LINKING PETROPHYSICAL AND GEOMECHANICAL CHARACTERIZATION TO PRODUCTION BEHAVIOR IN THE HAYNESVILLE SHALE

A Thesis

Submitted to the Graduate School Faculty of the University of Texas at Arlington,
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Geology
In
The Department of Earth and Environmental Sciences

By

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I remember fondly my late father, Evans Oguike, the first Geoscientist I ever knew, who inspired me to study Geology. I also acknowledge my mother, Nkechi Oguike, a gifted teacher, for instilling in me a love for education.

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Abstract

In recent years, the Haynesville shale has become a target for natural gas exploitation, especially with the advent of horizontal drilling and hydraulic fracturing. Located in East Texas and Northwest Louisiana, it is believed to be one of the largest producing natural gas plays in the U.S., with estimated recoverable reserves of around 75 TCF according to the Energy Information Administration (EIA, 2011). Current total daily production for the entire play is around 5.4 Bcf/d. The economic potential of the Haynesville shale gas play is propelled by recent gradual rebounds in natural gas prices, increased industrial utilization of gas, and expansion of LNG export terminals along the gulf coast due to the lifting of the decades-old ban on exporting petroleum products.

Consequently, it is imperative to properly evaluate the petrophysical attributes of the shale in order to understand the reservoir characteristics that may ultimately influence production. This study focused on the petrophysical evaluation of wells in East Texas and Northwest Louisiana. Wireline logs and core data were integrated to provide a predictive template for targeting and landing lateral wellbores within the shale in order to provide useful insight for hydraulic fracture stimulation with the view of optimizing production. The critical factors determined to influence the target zones include geomechanical properties such as brittleness, and geochemical properties such as the mineral volumes in the rock. These were calculated from logs using equations previously published in literature and correlated to nearby core measurements for verification. Already drilled and completed laterals were also evaluated to identify potential refracturing opportunities that could remedy production decline. The stimulation techniques

and production outcomes of these laterals were examined in an attempt to identify possible trends and contrasts accordingly.

The results show that the geomechanical properties vary across the shale play area. The geomechanical and geochemical properties can be useful in target selection for landing horizontal wells and effective fracture treatments, but they cannot by themselves guarantee productivity as other factors have to be taken into consideration such as completions method. The various operational constraints and development patterns such as different lateral lengths and age/style of completions make it difficult to do effective well-to-well production comparison; however the results points to trends such as longer lateral lengths with greater fracture stages to boost production. Additionally, in some areas, it has been established via the petrophysical analysis that there may be additional intervals in which to land a second horizontal well. This will surely lead to better exploitation and increased production from the reservoir.

