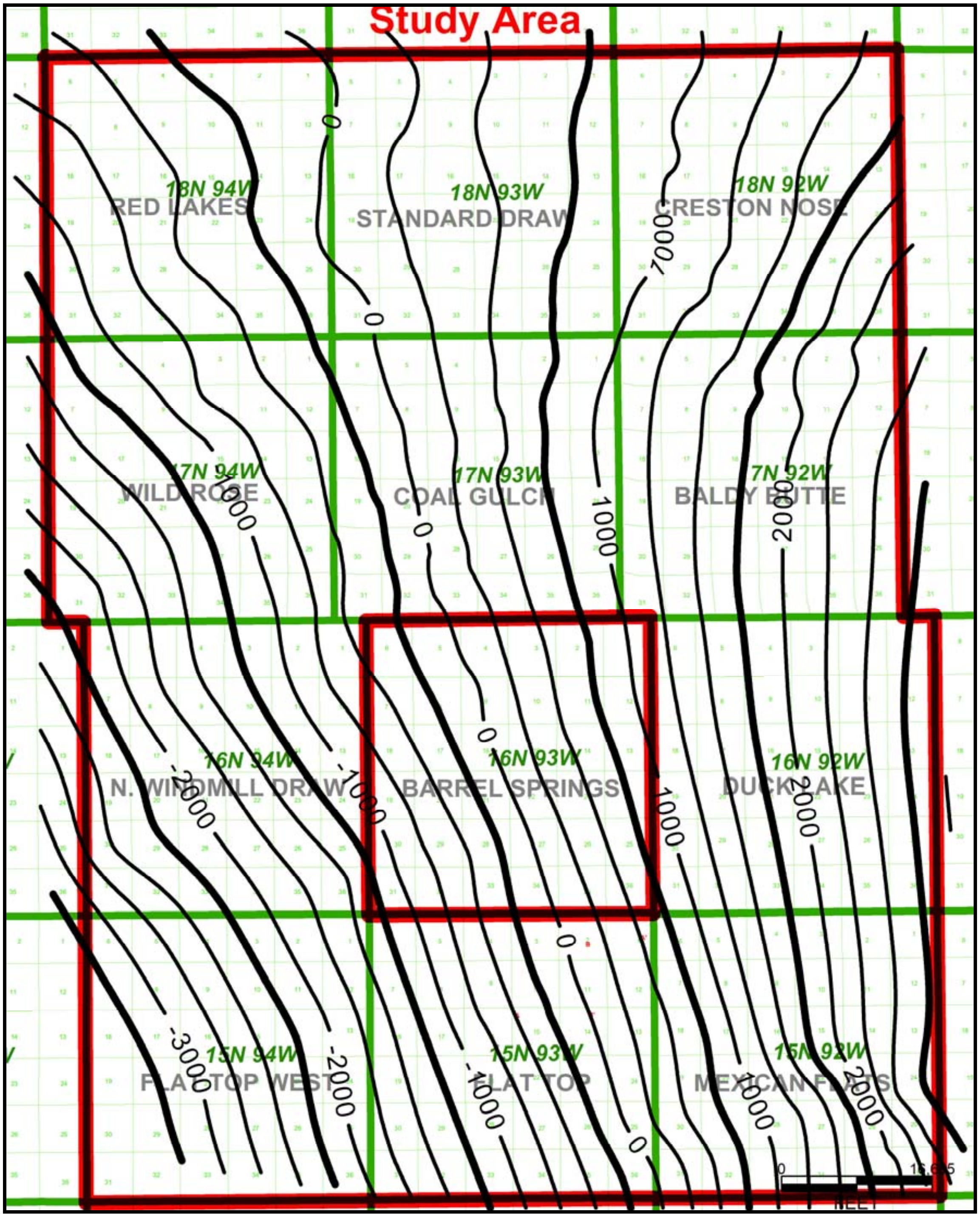


Figure 14: Structure map of the study area contoured on the Fox Hills Formation

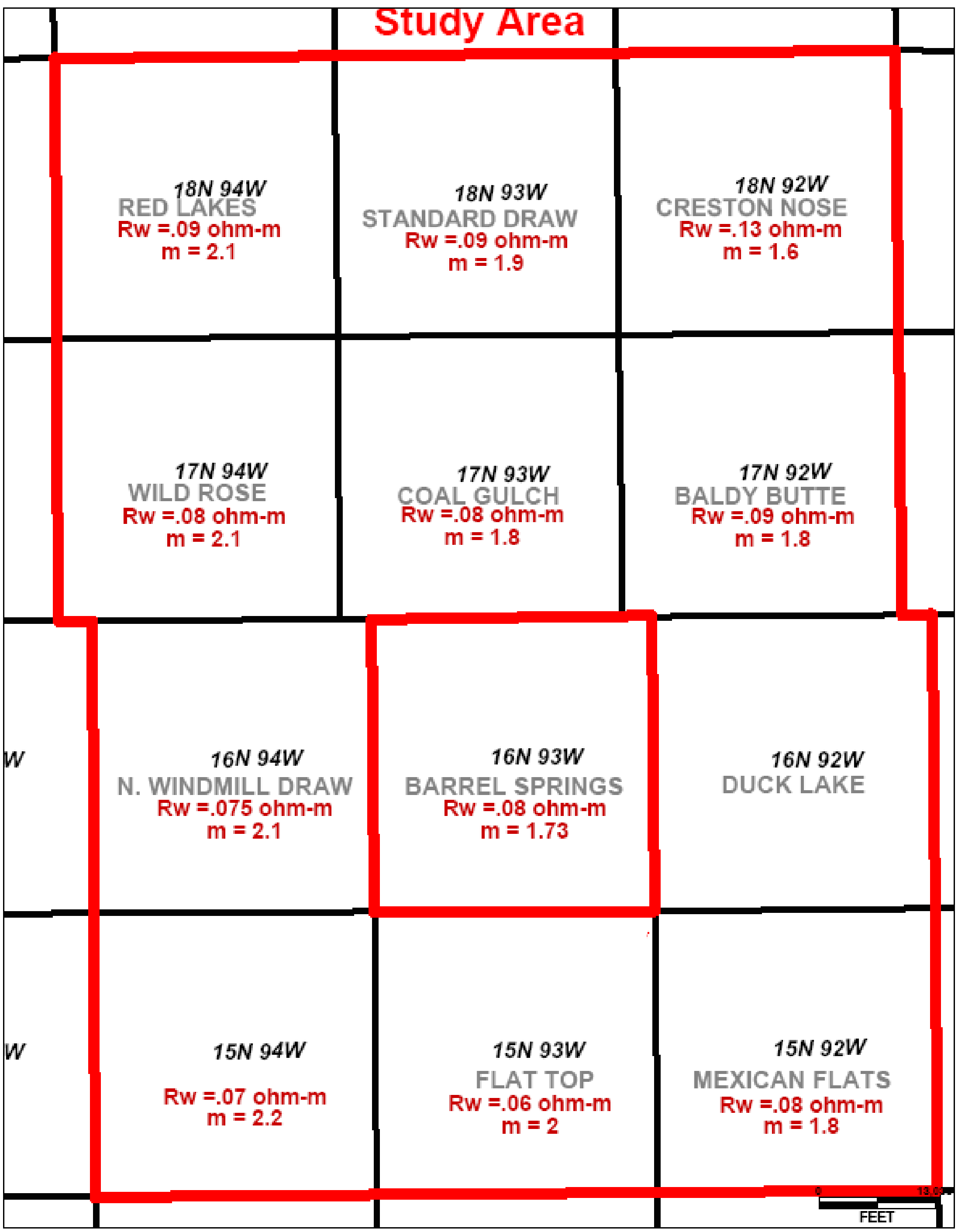


Figure 15: *Rw* and cementation factor calculation by township within the study area.

Water Saturation

Once *Rw* and porosity values were calculated, the standard Archie equation (Archie, 1942) for water saturation (*Sw*) was used. Each township was calculated separately using the *Rw* and cementation factors assigned to that township.

Archie equation

$$S_w = \left(\frac{a}{\phi^m} \times \frac{R_w}{R_t} \right)^{\frac{1}{n}}$$

Gas-bearing Sandstone

In order to construct an accurate *Sw* model to establish economic limits, a maximum economic *Sw* value or threshold must be established. The BSU 20-14-19-93 in section 14 of the Barrel Springs Township was used to determine maximum acceptable *Sw* because it has produced the highest volume of water of the current wells producing from the Lance Formation (Figure 14). The BSU 20-14-19-93 initially produced 77 thousand cubic feet per day (MCF/D) and 42 barrels of water per day (BBLW/D) solely from the Lance. The average *Sw* for the producing zone of interest is 49.59% (Table 12). For this project, a water saturation threshold of 50% ($Sw < 50\%$), gamma ray < 85 API units and porosity > 8% were established as limits that determine an economically predictable gas reservoir.

Depth (ft)	Porosity (%)	*Rw* *(ohm-m)*	Rt (ohm-m)	*Sw*
5821	13	0.106	11.83	47.22%
5822	13	0.106	13.54	44.14%
5823	11	0.106	13.9	48.68%
5824	12	0.106	13.28	47.00%
5825	16	0.106	12.67	39.74%
5826	18	0.106	14.72	34.09%
5827	13	0.106	17.3	39.05%
5828	6	0.106	19.88	60.91%
5829	6	0.106	22.58	57.16%
5830	4	0.106	20.87	77.95%
Average				49.59%

Table 12: Calculated *Sw* for the BSU 20-14-16-93

Chapter VIII

Maps

The controls on gas accumulation in the Lance Formation are not well understood, so the relationship between production, sandstone thickness and possible gas sourcing coals was analyzed. To accomplish this, total sandstone, coal, gas reservoir thickness and other characteristics were mapped and the results were cross plotted against cumulative gas from Lance Formation wells in the Barrel Springs Township. The Lance wells in Barrel Springs Township were all completed in a similar manner and began producing within a few years of each other. As a result, variability in production volumes related to production depletion or completion technique was eliminated.

Total Sandstone Thickness

Sandstone is believed to be the primary reservoir in the Lance Formation. Areas with high percentages of sandstone could be higher volume gas producing areas. Total sandstone (defined as gamma-ray < 85 API and density porosity $< 30\%$) was counted and summed for every ½ foot thick interval in each well (Figure 17). Figure 18 is contoured on the summed thickness of sandstone in the lower Lance Formation in the Barrel Springs Township. Values ranged from approximately 100’ (white) to over 280’ (dark yellow). The best Lance producer (Table 13), the Barrel Springs II 10-15-16-93 has the largest sandstone thickness (155 feet). However, the worst well, the Barrel Springs Unit 20-14-16-93 had the second highest sandstone (Table 13). Total sandstone was cross-plotted with production to yield an R^2 value of 0.22, demonstrating very little support for the hypothesis that total sandstone thickness is related to production (Figure 19). Figure 18 illustrates total sandstone thickness across the entire study area. Comparing total sandstone in Barrel Springs to that of the study area illustrates the high variability of gross sandstone in each map.

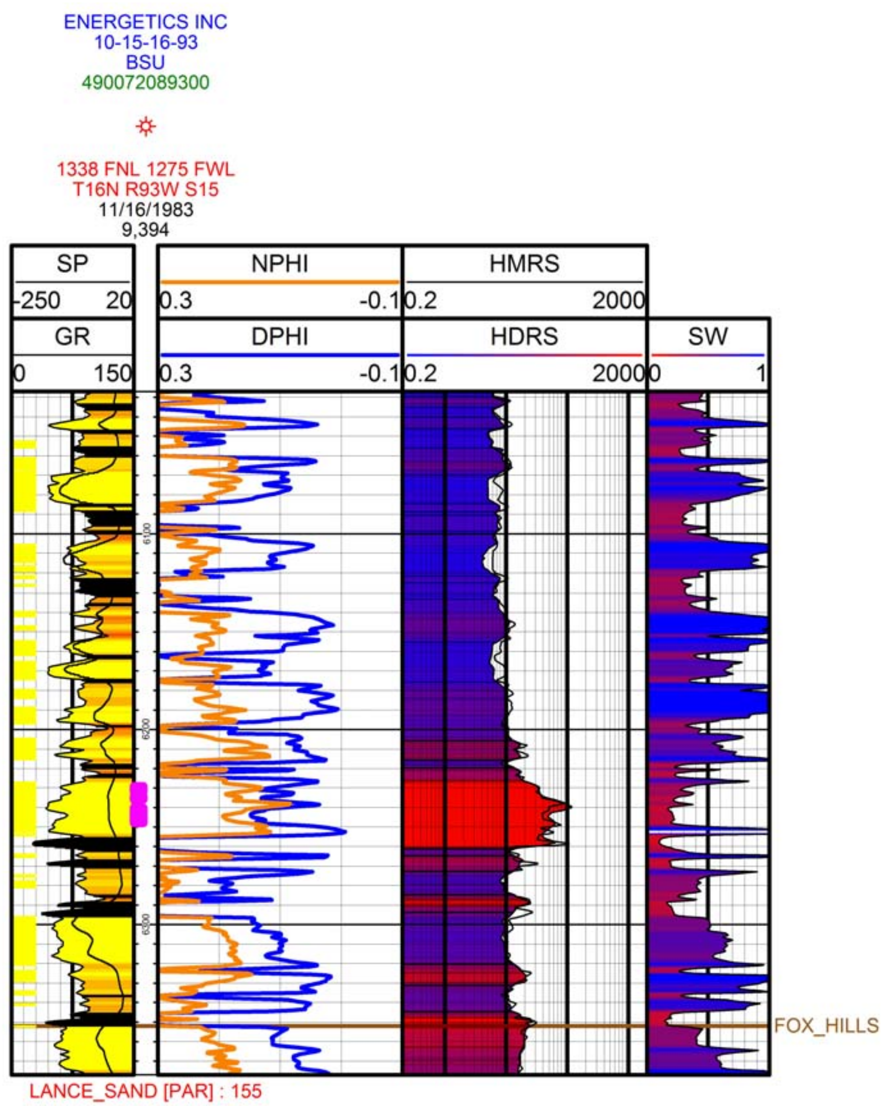


Figure 16: The BSU 10-15-16-93 type log illustrating sand counts (yellow notches in track 1) with the sum of 155 feet

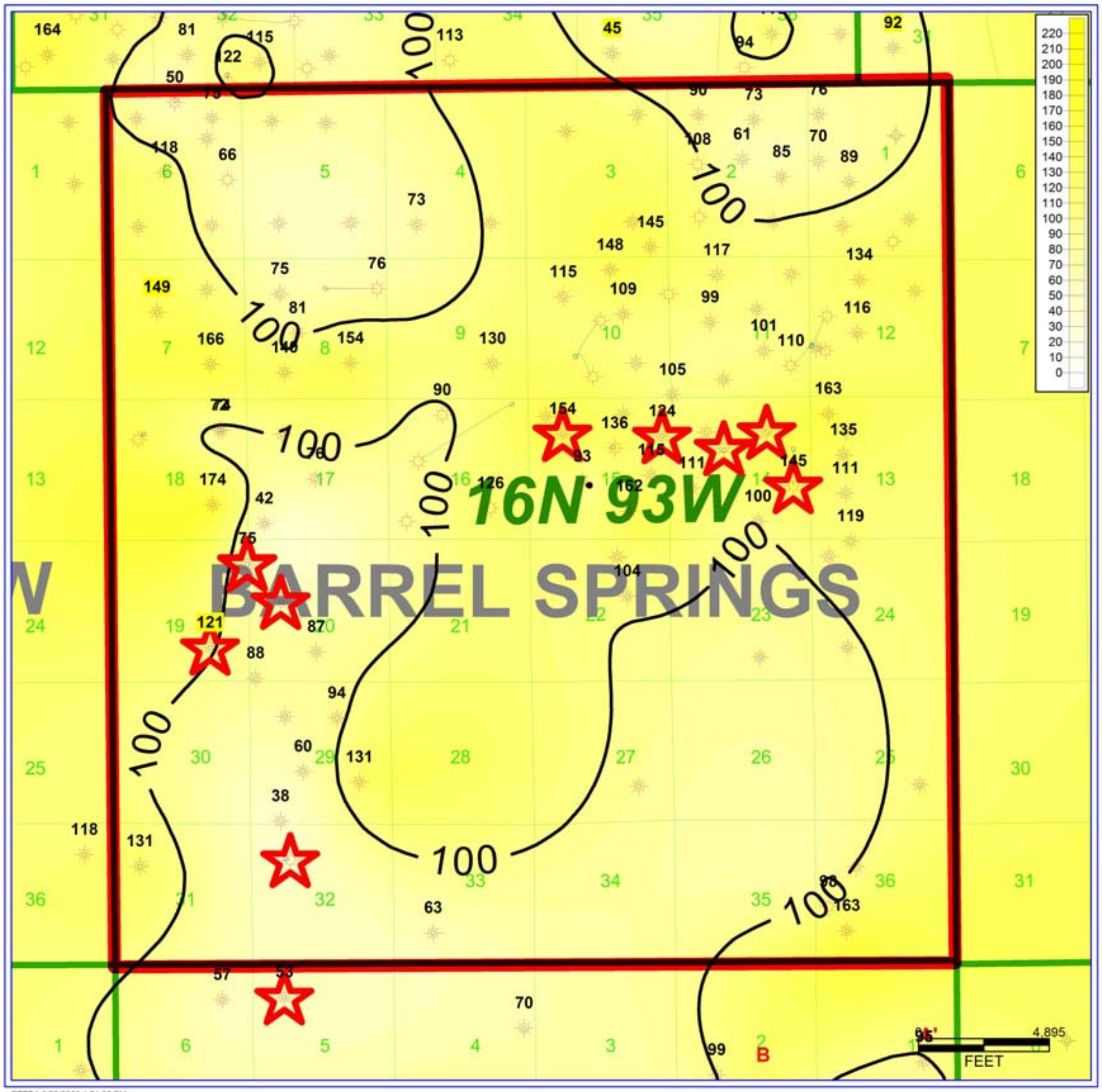


Figure 17: Cumulative sandstone thickness in lower 300 feet of the Lance Formation in the Barrel Springs Township. Red stars indicate wells producing from the Lance Formation. Values range from 38 to 174.

Figure 18: Cumulative thickness of sandstone in the lower 300 feet of the Lance Formation. Values range from 40 to 120.

