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Geologic Controls on Oil and Gas Accumulation and Production from Missourian Stage Granite Wash Reservoirs in the Western Anadarko Basin, Wheeler County, Texas

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by

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ABSTRACT

Up-to-date regional and local Granite Wash data of any form is either too scarce to reference or highly privatized by exploration and production companies operating in the region. The objective of this research is to correlate horizontal production data with mapped depositional trends from Upper Pennsylvanian (Missourian Stage) Granite Wash reservoirs in the Western Anadarko Basin in northeastern Wheeler County, Texas. The correlation of raster logs to define various trap type and geometries in Missourian Granite Wash reservoirs of Wheeler County, Texas is used to understand the geologic controls on oil and gas accumulation and production. The analysis includes detailed stratigraphic mapping of individual Wash reservoir units and the linking of these maps to oil and gas production data. The majority of the Hogshooter Wash produces from intervals of relatively clean sandstones defined by the gamma ray signatures and porosity values. Isolith mapping of the Lower Hogshooter Wash interval strongly suggest that the production comes from the central area of Wheeler County adjacent to the faulted zone. Production from the upper interval appears to be located in the northwestern and southeastern areas of the Lower Cottage Grove Wash isopach displays a thinning of the interval from south to north. Production from the Lower Cottage Grove Wash appears to come from an area that trends south-north from the southern margin of the study area. Production from the Upper Cottage Grove Wash appears to come from areas trending along the down-thrown block of the fault zone and perpendicular to the fault to the northeast. Faulting that trends parallel to the mountain front controls well placement for both the Hogshooter and Cottage Grove intervals. Academic research would be a valuable asset to industry professionals who must sacrifice attention to detail in order to minimize the financial costs of a prolonged geological analyses.

ACKNOWLEDGEMENTS

I would like to thank my thesis advisor, Dr. Zachry, for simultaneously guiding me as a student and researcher and fulfilling other his many other obligations. I would like to thank the members of my thesis committee, Dr. Liner and Dr. Guccione. Their questions, ideas, and edits were invaluable and thought provoking resources during the development of my thesis. I would also like to thank JoAnn, Lisa, and Teresa for keeping a seat saved for me in the main office when I needed to take a break.

I would especially like to thank John Mitchell. I approached John as a first year grad student not knowing exactly what I wanted to research. All that I knew is that I was interested in any topic that involved oil and gas. Soon after my initial inquisition for thesis data, John emailed a PowerPoint presentation with four thesis topics to choose from. After taking some time to review my options, I chose the Granite Wash. After my selection, it was off to the races. John provided me with his own personal data and served as a tutor for the Petrel software program, in which the analyses of all the data was completed. In addition to all of this, John committed to driving three hours from Tulsa, Oklahoma to Fayetteville, Arkansas numerous times to personally sit down and assist me when I needed help. I would also like to thank John's wife for her support and understanding when John was away from her in order to support me.

I would also like to thank Dr. Kar, whose mentorship has undoubtedly led me to everything that I have accomplished since I began my collegiate career seven years ago.

Last but not least, I would like to thank my family. My mother, grandmother, and father offered unwavering encouragement and support. Striving to ensure that their encouragement and support were not given in vain was the ultimate fuel that drove me to accomplish all of the tasks required to graduate from the University of Arkansas.

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1. INTRODUCTION

1.1 Problem

Granite Wash is the formal name for the hydrocarbon rich play area located within the Anadarko Basin, Up-to-date regional and local Granite Wash data of any form is either too scarce to reference or highly privatized by exploration and production companies operating in the region. Industry professionals would benefit significantly from academic research conducted throughout the Granite Wash region if horizontal and vertical well data were more easily accessible for analysis and interpretation. The open provision of vertical and horizontal well data can increase the overall understanding of the geomorphic, depositional, tectonic, and hydrocarbon accumulation history of the Granite Wash.

1.2 Objective

The objective of this research is to understand the geologic controls on oil and gas accumulation and production in alluvial fan and fan delta deposits. This is accomplished by correlating horizontal production data with mapped depositional trends from Upper Pennsylvanian (Missourian Stage) Granite Wash reservoirs in the Western Anadarko Basin in northeastern Wheeler County, Texas.

1.3 Background

The Anadarko Basin is a complex region of hydrocarbon-rich reservoirs that are compartmentalized, due to vertical restrictions, stratigraphic trapping or structural trapping, but are generally laterally continuous. The Amarillo-Wichita Mountain Front fault system bounds the basin to the southwest (Evans, 1979) and provided much of the source area of the sediment fill in the basin. The Anadarko Basin is bounded to the west by the Cimarron Arch and the Hugoton Embayment, to the north by the Kansas Shelf and to East by the Nemaha Uplift. The reservoirs of the Anadarko Basin are characterized by varying assemblages of boulder-bearing conglomerates, arkosic sandstones, and carbonates. By convention, and in this paper, the innumerable heterogeneities of these reservoirs have been consolidated into the term "Granite Wash".

The first Granite Wash well in the western Anadarko Basin was drilled in 1920 and the first horizontal well was drilled in 2002. Producing intervals of the play range in age from Early Pennsylvanian to Early Permian. The Pennsylvanian age Granite Wash play extends over 125 miles from Roberts County, TX to Washita County, OK.

Prior to 2002 exploitation of the Granite Wash reservoirs in the western Anadarko Basin were with vertical wells. Approximately 5,340 vertical oil and gas wells have been drilled in the proposed study area since 1887. Since the advent of horizontal drilling technology in 2002, approximately 975 horizontal wells have been drilled in the Pennsylvanian Granite Wash reservoirs in Wheeler County since, with the majority of wells drilled since 2010. These wells were commonly marginally economic because of poor recovery due to the low reservoir permeability. The complex geometries and low permeability of the granite wash reservoirs are not suitable for efficient production from vertical wells.

The western Anadarko Basin horizontal Pennsylvanian Granite Wash play in Pennsylvanian age wash reservoirs has had approximately 2,100 horizontal wells drilled since 2002. The prolific areas of the horizontal play occur within the structurally deeper parts of the basin where the targeted reservoirs are usually more than 10,000 feet deep. The majority of oil and gas production to date has been from the Desmoinesian stage Marmaton Washes. The Desmoinesian Wash has produced 54 million barrels of oil (MMBO) and 1.4 trillion cubic feet of gas (TCFG) from 1,205 horizontal wells since 2002. Horizontal drilling technology, combined with multi-stage fracture stimulation, has caused a massive expansion of the resource potential with numerous attractive vertically stacked oil and gas development opportunities. The development of horizontal drilling and completion technology has greatly increased the oil, gas, and condensate production from the Granite Wash by allowing much more effective reservoir access and stimulation in the heterogeneous low permeability reservoirs.

Although these technologies have helped with petroleum production, the ultimate potential for petroleum recovery is still developing. With increasing well density in the play area, the need for accurate and detailed analyses of the producing formations is critical for successful exploration and production of the reservoirs. Detailed structural and stratigraphic analyses require the correlation of potential reservoir units using digital or raster logs, seismic surveys, geochemical and petrophysical data.

1.4 Study Area

The area of interest lies within Wheeler County, and covers an area of approximately 178 sq. mi. There are four stratigraphic play intervals from which formation tops are selected. These intervals consist of the Cottage Grove Wash, Hogshooter Wash, Checkerboard Wash, and Cleveland Wash. This research concentrates on the Hogshooter and Cottage Grove Wash intervals. In addition to interpretation of stratigraphic tops of the play intervals, horizons have also been interpreted for the corresponding flooding surfaces within each stratigraphic interval.

The two Wash intervals of interest to this study feature distinct log signatures, which mark the top of each interval and two prominent flooding surfaces that occur within each interval.

1.5 Approach

The approach used for this study involves the correlation of raster logs to define various trap type and geometries in Missourian Granite Wash reservoirs of Wheeler County, Texas. The analysis includes detailed stratigraphic mapping of individual Wash reservoir units and the linking of these maps to oil and gas production data. Using open-hole logs from several hundred vertical wells drilled in the play area allows for the reservoir delineation of the producing stratigraphic intervals. The resulting structural, isopach, net porosity, and other interpretive maps combined with available production data provided an exceptional basis to make interpretations of the controls on oil accumulation and production from the play.

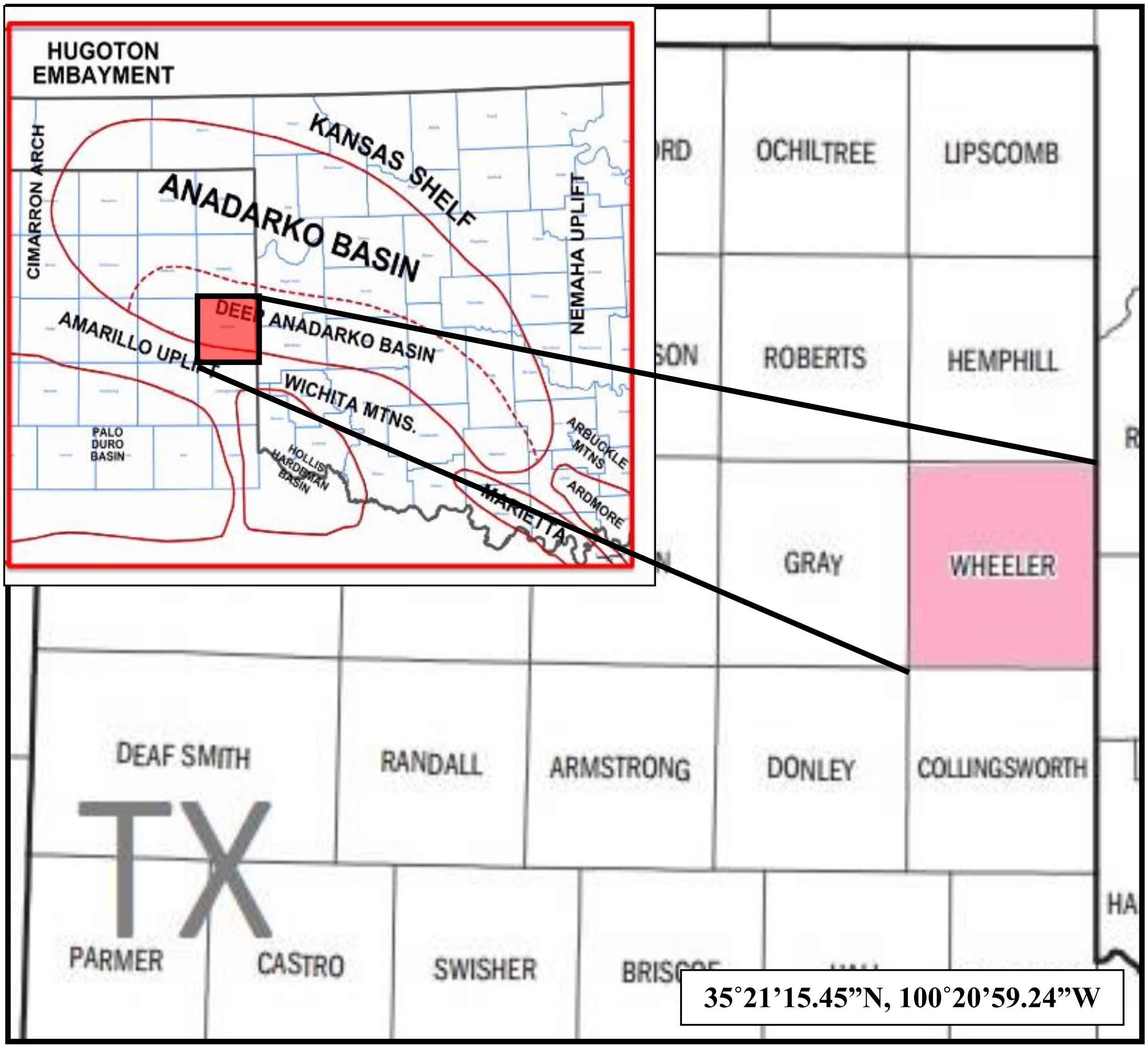

Figure 1: Texas County map highlighting Wheeler County study area with a regional Granite Wash map (LoCricchio, 2012) inset.

2. GEOLOGIC SETTING

2.1 Tectonic Development

Gallardo and Blackwell (1999), Nielsen and Stern (1985), and Perry (1988) have divided the structural history of the Anadarko Basin region into four stages with similarly cited references and subtle differences: (1) Lower to Middle Cambrian rifting, (2) Late Cambrian transgression and subsidence, (3) Mississippian orogenic events related to the Ouachita-Wichita uplift and, (4) the diminution of tectonic activity in the Permian.

2.1.1 Stage I

The first tectonic stage is a failed third arm of a triple junction (South Oklahoma Aulacogen). This arm extended from northwest Louisiana through southwest Oklahoma to northwest Texas (Perry, 1989). The rifting event is associated with the opening of the proto-Atlantic ocean, and the bimodal intrusion of gabbros and granites and extrusion of basalts and rhyolites (Perry 1989). The igneous extrusives include the Carlton Rhyolite Group/Timbered Hills Group.

2.1.2 Stage II

The second tectonic stage is the transgression of Late Cambrian seas (Gallardo and Blackwell, 1999) as widespread subsidence of the Aulacogen accrued from the elastic lithospheric flexure caused by cooling of the lithosphere (Nielsen and Stern, 1985). Increased subsidence rates in the area of the aulacogen (Gallardo and Blackwell, 1999) as differential subsidence along reactivated faults of the Southern Oklahoma Aulacogen (Nielsen and Stern

1985). As a result, the subsiding aulacogen received twice the sediment thickness compared to the surrounding craton (Gallardo and Blackwell, 1999). Nearly three kilometers of shallow-water carbonates, quartz arenties, and shales were deposited during this stage (Nielsen and Stern, 1985; Gallardo and Blackwell, 1999). Subsidence rates began to decline during the Silurian (Gallardo and Blackwell, 1999) but lasted until the Devonian epoch (Nielsen and Stern, 1985).

2.1.3 Stage III

The third stage of tectonism started during the Mississippian, further developing the asymmetric Anadarko Basin along the northern edge of the southern Oklahoma Aulacogen (Perry, 1989). The tectonic development in this stage is likely a result of the collision between North America and Gondwanaland, or an intermediary micro-plate (Perry, 1989). The collision correlates to the development of the Ancestral Rock Mountains (Perry, 1989) and to the Ouachita-Marathon orogeny. The southern region of the Anadarko Basin was characterized by the propagation of southward-dipping reverse faults with a total structural relief in excess of 10 kilometers (Nielsen and Stern, 1985). The main tectonic activity occurred during several intervals of the early to late Pennsylvanian period (Gallardo and Blackwell, 1999). The Amarillo-Wichita uplift began in the Morrowan (Early Pennsylvanian) and was accompanied by the deposition of carbonate and chert fan-deltas derived from the previously deposited Paleozoic rocks of the uplift, blanketed by the fan-delta deposits known as the “Granite Wash” because the granitic Cambrian crystalline rocks were the source of the fan deltas (Gallardo and Blackwell, 1999).

2.1.4 Stage IV

The fourth tectonic stage began during the Permian, marked by a decreased subsidence rates (Gallardo and Blackwell, 1999) and post-orogenic sediment deposition (Nielsen and Stern, 1985). Permian sediments include red beds, evaporates (Gallardo and Blackwell, 1999), shale and minor conglomerates (Nielsen and Stern, 1985).

2.2 Paleogeography of the Late Pennsylvanian

Paleogeographic reconstruction of the Late Pennsylvanian depicts the mid-continent of North America covered by a shallow seas during the Amarillo-Wichita uplift. The basin extends across parts of what are now western Oklahoma, southwestern Kansas and the Texas Panhandle. The development of the Anadarko Basin is concomitant with the development of the Amarillo-Wichita uplift, which began during the Early Pennsylvanian and continued throughout the Lower Permian. Subsidence during the Pennsylvanian (Missourian) allowed approximately 40,000 feet of sedimentary rocks, accumulating primarily in marine environments. The basin fill is characterized by frequent to infrequent flooding and intermittent emergence. The uplift will be referred to as the “Mountain Front”.

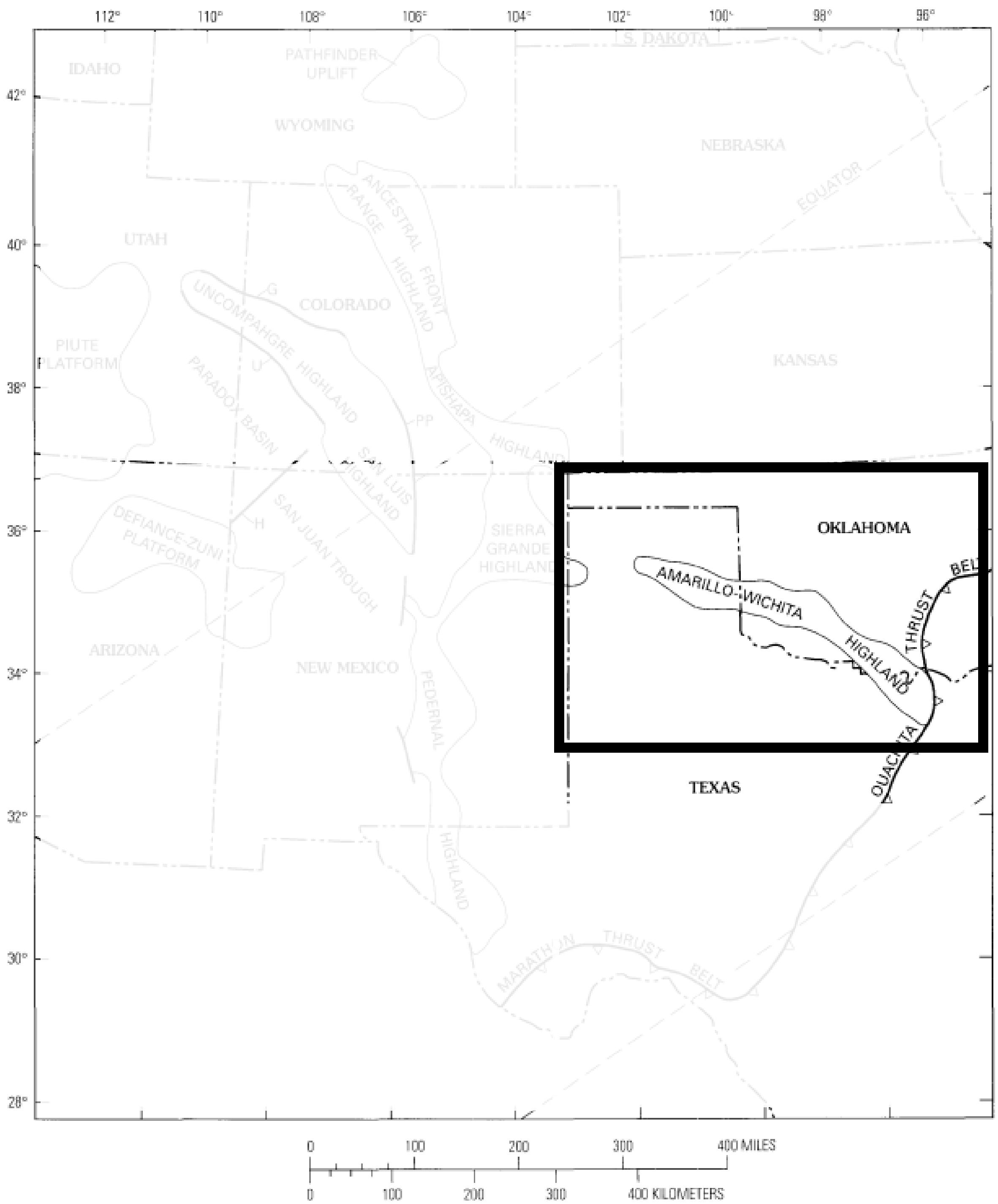

Figure 2: Paleogeography of Ancestral Rocky Region. Outlined section shows the geographic extent of the Amarillo-Wichita Uplift (modified from U.S. Geological Survey Bulletin 1808-O, 1993)

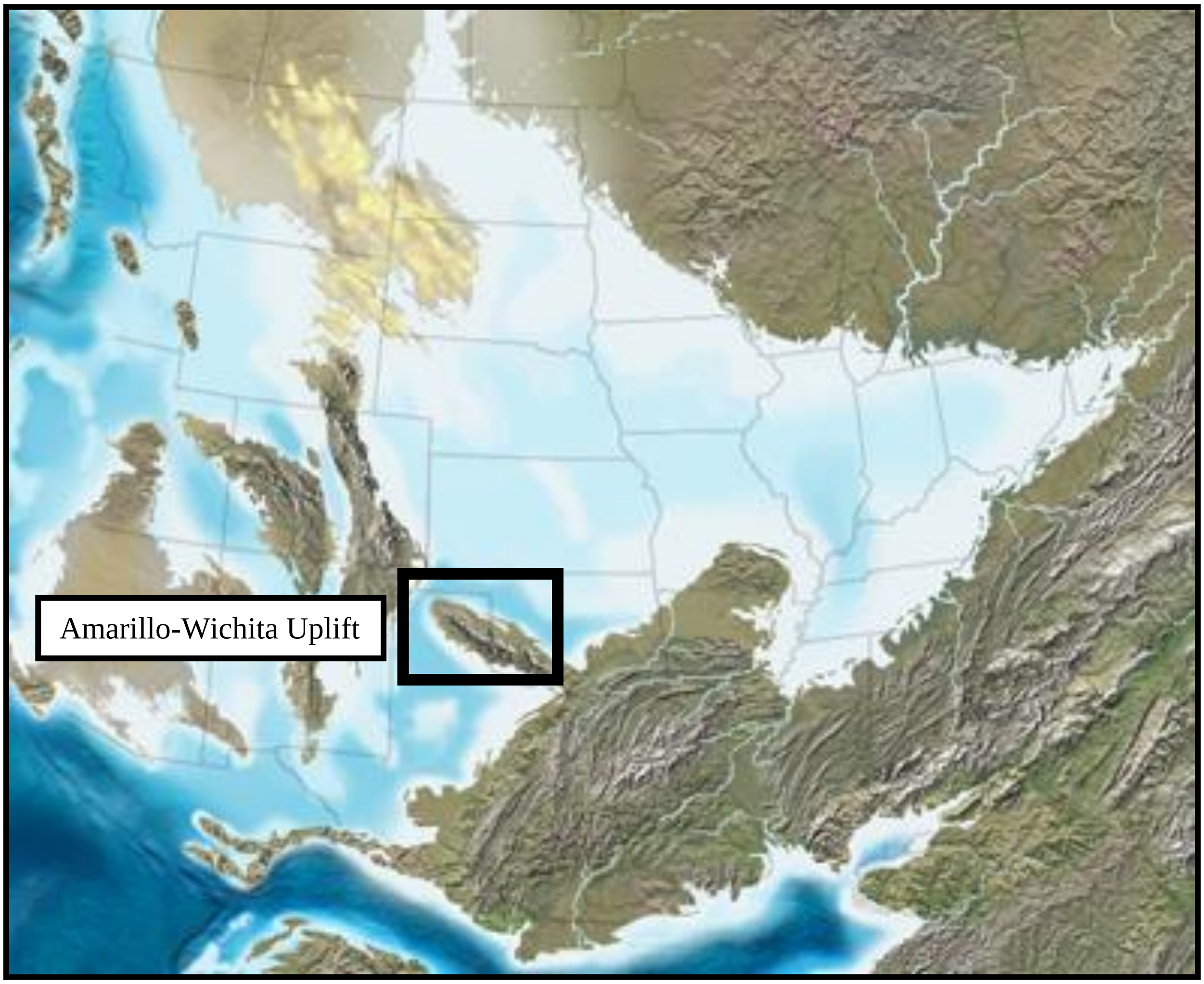

Figure 3: Late Pennsylvanian paleogeographic reconstruction shows the Amarillo-Wichita Uplift covering the most northeastern region of Texas (Blakey, 1980)