Chapter 1

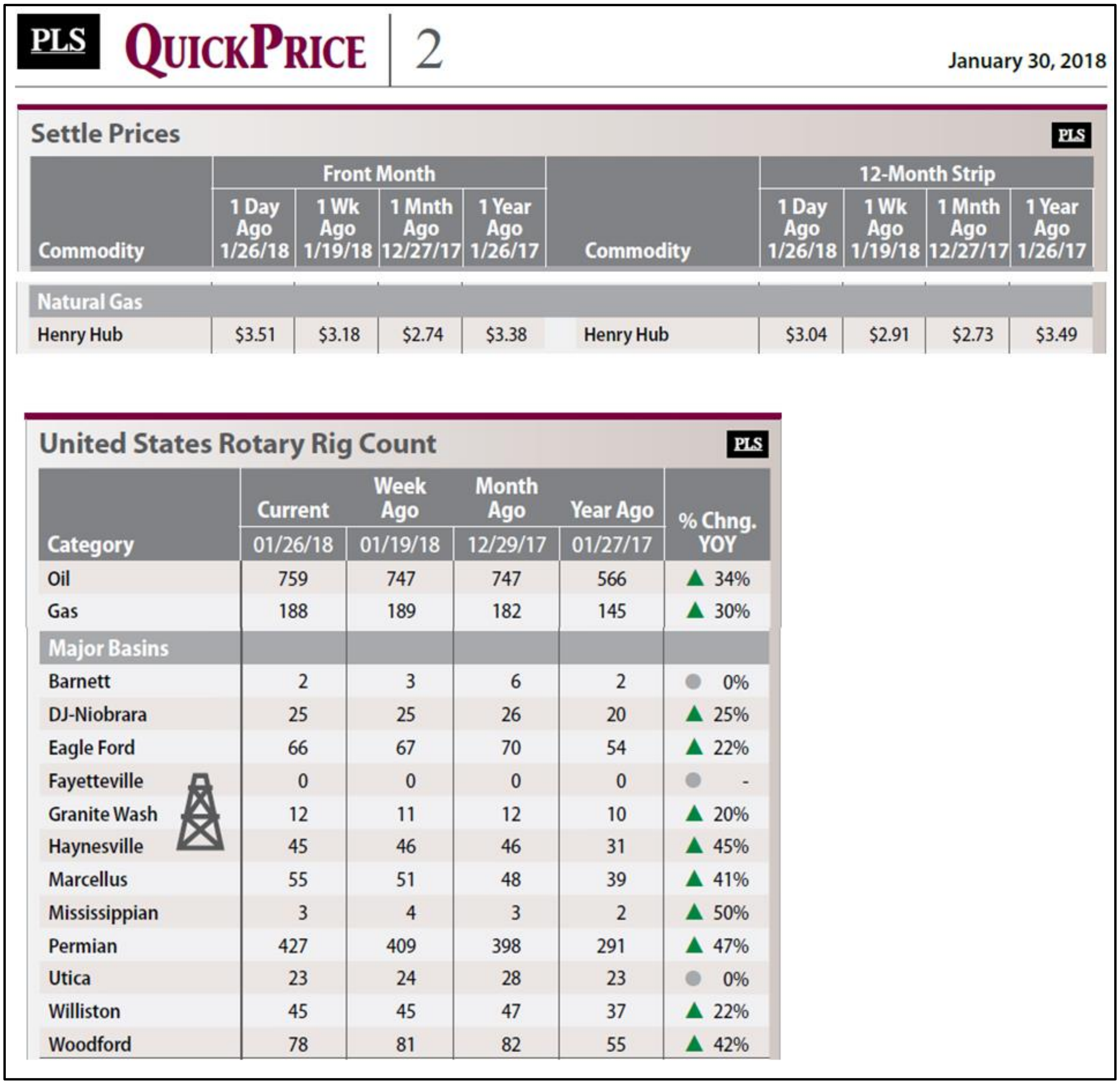
INTRODUCTION

The Haynesville Shale formation is currently a focus of significant drilling activity in east Texas and northwest Louisiana. Most of this activity occurs in the Texas counties of Harrison, Panola, Shelby, San Augustine, Nacogdoches, and in the Louisiana parishes of Caddo, De Soto and Bossier (Figure 1). The Haynesville shale is a Jurassic formation and its total extent of coverage is believed to be approximately 9000 square miles (Hammes et al, 2009). Observations from available well logs reveal the average subsea depth at which this formation is buried ranges from 10,500 in the northwest-northeast, to 14,000 ft. in the southwest portion of the play. Average thickness of the shale varies geographically, from about 150 feet on the Texas side, to about 350 feet on the Louisiana side. In some counties in East Texas, it is not uncommon for the Haynesville to be referred to as the “Lower Bossier Shale” due to the chronostratigraphic correlation with its Louisiana counterpart.

The Haynesville shale, a dark organic-rich shale, is overlain by the Bossier shale and underlain by the *Smackover/Haynesville* limestone (*name varies* subject to geographical occurrence and local use). The Bossier shale is occasionally a target for natural gas drilling, however the Haynesville is often preferred due to its deep burial, relatively high porosity as seen from well logs, and high reservoir pressures (Wang and Hammes, 2010). These qualities enhance of the attractiveness of the shale among oil and gas operators. According to data from leading industry tracking service PLS/Quickprice, current drilling rig count in the Haynesville shale play area is 45 rigs as of January 2018 (Figure 2). This is partly due to Henry Hub natural gas prices averaging $3/MCF within the past year, in addition to various LNG port facilities developed along the gulf coast in Texas and Louisiana to facilitate natural gas exports (Figure 3).

The purpose of this study is to develop a predictive model to optimize reservoir targeting for future development by petrophysical evaluation of well logs and core data as well as initial production data from existing wells.

*Figure 1. County Map showing Haynesville shale geographic area across East Texas/Northwest Louisiana (Modified after Parker et al, 2009).*Smaller aerial map created in ArcGIS with Haynesville shale area highlighted by red square.