Well	Lance Production (MCF)	Lance Cumulative Water (BBL)	Gross Sandstone (ft)	(MCF) per (ft) of Gross Sandstone
Barrel Springs Unit 9-14-16-93*	599,073	34,080	110	5446
Barrel Springs Unit 20-14-16-93	43,934	3,082	145	303
Barrel Springs 14-2*	669,699	2,041	110	6088
Barrel Springs Unit 20-15-16-93	601,144	9,957	124	4848
Barrel Springs II 10-15-16-93	2,085,083	5,884	155	13452
Barrel Springs Unit 1-19-16-93	671,296	10,672	75	8951
Barrel Springs 10-20-16-93*	149,606	15,460	80	1870
Barrel Springs 10-32-16-93*	231,263	52,143	40	5782
Federal 40-19-16-93	422,615	1,757	121	3493

Table 13: Comparison of gas production vs. total sandstone in the lower 300 feet of the Lance Formation, Barrel Springs Township. *thickness estimated from the contour map (Figure 17)

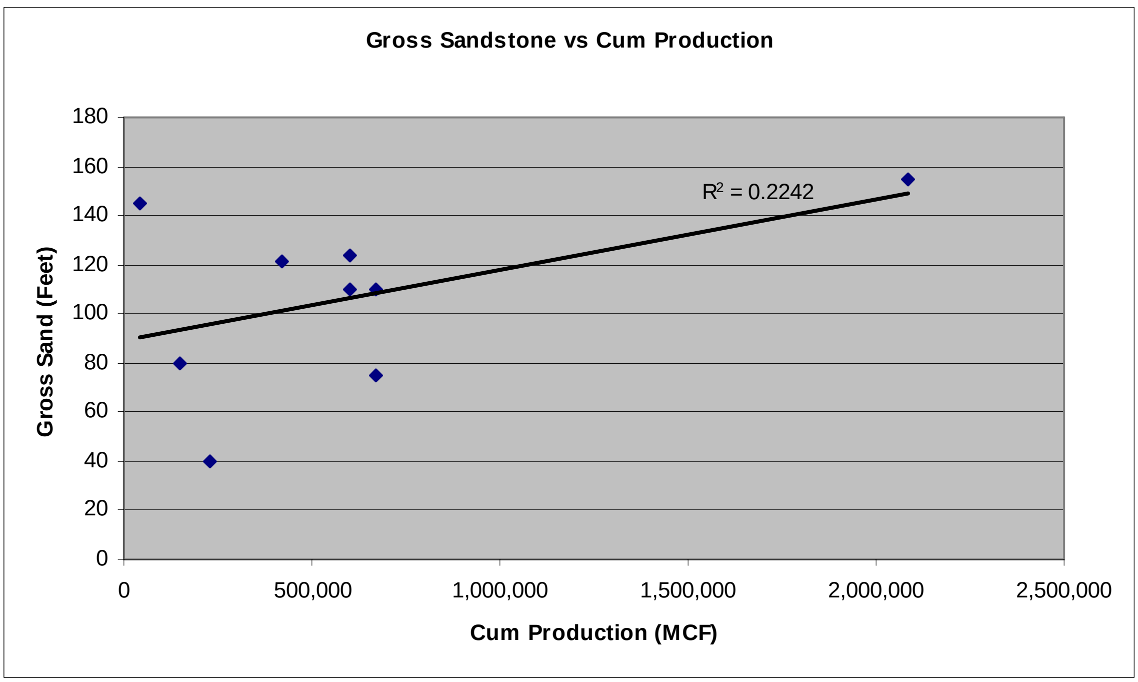


Figure 19: Scatter plot graph of total sandstone thickness (lower 300 feet of Lance Formation) versus cumulative gas production. Barrel Springs Township.

Elimination of thin (<4 feet) sandstone bodies

To achieve a better correlation of sandstone thickness to production, sandstones less than 4' thick were removed from the total sandstone count. This was based on the premise that sandstones less than 4’ are probably too thin and too tight to contribute significant volumes of gas. All sandstones > 4 feet were summed, mapped and cross-plotted against production (Figure 22). An R^2 value of 0.21 was calculated, indicating a very poor correlation and casting doubt on the proposed hypothesis. The lack of correlation enforces the idea that all sandstones, independent of thickness, contribute to gas production.

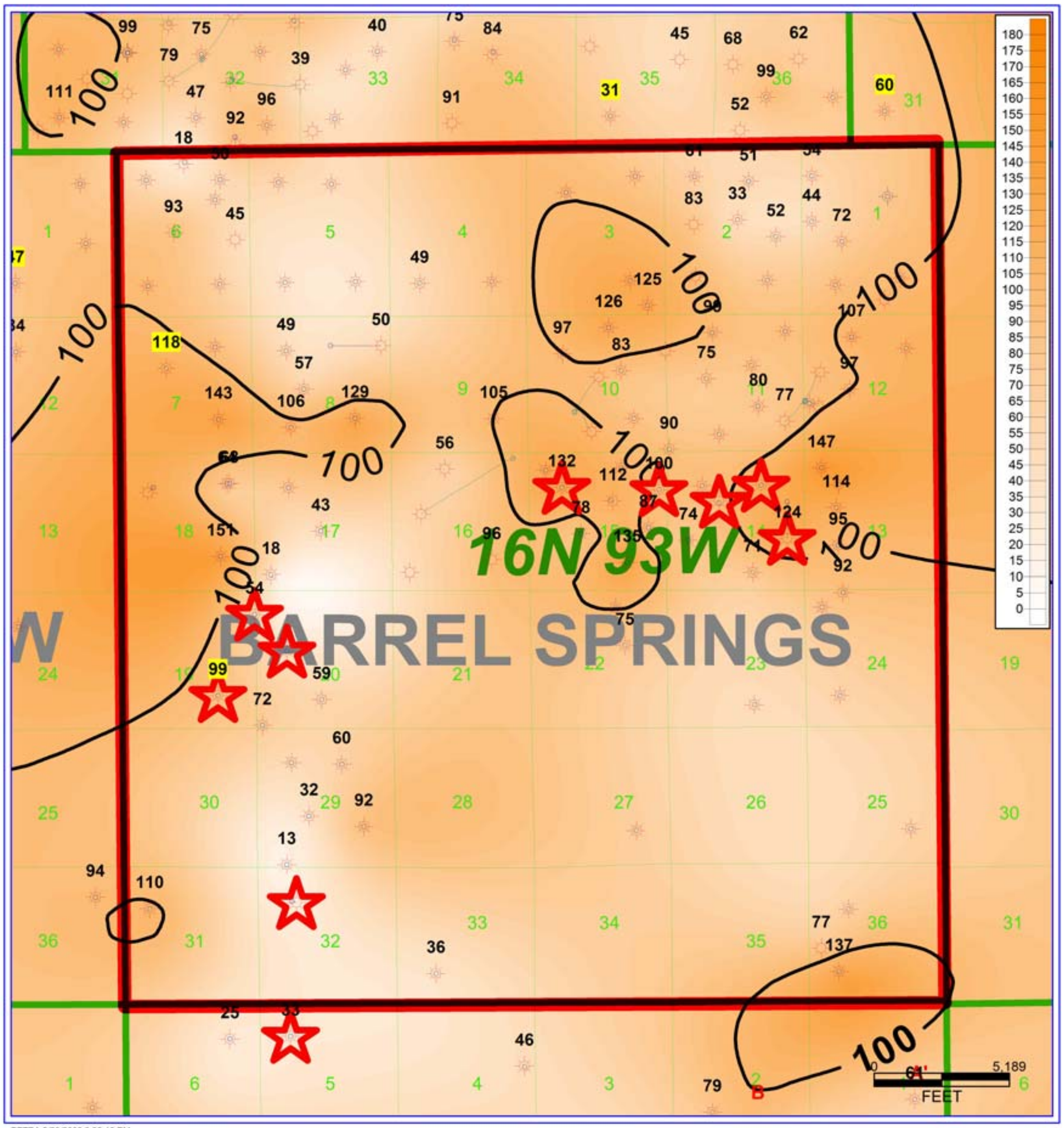


Figure 20: Total sandstone thickness, excluding sandstone bodies < 4feet thick. Values range from 13 to 151.

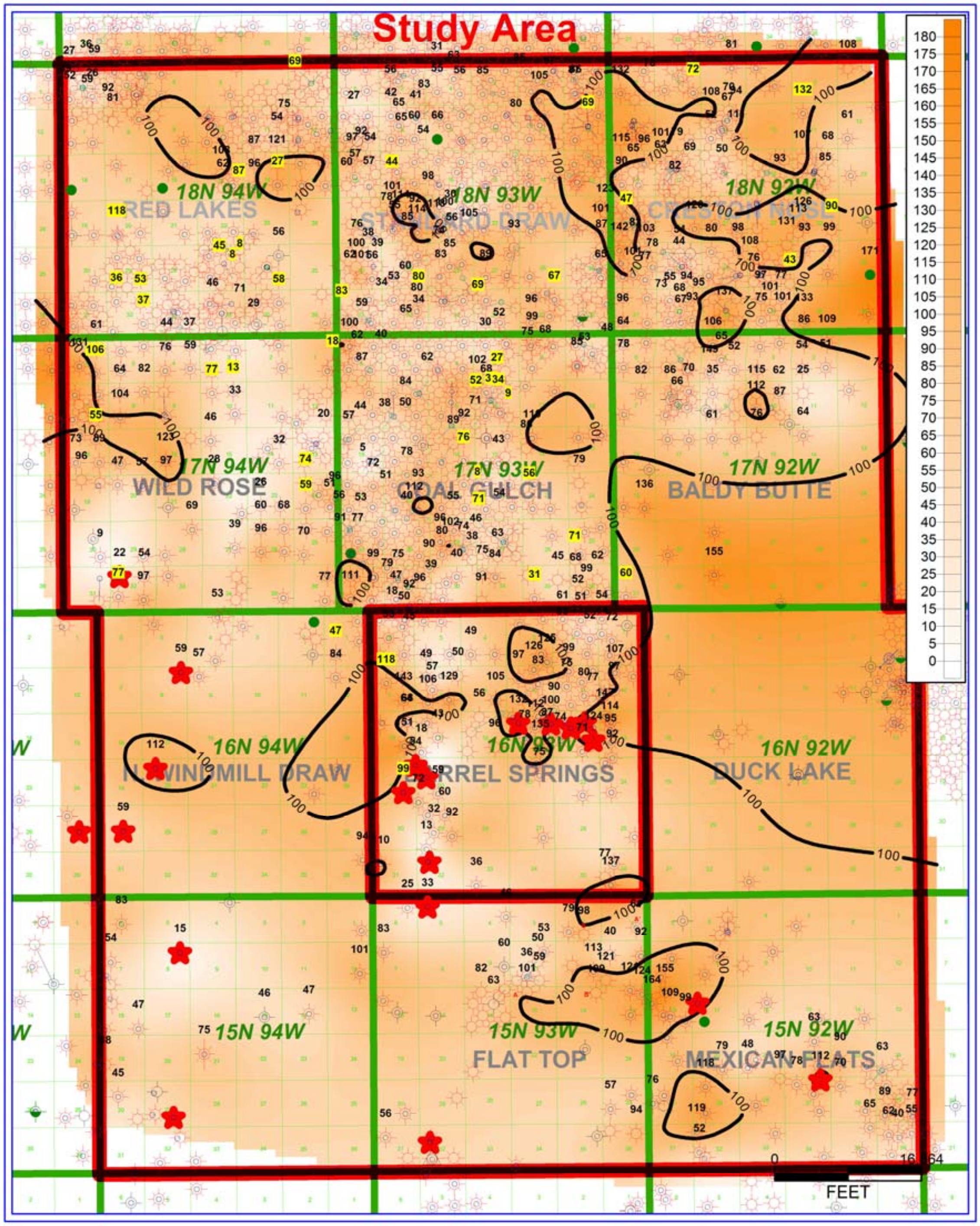


Figure 21: Total sandstone thickness across the study area, excluding sandstones less than 4' thick. Values range from 9 to 151.

Well	Lance Production (MCF)	Lance Cumulative Water (BBL)	>4' Sandstone (ft)	(MCF) per (ft) of Gross Sandstone
Barrel Springs Unit 9-14-16-93 *	599,073	34,080	90	6656
Barrel Springs Unit 20-14-16-93	43,934	3,082	124	354
Barrel Springs 14-2*	669,699	2,041	80	8371
Barrel Springs Unit 20-15-16-93	601,144	9,957	100	6011
Barrel Springs II 10-15-16-93	2,085,083	5,884	132	15796
Barrel Springs Unit 1-19-16-93	671,296	10,672	54	12431
Barrel Springs 10-20-16-93*	149,606	15,460	55	2720.
Barrel Springs 10-32-16-93*	231,263	52,143	20	11563
Federal 40-19-16-93	422,615	1,757	99	4269

Table 14: Gas production and thickness for sandstones >4 feet thick, lower 300 feet, Lance Formation. *estimated from the contour map (Figure 20).

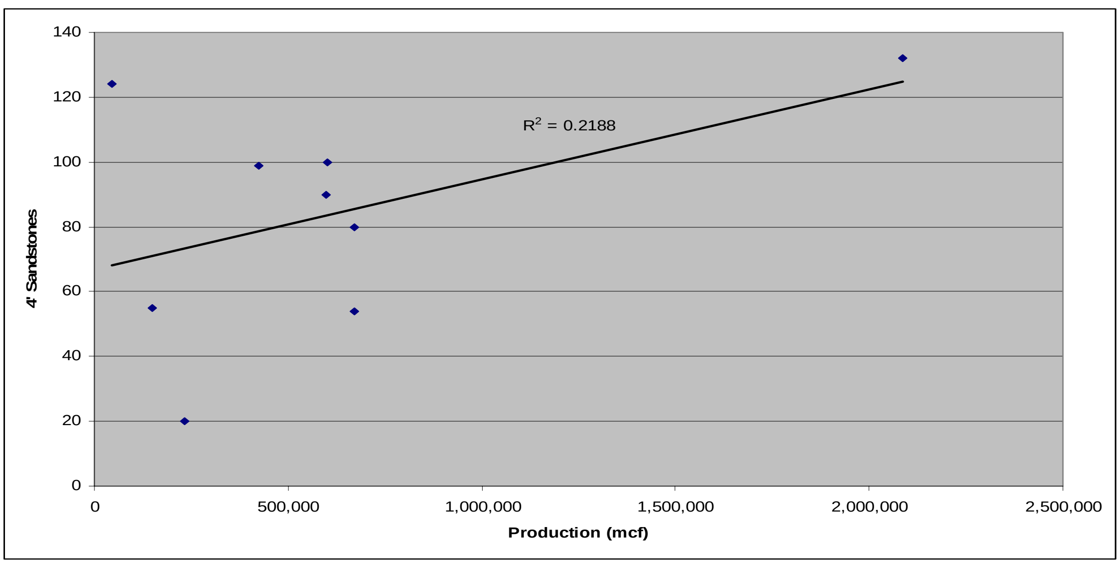


Figure 22: Scatter plot of total sandstone thickness (excluding sandstones <4 feet thick) vs. cumulative gas production.

Coal

Based on coal gas shows detected during drilling, it is possible that the lower Lance Formation is self-sourced by interbedded coals. If this is the case, coal must be identified to determine if they affect production. Coals may also act as reservoir and contribute gas to producing sandstones in the lower part of the Lance Formation. Coal, which was identified by density logs (density porosity greater than 30%) was summed and mapped for the Barrel Springs Township (Figure 23). Coal thickness was compared to gas production, and essentially no correlation between total coal and production was evident. Figure 25 illustrates the lack of correlation with a calculated R^2 of 0.03. Although there is no direct correlation between coal and production, there is a thick anomaly of coal within the Barrel Springs Township (Figure 23). The observed gas production in the Barrel Springs Township may be sourced from these thick coals, which are not evident in all townships. Thus, anomalously thick coals may be contributing to the isolated area of gas production in Barrel Springs Township.

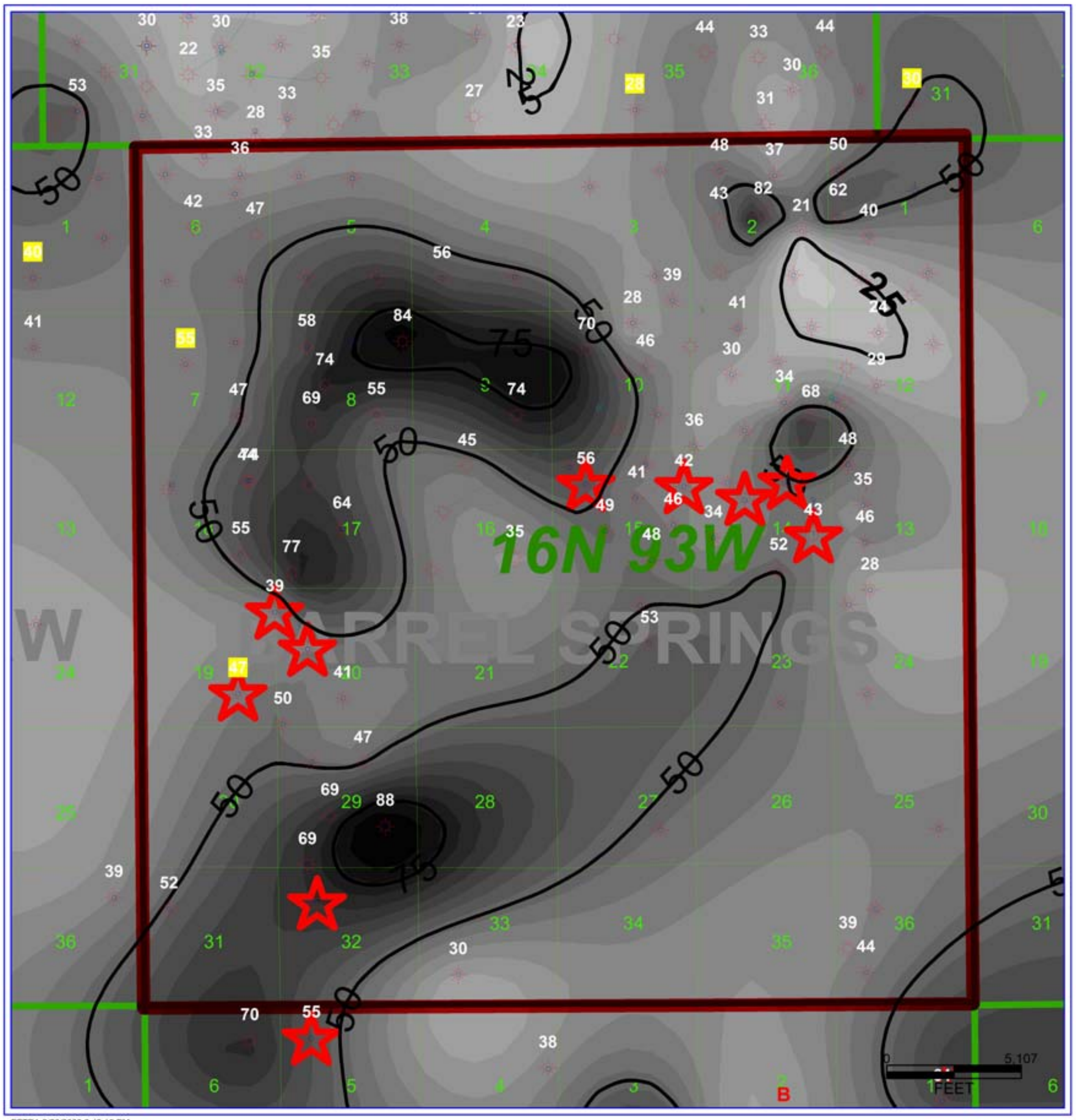


Figure 23: Total thickness of coal seams in Barrel Springs Township. Values range from 30 to 88.