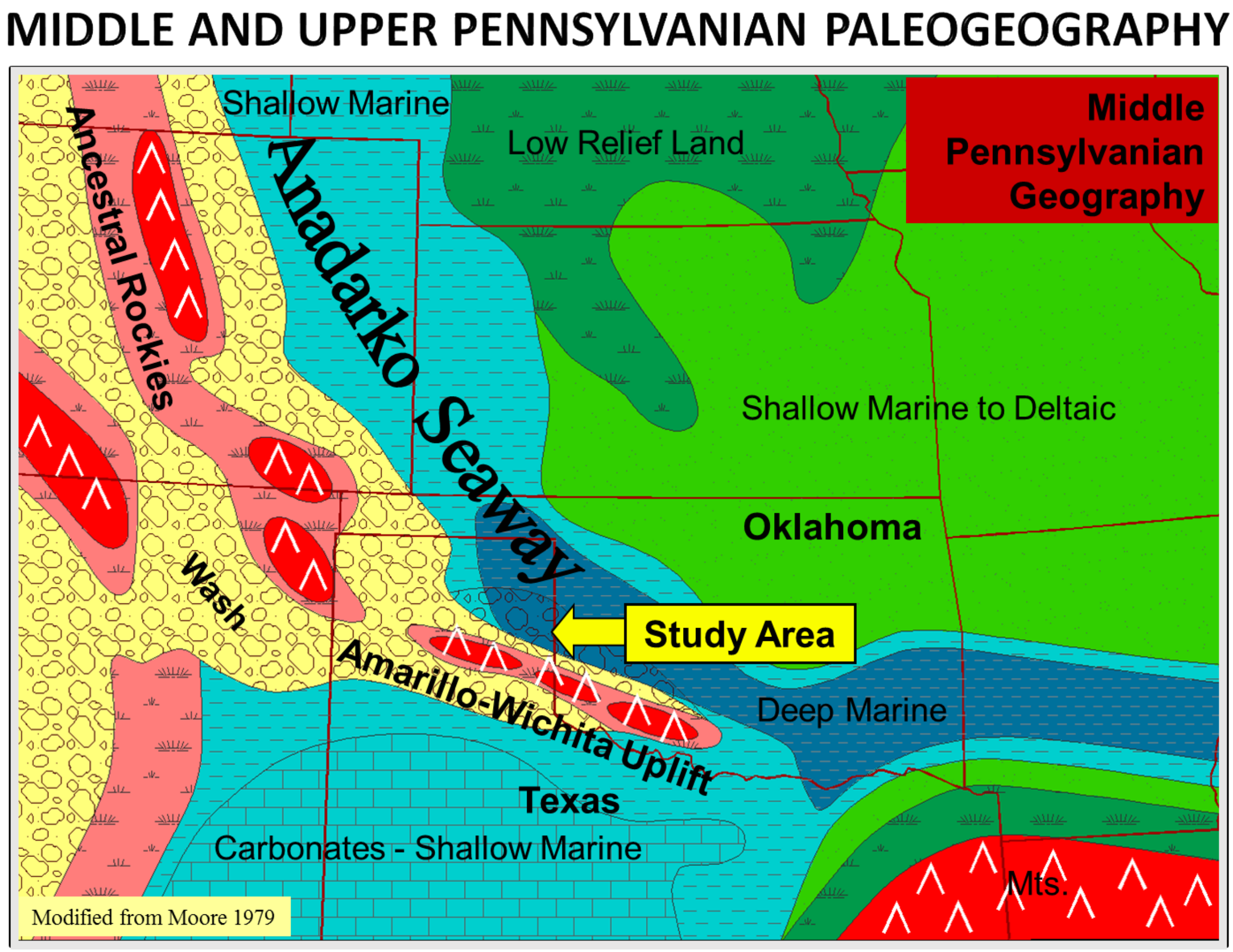

Figure 4: Middle Pennsylvanian Paleogeography (modified from Mitchell, 2014)

2.3 Basin Structure and Composition

The Anadarko Basin deepens structurally to the south-southeast of the study area, which correspond to the hydrocarbon rich areas of the basin. The Missourian Granite Wash intervals examined in this study, in ascending order, include the Cleveland Wash, Checkerboard Wash, Hogshooter Wash and Cottage Grove Wash. The named intervals fall within a larger marine shale interval and are characterized by regionally radioactive black-shale beds as well as less radioactive grey and black shales. The Missourian Series intervals are focus of this study discussed in greater detail in subsequent sections of this paper. Reservoir rocks are almost exclusively sandstone, reaching thickness of approximately 3,000 feet in the southeastern part of the basin. In the northwestern part of the play, where alternating limestone and shale units comprise a large part of the strata, hydrocarbon production is historically poor. The source of Granite Wash sediment originates from the Amarillo-Wichita Uplift, which bounds the southern margins of the play. Sediment variety includes a series of heterogeneous arkosic sandstones and conglomeratic sediments with detritus originating from the granite, rhyolite, gabbro, and sandstone. These sediments were deposited as stacked channel deposits that formed alluvial fans, fan deltas, proximal deltas, debris flows, distal fans, and deep-water submarine fans. The depositional trend of the Granite Wash primarily extends from southwest to northeast beginning at the “Mountain Front” or the northeastern margin of the Amarillo-Wichita uplift.

2.4 Granite Wash Lithology

The Anadarko basin is an asymmetric foreland basin of the deepest hydrocarbon-bearing basins within the North American craton. Granite Wash reservoirs have developed from varying depositional environments ranging from course grained sand rich alluvial fan deltas to deep water turbidite and debris flows (Mitchell, 2014). Reservoir sequences range in thicknesses from 50 to 400 feet, which are disconnected by radioactive shale marine flooding surfaces. Reservoir sequences are further divided by massive correlative highstand shales which range in thickness from 30 to 600 feet thick. These shales were deposited during sea level highstands and can be correlated across the study area.

2.4.2 Submarine Fan Development

The prominent conceptualization of the depositional environment of Granite Wash reservoirs within the Anadarko Basin is that the deposits accumulated during the progradation and deposition of fan delta sediments. The varying depositional character of each individual fan delta is influenced by a broad spectrum factors which influence the deposition and transport of sediments, which often requires generalized representations and analyses of turbidite complexes (Bouma, 2000). Although many classes of classifications exist, the two end members referenced by Bouma are sufficient to characterize Granite Wash sediments. The end members are fine-grained mud-rich and coarse-grained sand-rich grain size systems (Bouma, 2000). Given the overall mineralogical composition of sampled Granite Wash core data, a course-grained sand-rich model should be expected. Coarse-grained sand-rich systems exhibit high net to gross ratios. Due to a lack of very fine grained sediment the sediment transport distances are limited, causing a progradational depositional profile (Bouma, 2000).

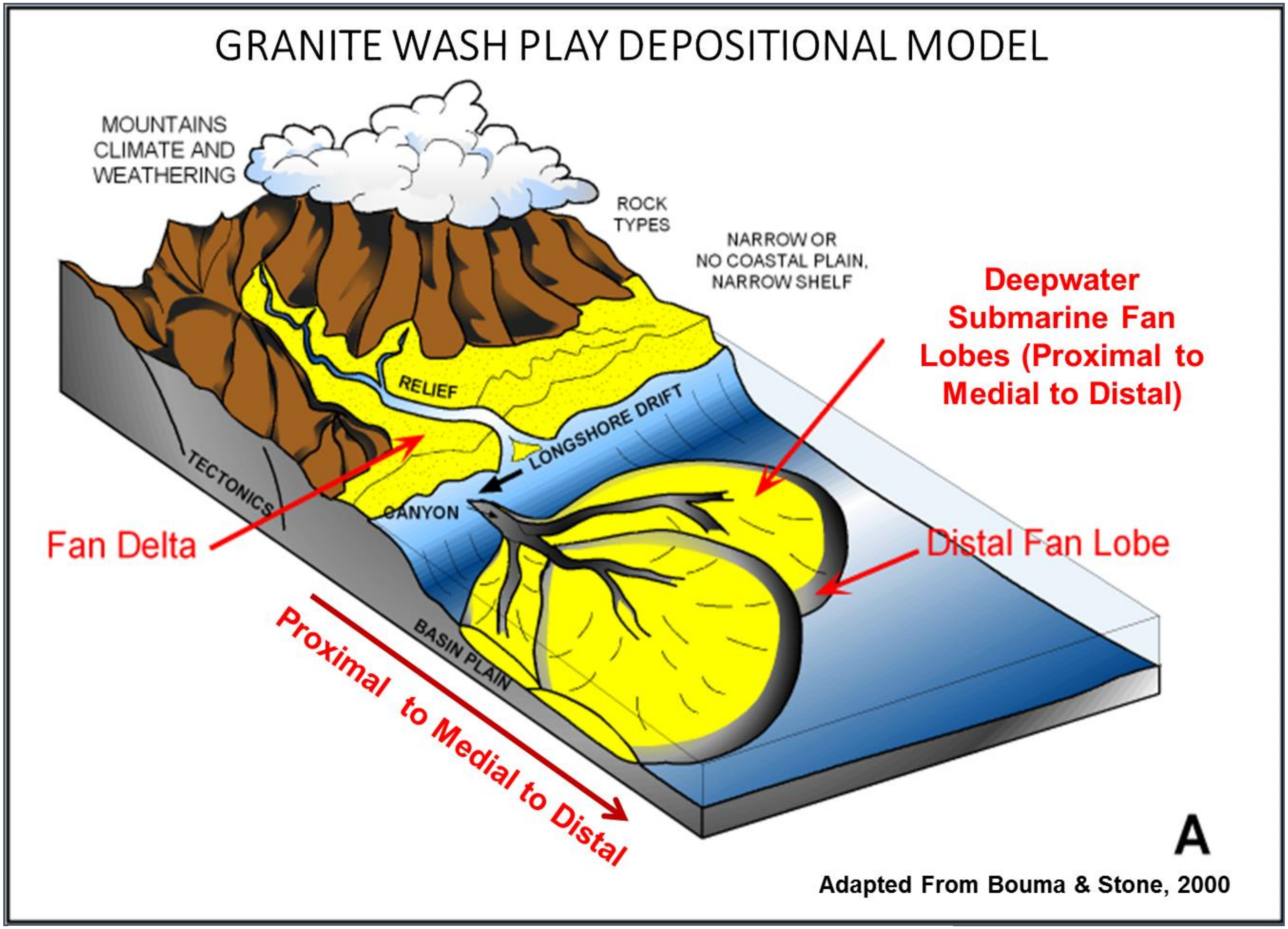

Figure 5: Granite Wash depositional model (Mitchell, 2014)

2.4.3 Parasequences

Reservoir intervals within the Granite Wash are parasequences separated by intervening massive shale intervals. The sequence boundary bounds the beginning of the sequence which represents the relative fall in sea level, and the parasequence boundary bounds the top of the sequence representing the relative rise in sea level (Mulholland, 1998). The parasequence boundary is more commonly referred to as a marine flooding surface.

2.4.4 Oragnic-rich Shale

The organic-matter-rich “hot shale” intervals contain from 2 to more than 15 weight percent total organic carbon (TOC) and are easily identified from their high gamma-ray values on logs. For this reason these stratigraphic intervals are commonly called “Hot Shales” (Gautier, 2005).

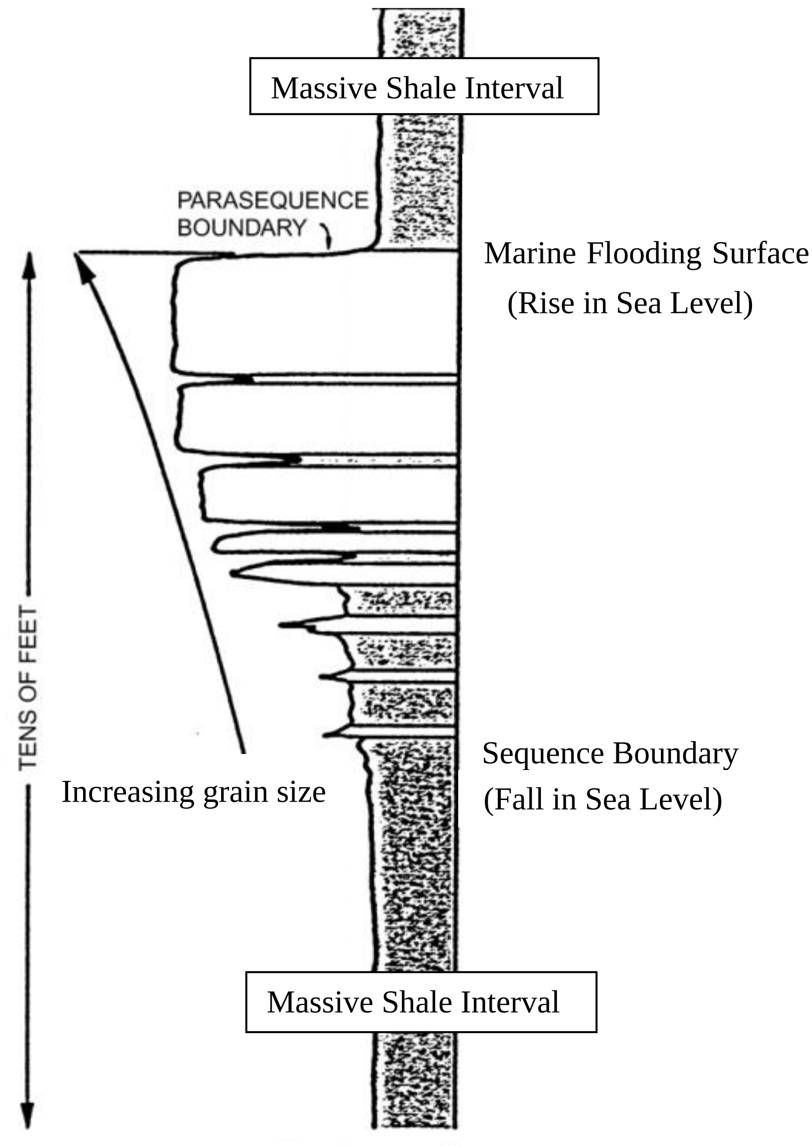

Figure 6: Parasequence interval bounded by the sequence boundary and marine flooding surface (Modified from Mulholland, 1998).

3. METHODOLOGY

3.1 Data Collection

Analyses and interpretation of Granite Wash subsurface stratigraphy was conducted using the IHS© geologic interpretation software, Petra. A geo-database was created by John Mitchell for the Pennsylvanian-Missourian Granite Wash play area of Oklahoma-Texas Panhandle. The database includes vertical well data files for portions of Roberts, Hemphill, Wheeler, Roger Mills, and Beckham counties. The well data below varied for each well:

- Well headers (General well information)
- Well locations
- Cumulative oil, gas, and water records
- Completion, spud, and permit dates
- Raster log images
- IP Tests

3.2 Study Area

The study area is limited to the northeastern region of Wheeler County, Texas. The study was restricted to this area because it contains the Mills Ranch field, a major producer of hydrocarbons from the Granite Wash from the deep Granite Wash play.

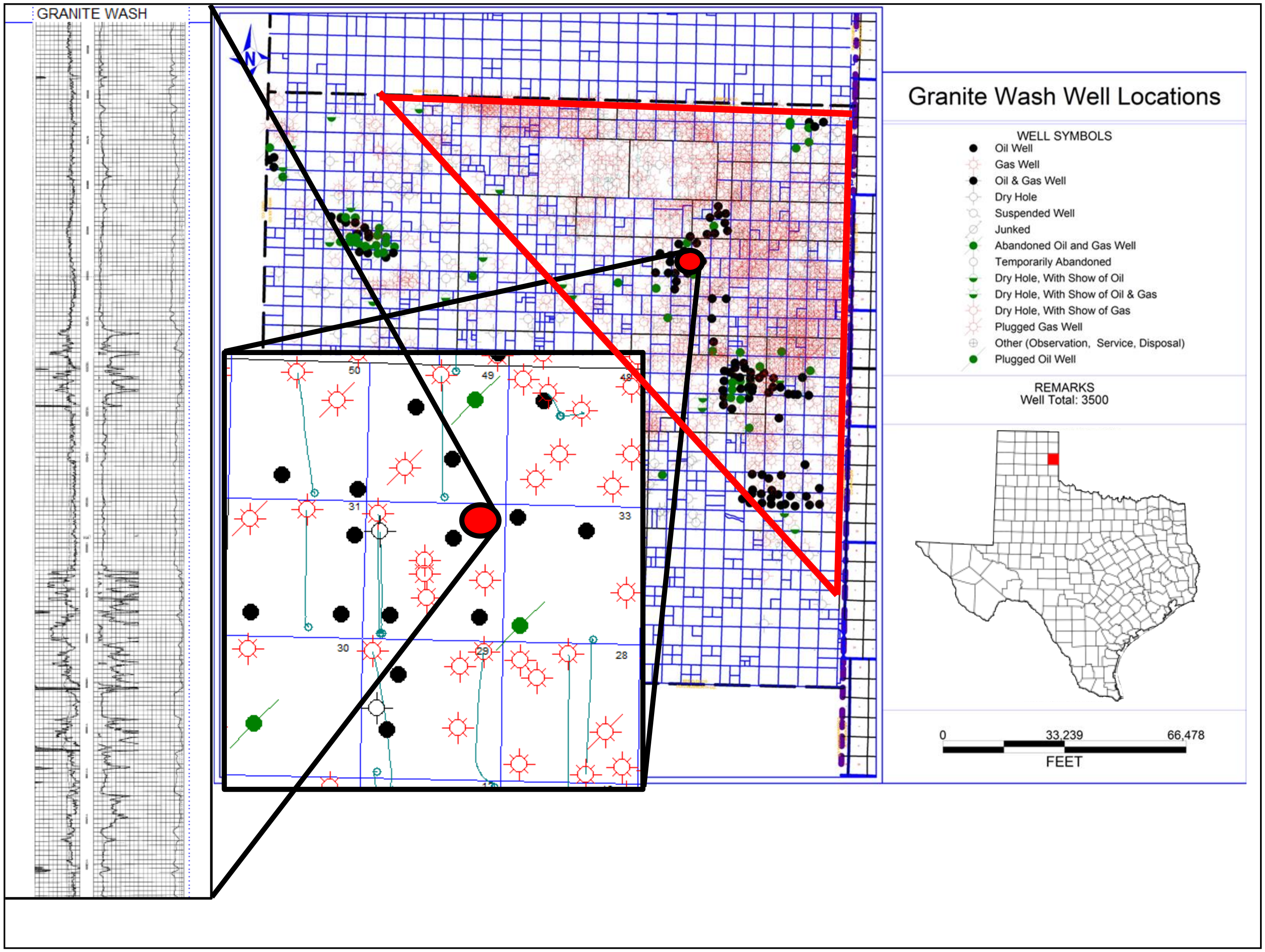

Figure 7: The north-eastern Wheeler County study area is outlined in red. Available vertical raster logs were used for the identification of stratigraphic markers and intervals.

3.3 Stratigraphy

Unfortunately the Granite Wash play area has inconsistent informal nomenclature across the study area because of multiple vendors, energy companies, and researchers. In this paper, the nomenclature, approximate locations of interval tops and intervening markers, are adopted from one of the leading experts of the field, John Mitchell. Formation tops for this study will be based upon the research conducted by John Mitchell in order to provide a uniform database. The foreseeable vastness of the analyses and interpretation of each of these intervals exceeded time constraints of the project. This study will focus only on the Cottage Grove and Hogshooter intervals of the Granite Wash play.

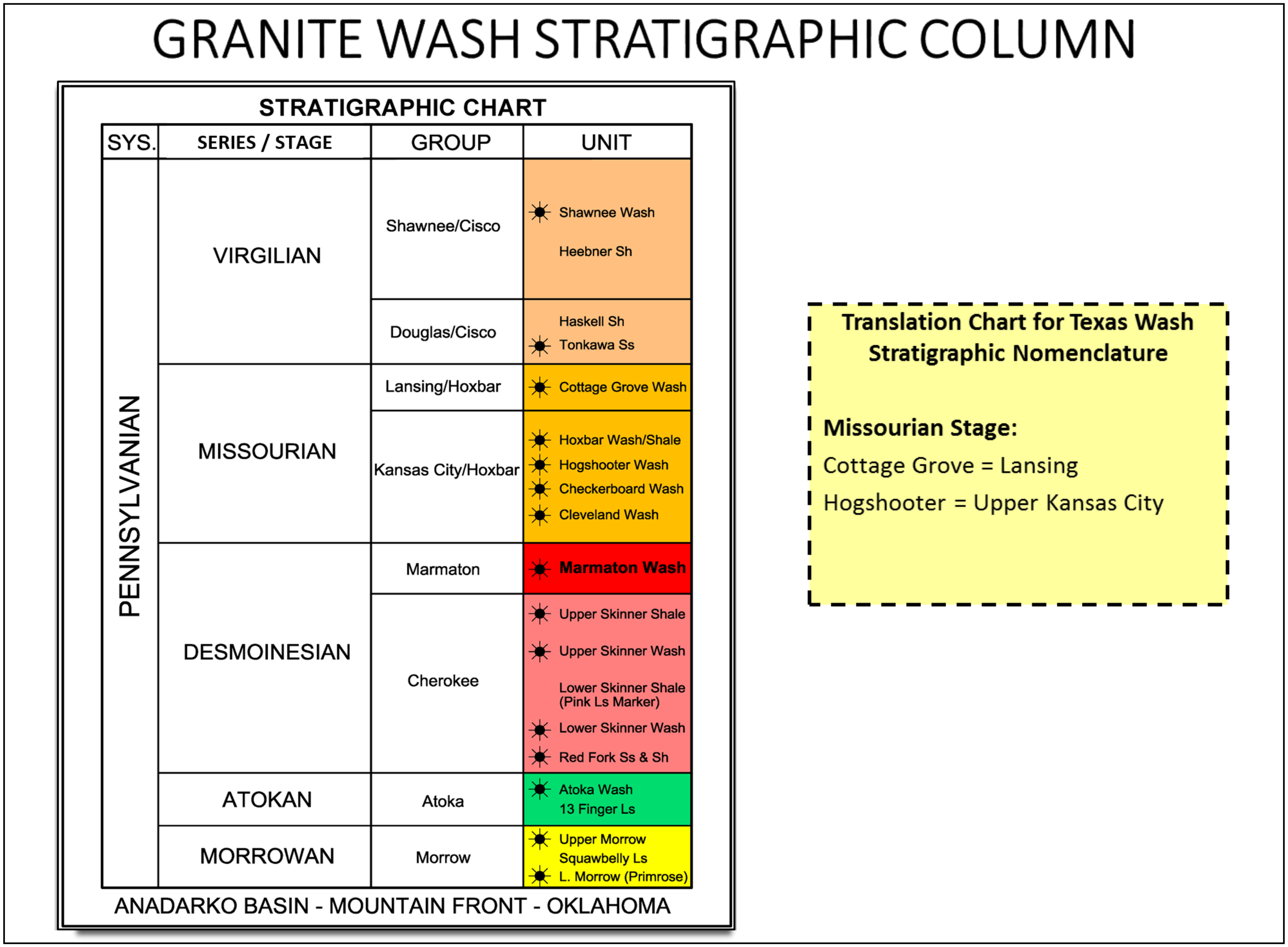

Figure 8: Granite Wash stratigraphic column. Analogous names for the Cottage Grove and Hogshooter Wash intervals used in this study are outlined (Mitchell, 2014).