PLS QUICKPRICE | 2

January 30, 2018

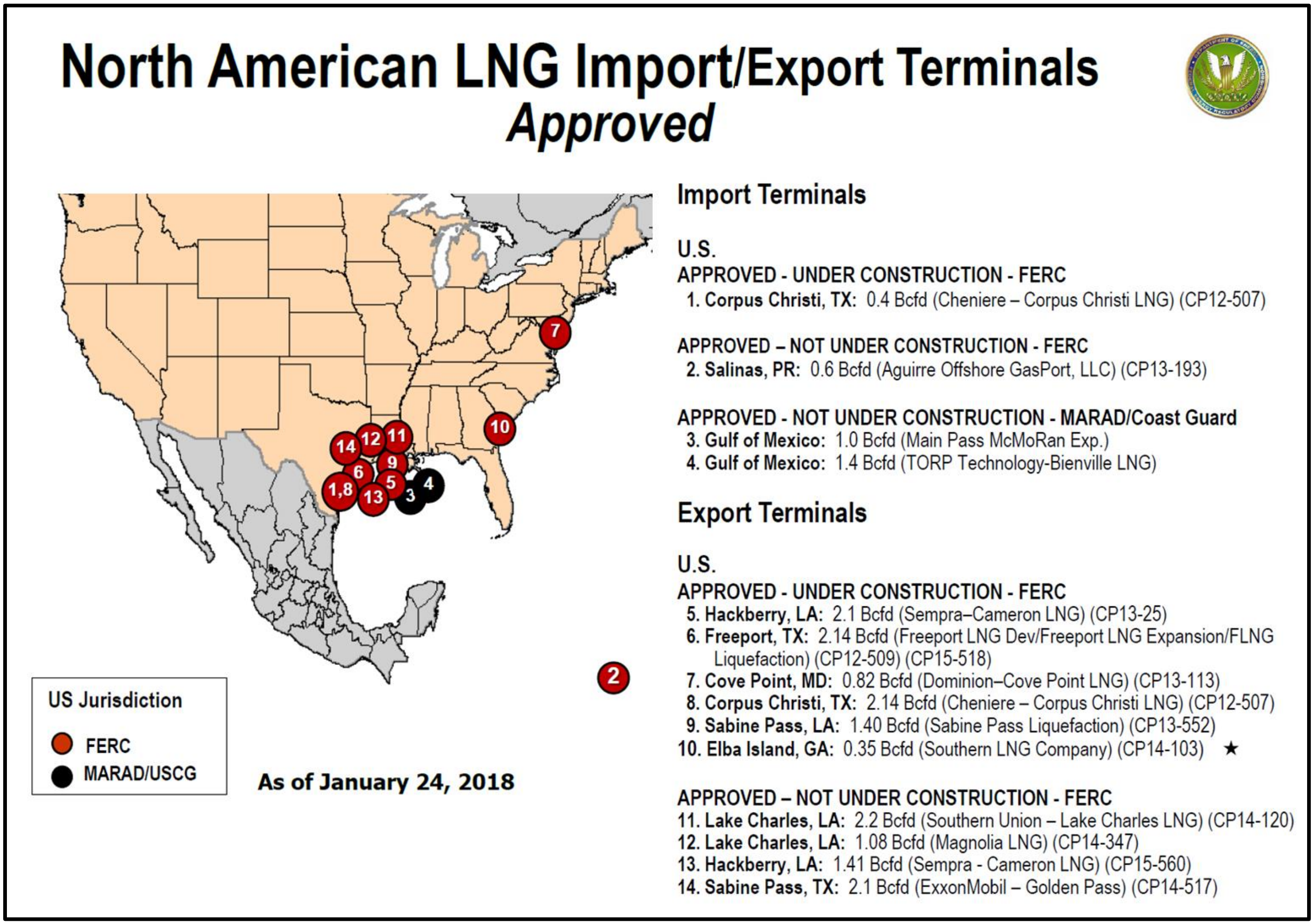
Settle Prices

Commodity	Front Month 1 Day Ago 1/26/18	1 Wk Ago 1/19/18	1 Mnth Ago 12/27/17	1 Year Ago 1/26/17	Commodity	12-Month Strip 1 Day Ago 1/26/18	1 Wk Ago 1/19/18	1 Mnth Ago 12/27/17	1 Year Ago 1/26/17
Natural Gas									
Henry Hub	$3.51	$3.18	$2.74	$3.38	Henry Hub	$3.04	$2.91	$2.73	$3.49