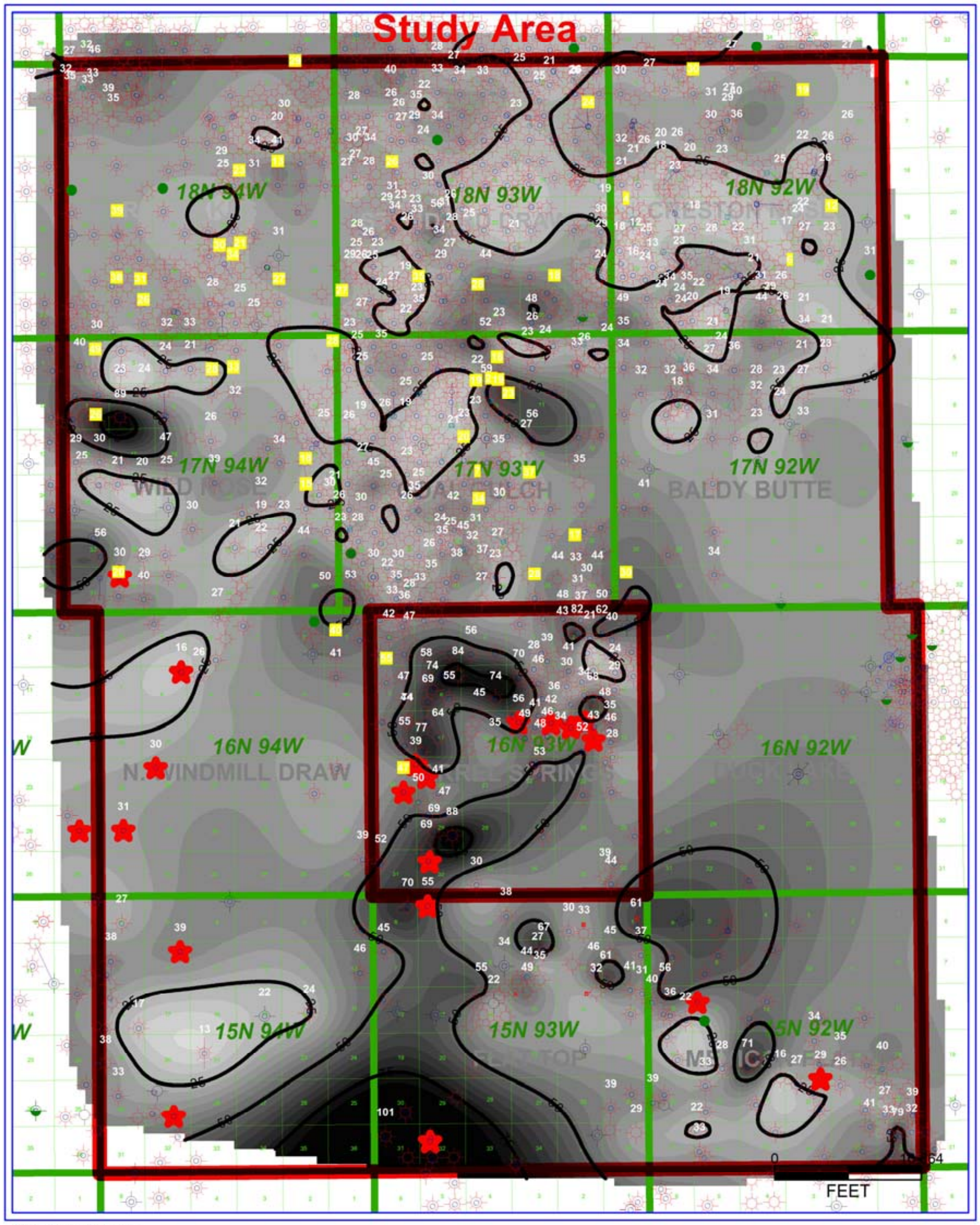


Figure 24: Total thickness of coal seams in the study area. Values range from 13 to 101.

Well	Lance Production (MCF)	Lance Cumulative Water (BBL)	Coal (ft)	(MCF) per (ft) of Total Coal
Barrel Springs Unit 9-14-16-93	599,073	34,080	42	14264
Barrel Springs Unit 20-14-16-93*	43,934	3,082	50	879
Barrel Springs 14-2*	669,699	2,041	40	16742
Barrel Springs Unit 20-15-16-93	601,144	9,957	41	14662
Barrel Springs II 10-15-16-93	2,085,083	5,884	52	40098
Barrel Springs Unit 1-19-16-93	671,296	10,672	38	17666
Barrel Springs 10-20-16-93*	149,606	15,460	30	4987
Barrel Springs 10-32-16-93*	231,263	52,143	60	3854
Federal 40-19-16-93	422,615	1,757	47	8992

Table 15: Comparison of Lance Formation production vs. coal in Barrel Springs Township. *estimated from the contour map (Figure 21).

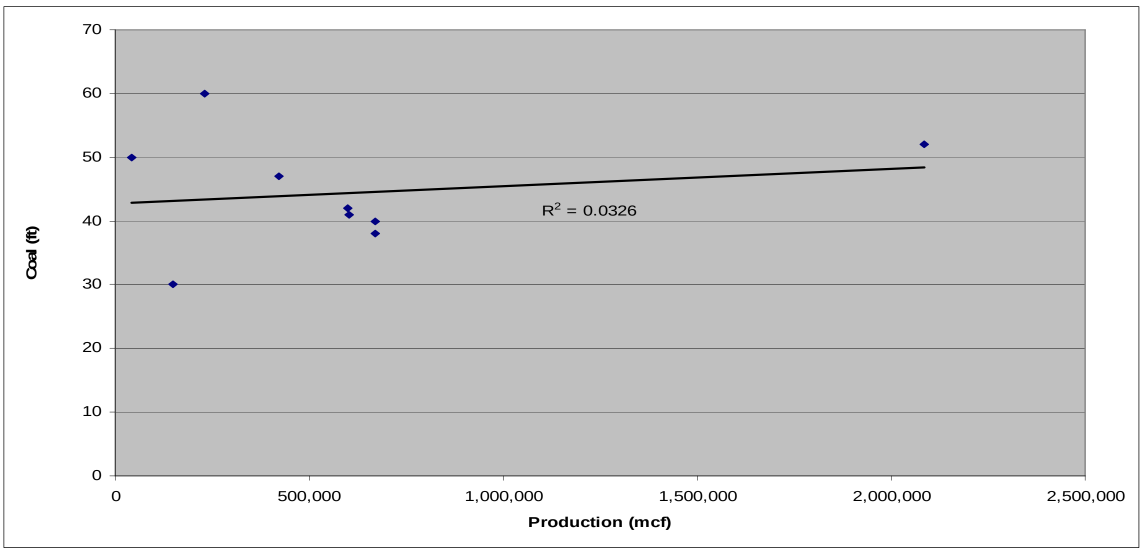


Figure 25: Scatter plot of cumulative coal thickness vs. gas production from the lower 300 feet of the Lance Formation, Barrel Springs Township.

Gas Producing Sandstone Reservoirs

Net thickness of gas producing sandstone in the lower 300 feet of the Lance Formation was calculated using the gamma ray curve, porosity curve and a *Sw* threshold. Since some evidence indicates that sandstones less than 4' thick can contribute to production, all sandstones with greater than 8% density porosity were analyzed if they met the criteria for gas production. A water saturation (Sw) parameter of 50% was used to determine gas producing sandstone. Gas producing pay flags were developed and compared to the depth perforations in the wells producing from the Lance Formation (Figure 26). The pay flags matched the perforated intervals reported on completion information in all gas wells (Appendix B) in Barrel Springs, indicating a high confidence in the calculations.

The Lance sandstones in Barrel Springs Township appear to have fewer feet of gas-bearing sandstones compared to the rest of the study area. This could be the result of using too high a value for *Rw* in the calculations in Barrel Springs Township or too low of value for the cementation factor for the sandstones in the areas outside of Barrel Springs. Another possibility is that the *Rw* and cementation value used in the Barrel Springs Township could be causing erroneously high *Sw* calculations. Based on calculations presented here, areas surrounding Barrel Springs have substantial amounts of gas-bearing sandstones.

The cross-plot of the thickness of gas-bearing sandstone vs. production gives an R^2 value of 0.45 (Figure 29). As more wells are completed in the Lance sandstone and sample size increases, the correlation coefficient may increase.

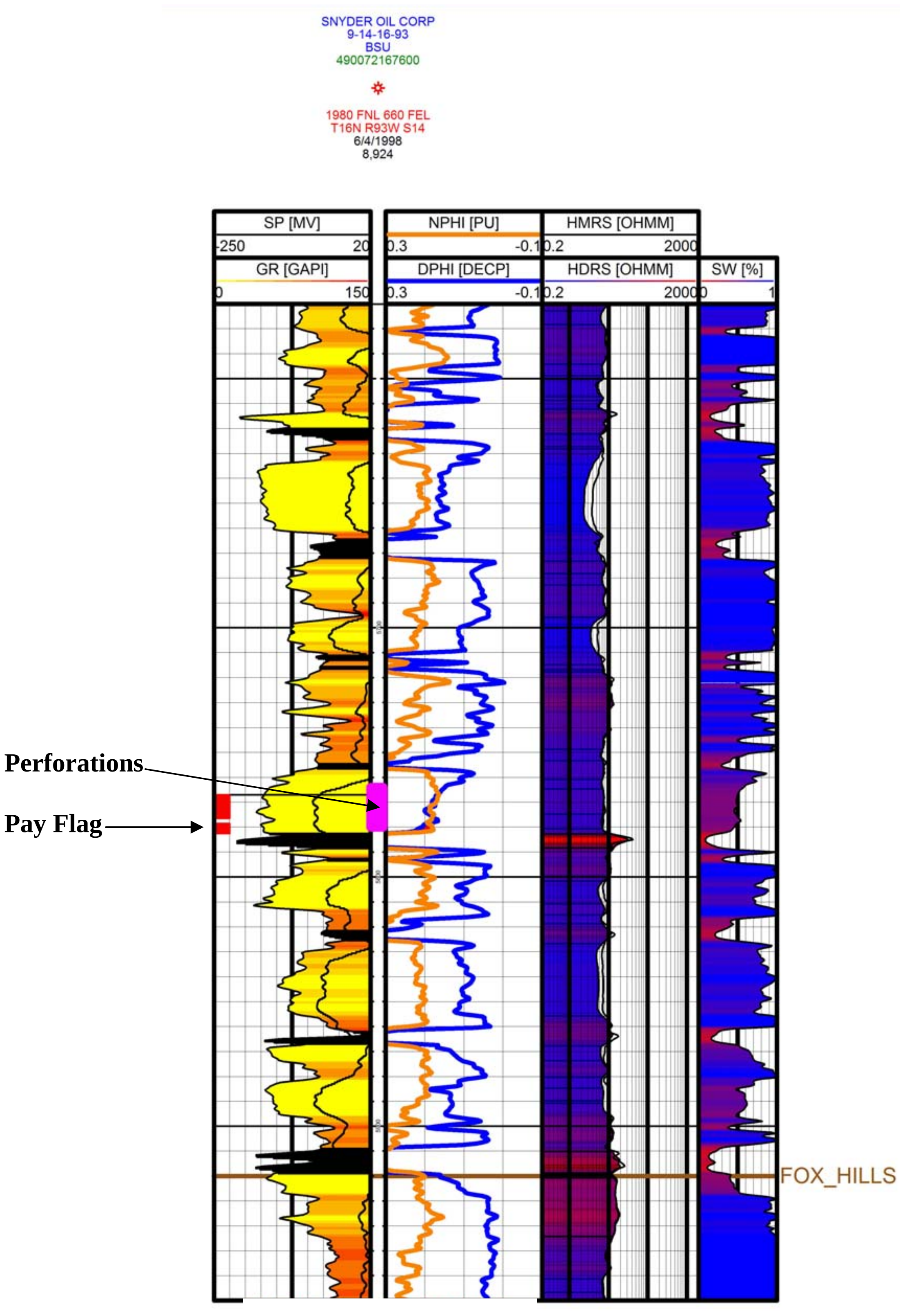


Figure 26: Comparison of pay flag to actual pay in the BSU 9-14-16-93

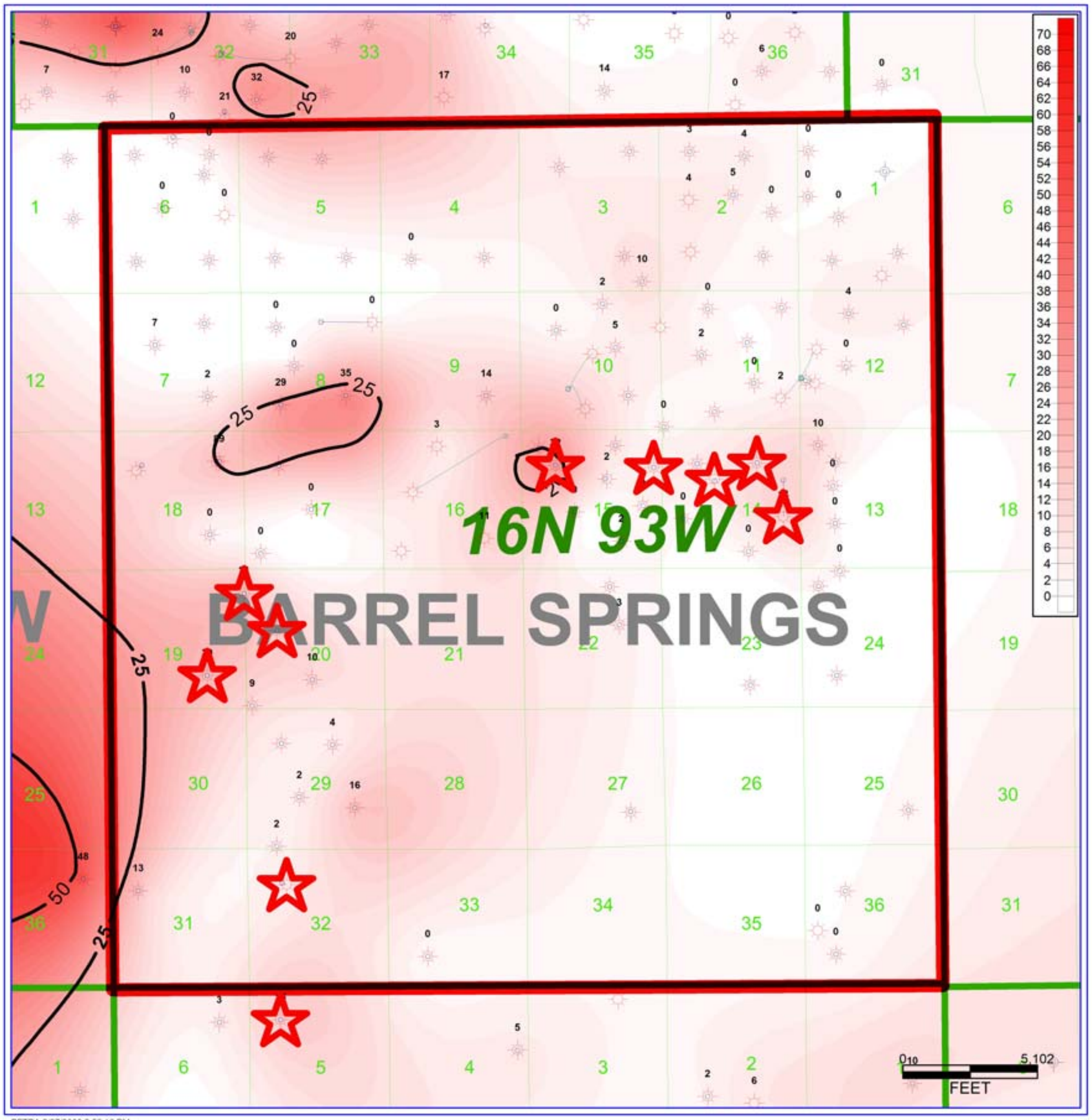


Figure 27: Thickness of gas-bearing sandstone in the Barrel Springs Township. Values range from 0 to 48.

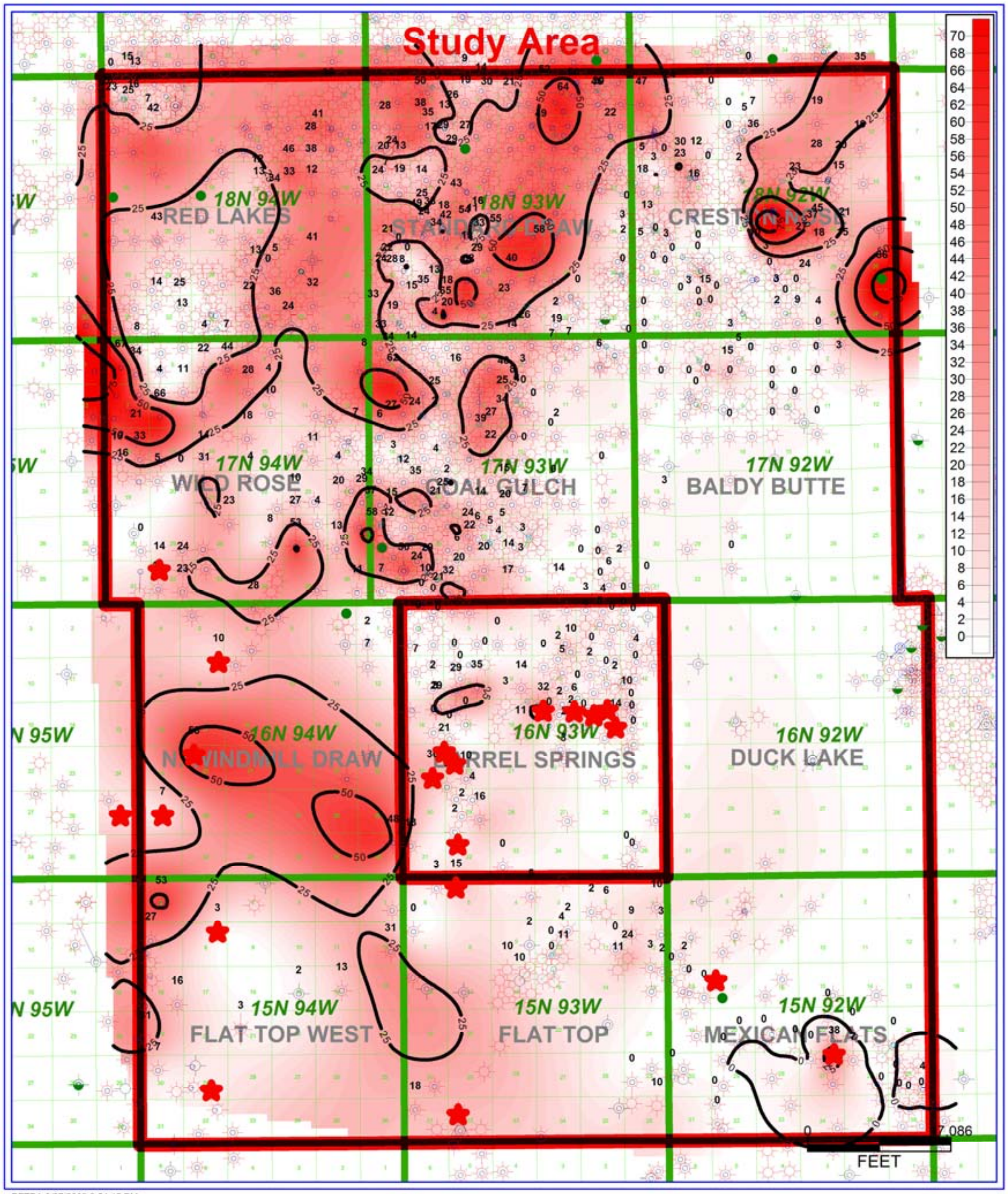


Figure 28: Thickness of calculated gas-bearing sandstone across the study area. Values range from 0 to 64.