3.4 Log Character

3.4.1 Tonkawa Flooding Surface [TNKFS]

The TNKFS, because it is an easily identifiable, was used as a marker to locate the top of the Cottage Grove Wash. The TNKWFS is not associated with the development of the Granite Wash and thus serves as a consistent marker to aid in the identification of the Cottage Grove top, in cases where the log character may be unintelligible.

3.4.2 Cottage Grove Wash [CGVW]

The Cottage Grove Wash is characterized by a slight down-hole sloping increase on the gamma log commonly below an expansive shale interval beneath the TNKFS. The CGVW is also characterized by the occurrence of two radioactive black shale intervals. The upper radioactive shale occurs approximately midway within the CCGVW, and the lower radioactive flooding surface occurs at the base of the CGVW. A regional massive shale interval continues below the CGVW to the top of the Hogshooter Wash.

3.4.3 Hogshooter Wash [HGSRW]

The Hogshooter Wash is identified using similar characteristics as that of the CGVW. The top of the HGSRW is characterized by an increase in the gamma curve at the end of a moderate shale interval. Two radioactive shale flooding surfaces occur near the top and mark the base of the HGSRW. A lesser shale interval is below the base of the HGSRW.

3.4.4 Checkerboard Wash [CCKBW]

The Checkerboard Wash is best identified by a progressive increase in resistivity 10-30 feet below the base of the Hogshooter Wash. The peak of the resistive signature is followed by a spike in the gamma log reading, which denotes an organic-rich shale interval.

3.5 Type Log Limits

To constrain the scope of the project analysis, data limits for selecting pay intervals were defined. Gamma and neutron-density (porosity) readings from raster log images were interpreted using defined limits. The cutoff for gamma logs was defined to include all readings less than 75 API units. This cutoff was chosen as an approximate value for potential clean and porous sands. The cutoffs for porosity values for this study were selected to be four percent and eight percent.

3.6 Interval Maps

Twenty-four interval isopach maps were computed using Petra. Isopach, gamma ray, four percent porosity, and eight percent porosity interval maps were generated for the Lower, Upper, and combined Hogshooter and Cottage Grove Wash intervals.

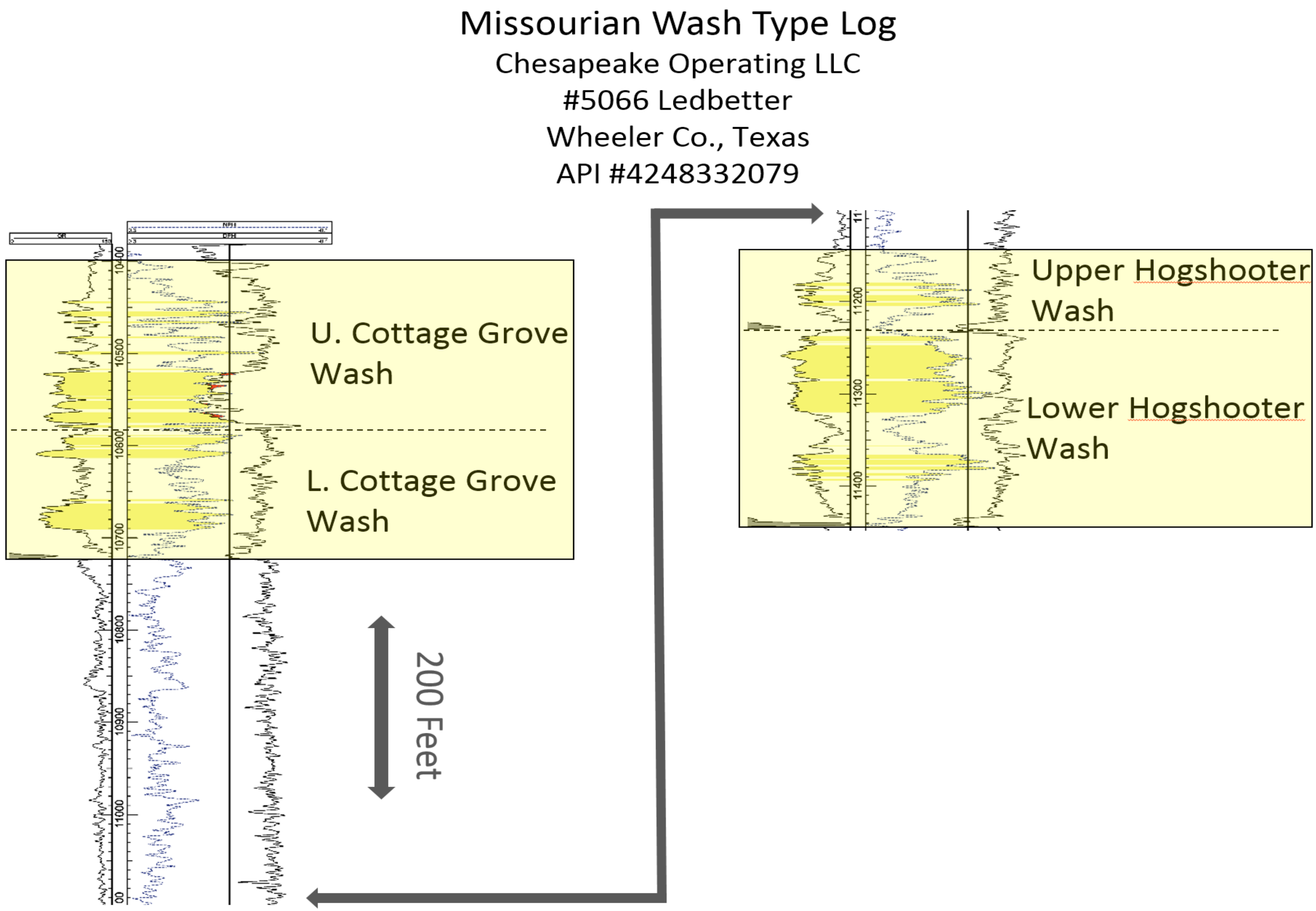

Figure 9: Neutron-Density Gamma Log showing typical signature responses from the Cottage Grove, Hogshooter, and Checkerboard Washes

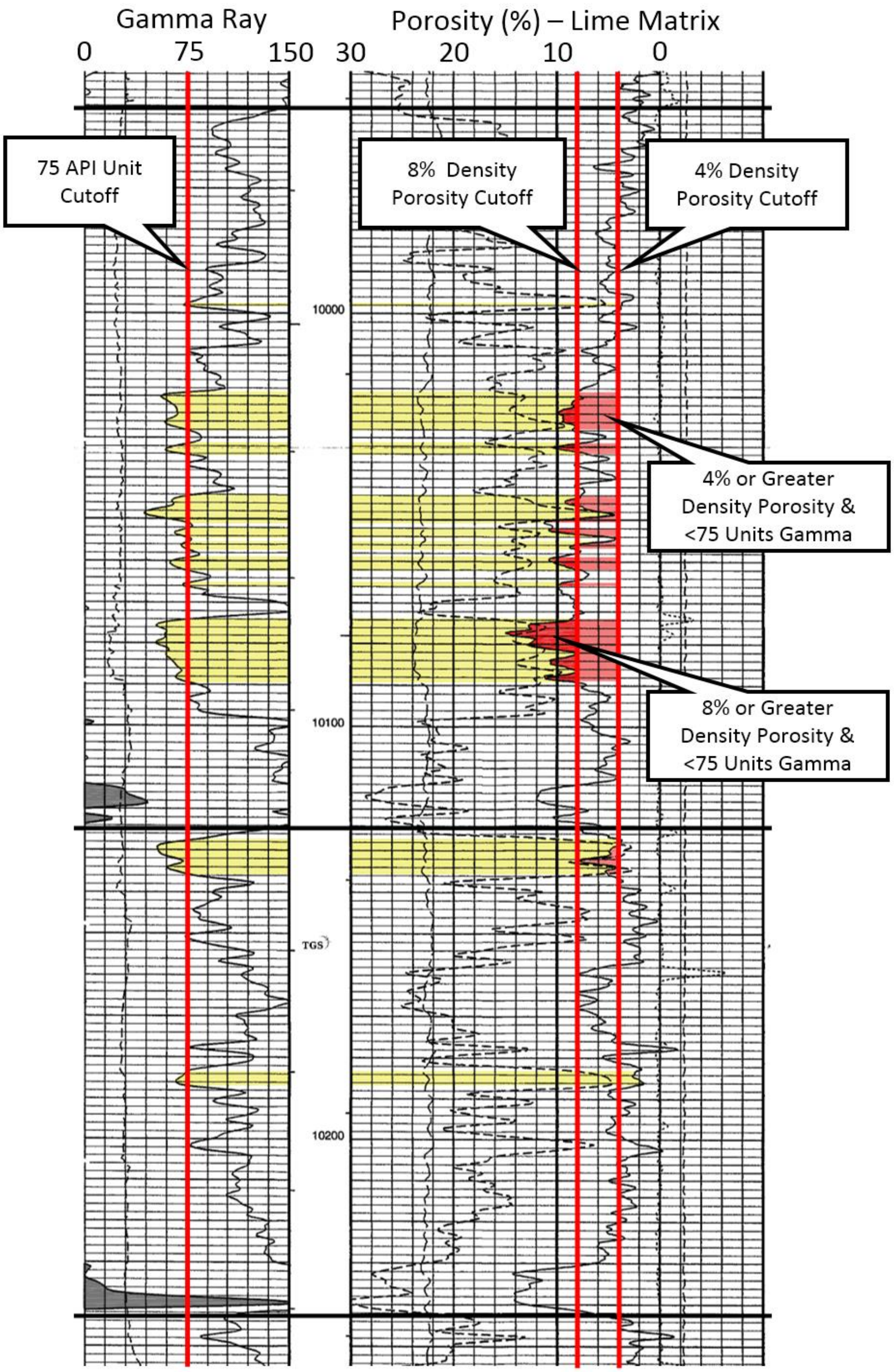

Figure 10: Type log showing gamma ray, >4% porosity, and >8% porosity cut off markers.

3.7 Well Control

The northeastern Wheeler County study area includes approximately 3,400 combined vertical and horizontal wells. For this study, stratigraphic horizons were picked from vertical raster log images. Log images available consisted primarily of, but were not limited to dual induction, compensated neutron density, bulk density, and resistivity logs. The following table presents the established well control for formation top, gamma, and porosity picks from raster images. For example: there are 835 wells with the top of the Cottage Grove Wash (CGVW) picked on the corresponding raster image. Similarly: there are 470 wells that have the Cottage Grove upper (the interval between the top of the Cottage Grove and the first flooding surface) picked with gamma reading less than 75 API units.

	Formation Tops	Gamma < 75API	Porosity > 4%	Porosity > 8%
CGVW	**835**	N/A	N/A	N/A
CGVW FS1	**843**	N/A	N/A	N/A
CGVW FS2	**848**	N/A	N/A	N/A
CGVW Upper Boundary	N/A	**470**	**405**	**419**
CGVW Lower Boundary	N/A	**470**	**405**	**419**
HGSRW	**850**	N/A	N/A	N/A
HGSRW FS1	**851**	N/A	N/A	N/A
HGSRW FS2	**850**	N/A	N/A	N/A
HGSRW Upper Boundary	N/A	**469**	**402**	**415**
HGSRW Lower Boundary	N/A	**470**	**403**	**416**

Table 1: Established well control for study area. Bullets represent non-applicable.

3.8 Cross Sections

To best illustrate the changes in the Cottage Grove and Hogshooter intervals four cross sections were generated. These cross sections are hung on the Tonkawa flooding surface, which proves to be a consistent marker throughout the study area. One cross section was generated to illustrate the northwest-southeast strike and three southwest-northeast cross sections were generated to illustrate the dip of the Hogshooter and Cottage Grove Wash intervals.

4. SUMMARY OF METHODS

The purpose of this study was to describe the stratigraphic and structural controls on oil and gas production from Missourian stage Granite Wash reservoirs in the western Anadarko Basin. To accomplish this a dense vertical well control network was built within the study area for the determination of formation tops, interval thicknesses, sandstone thickness, and porosity values for the Missourian stage intervals. The initial data set consisted of approximately 25,000 wells that spanned across a five county are. As work progressed, Wheeler County was chosen as the focus area for this thesis. This choice was due to the prolific Missourian age Granite Wash producing area in Mills Ranch field in the northern portion of the county.

This study gives insight to the variation in the origin, distribution, and character of the Hogshooter and Cottage Grove Wash intervals. The initial results of this study correlated horizontal and vertical well locations and production performances to the characteristics determined from the analysis of the Granite Wash intervals. The scope of this study was not structured to include an in depth analysis of the depositional history of the area. This was due in part to a lack of geological data such as well cores and borehole image logs that could better define stratigraphic sequences and rock types. Gamma ray values of less than 75 API units were chosen as the cutoff for clean sandstone. Density porosity values of 4% and 8% on a limestone matrix were used for porosity cutoffs. In many horizontal wells, the specific producing intervals (i.e. lower or upper intervals) were not readily determined from directional surveys.

5. RESULTS

5.1 Hogshooter and Cottage Grove Wash Interval Maps

Well tops, gamma ray signatures, and porosity values were selected on approximately 850 combined raster log images. From the well tops, isopach maps for the lower, upper, and total Hogshooter and Cottage Grove intervals generated. Interval maps were created to visualize the distribution of clean sand within the study area. The porosity limits of values greater than four percent and greater than eight percent were used to create interval maps to display distribution trends in porous sands. Each interval map was plotted with two attributes: (1) wells used for visualization and (2) recent areas of horizontal hydrocarbon production from either the Hogshooter or Cottage Grove wash intervals.

5.1.1 Lower Hogshooter Wash Isopach Map

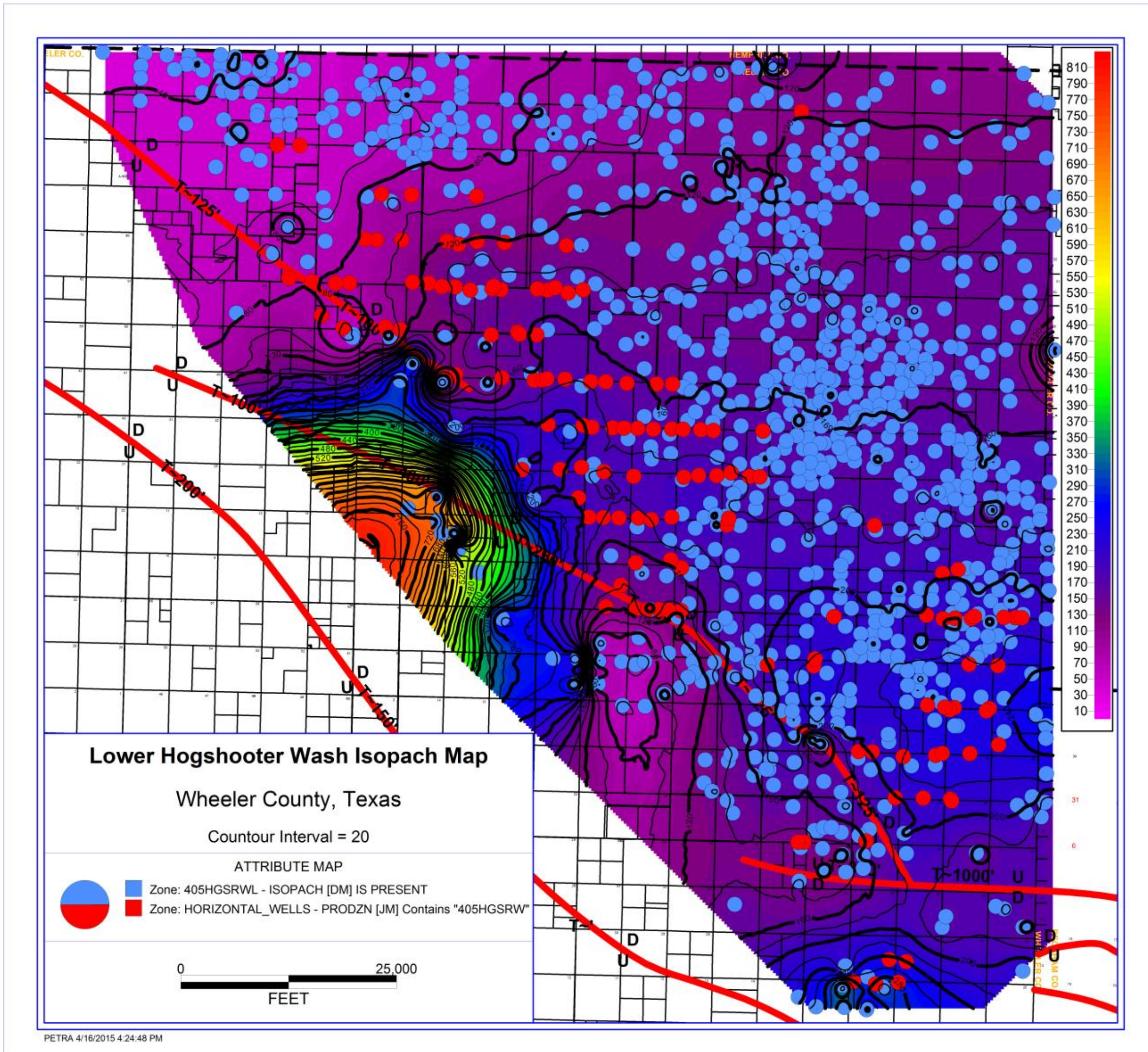

Figure 9: Lower Hogshooter Wash isopach map. Blue dots represent the well control used for map generation. Red dots represent recent horizontal production from the Hogshooter Wash.

5.1.2 Upper Hogshooter Wash Isopach

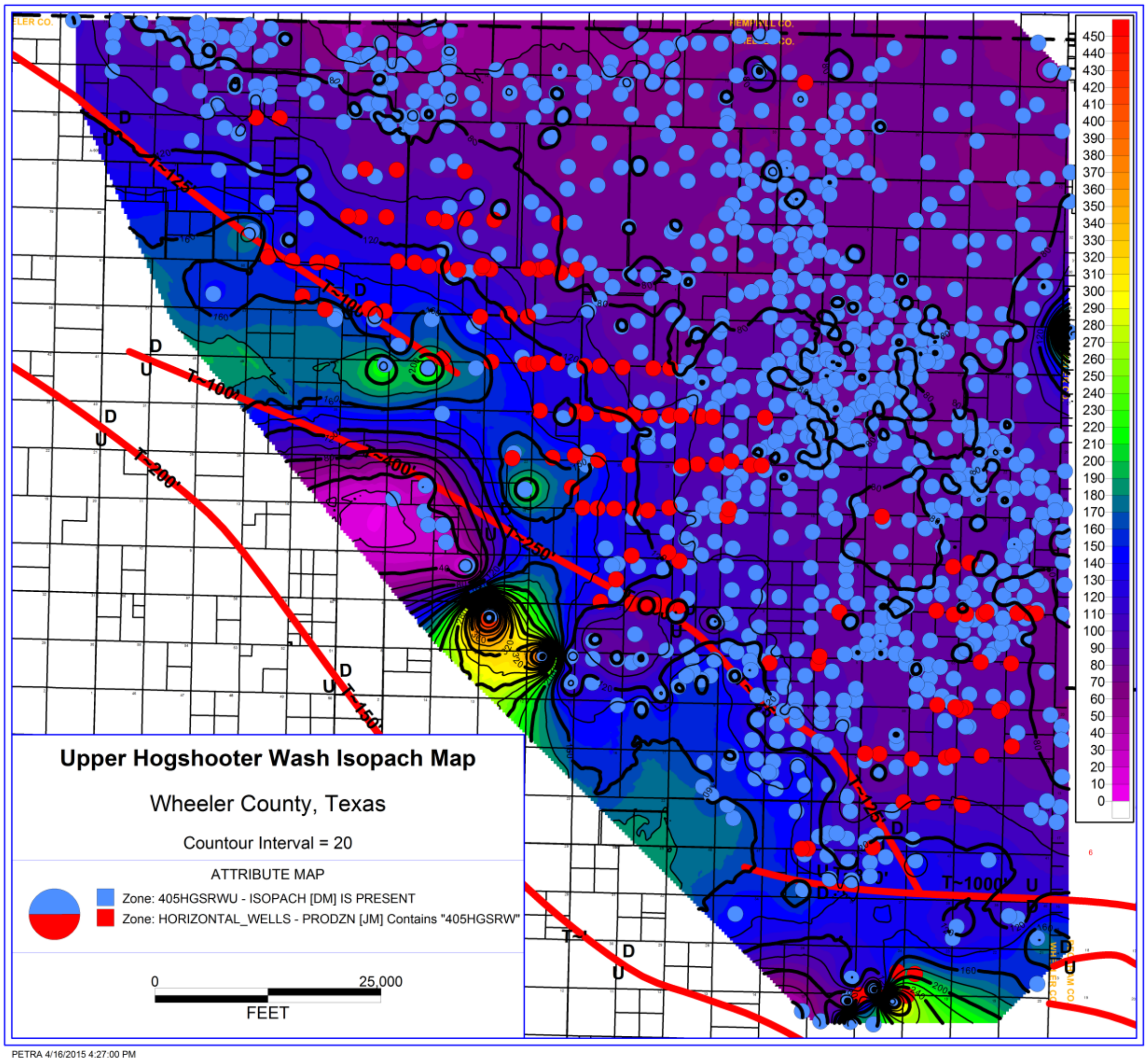

Figure 10: Upper Hogshooter Wash isopach map. Blue dots represent the well control used for map generation. Red dots represent recent horizontal production from the Hogshooter Wash.