United States Rotary Rig Count

Category	Current 01/26/18	Week Ago 01/19/18	Month Ago 12/29/17	Year Ago 01/27/17	% Chng. YOY
Oil	759	747	747	566	▲ 34%
Gas	188	189	182	145	▲ 30%
Major Basins					
Barnett	2	3	6	2	● 0%
DJ-Niobrara	25	25	26	20	▲ 25%
Eagle Ford	66	67	70	54	▲ 22%
Fayetteville	0	0	0	0	● -
Granite Wash	12	11	12	10	▲ 20%
Haynesville	45	46	46	31	▲ 45%
Marcellus	55	51	48	39	▲ 41%
Mississippian	3	4	3	2	▲ 50%
Permian	427	409	398	291	▲ 47%
Utica	23	24	28	23	● 0%
Williston	45	45	47	37	▲ 22%
Woodford	78	81	82	55	▲ 42%

Figure 2. U.S. Rig count in major basins and natural gas prices (culled from PLS Quickprice bulletin, January 30, 2018)



North American LNG Import/Export Terminals

Approved

Import Terminals

U.S.

APPROVED - UNDER CONSTRUCTION - FERC

1. **Corpus Christi, TX:** 0.4 Bcfd (Cheniere – Corpus Christi LNG) (CP12-507)

APPROVED – NOT UNDER CONSTRUCTION - FERC

2. **Salinas, PR:** 0.6 Bcfd (Aguirre Offshore GasPort, LLC) (CP13-193)

APPROVED - NOT UNDER CONSTRUCTION - MARAD/Coast Guard

3. **Gulf of Mexico:** 1.0 Bcfd (Main Pass McMoRan Exp.)
4. **Gulf of Mexico:** 1.4 Bcfd (TORP Technology-Bienville LNG)

Export Terminals

U.S.

APPROVED - UNDER CONSTRUCTION - FERC

5. **Hackberry, LA:** 2.1 Bcfd (Sempra–Cameron LNG) (CP13-25)
6. **Freeport, TX:** 2.14 Bcfd (Freeport LNG Dev/Freeport LNG Expansion/FLNG Liquefaction) (CP12-509) (CP15-518)
7. **Cove Point, MD:** 0.82 Bcfd (Dominion–Cove Point LNG) (CP13-113)
8. **Corpus Christi, TX:** 2.14 Bcfd (Cheniere – Corpus Christi LNG) (CP12-507)
9. **Sabine Pass, LA:** 1.40 Bcfd (Sabine Pass Liquefaction) (CP13-552)
10. **Elba Island, GA:** 0.35 Bcfd (Southern LNG Company) (CP14-103) ★

APPROVED – NOT UNDER CONSTRUCTION - FERC

11. **Lake Charles, LA:** 2.2 Bcfd (Southern Union – Lake Charles LNG) (CP14-120)
12. **Lake Charles, LA:** 1.08 Bcfd (Magnolia LNG) (CP14-347)
13. **Hackberry, LA:** 1.41 Bcfd (Sempra - Cameron LNG) (CP15-560)
14. **Sabine Pass, TX:** 2.1 Bcfd (ExxonMobil – Golden Pass) (CP14-517)

US Jurisdiction

● FERC

● MARAD/USCG

As of January 24, 2018

Figure 3: LNG Export terminals approved/under construction along the U.S. Gulf Coast (East Texas/West Louisiana) in close proximity to Haynesville Shale play area. Image sourced from Federal Energy Regulatory Commission (FERC) web page.

Chapter 2

GEOLOGIC OVERVIEW

2.1 Study Area

The Haynesville shale covers an area of approximately 9000 square miles (Hammes et al, 2009), cutting across various counties in east Texas and parishes in northwest Louisiana (Figure 1). The data used in this study was supplied by companies operating in specific areas of the play. Wells used are located in the Texas counties of Panola, Shelby, and San Augustine. Others are from the Louisiana parish of De Soto. While the overall geology of the play is summarized below, more attention will be given to the local geologic conditions around each group of well bores.

2.2 Structural Setting

The Haynesville shale occurs in the East Texas and Northern Louisiana depositional basins. These basins were formed in the Mesozoic era along the northern gulf coast due to rifting and extension of the lithosphere during the opening of the Gulf of Mexico in the late Triassic (Pilger, 1981). Consequently, the Gulf of Mexico is classified as a passive continental margin (Torsch, 2012; Pilger, 1981). The rifting of the crust gave rise to increased sediment deposition due to subsidence brought on by conductive cooling (Nunn et al, 1984). These rift basins, formed on thin continental crusts, were subsequently separated by structurally positive elements such as the Sabine uplift bounding the eastern edge of the East Texas basin and the Monroe arch bounding the northeastern flank of the Northern Louisiana basin (Foote et al, 1988; Nunn, 2012).