Well	Lance Production (MCF)	Lance Cumulative Water (BBL)	Gas-Bearing (ft)	(MCF) per (ft) of Total Pay
Barrel Springs Unit 9-14-16-93	599,073	34,080	14	14264
Barrel Springs Unit 20-14-16-93*	43,934	3,082	9	879
Barrel Springs 14-2*	669,699	2,041	12	16742
Barrel Springs Unit 20-15-16-93	601,144	9,957	8	14662
Barrel Springs II 10-15-16-93	2,085,083	5,884	32	40098
Barrel Springs Unit 1-19-16-93	671,296	10,672	21	17666
Barrel Springs 10-20-16-93*	149,606	15,460	10	4987
Barrel Springs 10-32-16-93*	231,263	52,143	2	3854
Federal 40-19-16-93	422,615	1,757	30	8992

Table 16: Comparison of Lance gas production vs. calculated pay in Barrel Springs. * indicates an estimate from the contour map (Figure 29).

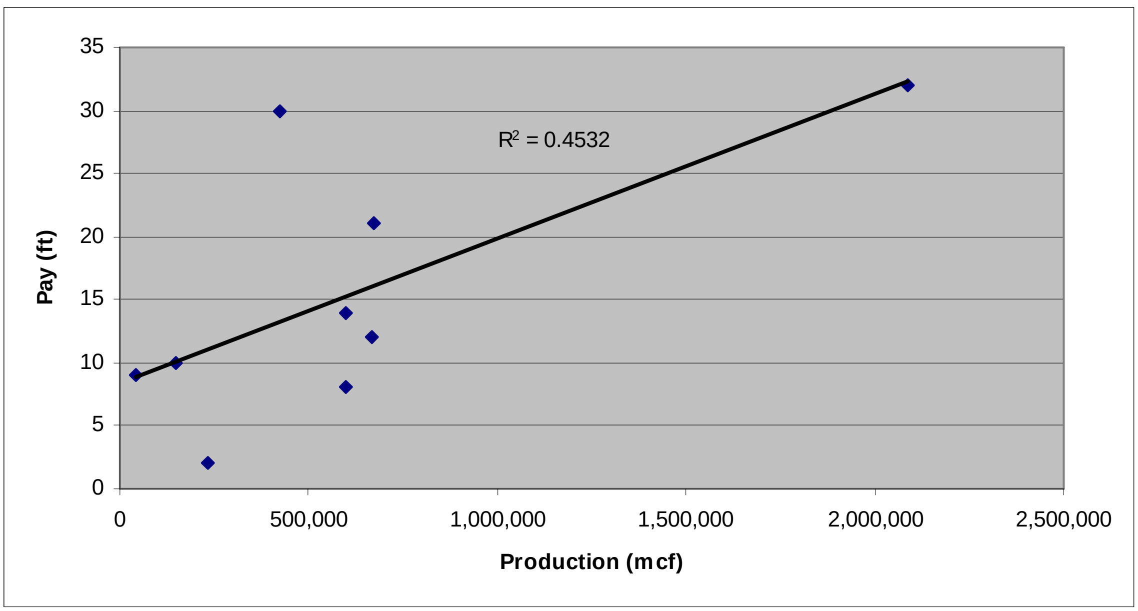


Figure 29: Scatter plot of the thickness of gas-bearing sandstone and gas production in Barrel Springs Township.

Gas Producing Potential by Sections

1. Using values for *Rw*, m and the *Sw* threshold that defines gas-bearing sandstones in Barrel Springs, the Lance Formation sandstones across the study area were analyzed for gas-producing potential.
2. *Sw* values were calculated using the petrophysical criteria assigned to each township.
3. Based on the *Sw* calculations, a color coded map (figure 31) was generated that estimates the gas-potential for each section. The codes include:
    - Green – The section has Lance producing wells or contains a recompletion candidate.
    - Blue – The section contains a recompletion candidate; however more information needs to be understood about the *Rw* in the area.
    - Yellow – Lance potential; however no recompletion candidates were identified.
    - Red – Unlikely Lance potential
    - White – Lack of well control to determine Lance potential

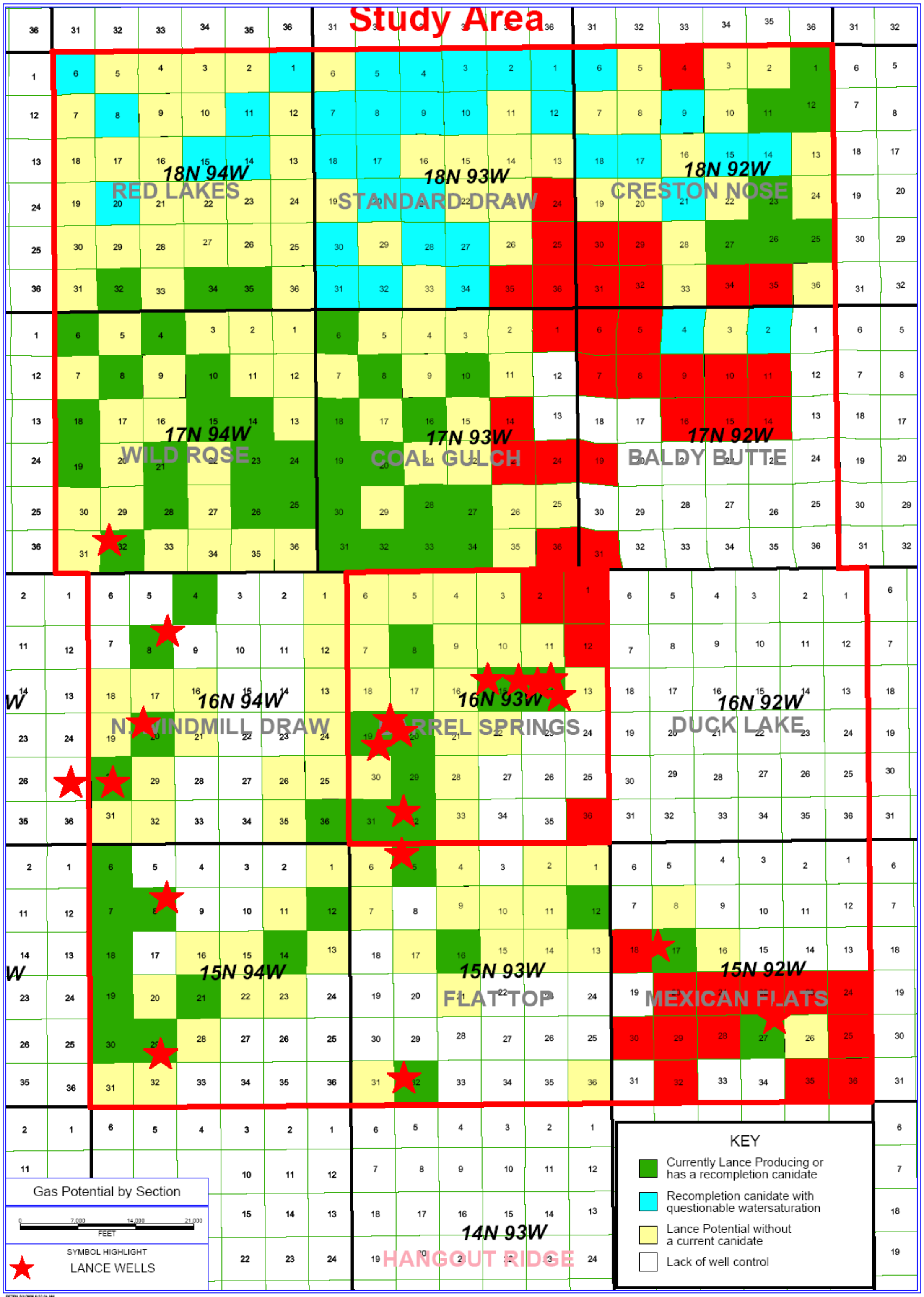


Figure 30: Gas production potential in the lower Lance Formation.

Chapter V

DISCUSSION

The Lance Formation in the Washakie Basin has been difficult to understand due to a lack of data. The intent of this thesis was not to only evaluate the data to date, but also acquire new data. However, because of an economic downturn at the time of this study, acquiring new data never occurred. It is recommended that more Lance Formation core be taken in the study area as well as a few recompletions away from well control in the Barrel Springs township. In the future as this data is acquired it can be incorporated with this study to further understand the Lance Formation, especially further away from the Barrel Springs Township.

While three cores were analyzed in this study only the core in the Barrel Springs township was used to assist in the petrophysical analysis. As mentioned in the core section of this study, the other two cores had significantly different reservoir characteristics. The core in Barrel Springs township was deposited far more distal and had a deeper burial history, which resulted in much tighter, fined grain sandstone.

The core to the south of the study area in the West Side Canal Field contained sandstone similar to a conventional gas sandstone with high porosity and permeability. It also had a definite structural trap caused by faulting and uplift of the Cherokee arch. Overall, the Lance Formation reservoir varied too much to use in this study.

Rw was determined by sampling produced water, core analysis and Pickett Plot calculations The *Rw* tended to decrease with depth as there is less contamination of meteoric, freshwater from outcrops of the Lance Formation to the east. Cementation values increased with depth as a result of deeper burial history towards the center of the Washakie Basin.

The bottom 300 feet of the Lance was the focus of this study because it was the only zone to have production history. This is probably the case because the sandstones in the Upper Lance Formation lack any kind of seal to prevent hydrocarbons from migrating. Also the Lower Lance Formation contains thick coals, that possibly act as the source rocks, which are not seen in the rest of the Lance Formation.

Correlating individual productive sandstones between wells was not possible. The productive sandstones are of fluvial to marginal marine origin and well control is currently not dense enough to correlate the individual channels.

While the lower Lance Formation has historically been productive, the rest of the Lance Formation and Fox Hills should not be excluded as potential gas-bearing reservoirs. Lance Formation potential is not limited to the study area. As the Lance Formation completions expand outwards its full potential in the Washakie Basin will be unveiled. This study demonstrates the gas-producing potential outside the Barrel Springs township, and this potential is believed to extend throughout the basin.

Chapter V

CONCLUSIONS

The Lance Formation in the Washakie Basin is a sparsely produced gas-bearing zone. The limited amount of gas production is restricted to the lower 300 feet of the unit. Within the lower part of the Lance Formation, porous sandstone reservoirs are widely distributed throughout the study area. As a result of this research to improve the petrophysical evaluation of Lance sandstone and evaluate the production potential for the Lance Formation in the area, the following conclusions are proposed.

1. The *Rw* for Lance Formation water is calculated to be 0.08 ohm-m in the Barrel Springs Township using 3 independent methods: Pickett Plot, core plug analysis and laboratory analysis of formation water samples.
2. Using Pickett Plots a cementation factor of 1.73 was determined in the Barrel Springs Township.
3. Petrophysical parameters a, m, and *Rw* were calculated by township and used to identify gas-bearing sandstones and accurately predicted gas-bearing zones in the lower Lance Formation
4. Based on gas-producing sandstones in the Barrel Springs Field a gas producing threshold of *Sw* ≈ 50% was determined.
5. Petrophysical data can be used to predict potential gas-producing sandstones in the Lance Formation.
6. There seems to be no relationship between sandstone thickness or coal thickness and gas production in the Lance Formation.

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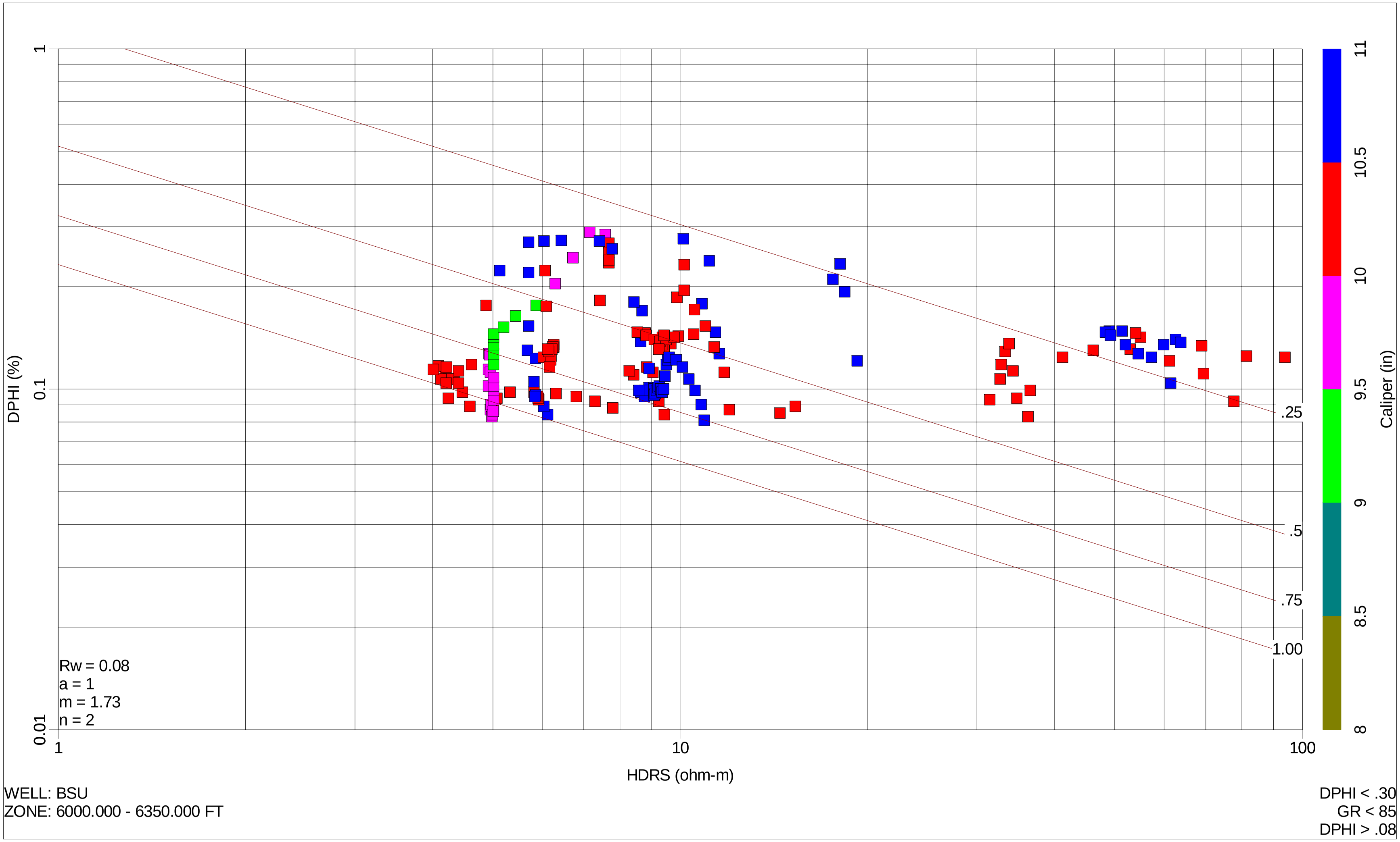
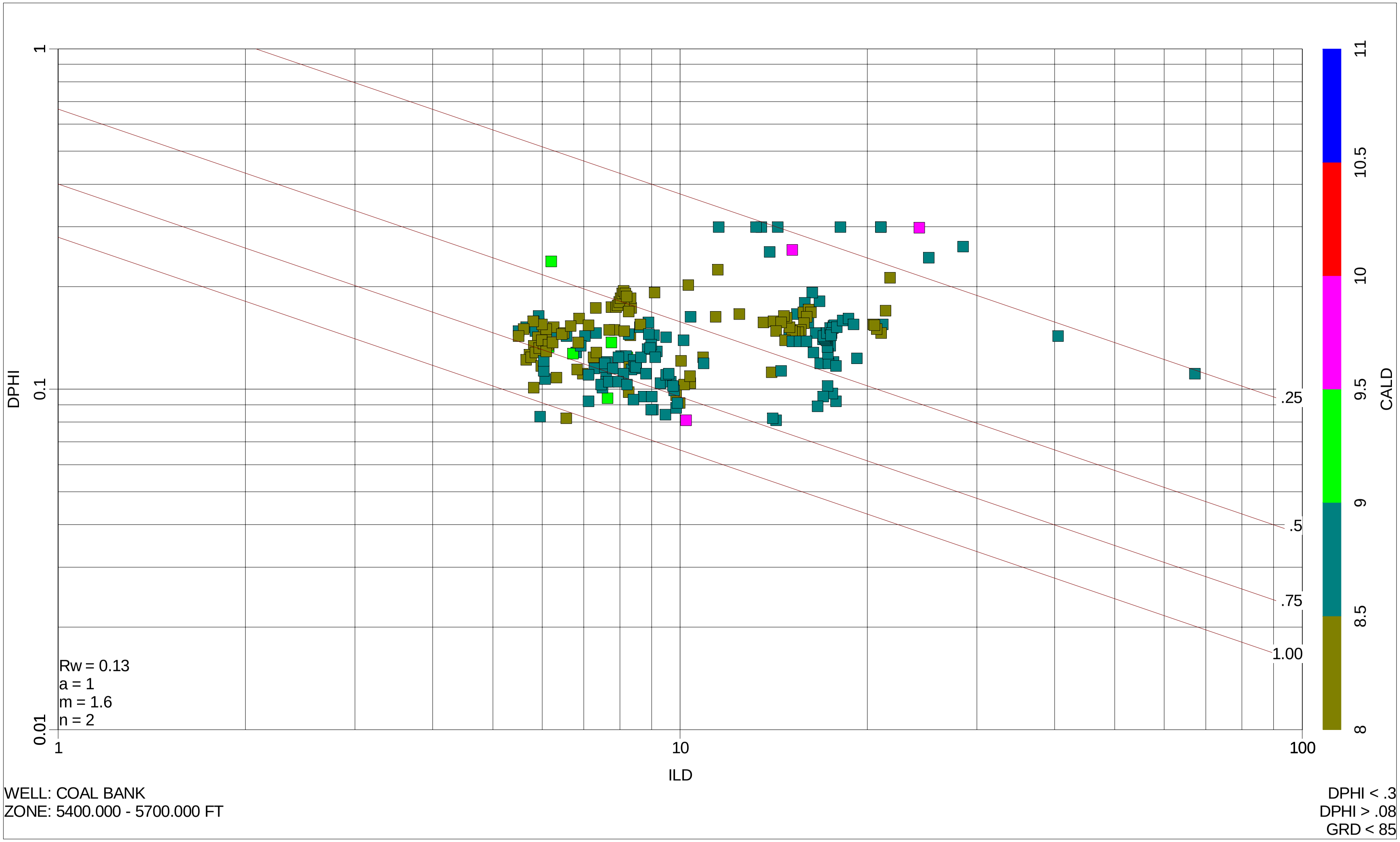
APPENDIX A