5.1.3 Total Hogshooter Wash Isopach

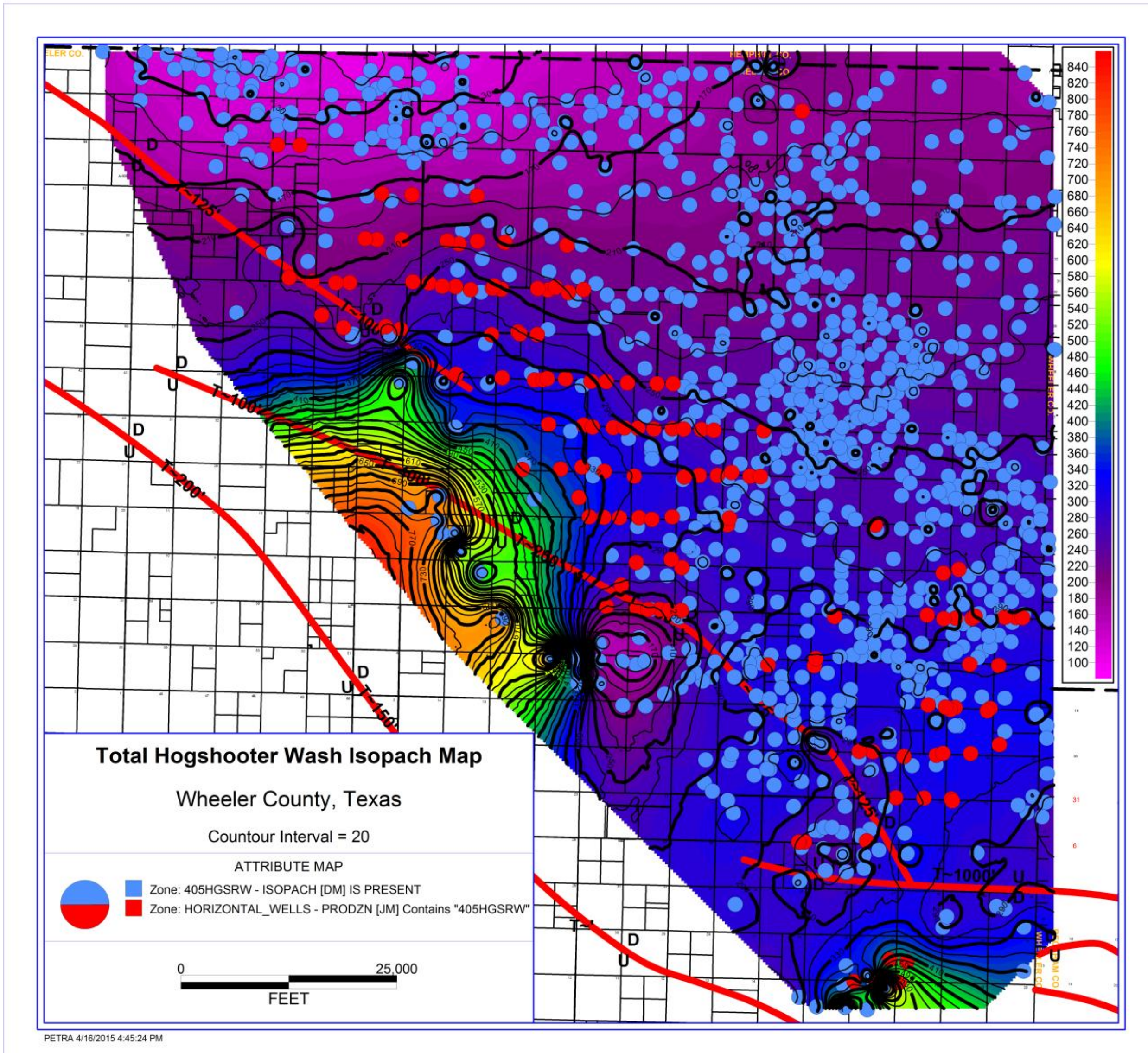

Figure 11: Total Hogshooter Wash isopach map. Blue dots represent the well control used for map generation. Red dots represent recent horizontal production from the Hogshooter Wash.

5.1.4 Lower Hogshooter Wash Gamma Ray > 75API Map

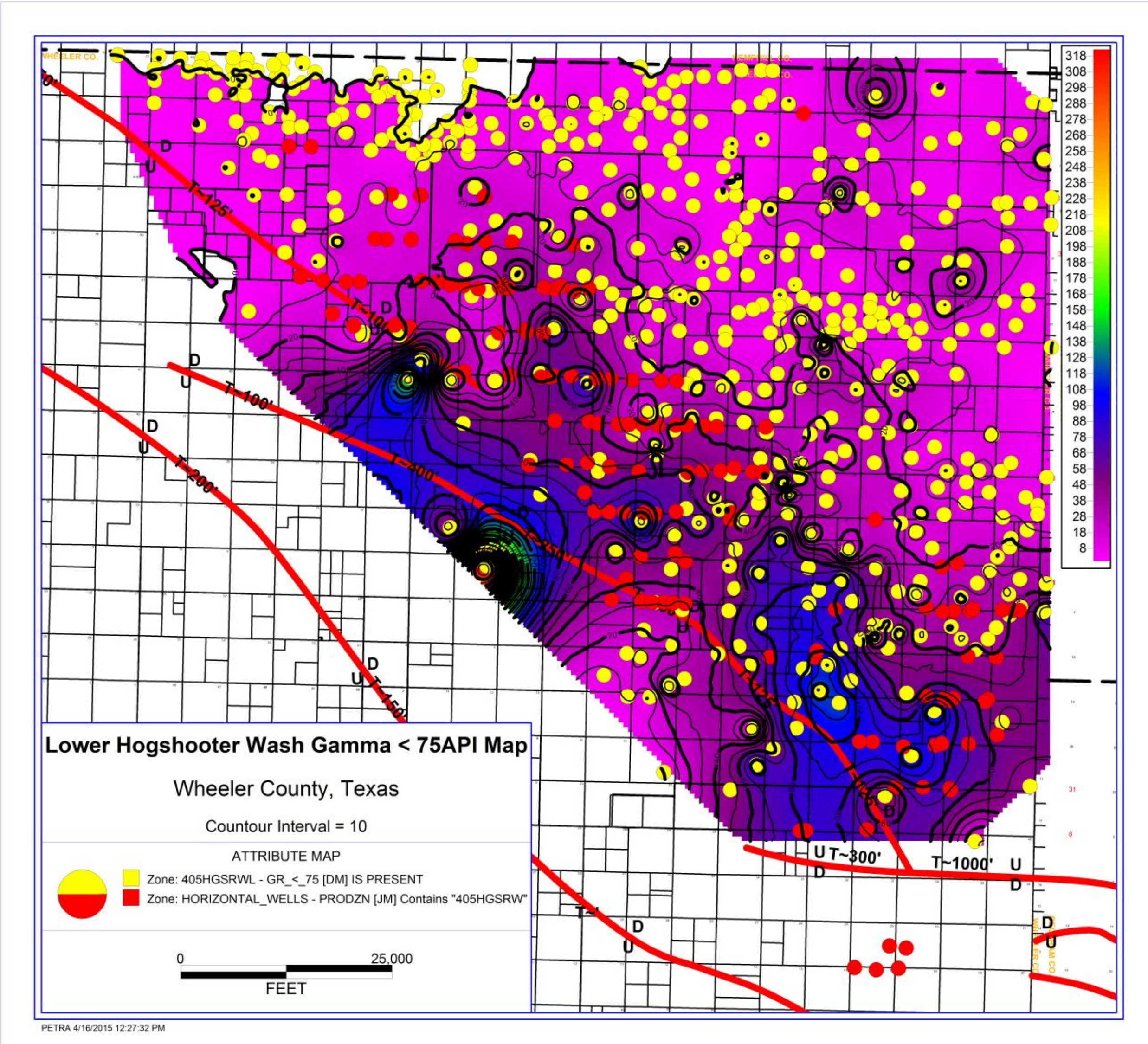

Figure 12: Lower Hogshooter Wash map displaying areas that are characterized by having a gamma ray signature less than 75API units. Yellow dots represent well control used for map generation. Red dots represent recent horizontal production from the Hogshooter Wash.

5.1.5 Upper Hogshooter Wash Gamma Ray > 75API Map

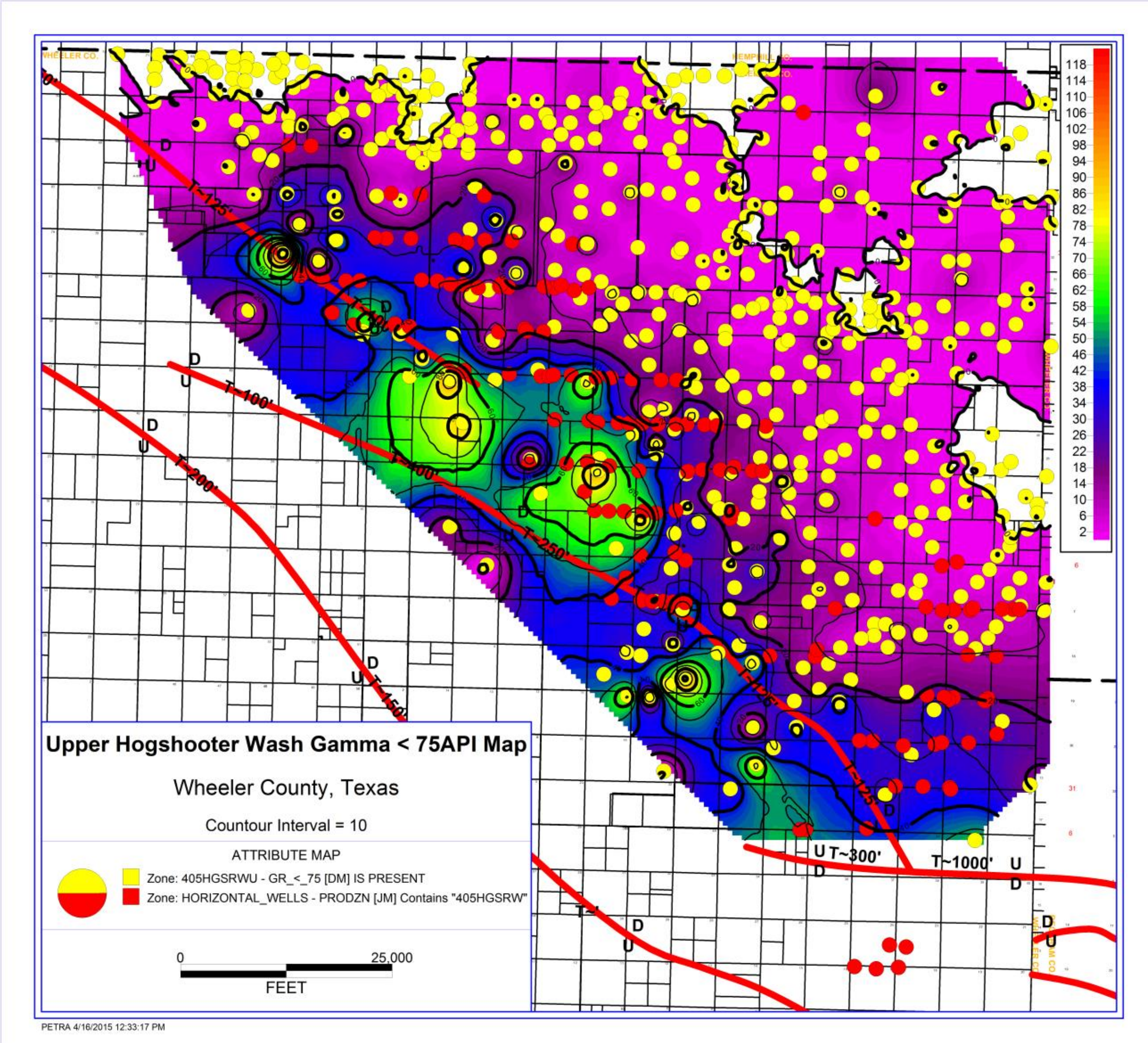

Figure 13: Upper Hogshooter Wash map displaying areas that are characterized by having a gamma ray signature less than 75API units. Yellow dots represent well control used for map generation. Red dots represent recent horizontal production from the Hogshooter Wash.

5.1.6 Total Hogshooter Wash Gamma Ray > 75API Map

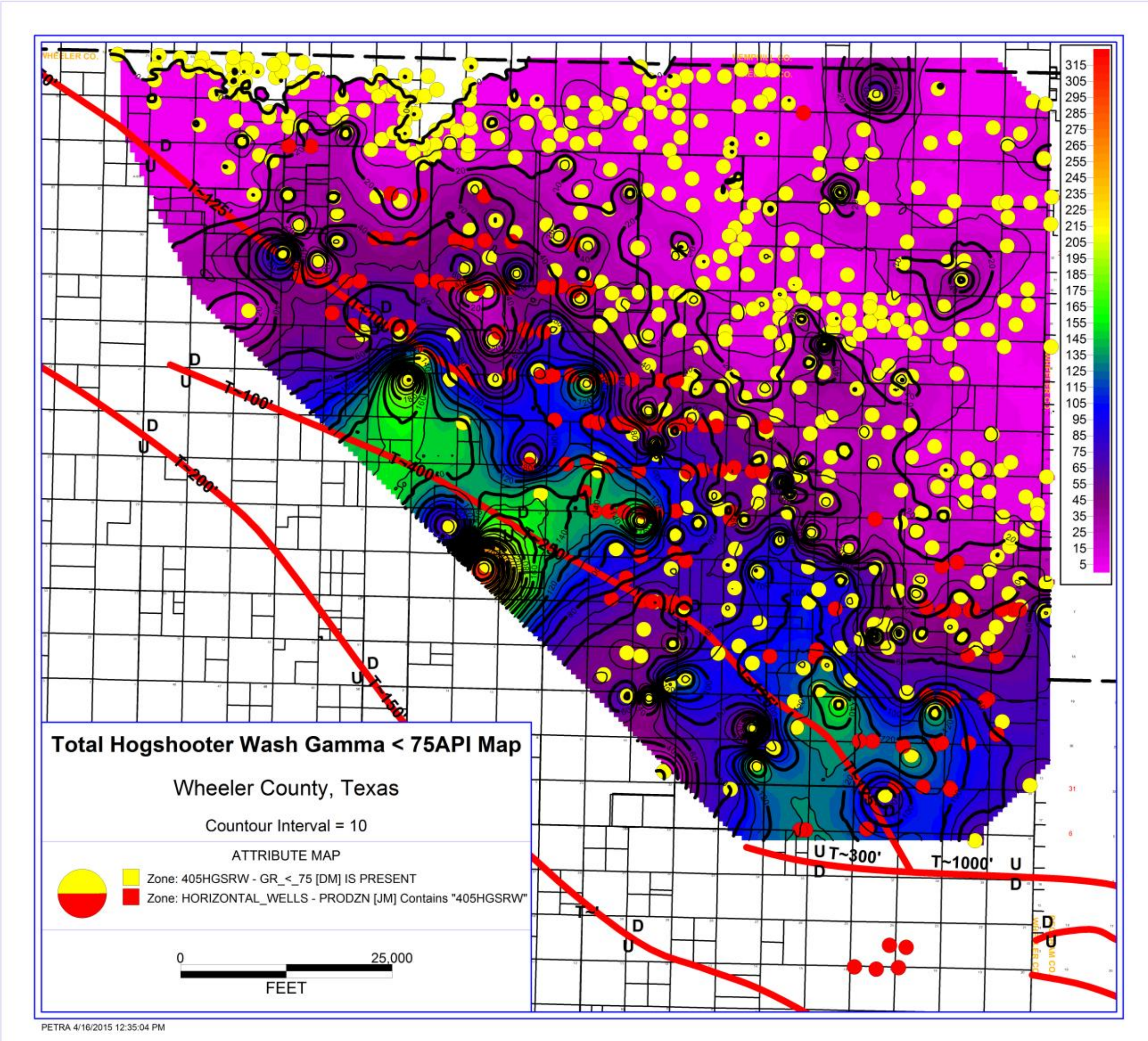

Figure 14: Total Hogshooter Wash map displaying areas that are characterized by having a gamma ray signature less than 75API units. Yellow dots represent well control used for map generation. Red dots represent recent horizontal production from the Hogshooter Wash.

5.1.7 Lower Hogshooter Wash Porosity > 4% Map

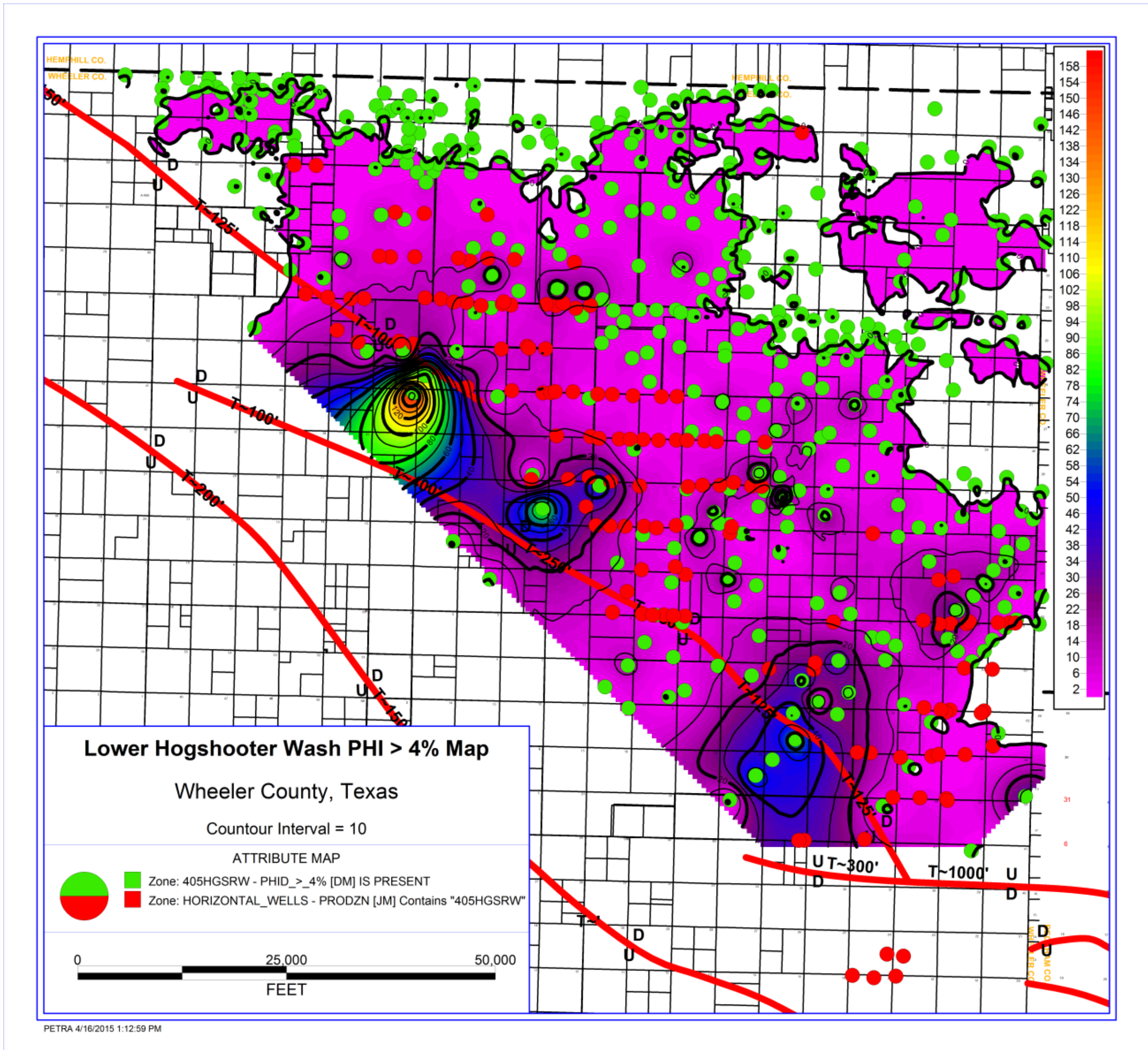

Figure 15: Lower Hogshooter Wash map displaying areas that are characterized by having porosity values greater than four percent. Green dots represent well control used for map generation. Red dots represent recent horizontal production from the Hogshooter Wash.