The continental margin of the Gulf of Mexico was also subjected to faults during the late Mesozoic era brought about by halokinetics of Jurassic aged salt (Martin, 1978). Ever since that era, regional subsidence has contributed to the deformation of Mesozoic strata deposited due to sediment loading over the Louann salt thereby causing gravitational sliding of the Louann salt and overlying sediments (Foote et al, 1988).   This gravitational sliding of the salt contributed to the development of multiple salt diapirs which in turn formed an inner belt of basins across the northern rim of the Gulf of Mexico, such as the East Texas, North Louisiana and Central Mississippi basins. Consequently, it was on these salt-supported structures and during a gradual transgression in the Late Jurassic that the Haynesville was deposited as the offshore equivalent of a carbonate build up around the shelf margins and platforms (Fig. 5).

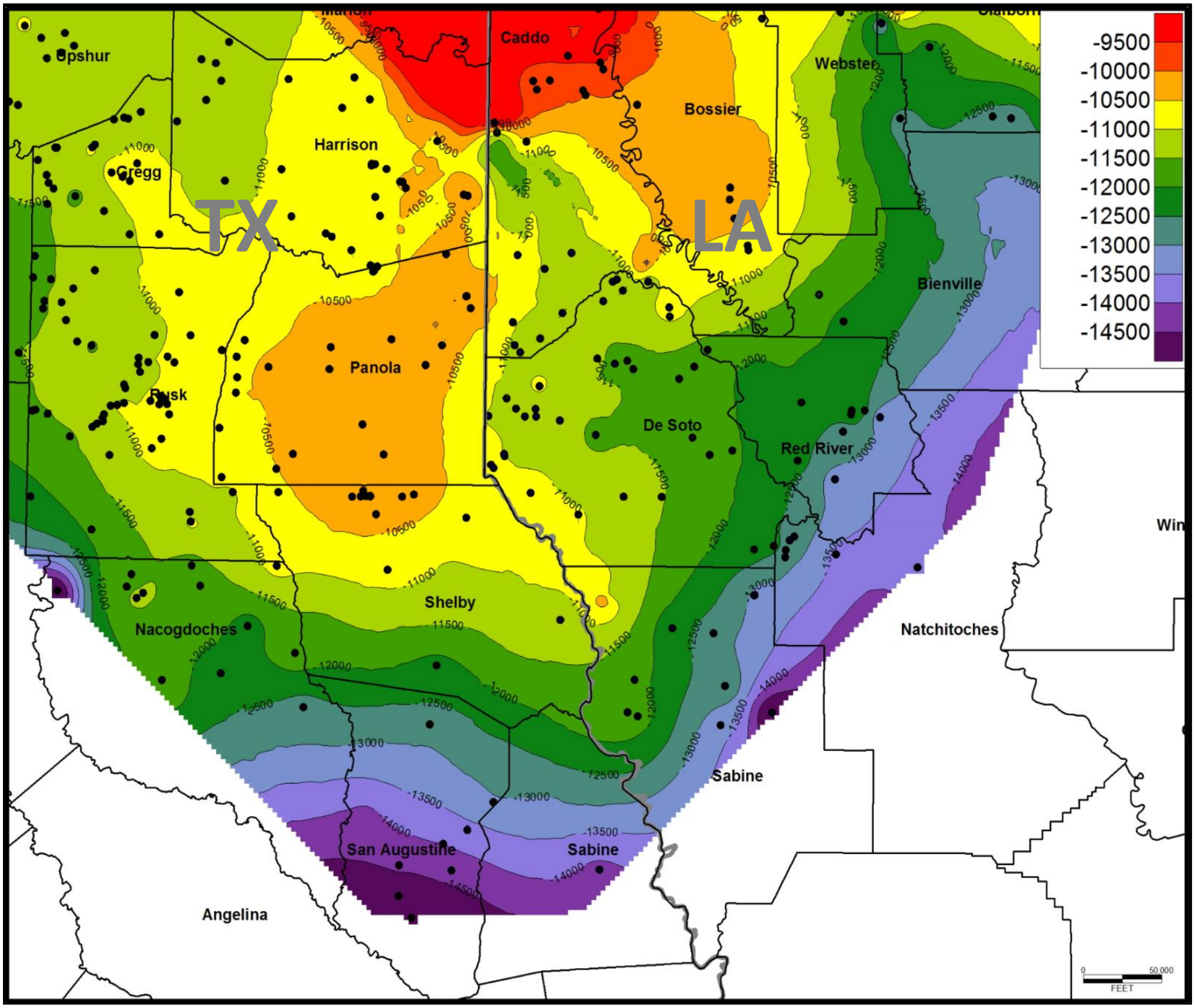


Figure 4. Structure contour map of the top of the Haynesville shale in East Texas/Northwest Louisiana (Map made in Petra software with tops picked from well logs).