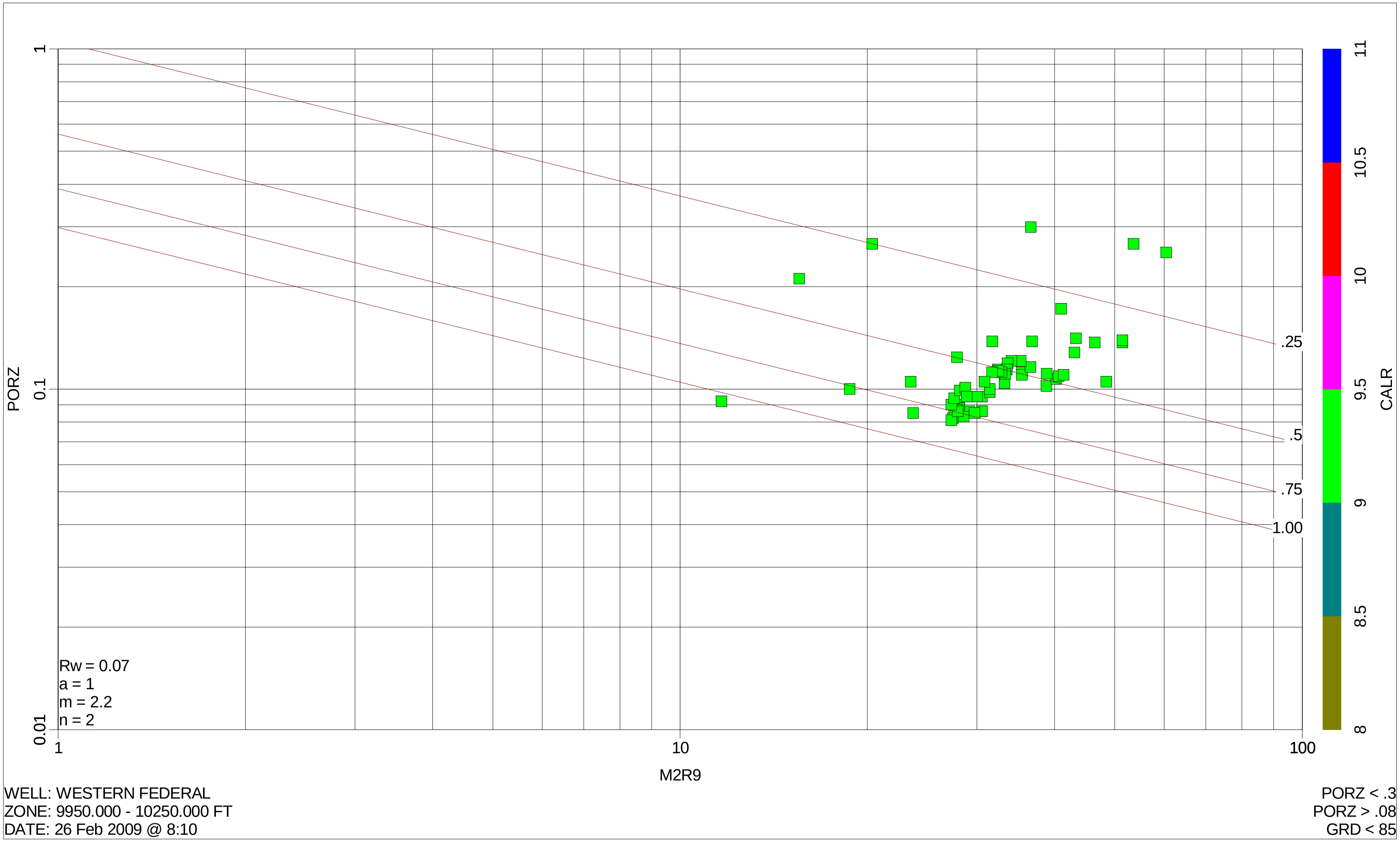
Pickett Plots



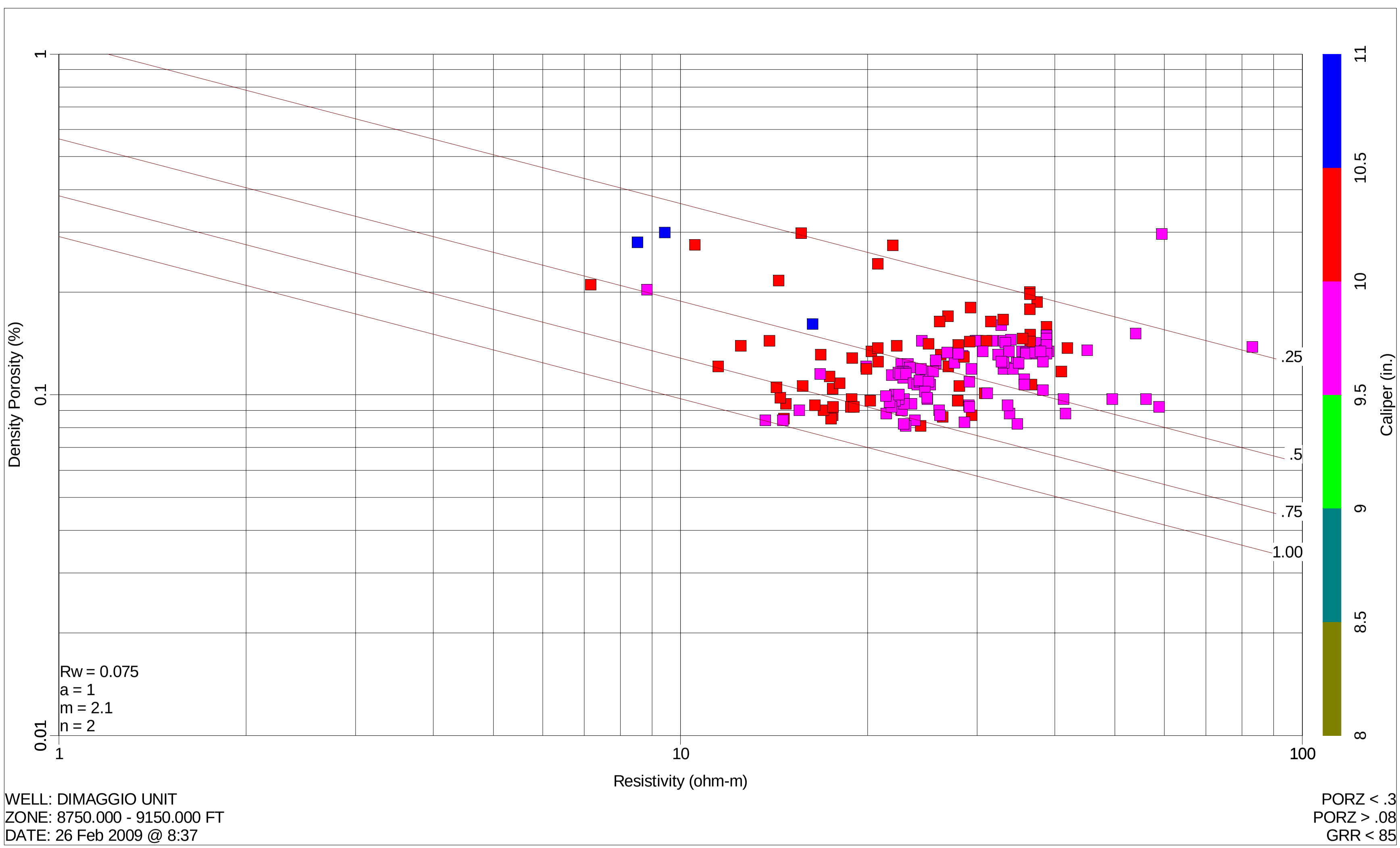
A. 1: Barrel Springs II 10-15-16-93 Pickett Plot