5.1.8 Upper Hogshooter Wash Porosity > 4% Map

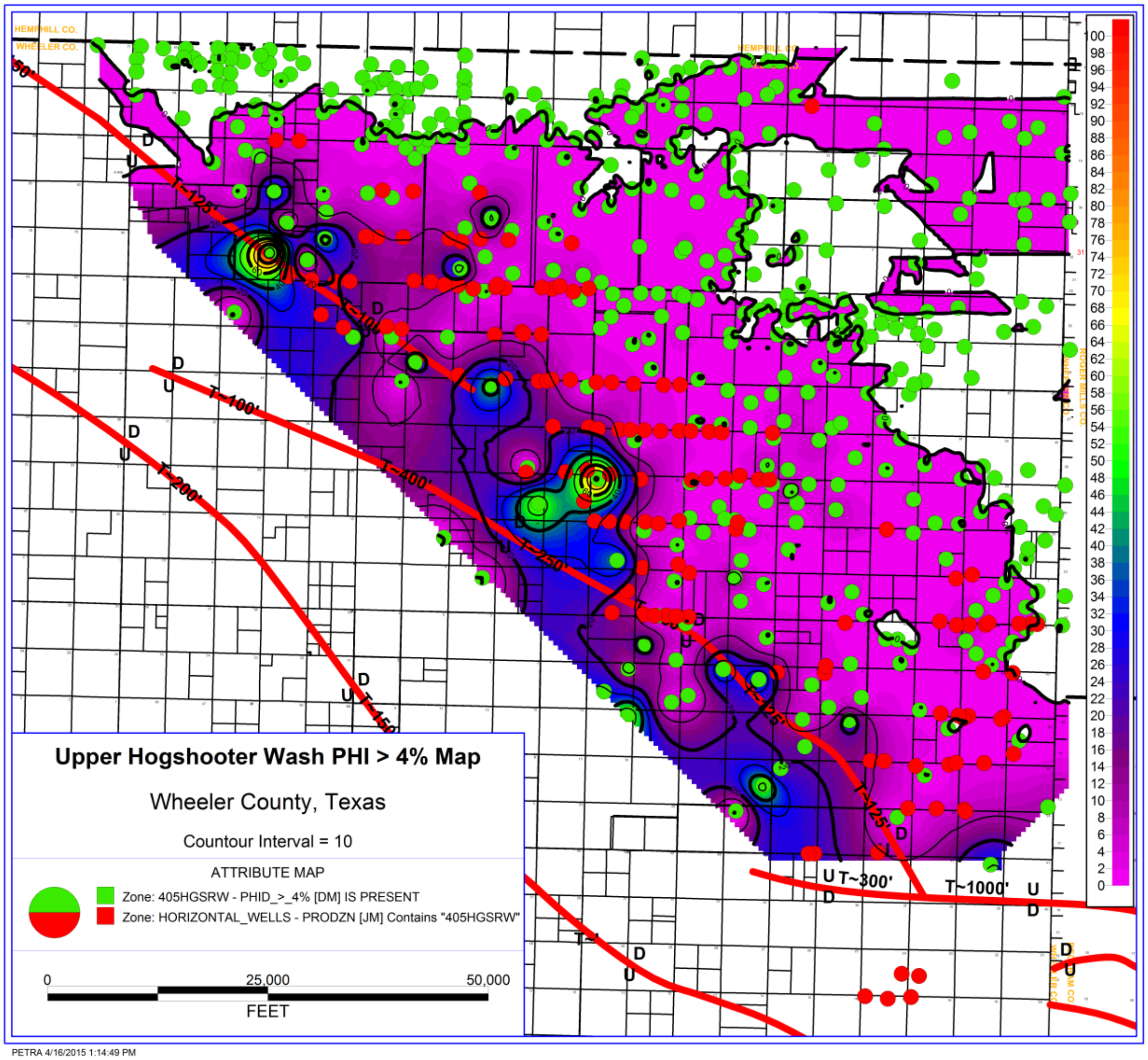

Figure 16: Upper Hogshooter Wash map displaying areas that are characterized by having porosity values greater than four percent. Green dots represent well control used for map generation. Red dots represent recent horizontal production from the Hogshooter Wash.

5.1.9 Total Hogshooter Wash Porosity > 4% Map

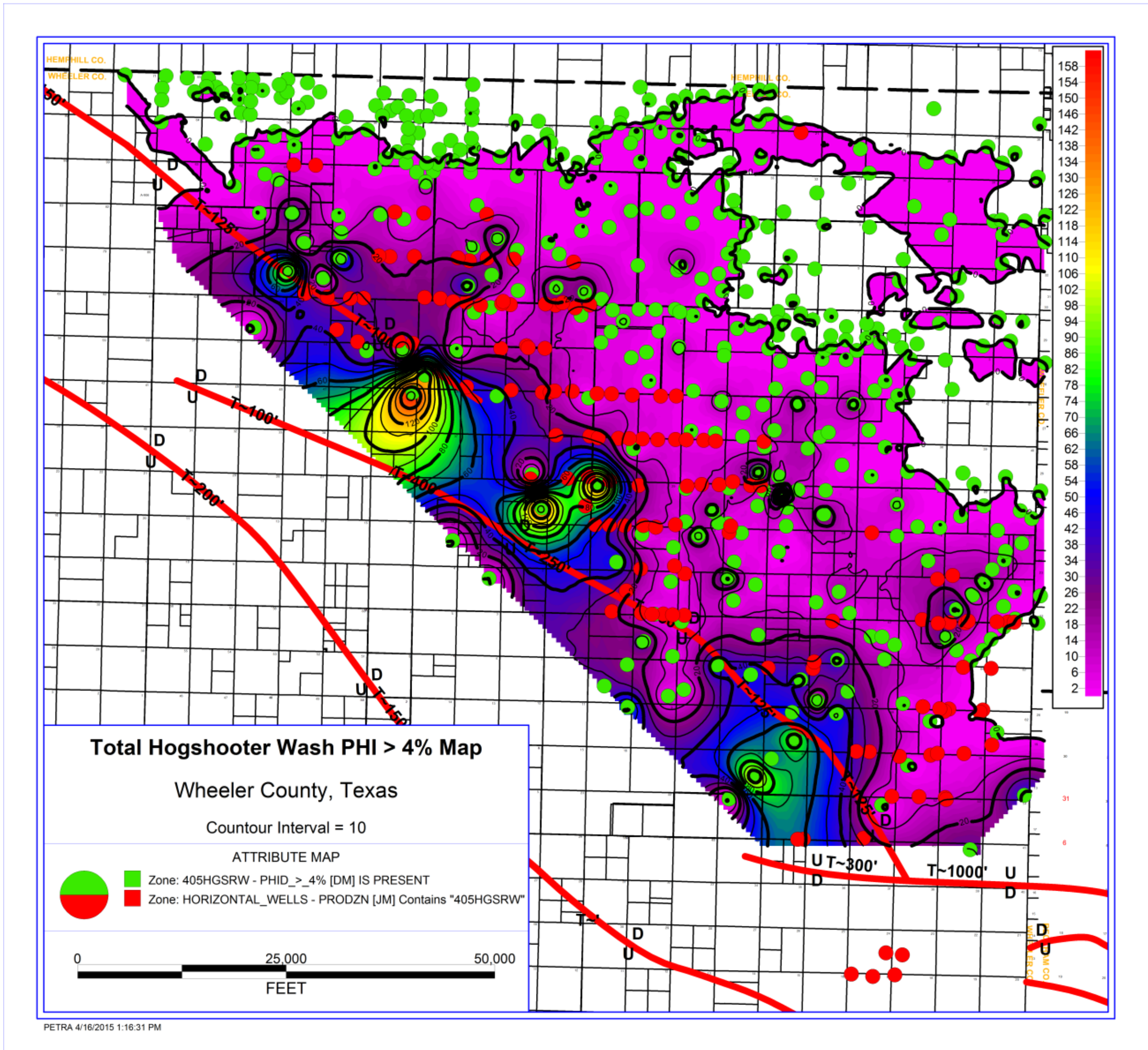

Figure 17: Total Hogshooter Wash map displaying areas that are characterized by having porosity values greater than four percent. Green dots represent well control used for map generation. Red dots represent recent horizontal production from the Hogshooter Wash.

5.1.10 Lower Hogshooter Wash Porosity > 8% Map

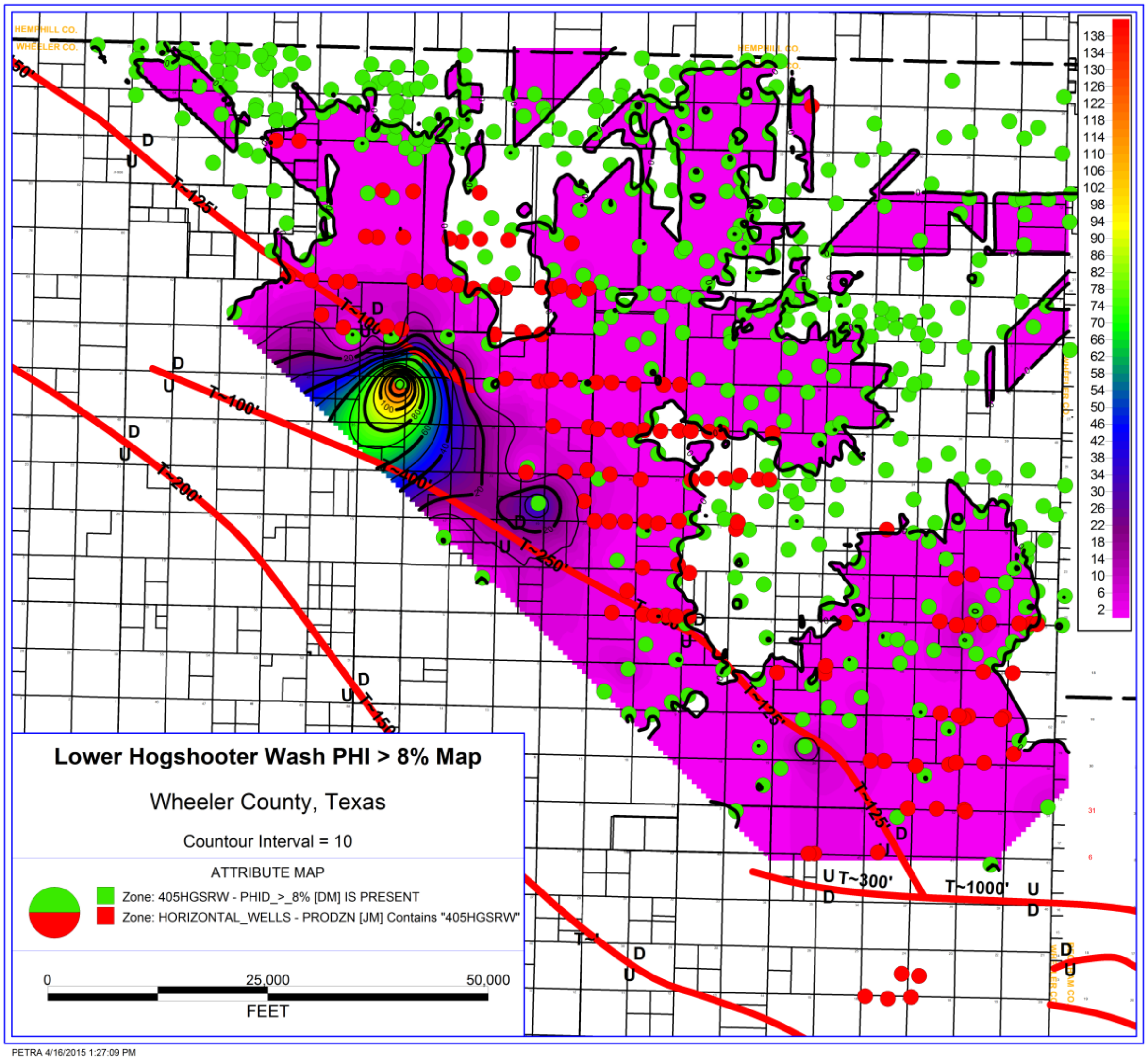

Figure 18: Lower Hogshooter Wash map displaying areas that are characterized by having porosity values greater than eight percent. Green dots represent well control used for map generation. Red dots represent recent horizontal production from the Hogshooter Wash.

5.1.11 Upper Hogshooter Wash Porosity > 8% Map

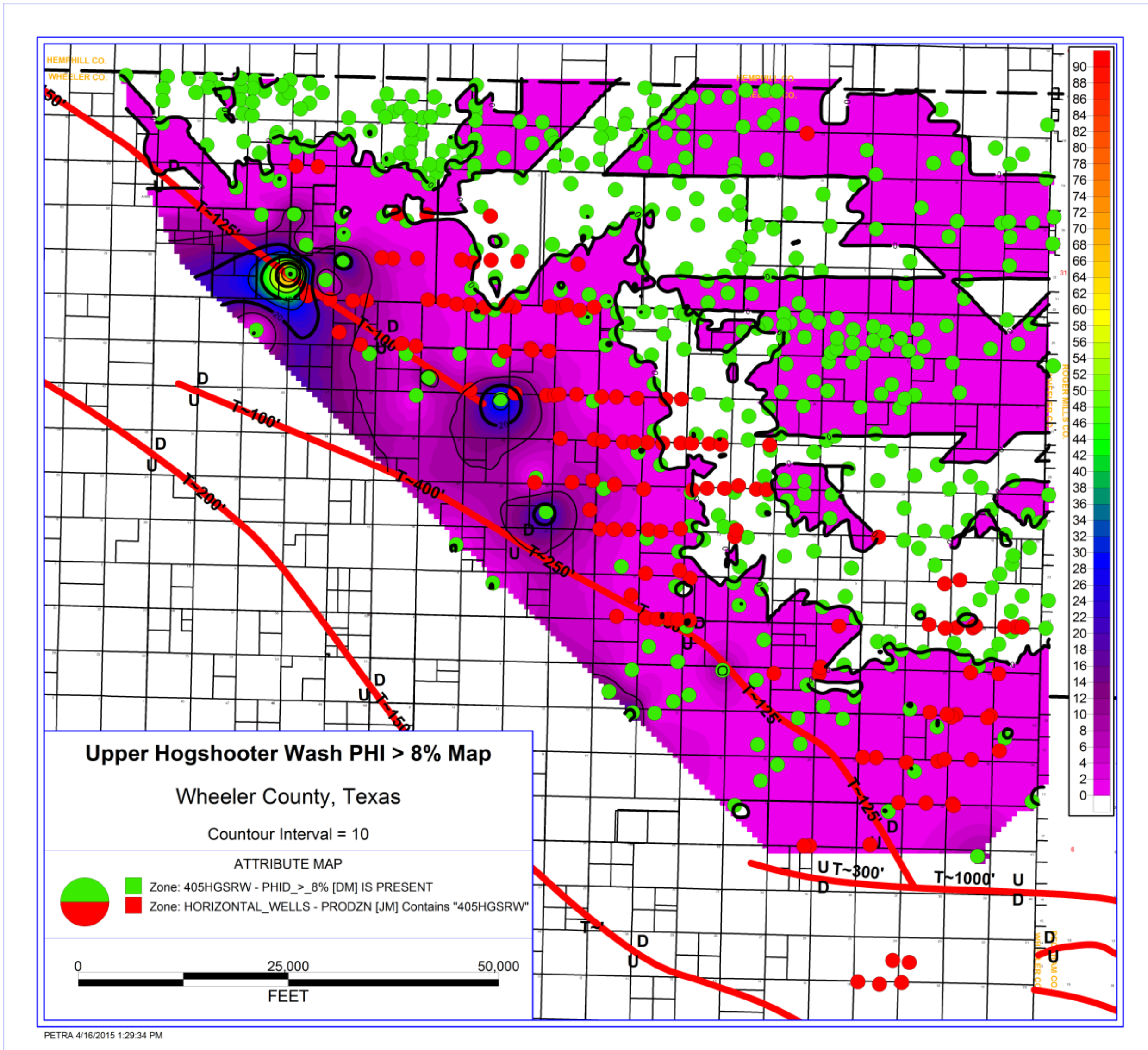

Figure 19: Lower Hogshooter Wash map displaying areas that are characterized by having porosity values greater than eight percent. Green dots represent well control used for map generation. Red dots represent recent horizontal production from the Hogshooter Wash.

5.1.12 Total Hogshooter Wash Porosity > 8% Map

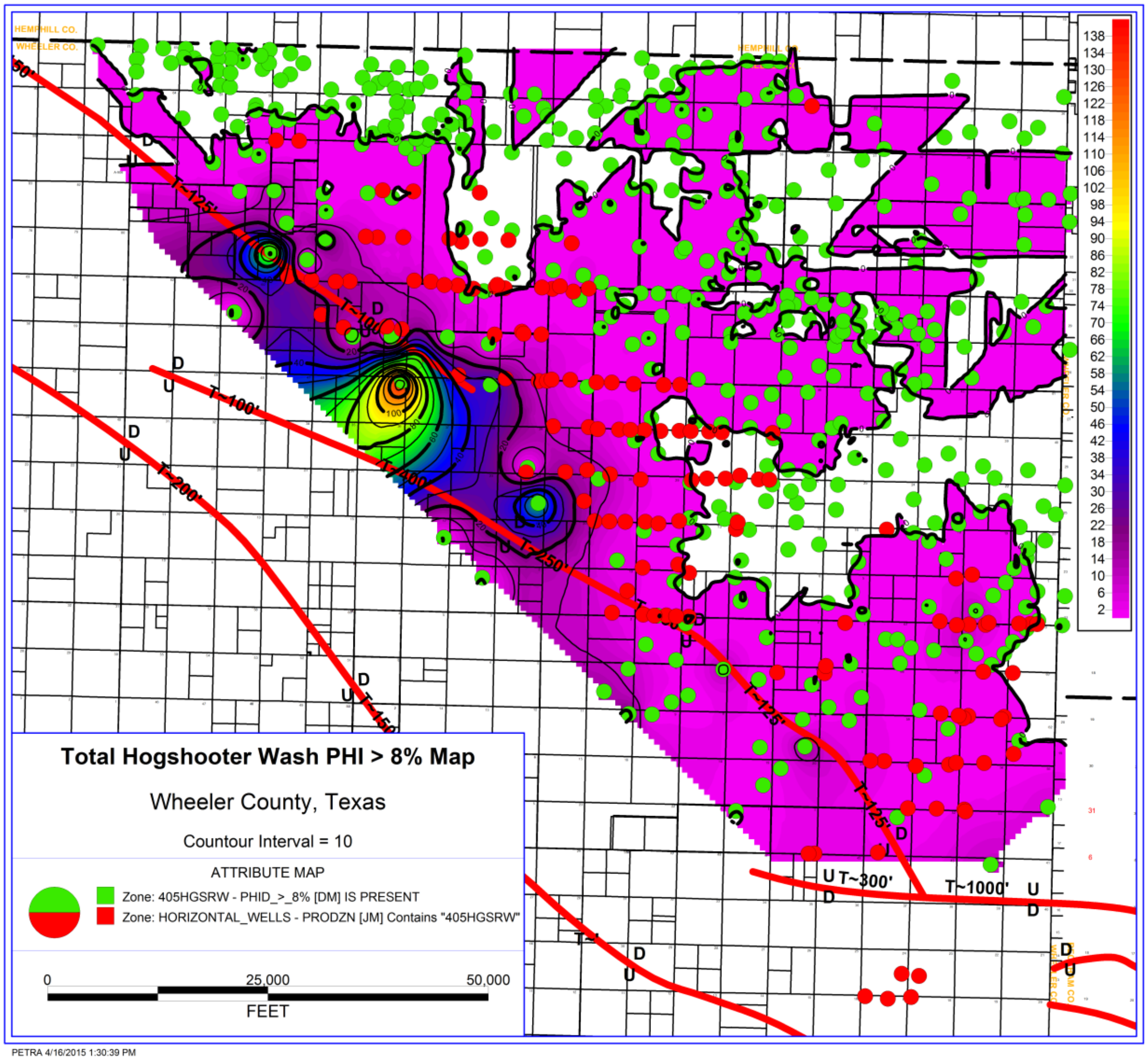

Figure 20: Lower Hogshooter Wash map displaying areas that are characterized by having porosity values greater than eight percent. Green dots represent well control used for map generation. Red dots represent recent horizontal production from the Hogshooter Wash.

5.1.13 Lower Cottage Grove Wash Isopach

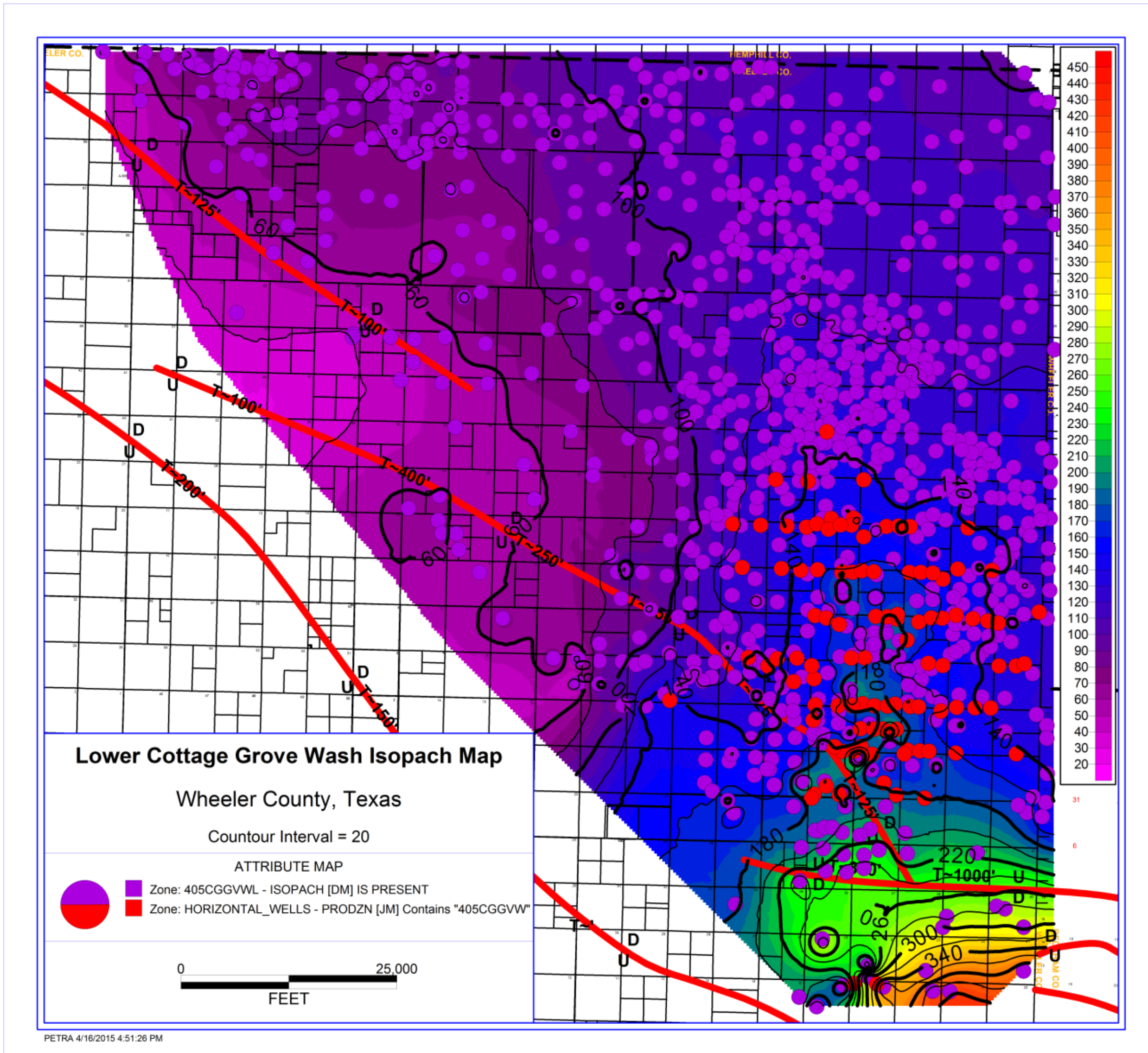

Figure 21: Lower Cottage Grove Wash isopach map displaying interval thickness trends. Purple dots represent the well control used for map generation. Red dots represent recent horizontal production from the Cottage Grove Wash.