2.3 Depositional Environment/Stratigraphy

The Haynesville shale, a naturally fractured organic-rich black mud rock, was deposited in a restricted basin under mostly anoxic conditions that preserved the organic matter. The deposition of the Haynesville was influenced by basement structures, local carbonate platforms and salt movement associated with rifting in the Gulf of Mexico basin. The movement of salt in particular may have triggered differential subsidence causing variations in facies and thickness of the shale across the basin (Hammes and Frebourg, 2012). The mud rock consists of calcareous-dominated facies near carbonate platforms toward the southern edges of the Gulf of Mexico basin, to siliceous-dominated facies towards the northern edge where deltas prograde into the basin and dilute organic matter (Hammes et al, 2012). Subsequent tectonic activity in the Cretaceous and Cenozoic may have influenced heat flow and burial history thereby encouraging organic facies maturation. The Haynesville and Lower Bossier shales make up the upper-most units of a transgressive systems tract (TST) with alternating carbonate and clastic facies representing simultaneous progradational and retrogradational facies.

Within the context of deposition in the East Texas basin, deposition of the Haynesville shale varies in terms of its lithofacies; the western portion is more carbonate-dominated and fairly restricted from siliciclastic sedimentation, while the eastern portion is dominated by more siliciclastic facies as shown in Figure 5, due to increased sediment supply from the Paleo Mississippi (Cicero and Steinhoff, 2013). The variations in depositional environments of the shales can be attributed to eustatic sea-level fluctuations, paleogeography, and local subsidence and sedimentation rates.