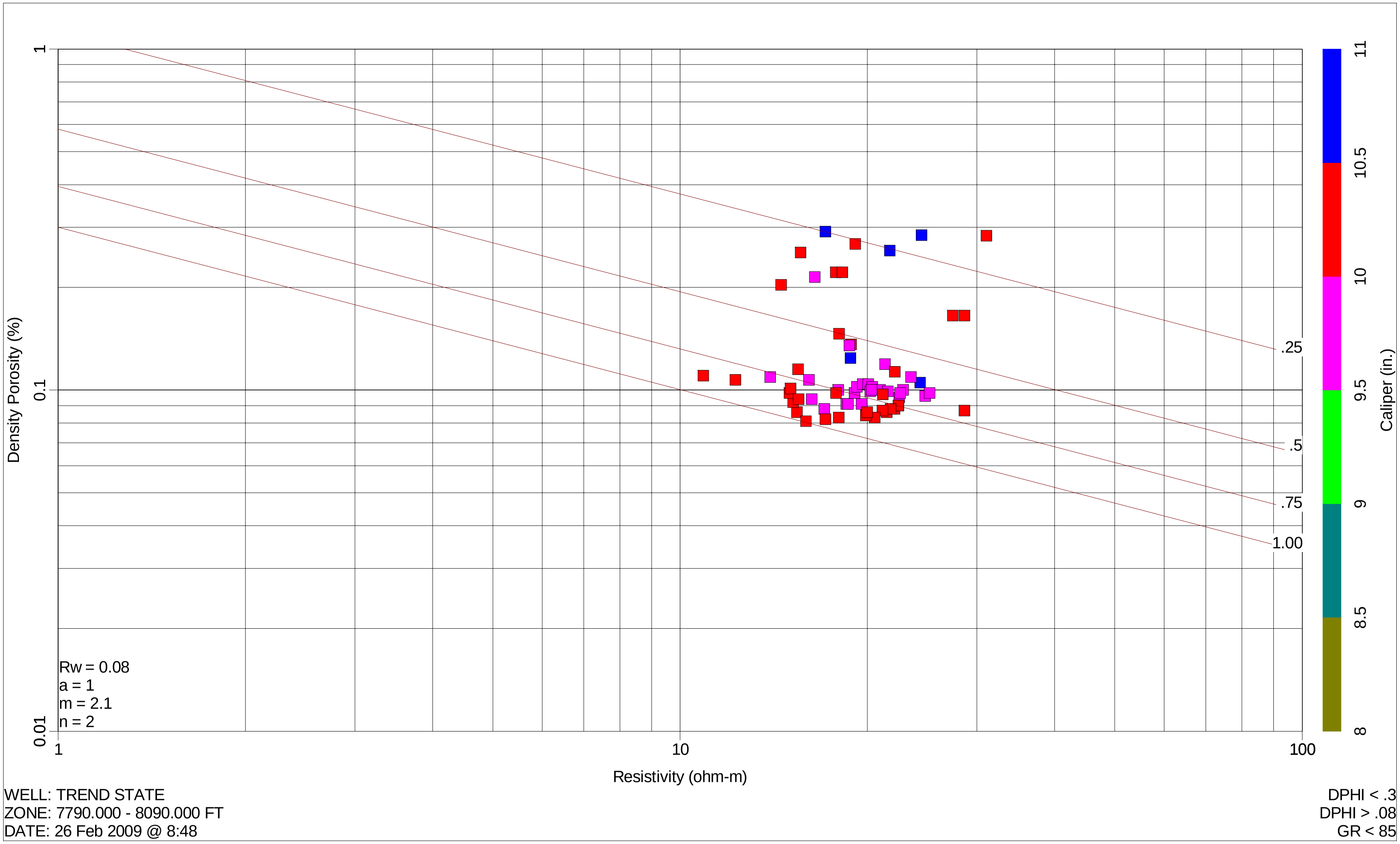
A. 2: Coal Bank 1-2 Pickett Plot



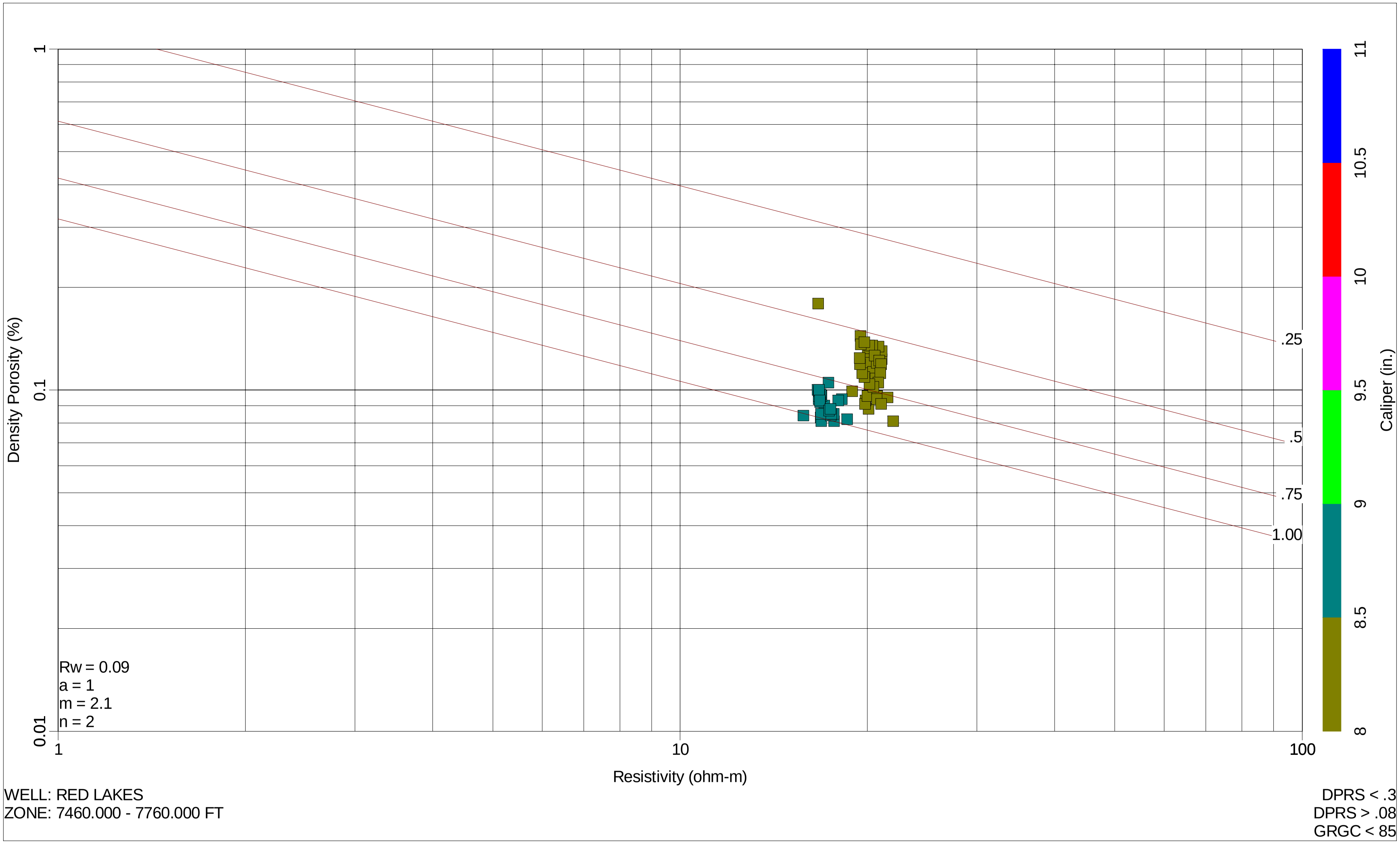
A. 3: Western Federal 22-7 Pickett Plot



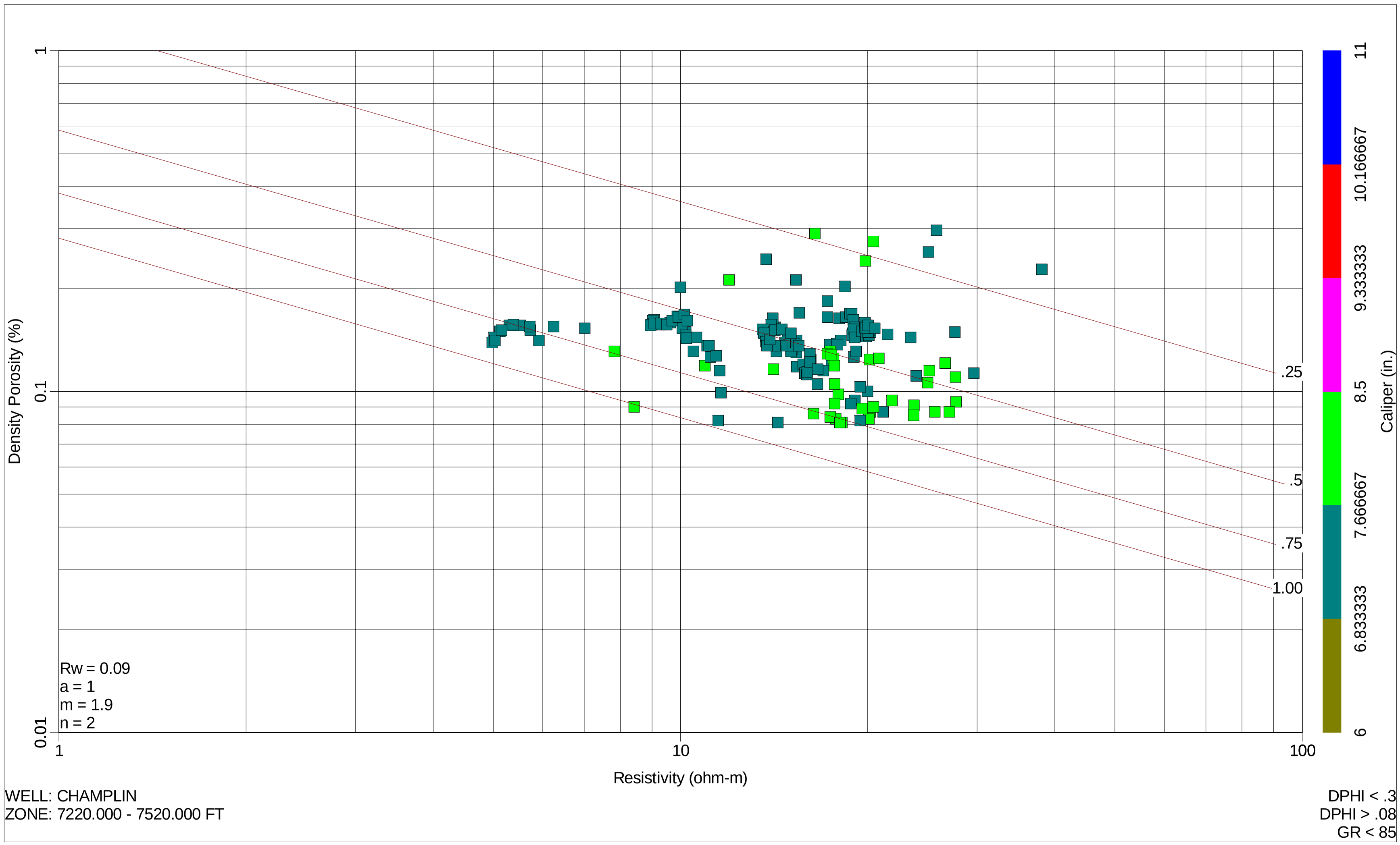
A. 4: DiMaggio Unit 2 Pickett Plot



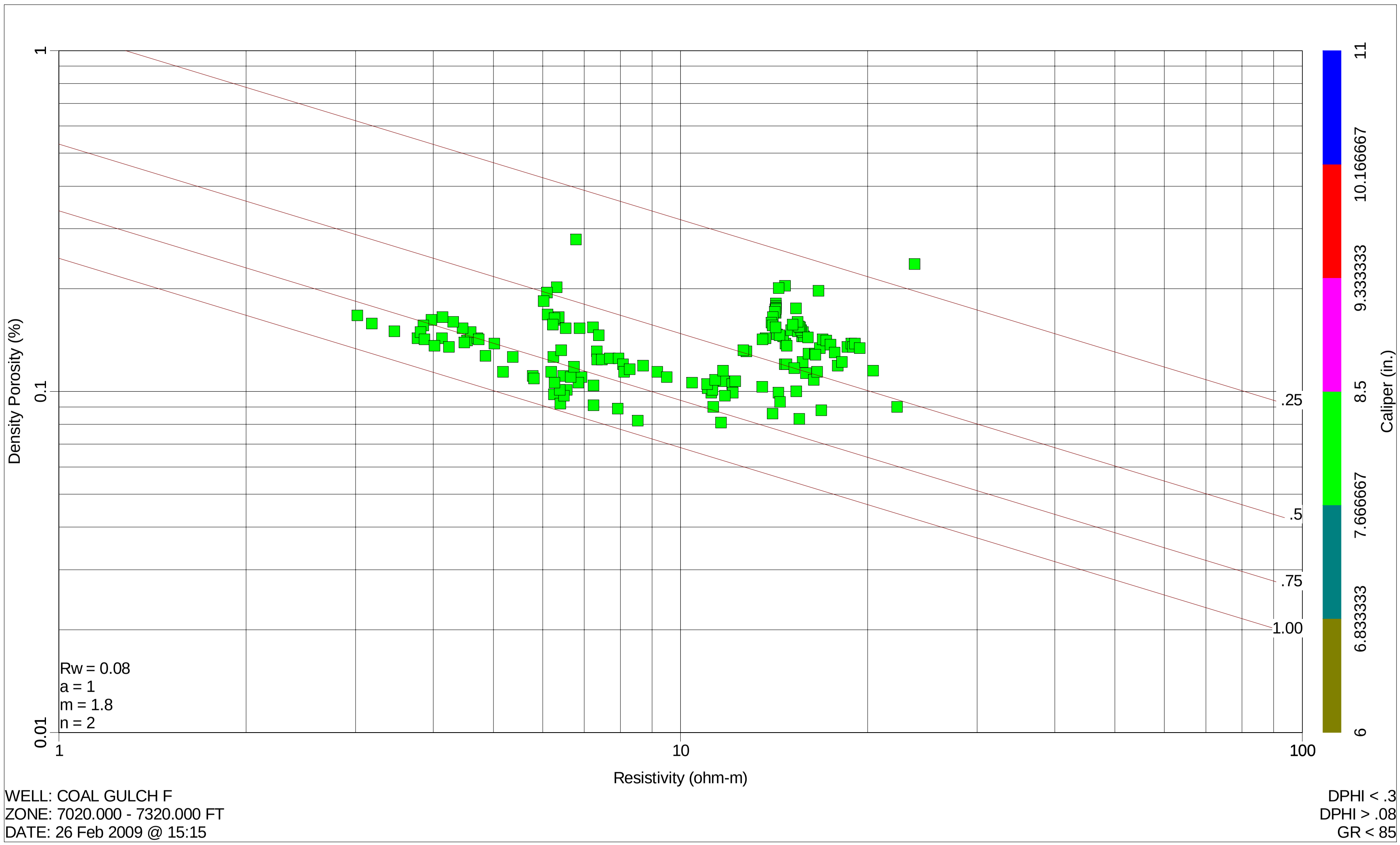
A. 5: Trend State 1-18 Pickett Plot



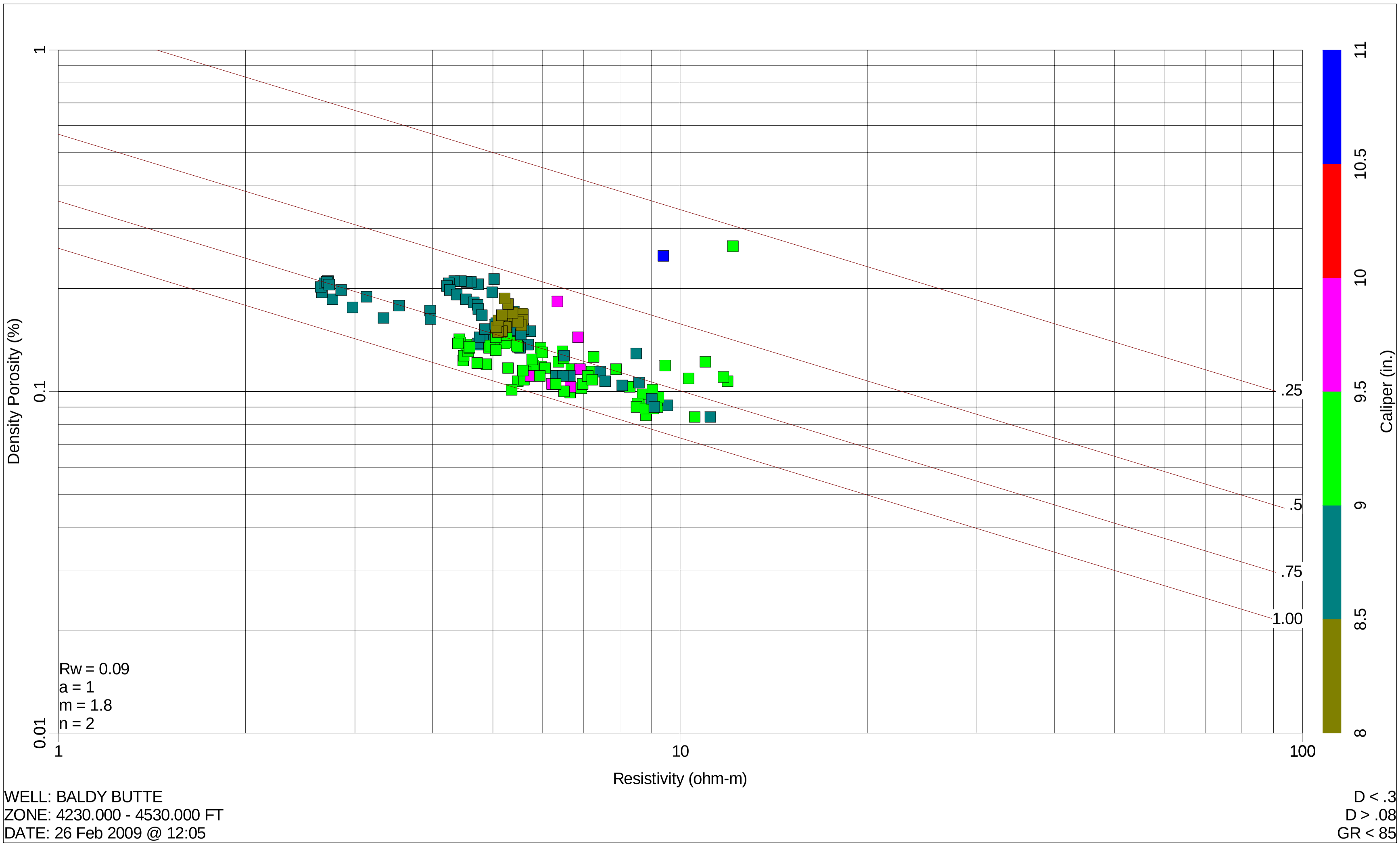
A. 6: Red Lakes 15-6-18-94 Pickett Plot



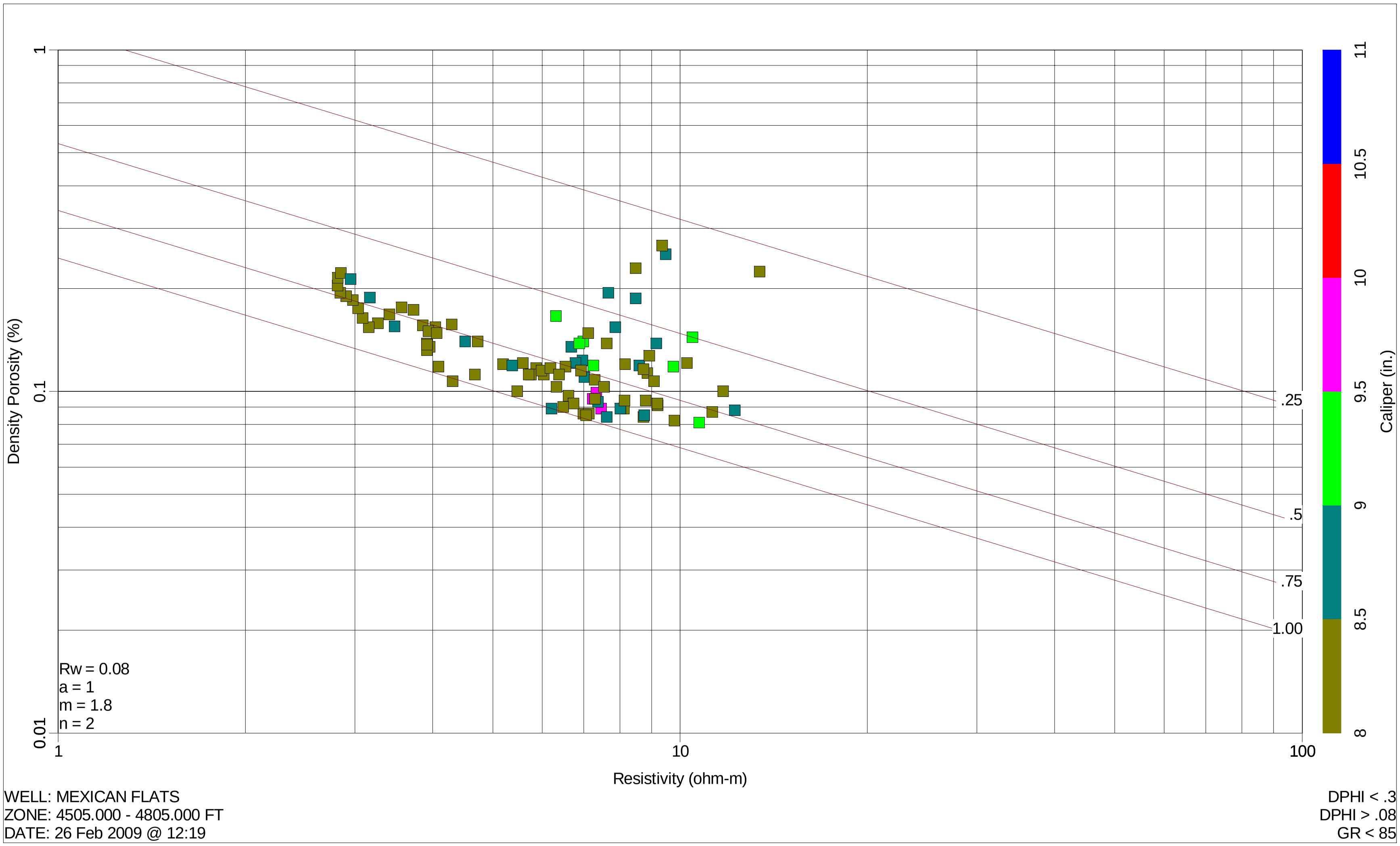
A.7 : Champlin 261 D-12D Pickett Plot



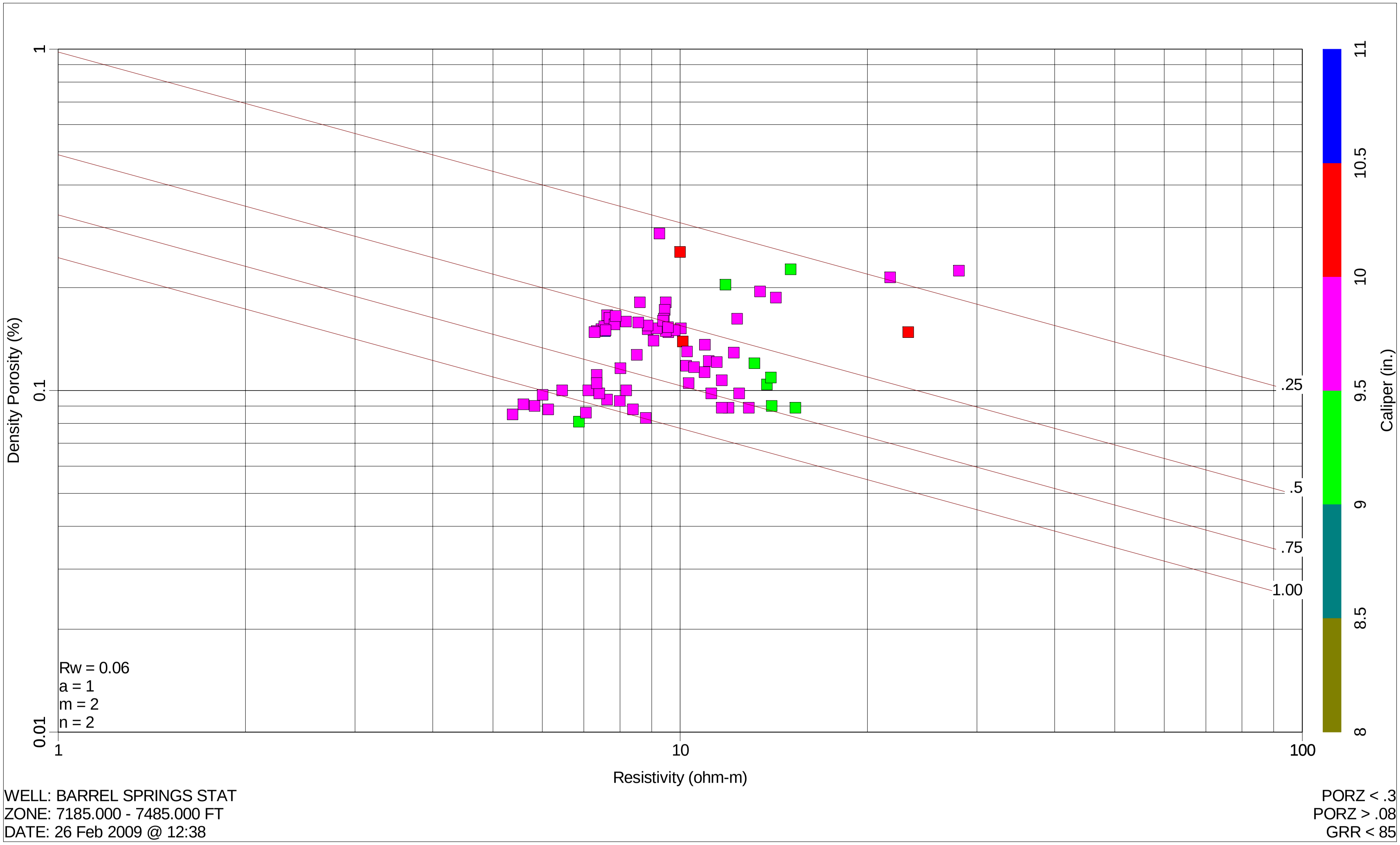
A. 8: Coal Gulch F10D Pickett Plot



A. 9: Baldy Butte 4-14-17-93 Pickett Plot