5.1.14 Upper Cottage Grove Wash Isopach

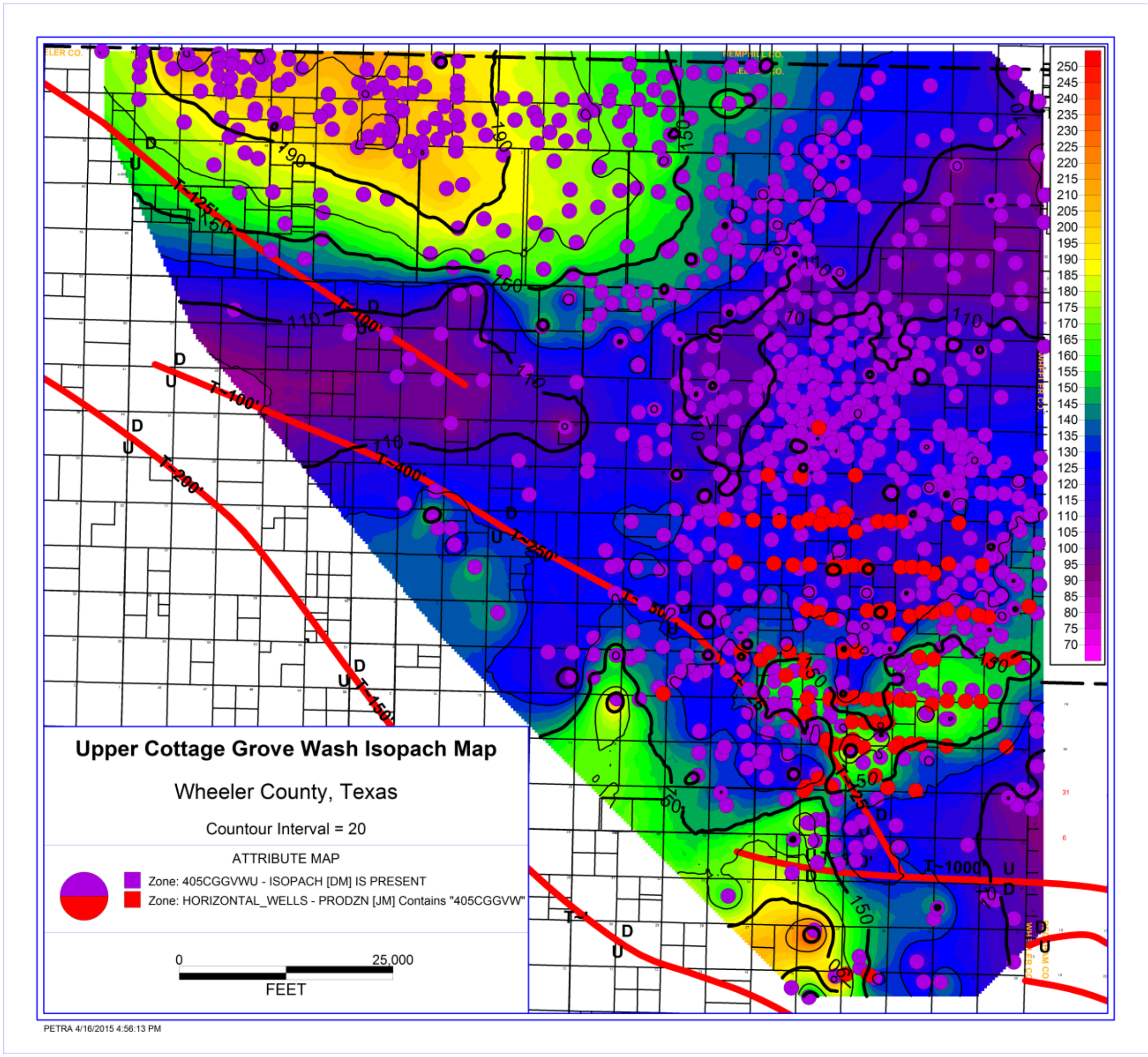

Figure 22: Upper Cottage Grove Wash isopach map displaying interval thickness trends. Purple dots represent the well control used for map generation. Red dots represent recent horizontal production from the Cottage Grove Wash.

5.1.15 Total Cottage Grove Wash Isopach

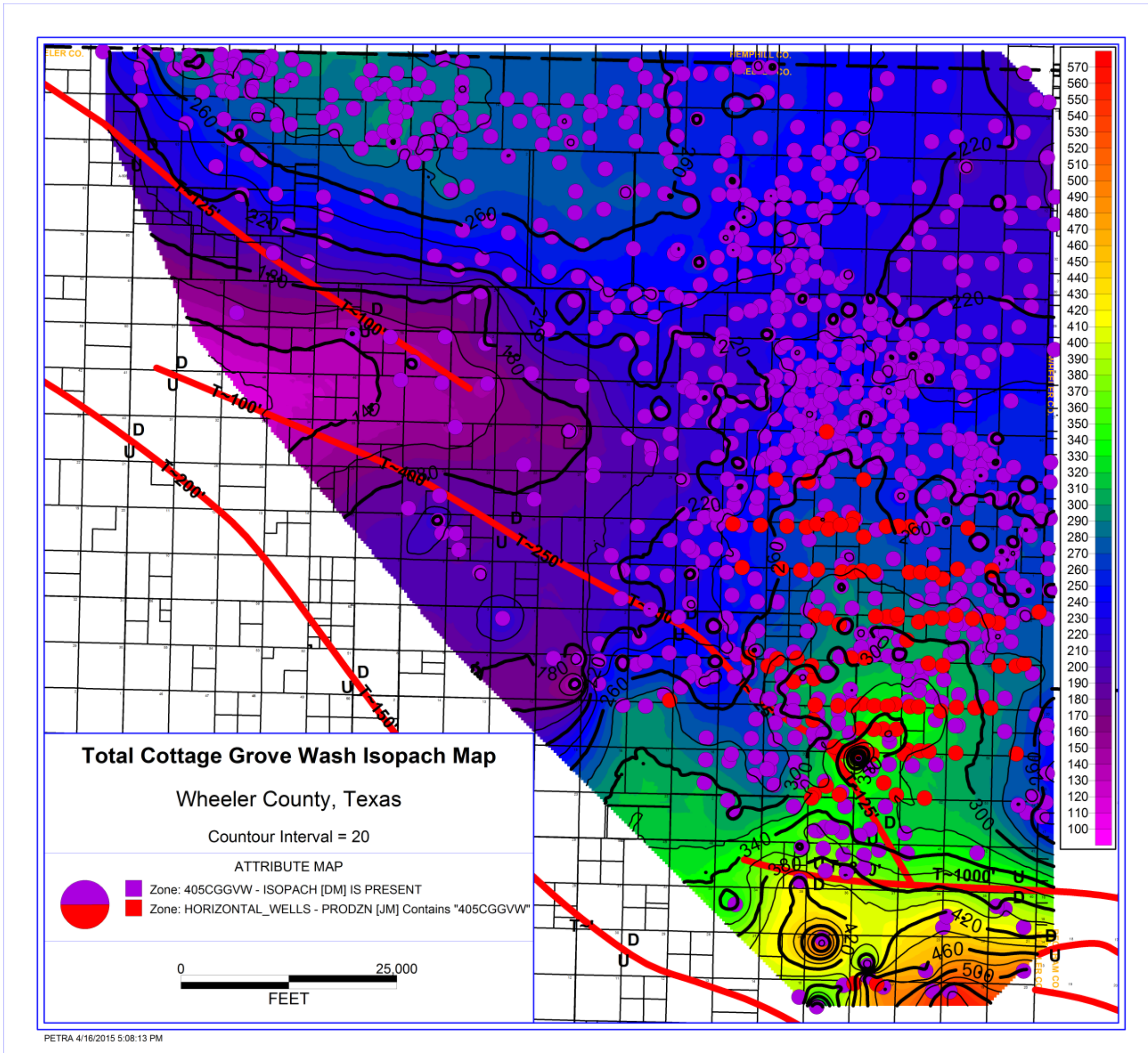

Figure 23: Total Cottage Grove Wash isopach map displaying interval thickness trends. Purple dots represent the well control used for map generation. Red dots represent recent horizontal production from the Cottage Grove Wash.

5.1.16 Lower Cottage Grove Wash Gamma Ray > 75API

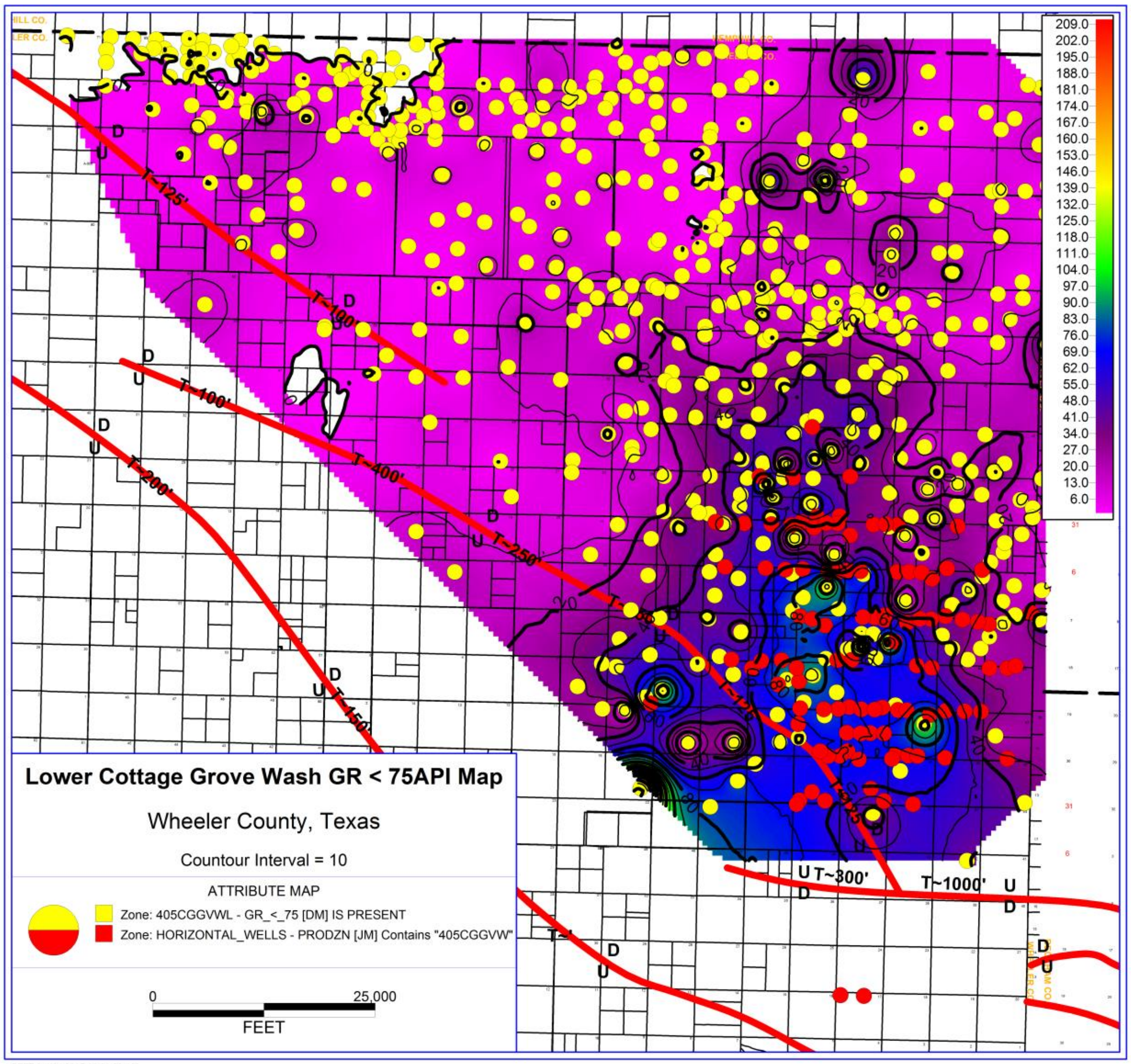

Figure 24: Lower Cottage Grove Wash map displaying areas that are characterized by having a gamma ray signature less than 75API units. Yellow dots represent well control used for map generation. Red dots represent recent horizontal production from the Cottage Grove Wash.

5.1.17 Upper Cottage Grove Wash Gamma Ray > 75API

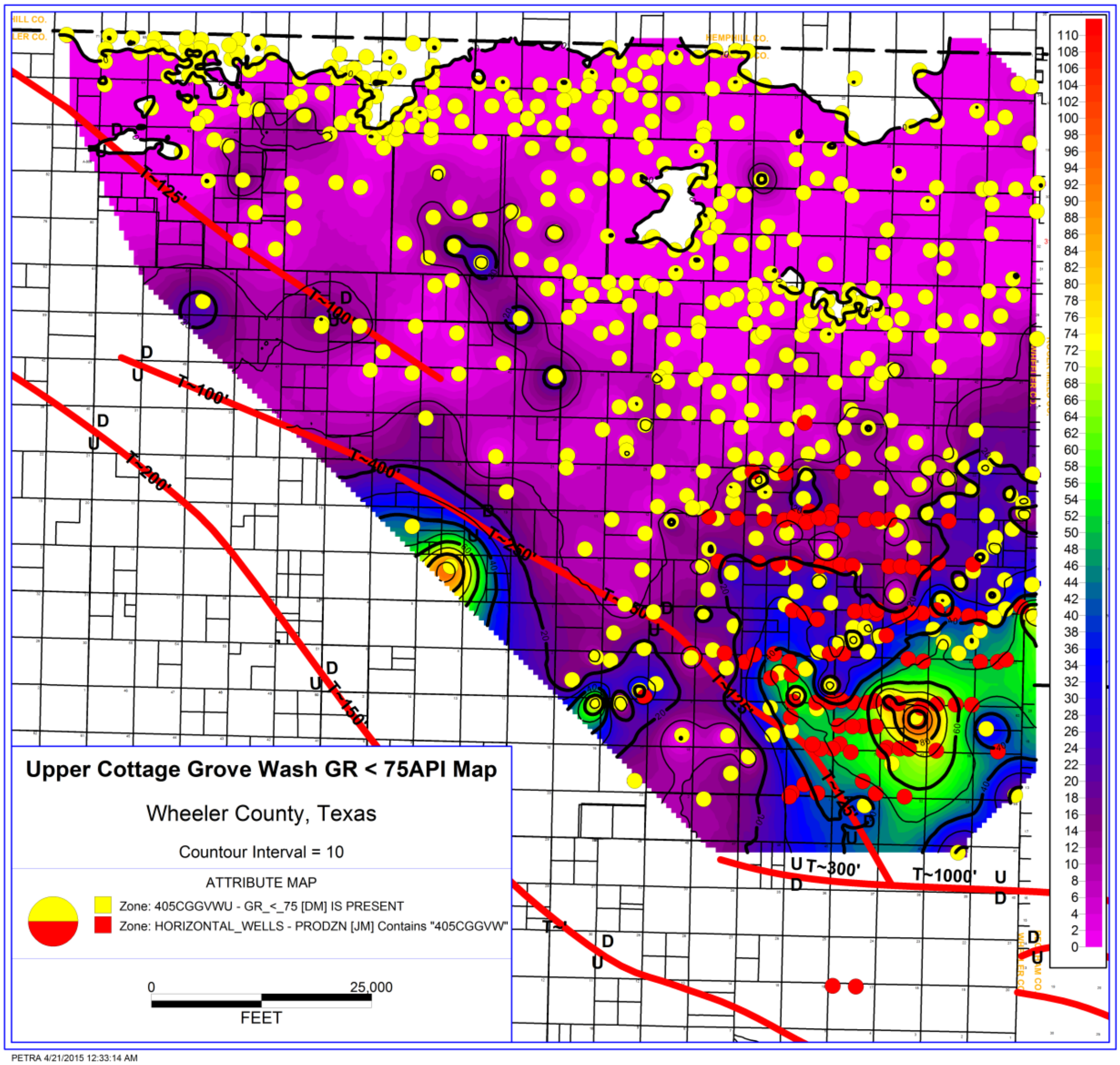

Figure 25: Upper Cottage Grove Wash map displaying areas that are characterized by having a gamma ray signature less than 75API units. Yellow dots represent well control used for map generation. Red dots represent recent horizontal production from the Cottage Grove Wash.

5.1.18 Total Cottage Grove Wash Gamma Ray > 75API

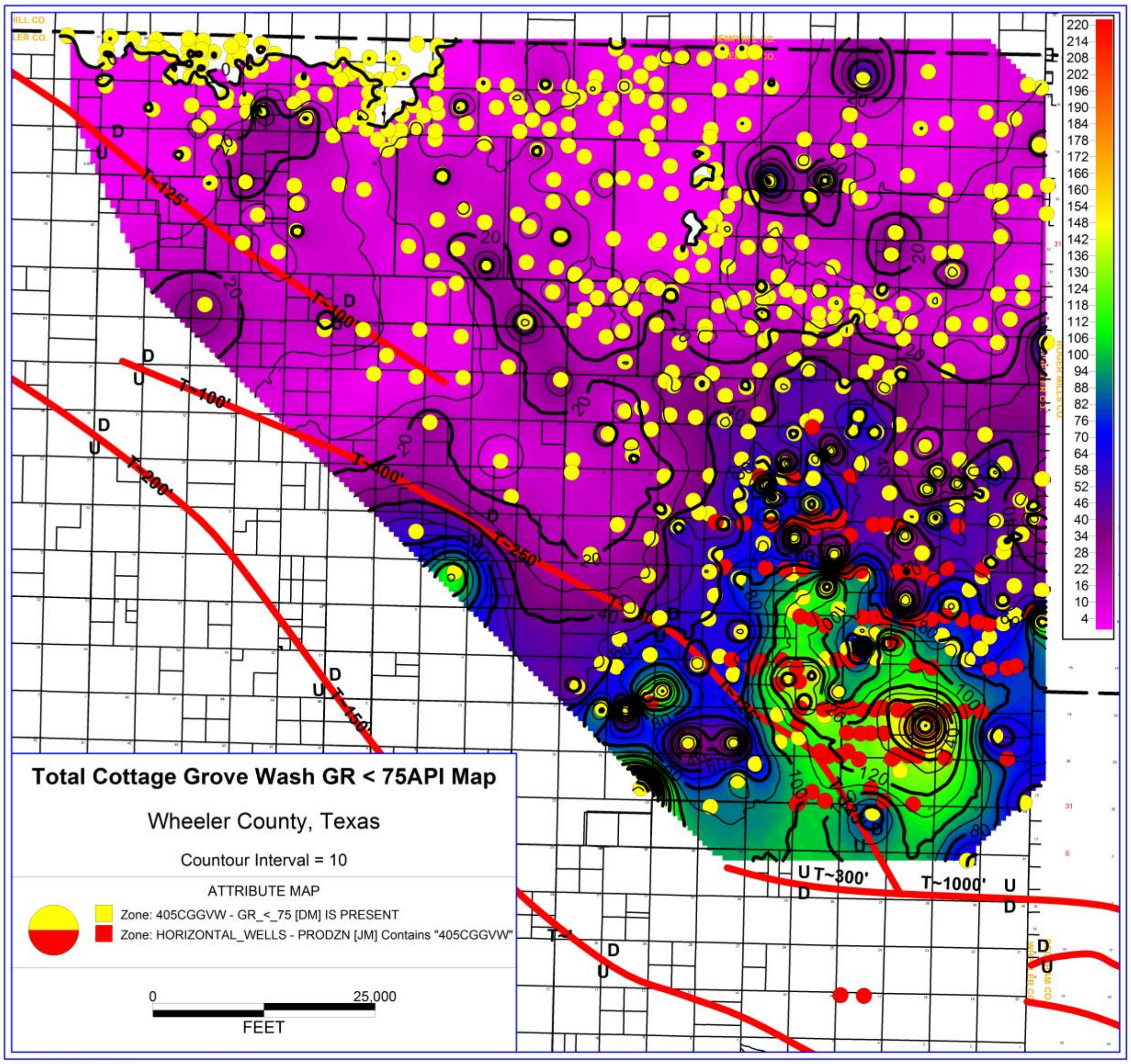

Figure 26: Total Cottage Grove Wash map displaying areas that are characterized by having a gamma ray signature less than 75API units. Yellow dots represent well control used for map generation. Red dots represent recent horizontal production from the Cottage Grove Wash.

5.1.19 Lower Cottage Grove Wash Porosity > 4%

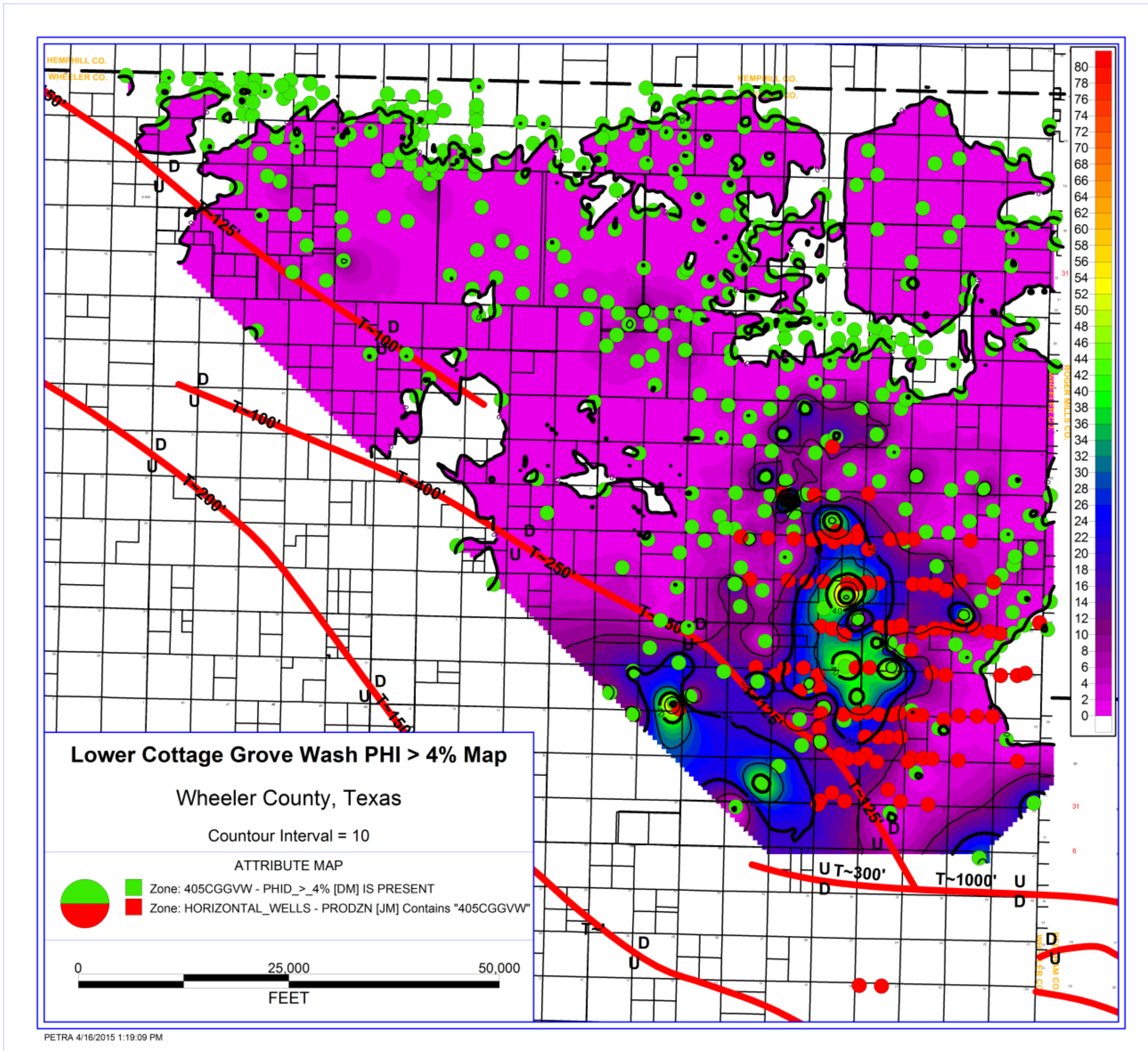

Figure 27: Lower Cottage Grove Wash map displaying areas that are characterized by having porosity values greater than four percent. Green dots represent well control used for map generation. Red dots represent recent horizontal production from the Cottage Grove Wash.