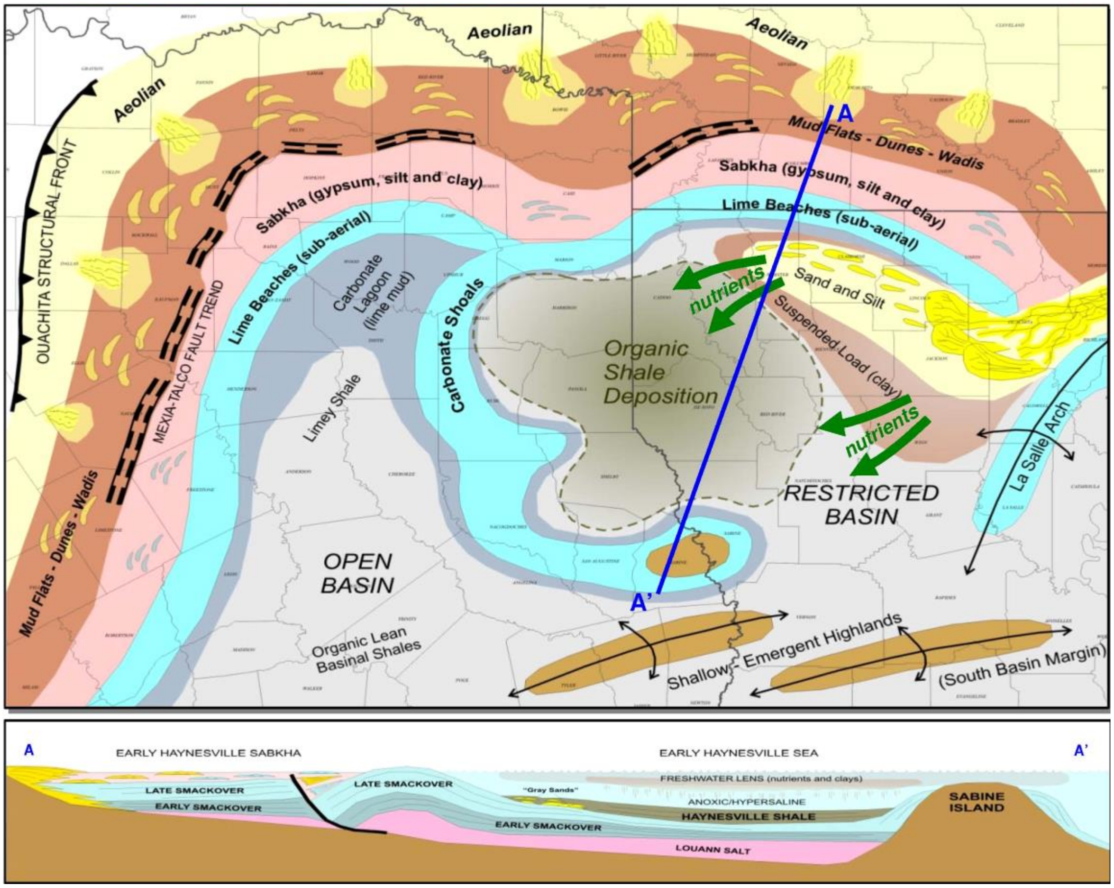


Figure 5. Depositional environment: Gulf Coast showing Haynesville organic shale deposition (culled from PVA Corp. Technical presentation, 2010)

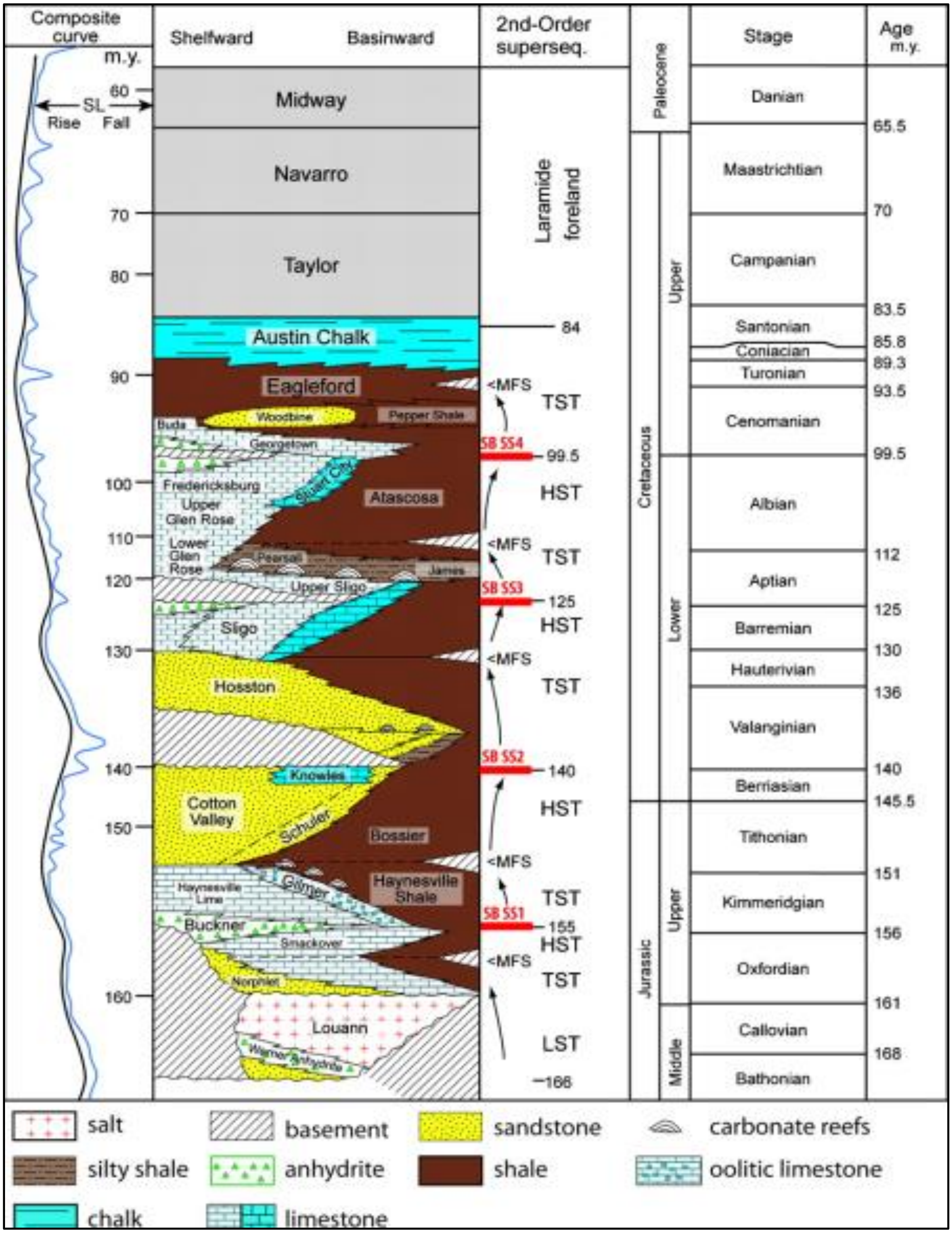


Figure 6. Stratigraphic Column of Northeast Texas/Northwest Louisiana showing Haynesville shale (Culled from Goldhammer, 1998; Hammes et al, 2011) (TST= Transgressive Systems