A. 10: Mexican Flats 4-26-15-92 Pickett Plot

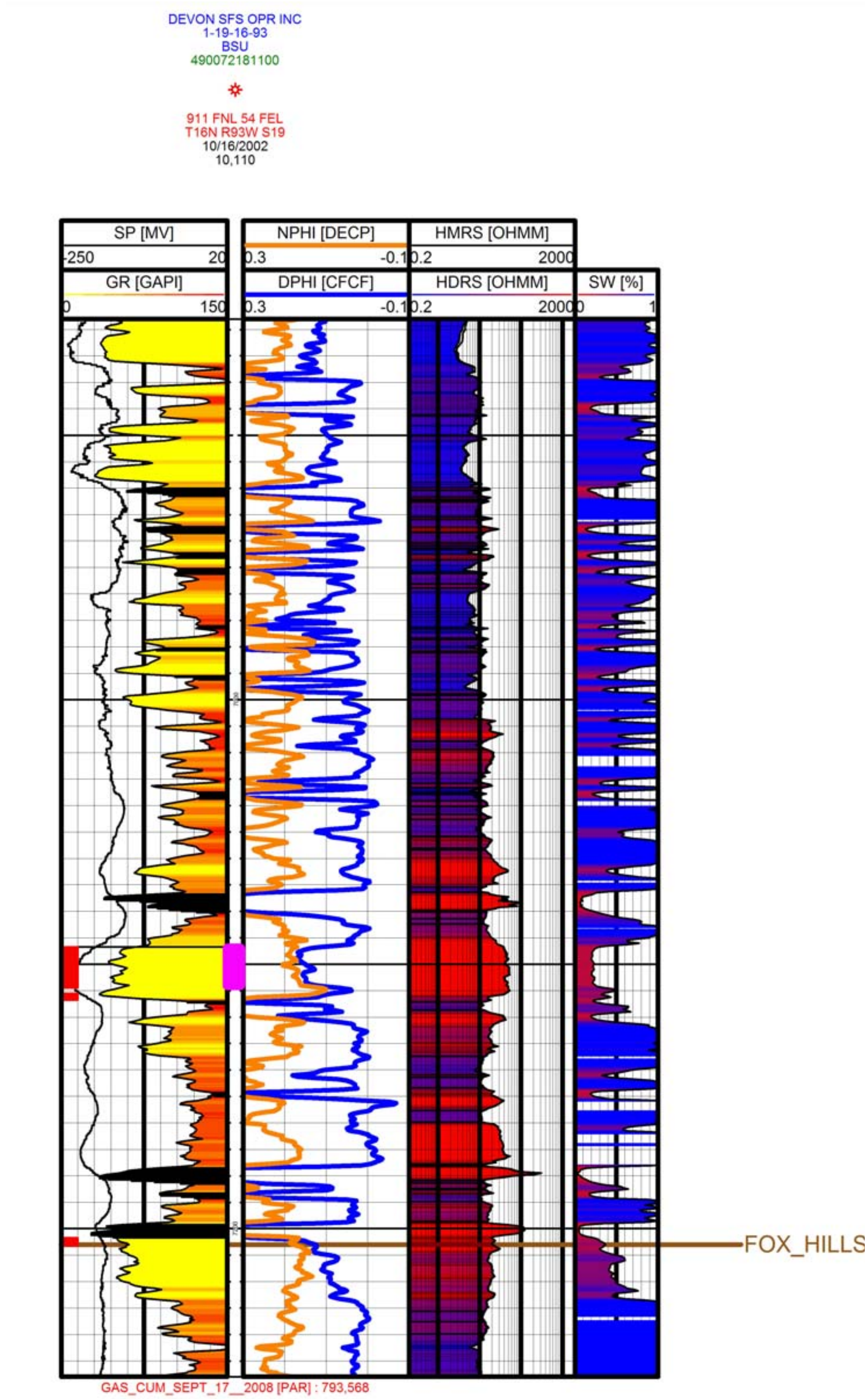


A. 11: Barrel Springs State 2X Pickett Plot

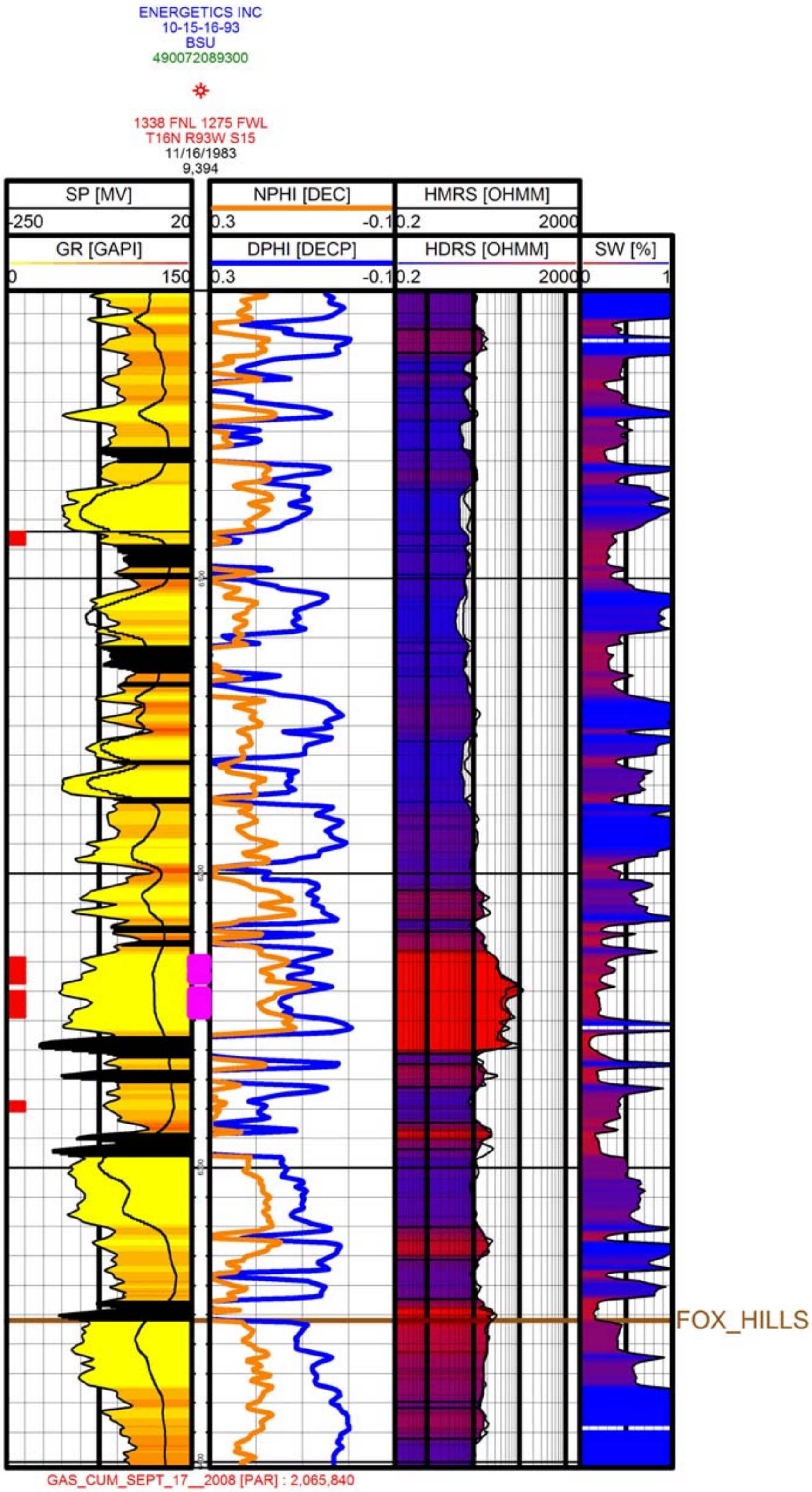
APPENDIX B

Barrel Springs, Lance Formation Gas Producing Zones Compared

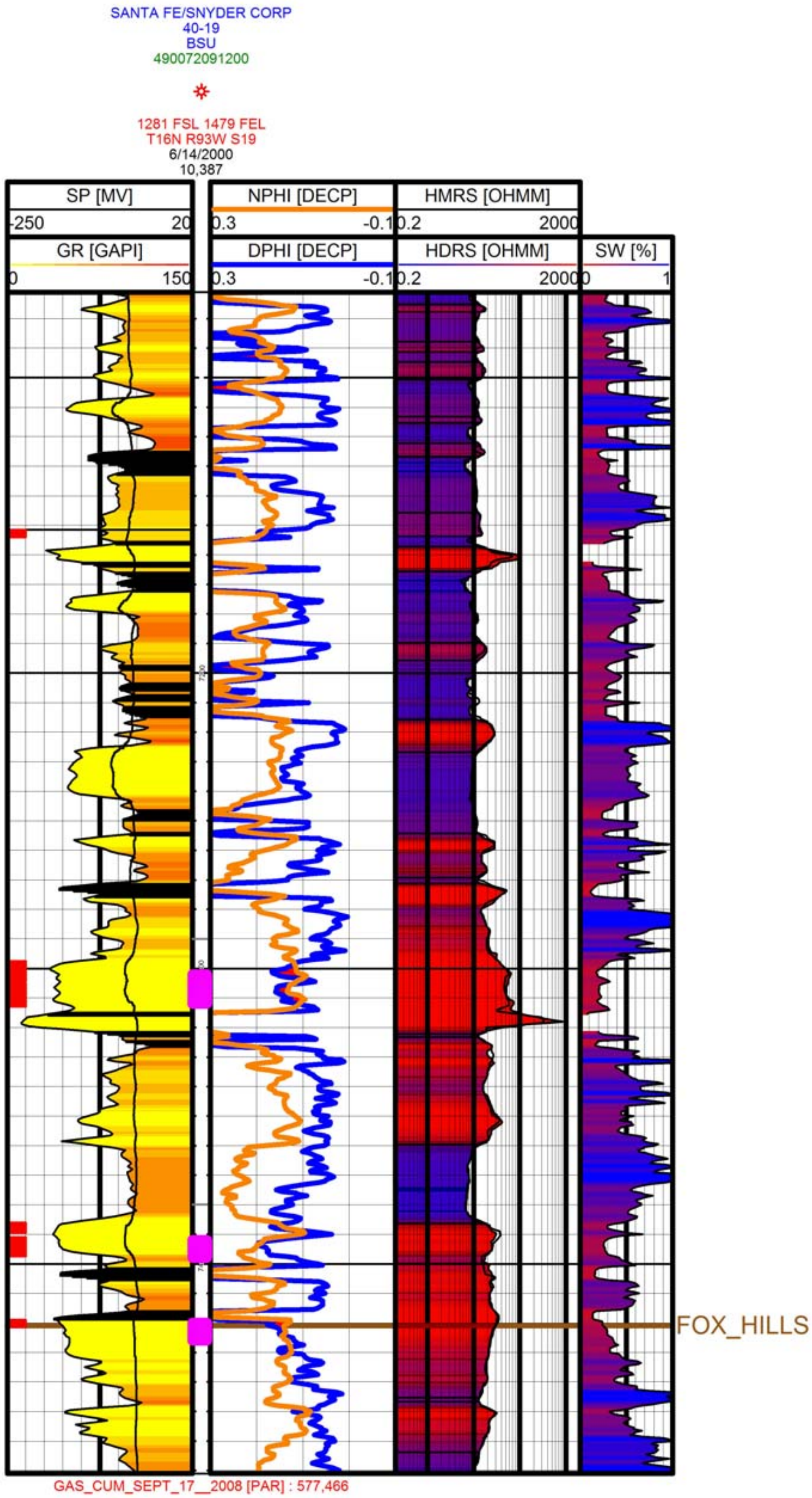
to Calculated Pay (Flags)



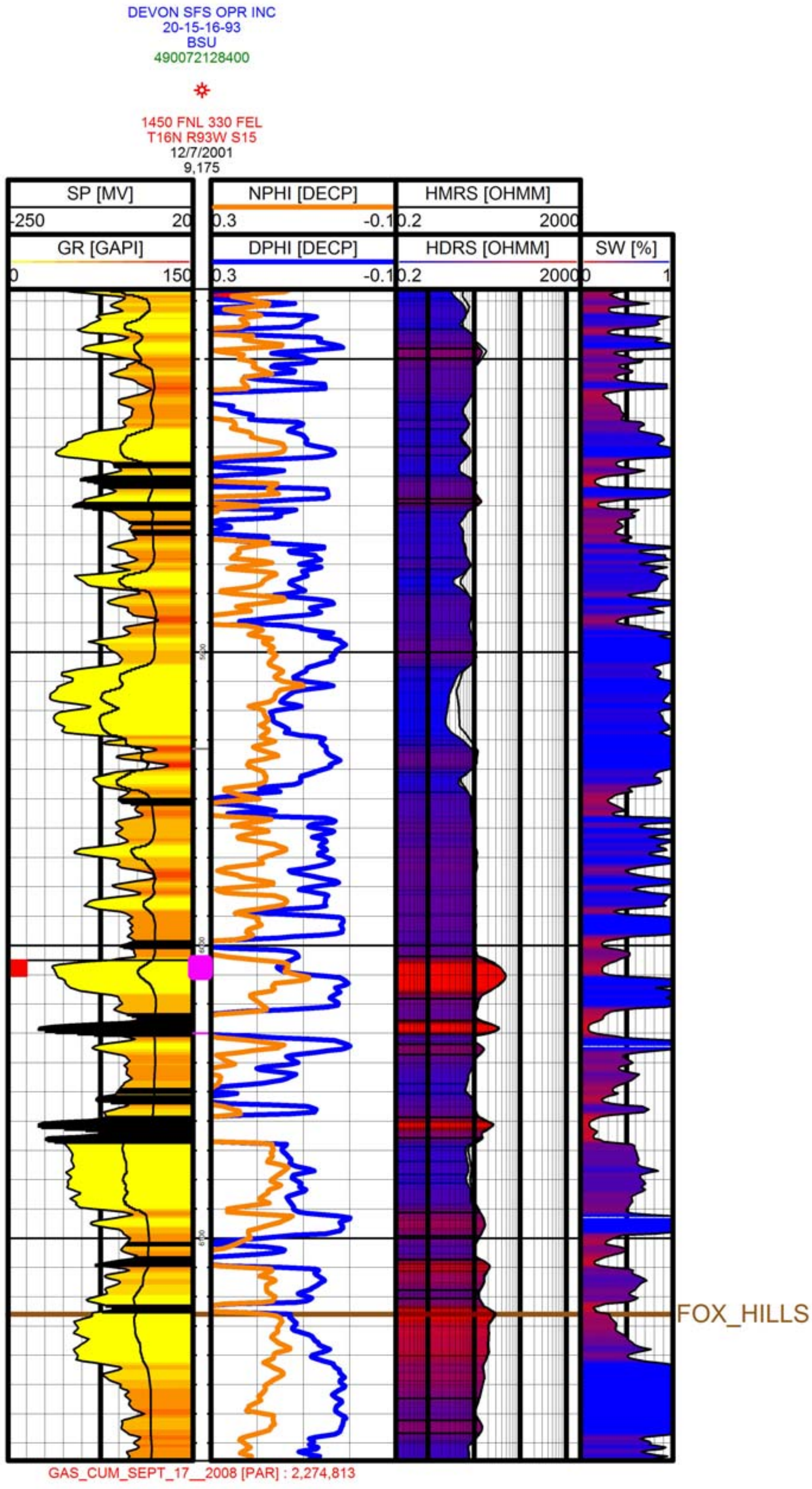
Comparison of pay flag to actual pay in the BSU 1-19-16-93



Comparison of pay flag to actual pay in the BSU 10-15-16-93



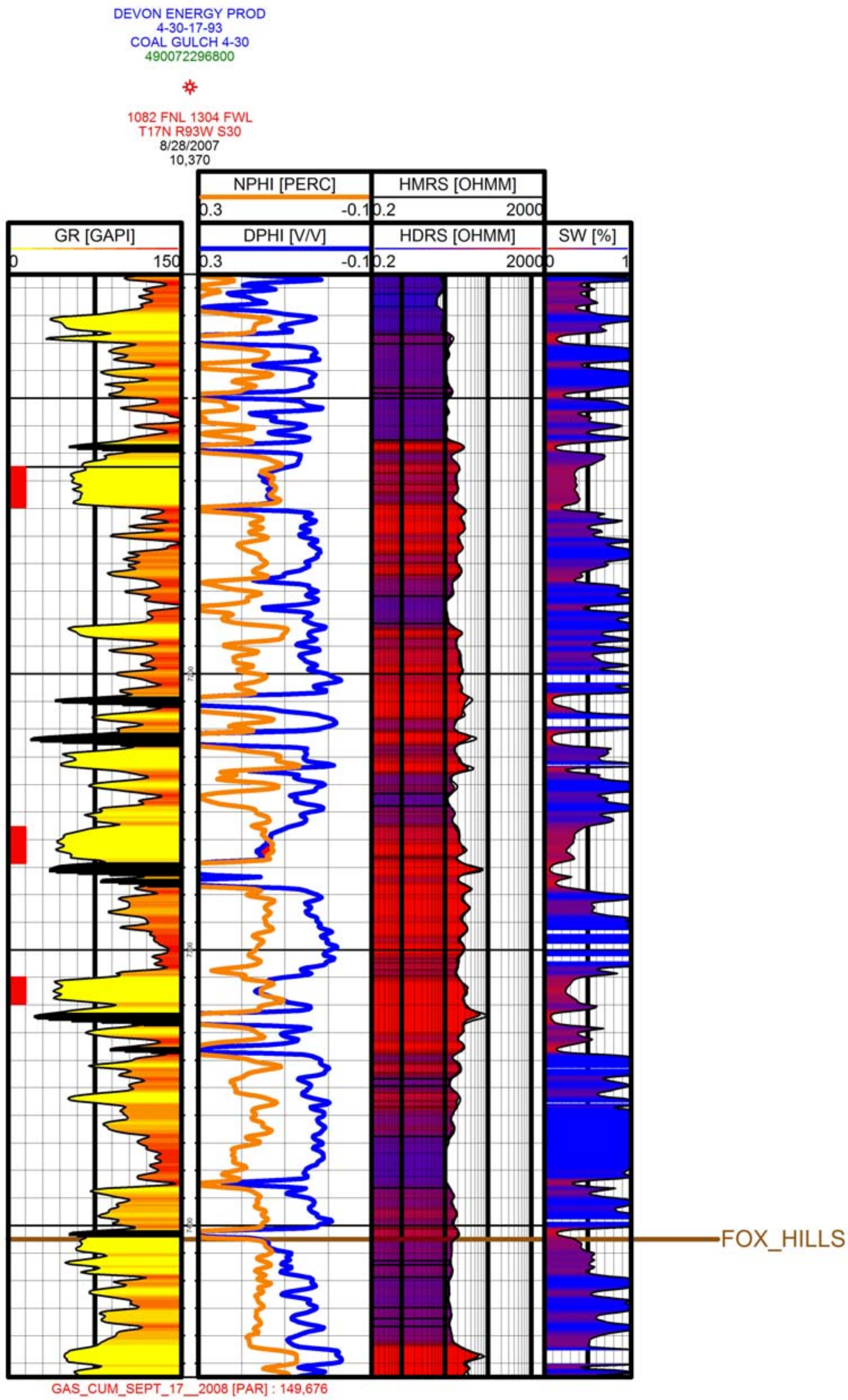
Comparison of pay flag to actual pay in the BSU 40-19-16-93