5.1.20 Upper Cottage Grove Wash Porosity > 4%

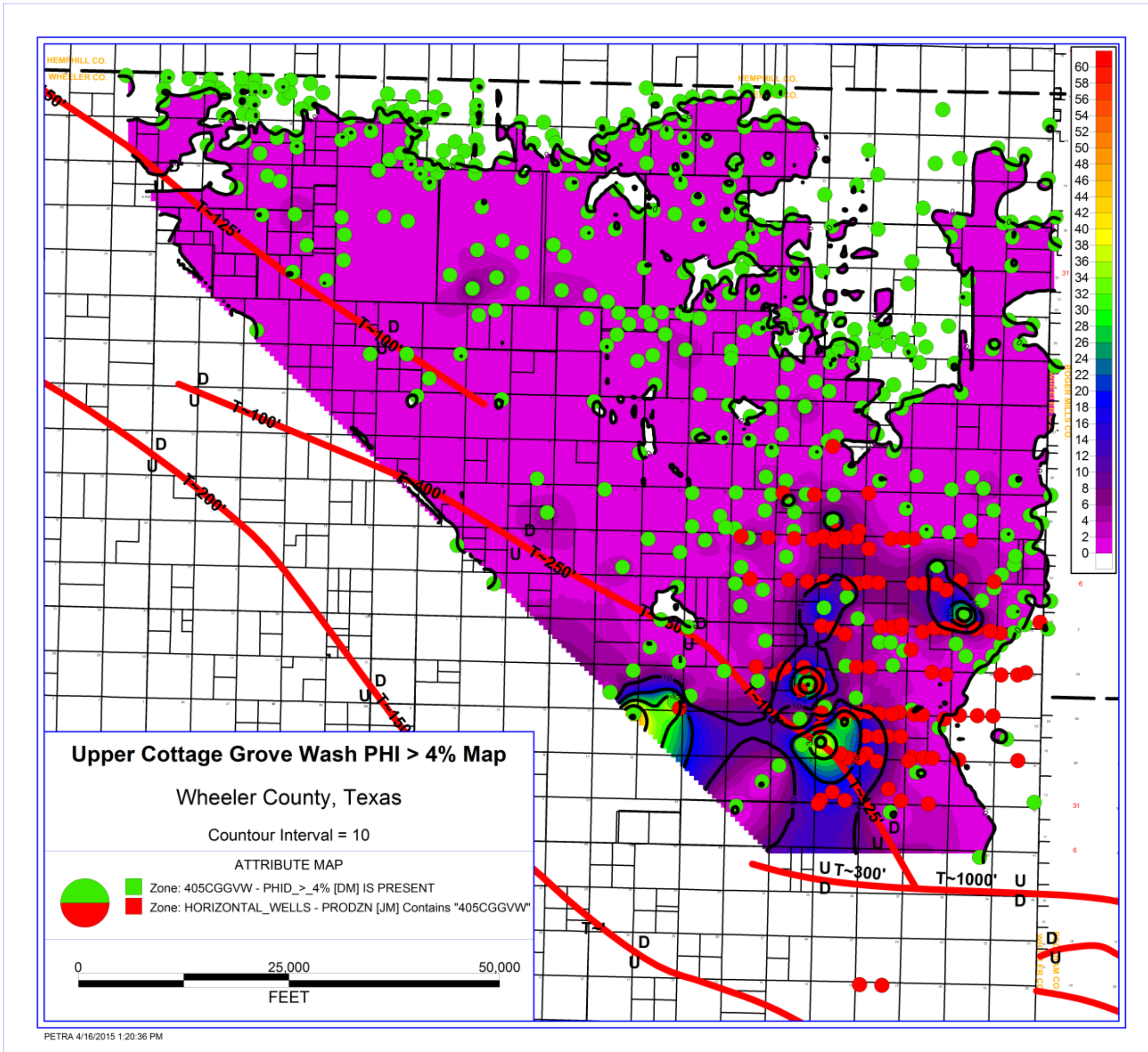

Figure 28: Upper Cottage Grove Wash map displaying areas that are characterized by having porosity values greater than four percent. Green dots represent well control used for map generation. Red dots represent recent horizontal production from the Cottage Grove Wash.

5.1.21 Total Cottage Grove Wash Porosity > 4%

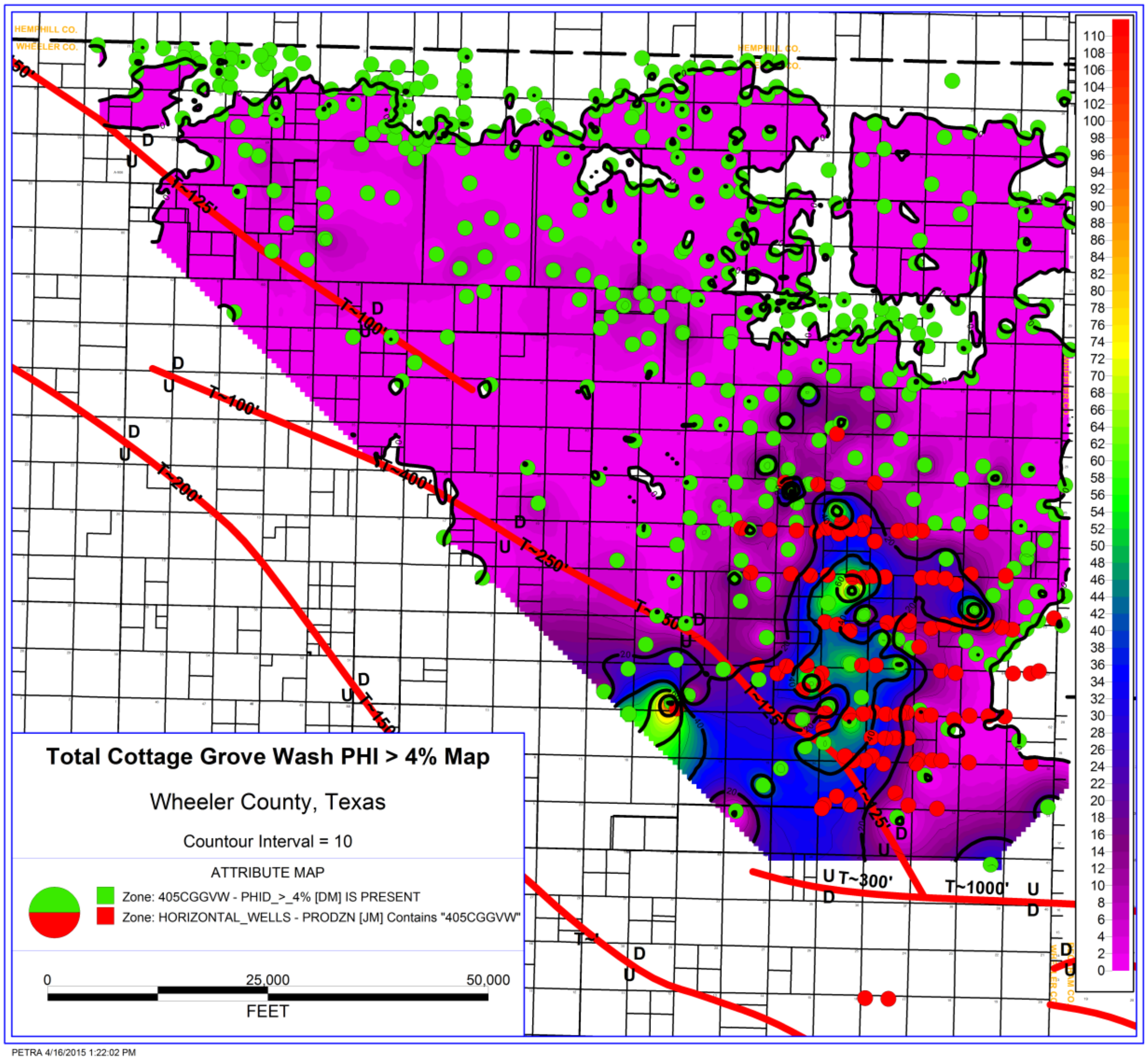

Figure 29: Total Cottage Grove Wash map displaying areas that are characterized by having porosity values greater than four percent. Green dots represent well control used for map generation. Red dots represent recent horizontal production from the Cottage Grove Wash.

5.1.22 Lower Cottage Grove Wash Porosity > 8%

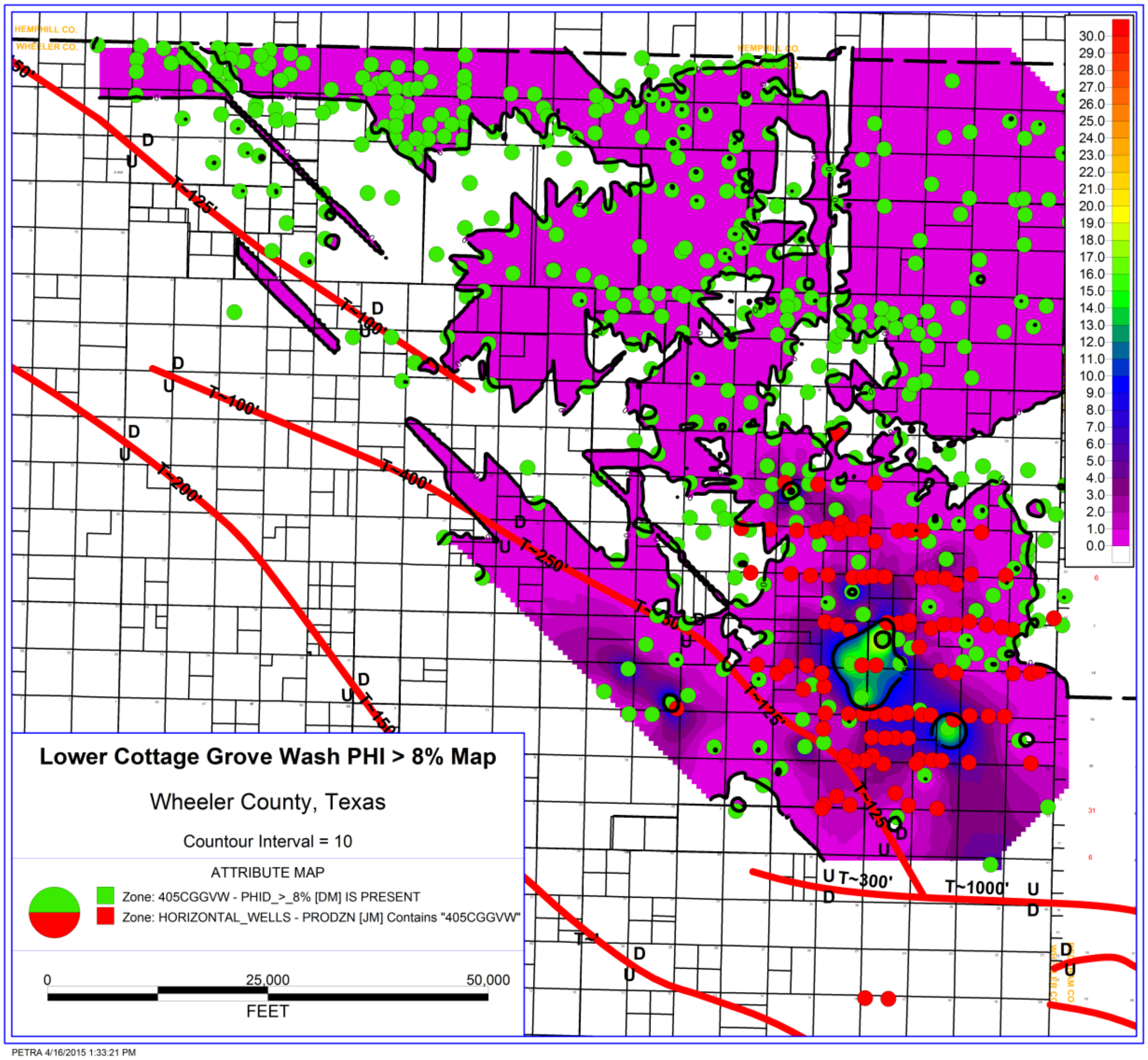

Figure 30: Lower Cottage Grove Wash map displaying areas that are characterized by having porosity values greater than eight percent. Green dots represent well control used for map generation. Red dots represent recent horizontal production from the Cottage Grove Wash.

5.1.23 Upper Cottage Grove Wash Porosity > 8%

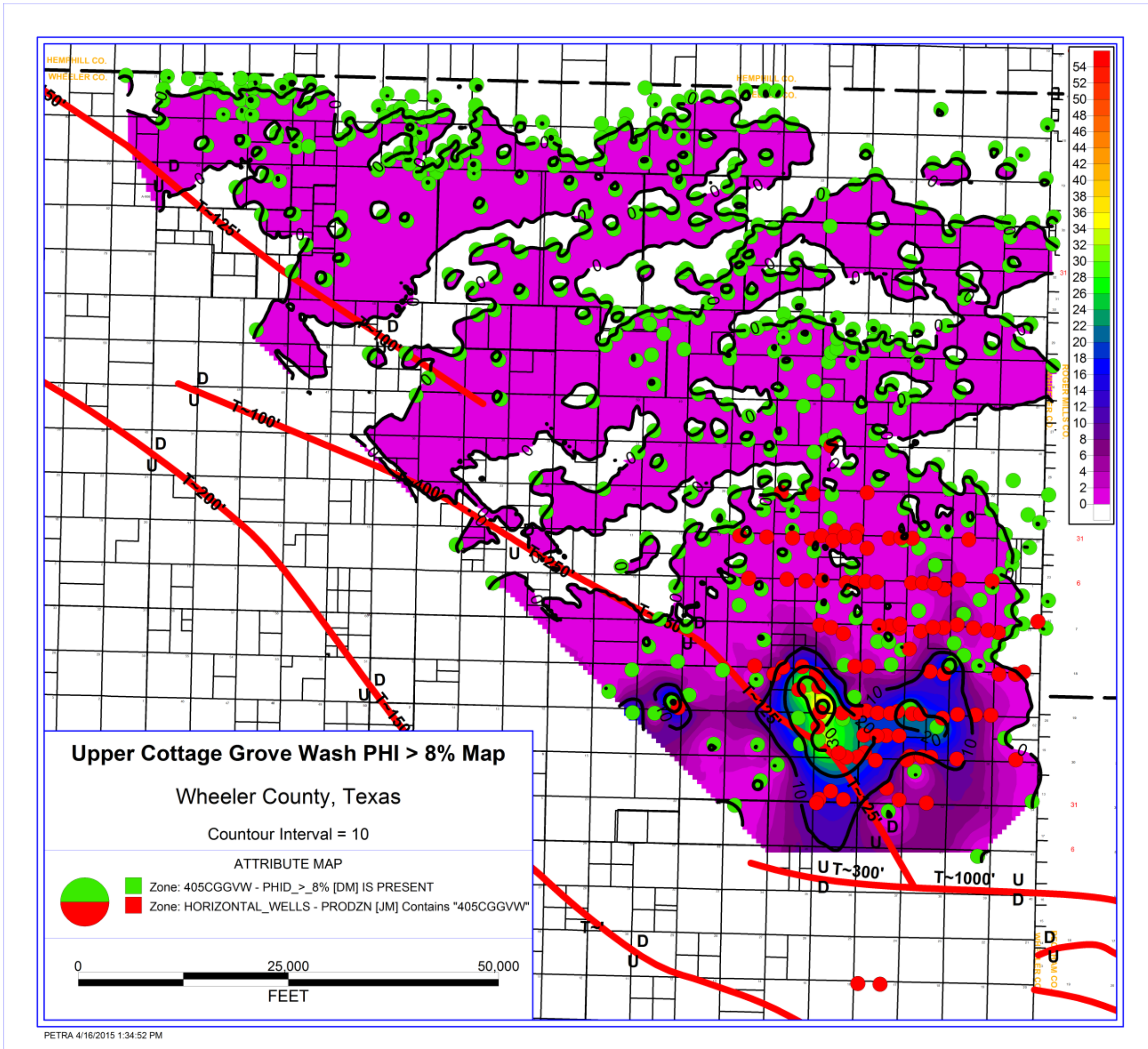

Figure 31: Upper Cottage Grove Wash map displaying areas that are characterized by having porosity values greater than eight percent. Green dots represent well control used for map generation. Red dots represent recent horizontal production from the Cottage Grove Wash.

5.1.24 Total Cottage Grove Wash Porosity > 8%

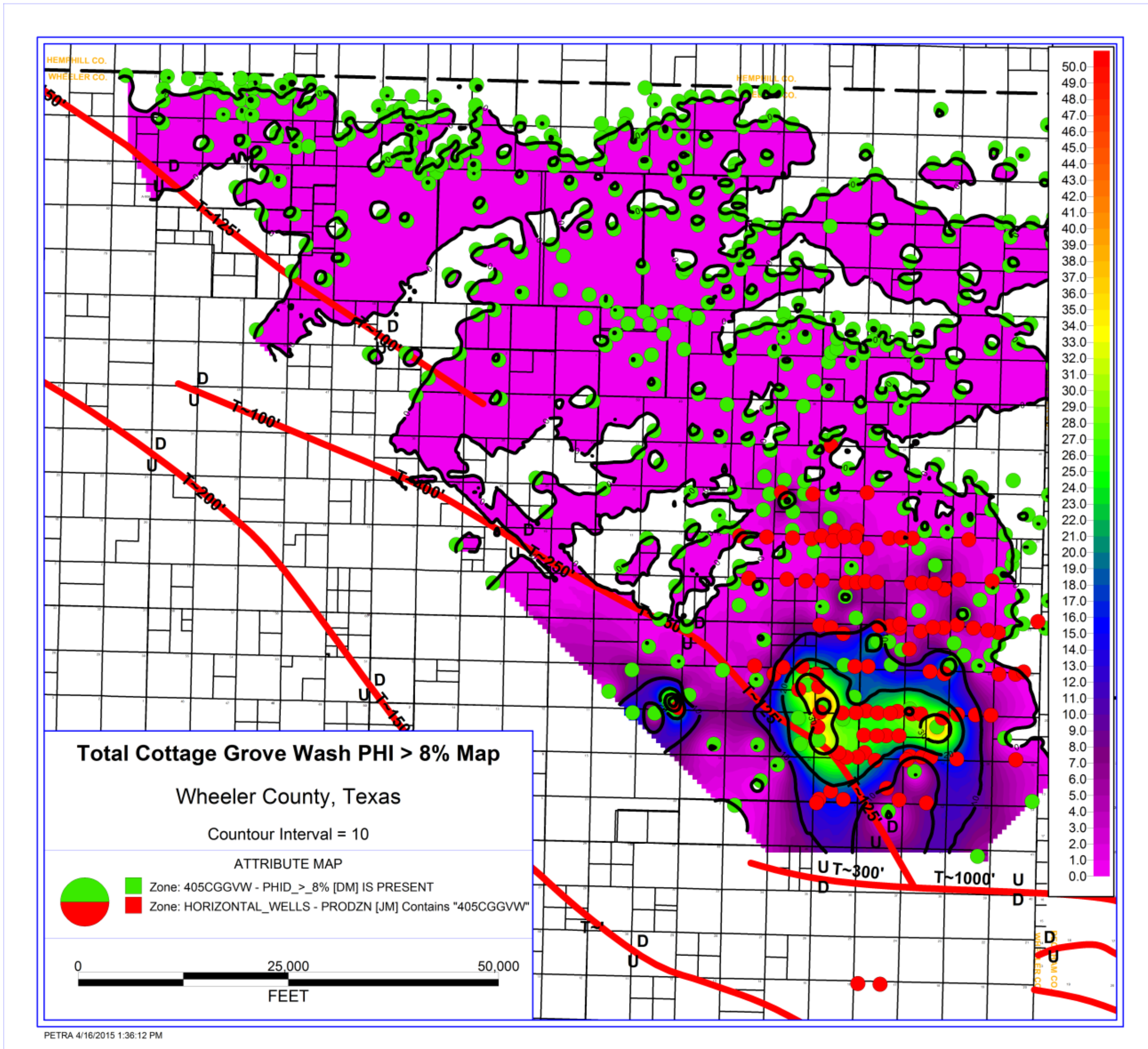

Figure 32: Total Cottage Grove Wash map displaying areas that are characterized by having porosity values greater than eight percent. Green dots represent well control used for map generation. Red dots represent recent horizontal production from the Cottage Grove Wash.

5.2 Cross Sections

Four cross sections were created to display the stratigraphy of the study area. Cross section A-A’ follows the NW stratigraphic strike of the area. Cross section B-B’, C-C’, and D-D’ are selected to characterize to stratigraphic dip. In the following cross sections, the Cottage Grove Wash is annotated with purple correlation lines and the Hogshooter Wash is annotated with Blue correlation lines. The Cleveland and Checkerboard Wash intervals are marked with unlabeled correlation lines due to the focus on the stratigraphically higher intervals in this study. The cross sections are hung on the Tonkawa flooding surface, which served as a consistent correlation top throughout the study area.