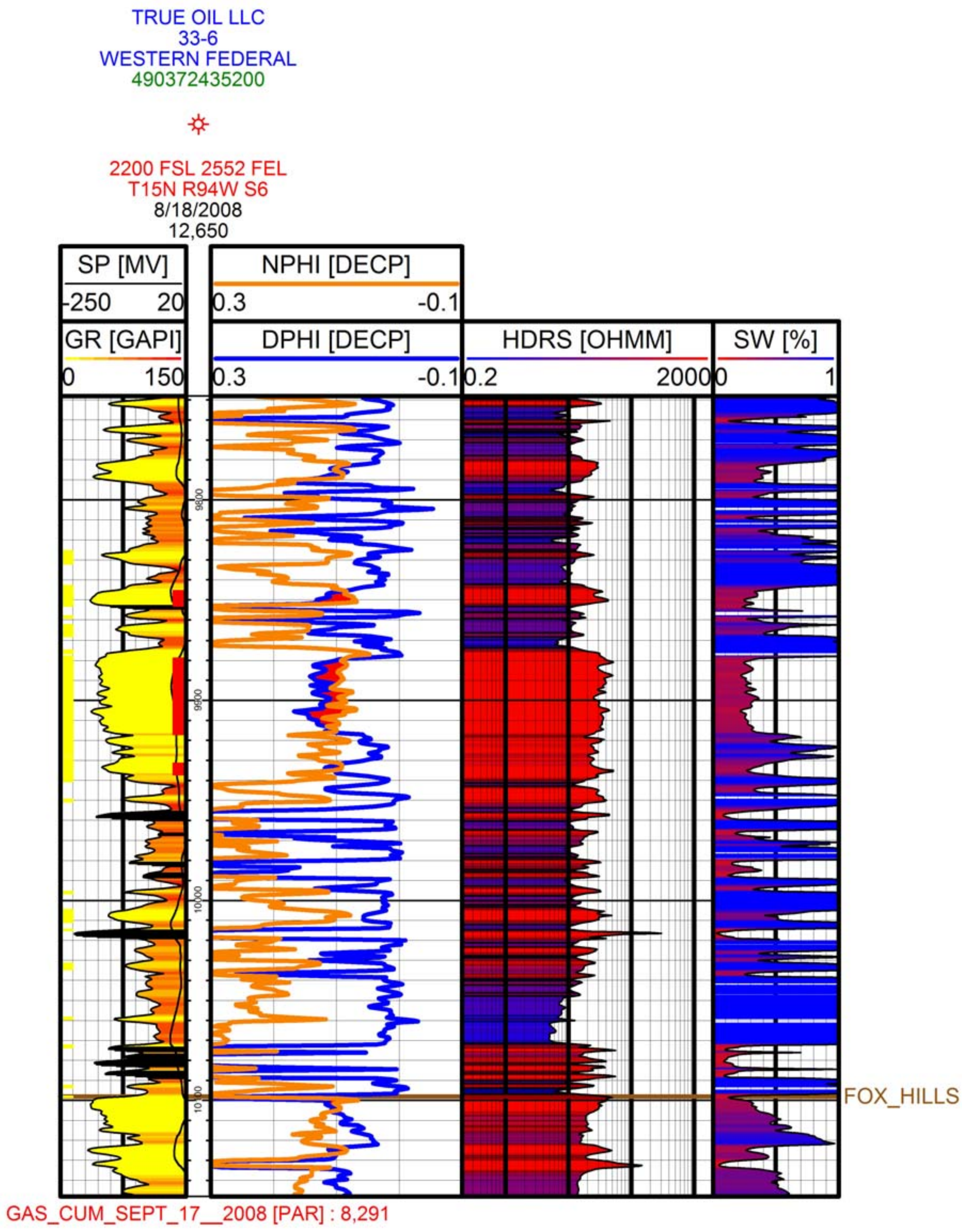


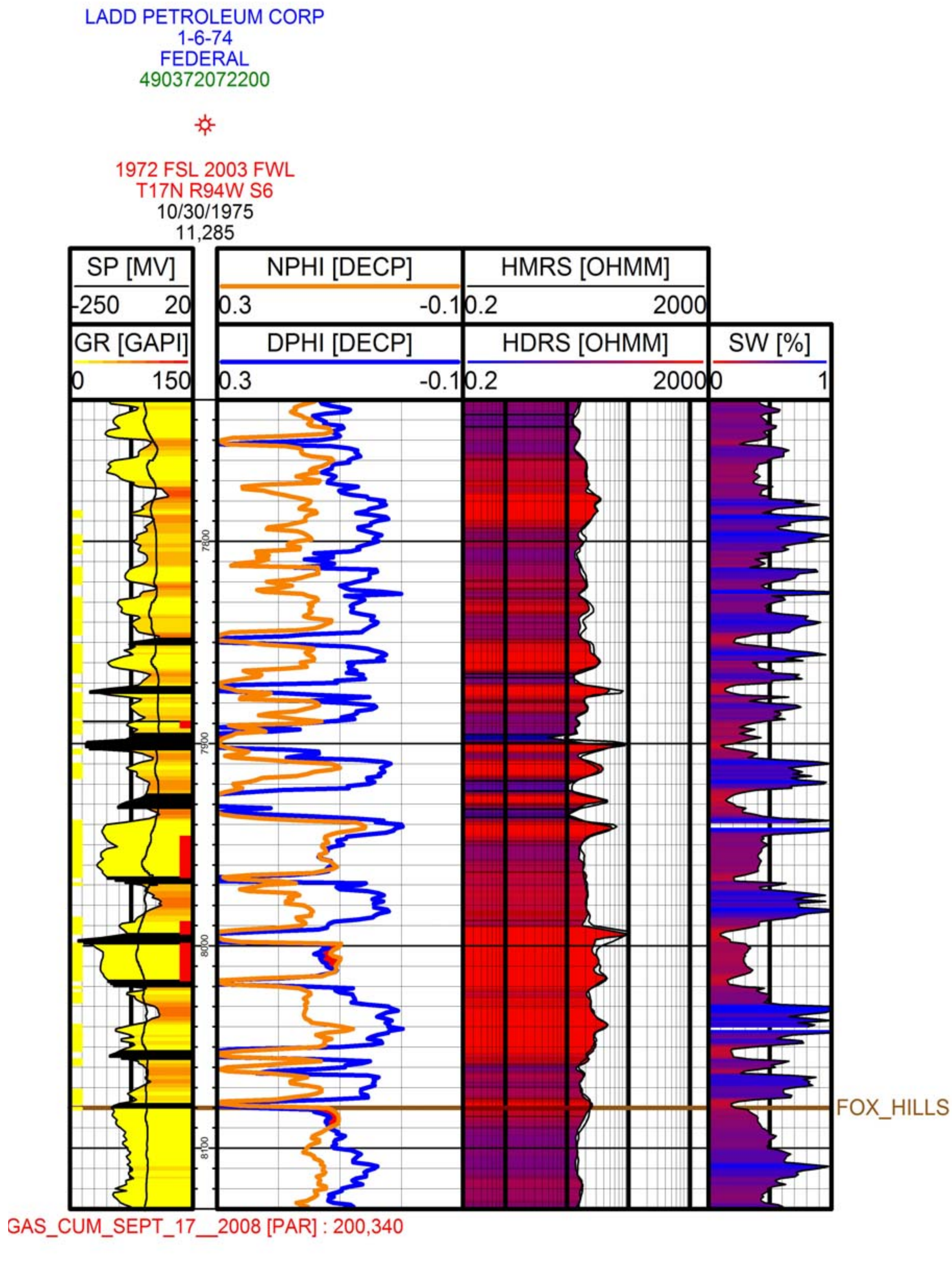
Comparison of pay flag to actual pay in the BSU 20-15-16-93

Appendix C:

Wells with Possible Gas-Bearing Zones (Potential) in the Lance Formation


DEVON ENERGY PROD
4-30-17-93
COAL GULCH 4-30
490072296800
1082 FNL 1304 FWL
T17N R93W S30
8/28/2007
10,370
NPHI [PERC]
0.3
-0.1
HMRS [OHMM]
0.2
2000
GR [GAPI]
0
150
DPHI [V/V]
0.3
-0.1
HDRS [OHMM]
0.2
2000
SW [%]
0
1
FOX_HILLS
GAS_CUM_SEPT_17__2008 [PAR] : 149,676

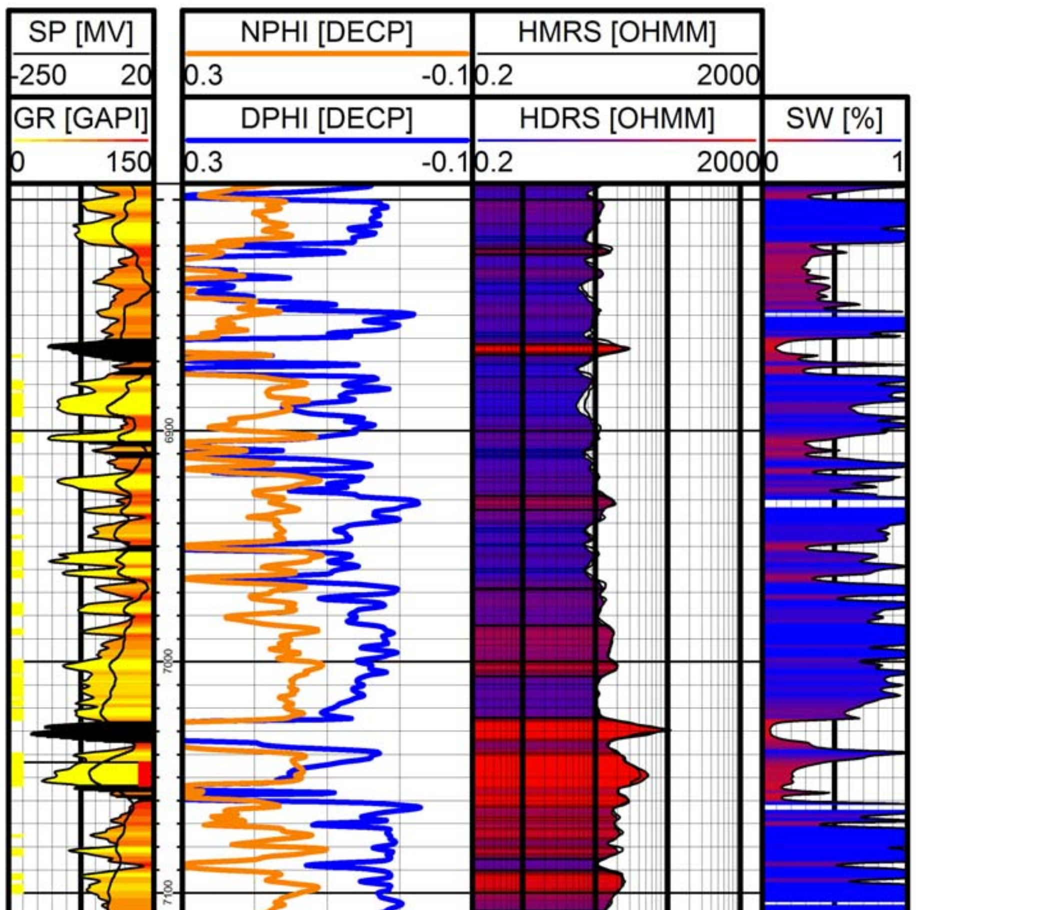

TRUE OIL LLC
33-6
WESTERN FEDERAL
490372435200
2200 FSL 2552 FEL
T15N R94W S6
8/18/2008
12,650
SP [MV]
-250 20
GR [GAPI]
0 150
NPHI [DECP]
0.3 -0.1
DPHI [DECP]
0.3 -0.1
HDRS [OHMM]
0.2 2000
SW [%]
0 1
9800
9900
10000
FOX_HILLS
GAS_CUM_SEPT_17__2008 [PAR] : 8,291



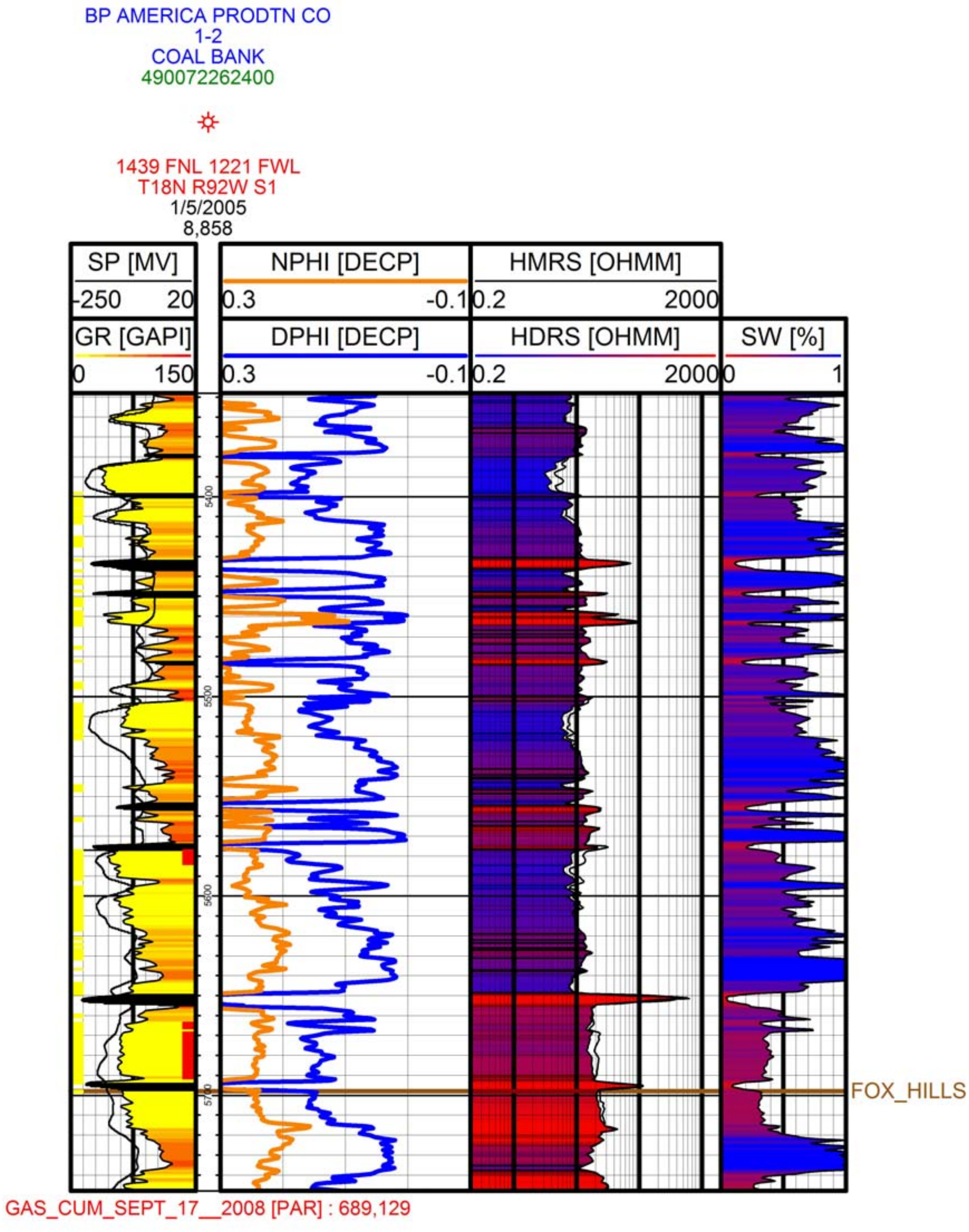
LADD PETROLEUM CORP
1-6-74
FEDERAL
490372072200
1972 FSL 2003 FWL
T17N R94W S6
10/30/1975
11,285
SP [MV]
-250 20
GR [GAPI]
0 150
NPHI [DECP]
0.3 -0.1
DPHI [DECP]
0.3 -0.1
HMRS [OHMM]
0.2 2000
HDRS [OHMM]
0.2 2000
SW [%]
0 1
7800
7900
8000
8100
FOX_HILLS
GAS_CUM_SEPT_17__2008 [PAR] : 200,340

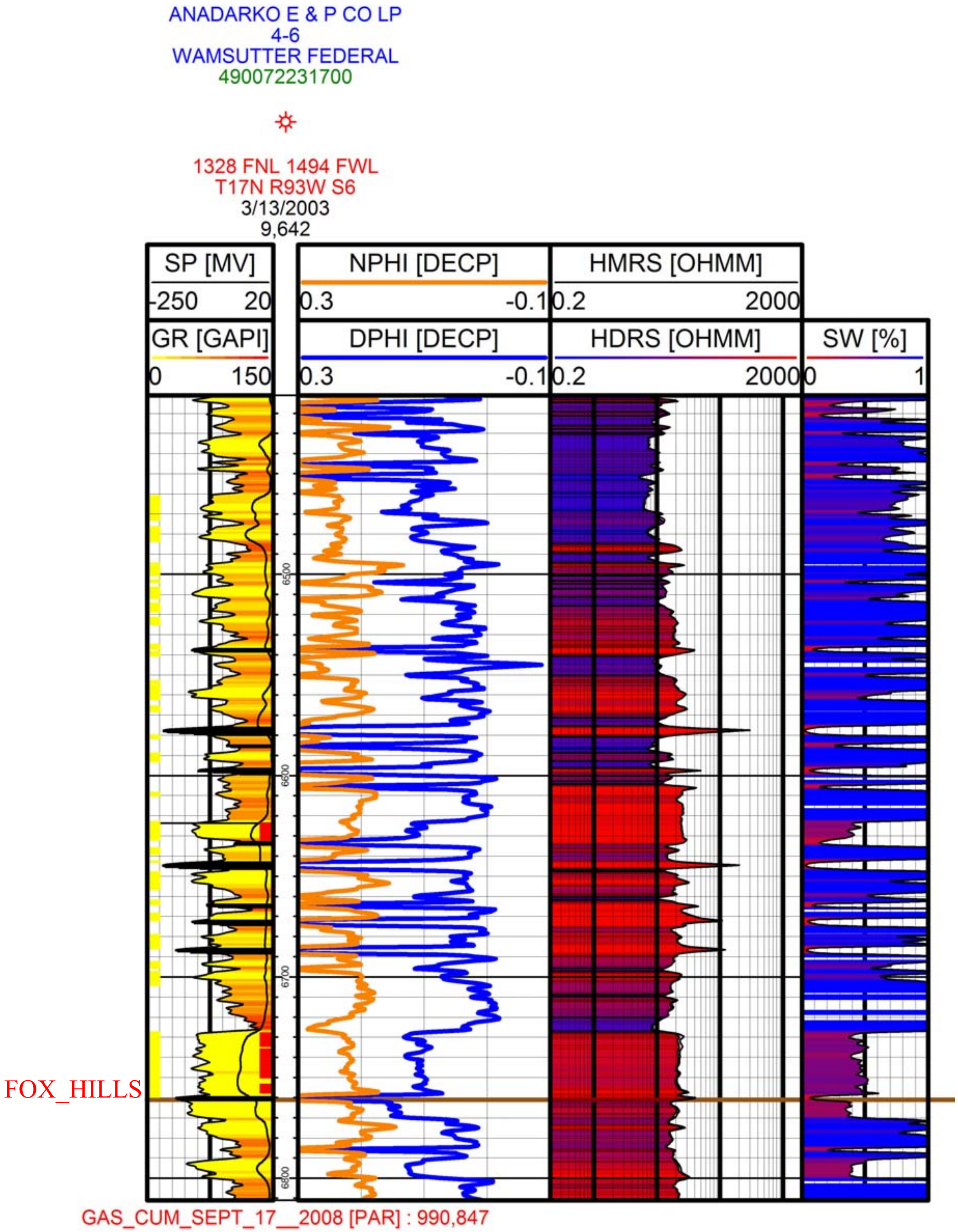
SNYDER OIL CORP
BSU14-20-16-93
BSU
490072143300

1127 FSL 2492 FWL
T16N R93W S20
9/11/1998
10,120



GAS_CUM_SEPT_17__2008 [PAR] : 804,373


BP AMERICA PRODTN CO
1-2
COAL BANK
490072262400
1439 FNL 1221 FWL
T18N R92W S1
1/5/2005
8,858
SP [MV]
-250 20
GR [GAPI]
0 150
NPHI [DECP]
0.3 -0.1
DPHI [DECP]
0.3 -0.1
HMRS [OHMM]
0.2 2000
HDRS [OHMM]
0.2 2000
SW [%]
0 1
5400
5500
5600
5700
FOX_HILLS
GAS_CUM_SEPT_17__2008 [PAR] : 689,129


ANADARKO E & P CO LP
4-6
WAMSUTTER FEDERAL
490072231700
1328 FNL 1494 FWL
T17N R93W S6
3/13/2003
9,642
SP [MV]
-250
20
GR [GAPI]
0
150
NPHI [DECP]
0.3
-0.1
DPHI [DECP]
0.3
-0.1
HMRS [OHMM]
0.2
2000
HDRS [OHMM]
0.2
2000
SW [%]
0
1
6500
6600
6700
6800
FOX_HILLS
GAS_CUM_SEPT_17__2008 [PAR] : 990,847