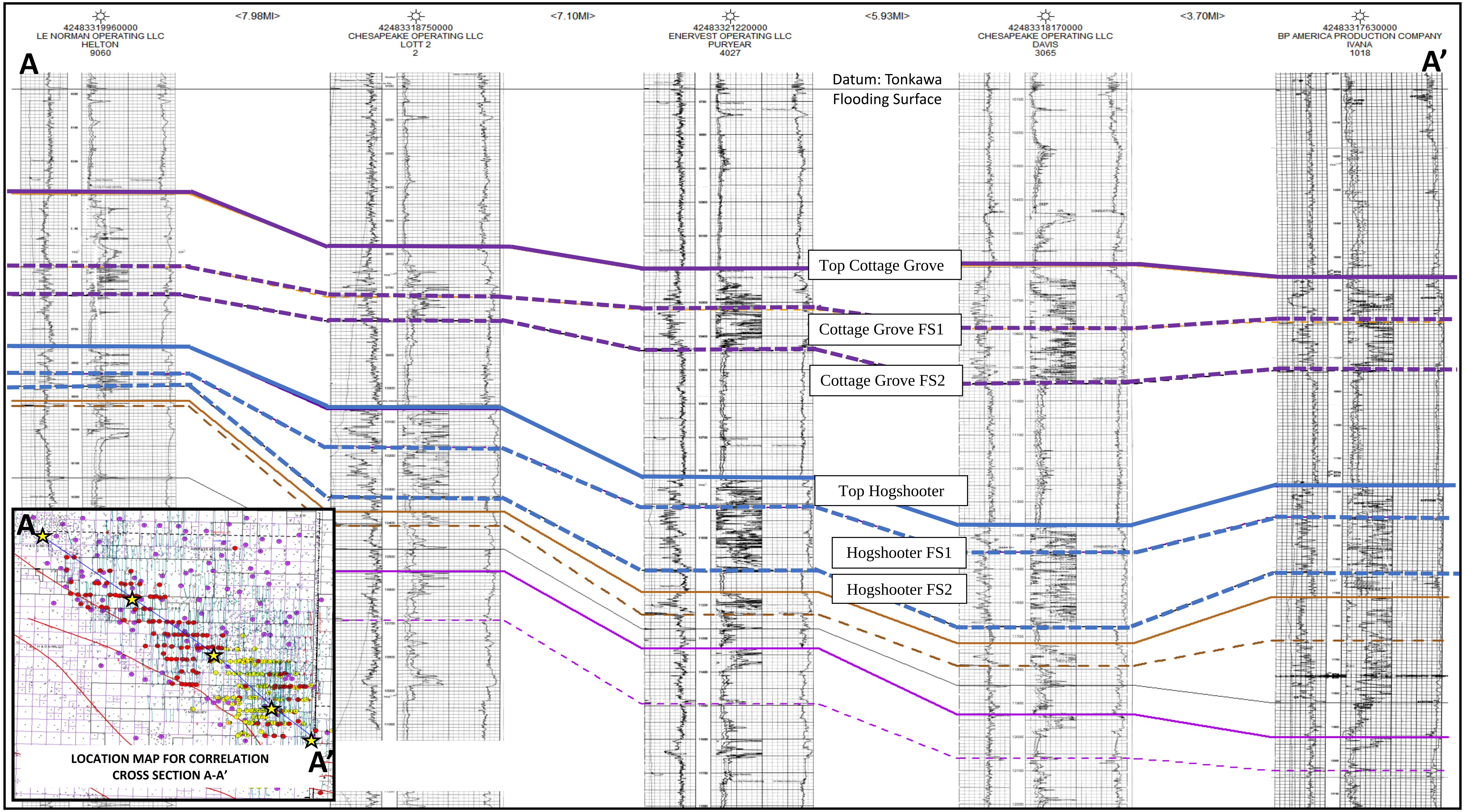

Figure 33: Correlation cross section A – A' stratigraphic strike section using small scale resistivity logs at 1" = 100 feet.

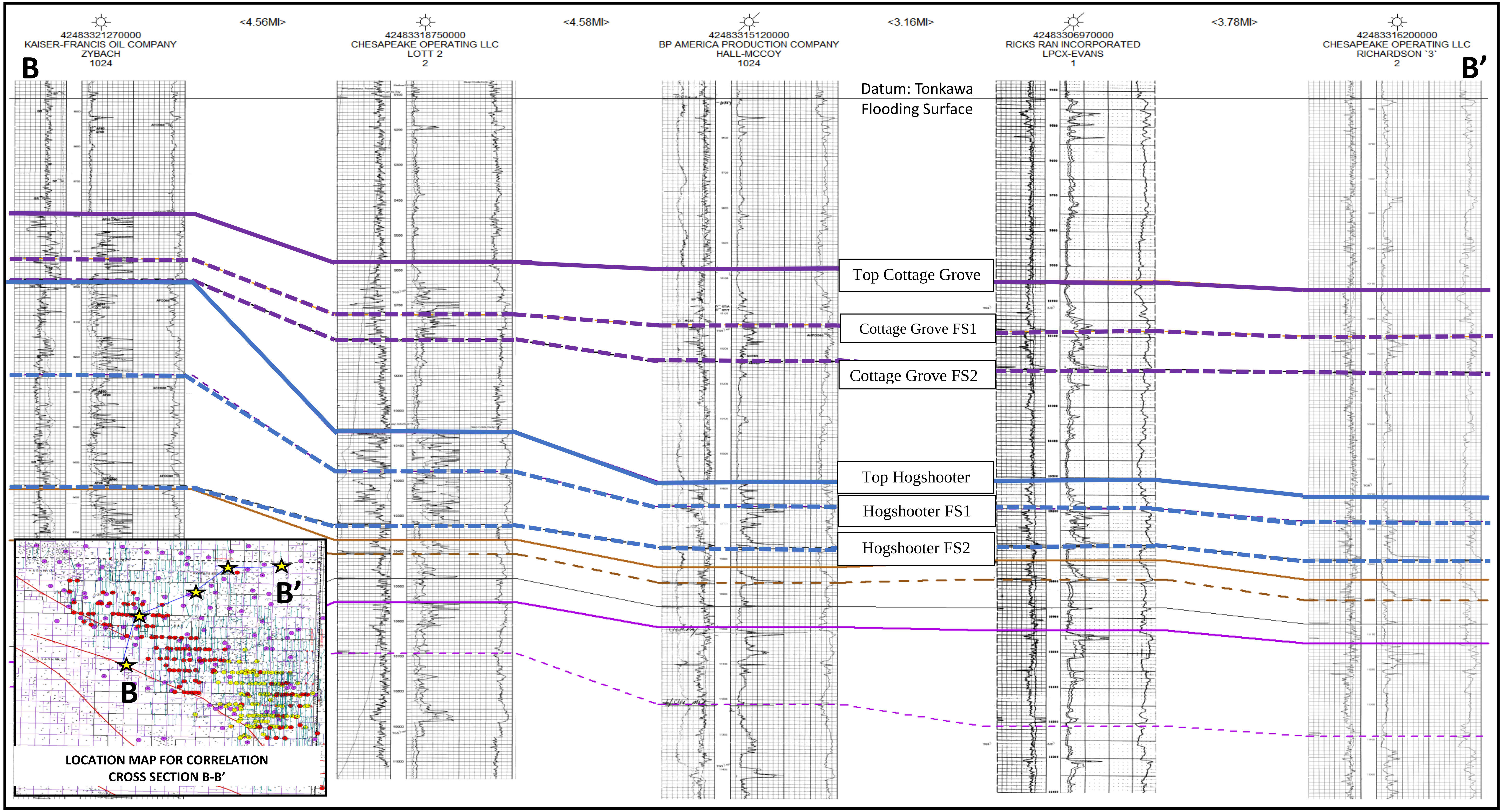

Figure 34: Correlation cross section B – B' stratigraphic dip section using small scale resistivity logs at 1" = 100 feet.

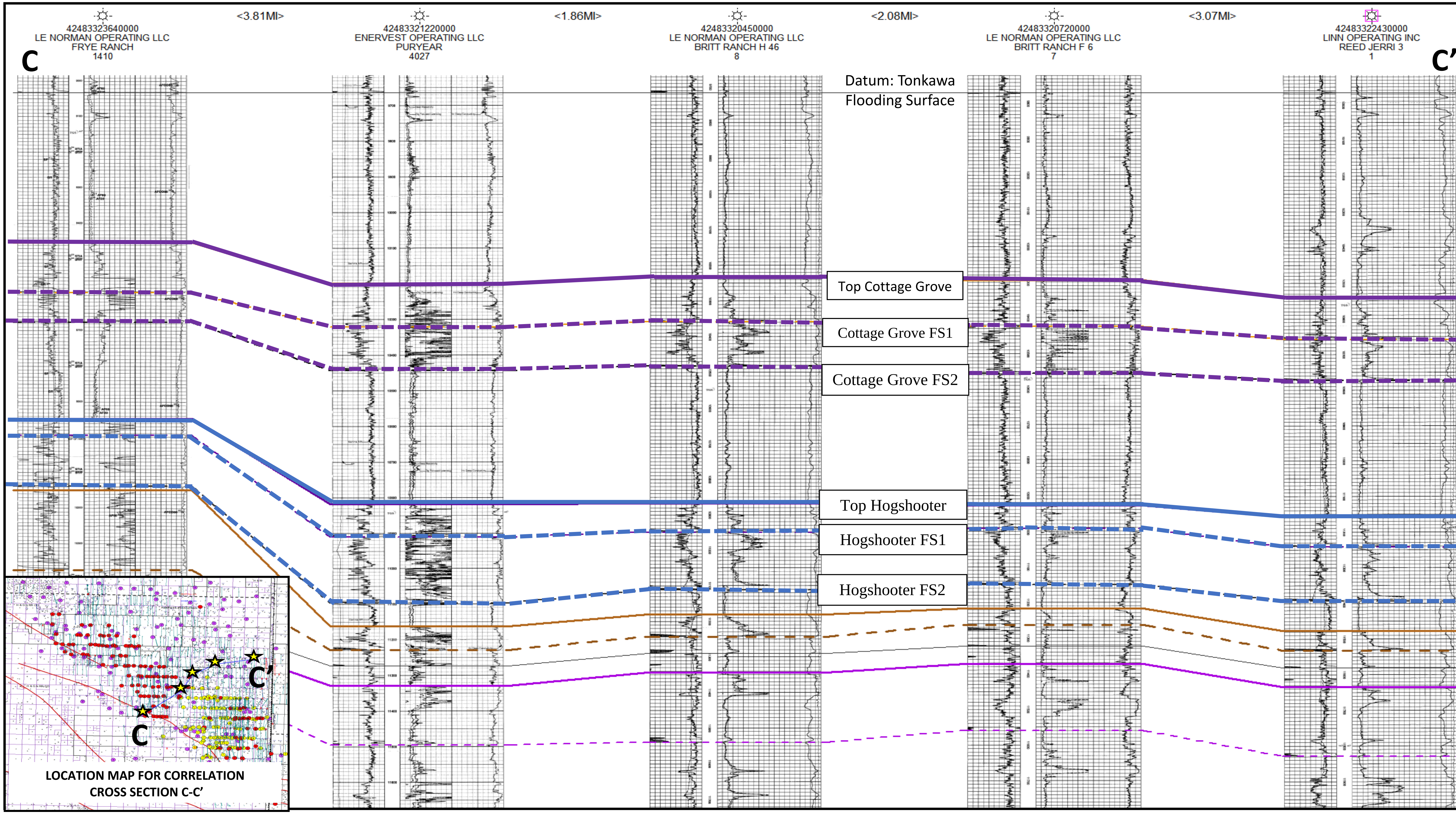

Figure 35: Correlation cross section C – C' stratigraphic dip section using small scale resistivity logs at 1" = 100 feet.

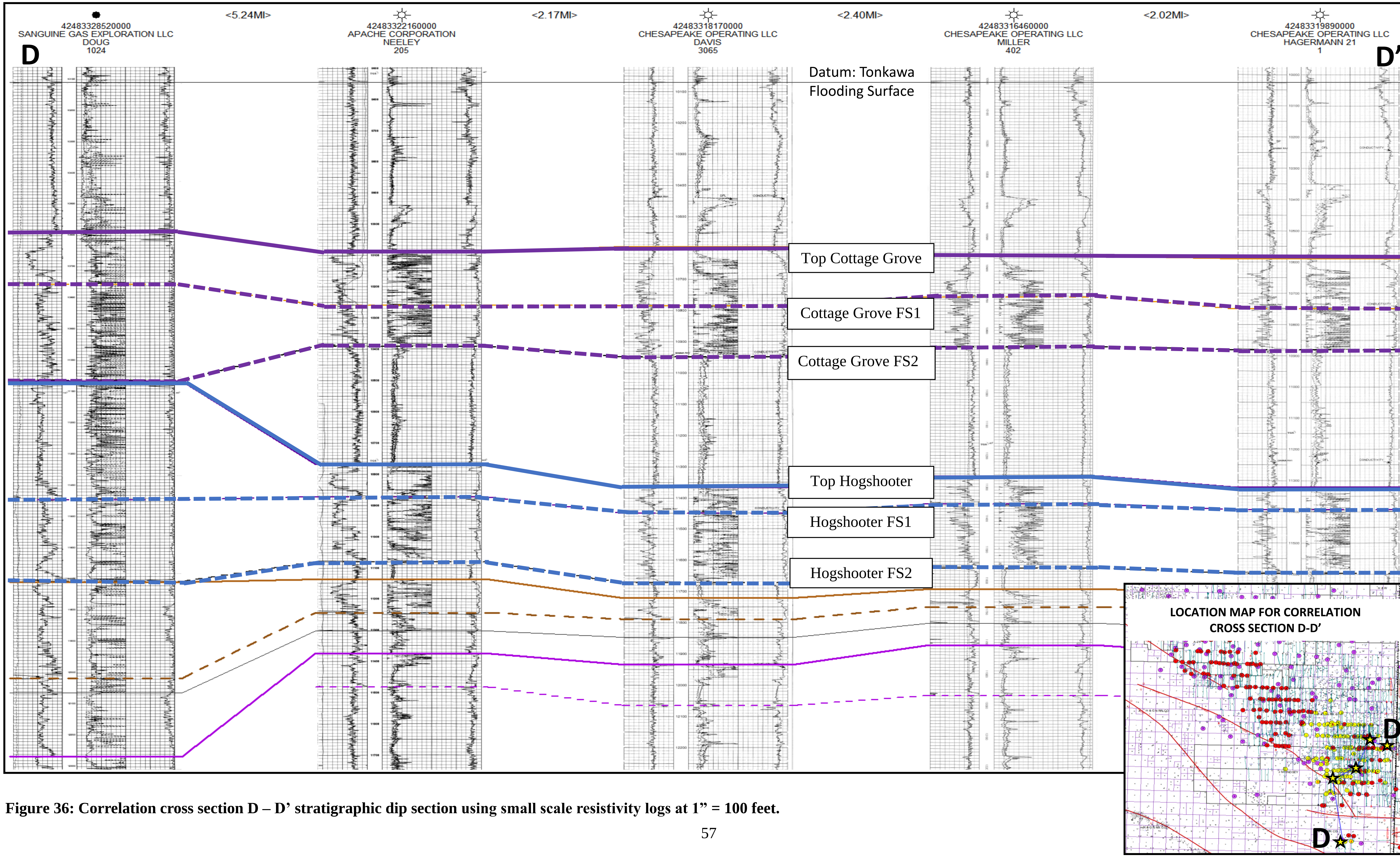

Figure 36: Correlation cross section D – D' stratigraphic dip section using small scale resistivity logs at 1" = 100 feet.

5.3 Hogshooter Wash Interpretations

The majority of the Hogshooter Wash produces from intervals of relatively clean sandstones, as defined by the gamma ray signatures and porosity values. In these wells, projected assignments for the lower and upper Hogshooter producing intervals were made by the author. Isolith mapping based upon gamma ray cutoffs along with log signatures from the Lower Hogshooter Wash interval (Figures 14 and 15), strongly suggest that the production comes from the central areas.

Production from the upper interval appears to be located in the northwestern and southeastern areas. To the northeast, the Lower Hogshooter Wash gamma map shows horizontal production in areas where the maximum thickness values are in the range of 10 feet of clean sand.

The southeastern region of the Hogshooter Wash producing area contains thicker intervals of clean sandstone development, with a substantial area of 100 foot thickness. The porosity maps for the Hogshooter Wash indicate that most of the current production occurs in areas where reservoir porosity intervals that are less than 10 feet thick. The central region of the Hogshooter producing area is north of the Lips fault zone where two-hundred fifty (250) feet of vertical offset occurs. This area is centered on sections 29 thru 32 in the H&GN RR Co. Survey, Block A3, located approximately nine miles west of the Oklahoma-Texas state line and nine miles south of the Hemphill-Wheeler county line. Here, the gamma and porosity maps define an area where the thicknesses of the corresponding intervals are larger. Accordingly, a large number of Hogshooter horizontal wells are located here. The Lips fault zone that trends parallel to the mountain front that appears to impact well placement. The areas of production from the

Hogshooter Wash are limited on the southwest by the two northwest to southeast trending faults of the Lips fault zone.

5.4 Cottage Grove Wash Interpretations

The Cottage Grove Wash shows an isopach distributional character that is indicative of a southern source and depositional center. The migration of the depocenter from the southwest that characterizes the sediment source for the Hogshooter Wash intervals is not anomalous to what is expected. The change in depocenter can be attributed to a change in sediment transport rates along the Mountain Front. The Lower Cottage Grove Wash isopach displays a thinning of the interval from south to north. Production from the Lower Cottage Grove Wash appears to come from the area that trends south-north. This area is clearly highlighted from the four percent porosity map approximately 7,000 feet to the northeast of the Lips fault (Figure 29). This south-north trend is prevalent in the gamma and isopach interval maps. Production from the Upper Cottage Grove Wash is similar to the Lower Cottage Grove Wash, appearing to come from areas trending along the down thrown expanse of the Lips fault and then perpendicular to the fault trending to the northeast, shown in the isopach map (Figure 24). The gamma and map for the interval shows significant accumulations in the southern area of map (Figure 27) which appear to be concomitant with the porosity and isopach values.

5.5 Cross Section A – A' Interpretations

Cross section A – A' parallels the stratigraphic strike of the study area from northwest to southeast. The Cottage Grove Wash experiences an overall thickening the southwest and begins to thin as the section approaches the boundaries of the study area. The massive shale interval which separates the Cottage Grove Wash and the Hogshooter Wash interval follows the same trend, experiencing maximum thicknesses of approximately 400 feet of shale. The Upper Hogshooter Wash interval remains primarily stagnant in variation, maintaining an average thickness of approximately 100 feet. The Lower Hogshooter Wash interval thickens to the southeast, with interval values ranging from 50 feet to the northwest to approximately 200 feet.

5.6 Cross Section B – B' Interpretations

Cross section B – B' follows the stratigraphic dip of the study area. The section trends southwest to northeast beginning at the southern fault and crossing the northern fault in the area. At the southern fault there little to no shale interval to separate the Cottage Grove and the Hogshooter Wash interval. The throw across the fault is approximately 250 feet. The Hogshooter Wash interval shows a significant decrease in thickness northeastward across the fault. Thicknesses decrease from approximately 400 feet to 100 feet across the fault. Wash interval thicknesses northeast of the fault remain consistent to the end of the section and the study area, with a gradational increase in the intermediate massive shale interval between the base of the Cottage Grove Wash and the top of the Hogshooter Wash.

The absence of shale at the southern fault due to the development of thick granite wash deposits is indicative of the proximity to the mountain front. This absence of the massive marine shale south of the fault suggests that Cottage Grove Wash deposition post-dates faulting. The development of the shale interval to the northeast away from the mountain front strongly suggests an increase in water depth during deposition and a lack of coarse arkosic sediment supply away from the mountain front.

5.7 Cross Section C – C' Interpretations

Cross Section C – C' follows the stratigraphic dip of the study area. The section trends southwest to northeast beginning at the mid-point of the southern fault. The section illustrates a slight overall thickening in both the Cottage Grove and Hogshooter Wash intervals away from the fault.

5.8 Cross Section D – D' Interpretations

Cross Section D – D' follows the stratigraphic dip of the study area. The section trends southwest to northeast beginning south of the southernmost fault of the study area. Across the fault, the Upper Cottage Grove Wash does not experience a significant change in thickness. A substantial decrease in interval thicknesses is shown in the Lower Cottage Grove ~~Wash~~ and ~~the~~ Hogshooter Wash intervals. Thickness differences range from a maximum of approximately 350 feet to approximately 50 foot intervals across the fault. Southwest of the southernmost fault, the intermediate massive shale is not present.

6. CONCLUSIONS

Sediments from the Hogshooter and Cottage Grove Wash intervals are derived from different depocenters. Production in the study area appears to be partially controlled by faulting. The absence of the massive marine shale interval that separates the Cottage Grove Wash the Hogshooter Wash intervals crossing the fault, suggest that the deposition of the Cottage Grove Wash post-dates faulting.

Proprietary production data limits the accuracy of isopach and isolith interpretations based upon the locations of horizontal production. For this reason, the analysis of horizontal directional surveys from producing wells to the approximate interval formation depths must be conducted in order to accurately determine the producing intervals within each Wash. Generally, producing horizontal wells do not relate accurately to conventional gamma ray and porosity values. Without core samples, depositional settings and characteristics must be generalized.

Isopach and isolith maps show lobate-shaped trends oriented northeast-southwest that grade into much thicker massive sandstone intervals to the southwest and become more shale-rich to the northeast. Characterizing these trends as fan deltas prograding northeastward into turbidites are consistent with the Granite Wash depositional model.

7. FUTURE WORK

This research is one of just a few current publications that seek to describe the stratigraphic distribution and related properties of the Granite Wash reservoirs of the western Anadarko Basin. This research will not only help characterize subsurface properties related to hydrocarbon distribution and production, but will also help to develop the understanding of the tectonic and depositional development of the area. This research opens several avenues for continued study and analyses of the Anadarko Basin:

1) The expansion of this study to include the Checkerboard and Cleveland Wash intervals with the addition of production data, if available, for those intervals. If production data is not available, trends examined in this study could be used to compare depositional characteristics to forecast potential zones for the exploration and production of hydrocarbons.
2) The in-depth study of the geological history of basin sediments analyzed from the data set. This study would incorporate the depositional trends and structural features of the study area to build or conceptualize the variations in sediment distribution and transport throughout the Pennsylvanian period.
3) The expansion of this study to include a regional area with complete well control to more accurately characterize sediment distribution and depositional trends throughout the Anadarko Basin.
4) This study would benefit from the cross referencing of directional surveys from the producing horizontal wells with the interval depths of the parasequnces within the

Cottage Grove and Granite Wash intervals. The determination of producing intervals would clarify the relationships between clean sands and porosity.

Horizontal drilling technology has revitalized oil production in the Anadarko Basin. The new production will provide the stimulus for new research into the geologic factors controlling this production. Detailed analyses conducted by academic researchers could prove an invaluable asset to industry professionals who must sacrifice attention to detail in order to minimize the financial costs of a prolonged geological analysis.

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