Tract, HST= Highstand Systems Tract, LST= Lowstand Systems Tract). Note- Error: diagonal lines identified as "basement" actually symbolize "unconformity.")

The Haynesville shale overlies sequences of carbonates such as the Haynesville Limestone and the Smackover Limestone as shown in Figure 6 above. Consequently, these sequences are indicative of a transgressive carbonate depositional system of which the top of the Haynesville represents a maximum flooding surface or MFS (Cicero and Steinhoff, 2013). The Bossier shale overlies the Haynesville and its log characteristics are distinct from the Haynesville, being less organic rich, containing more clay and silica, and possessing different lithofacies and stacking patterns. There are three different mudstone facies identified within the Haynesville: unlaminated peloidal siliceous mudstone, laminated peloidal calcareous mudstone, and bioturbated calcareous or siliceous mudstone (Hammes, 2012). Accordingly, it has been noted that a transition occurred from a generally transgressive, carbonate-dominated system during Smackover through Haynesville time, to a more progradational, argillaceous system during the deposition of the Upper Bossier shale formation. Within the shale facies of the Haynesville system, flooding surfaces and sequence boundaries are easily identifiable due to the similarities between facies assemblages and log stacking pattern. However, differences occur between the western shelf of the basin and the eastern shelf. The western shelf is rimmed by carbonate banks and shoals (Hammes et al., 2011) thus giving the log stacking patterns a retrogradational outlook indicative of back-stepping carbonate facies that eventually drown out the carbonate platform during the deposition of the Bossier. With the assumption of constant eustatic sea level across the western shelf, it can be deduced that subsidence rates outpace sediment supply, giving rise to retrogradation. On the Eastern shelf of the Haynesville system, a continental drainage system was in place as early as Smackover time, providing clastic input to the Haynesville basin and creating an overall progradational system by sedimentation exceeding subsidence rates, filling available accommodation space and spilling basinward (Cicero and Steinhoff, 2013). Log signatures show fluvial-deltaic sand leading to the conclusion that clastic influx was very high during Haynesville time and younger.

Many authors and industry professionals split the Haynesville formation into two parts: the Upper Haynesville and the Lower Haynesville (Fig. 7). The lower Haynesville is the facies characterized by very high gamma ray readings on well logs (API >150), also referred to as “hot shales”, indicating the organic rich material (Buller and Dix, 2009). It represents continued basin deepening and is the lowermost portion of the Transgressive Systems Tract (TST) of the Haynesville sequence. It is primarily back-stepping carbonates grading basinward into organic rich marine shales. Features from cores show that the lower Haynesville was deposited in the deepest and most anoxic part of the Haynesville basin in subaqueous conditions (Hammes et al, 2011), hence creating the potential for the enrichment and preservation of the total organic carbon (TOC). The upper Haynesville has a somewhat similar depositional environment to its lower counterpart; the marked difference being that its log response has slightly lower gamma ray values (API ~100) hence it is inferred that its deposition occurred under slightly more siliceous conditions as the continental drainage system became stronger during this period thus increasing siliciclastic sediment supply into the Haynesville basin (Cicero and Steinhoff, 2013).

The porosity in the Haynesville is comprised mostly of organic matter hosted pores and inter-granular-type pores. The mineralogy of the Haynesville shale as seen in core samples is dominated by calcite, quartz and clay. Permeability occurs in the order of nanodarcies; therefore economic recovery will be impossible without hydraulic fracturing. Formation temperature in certain areas can exceed 300 degrees Fahrenheit (Male et al., 2015). Total Organic Carbon (TOC) values are within the range of 2-6%. Overall, it is mostly thermally mature and contains primarily dry gas. The formation is also highly pressurized with some wells recording initial pressure of 13,000psi (~ 0.9psi/ft. pressure gradient) and initial production rates of around 9-14 Mmcf/d.

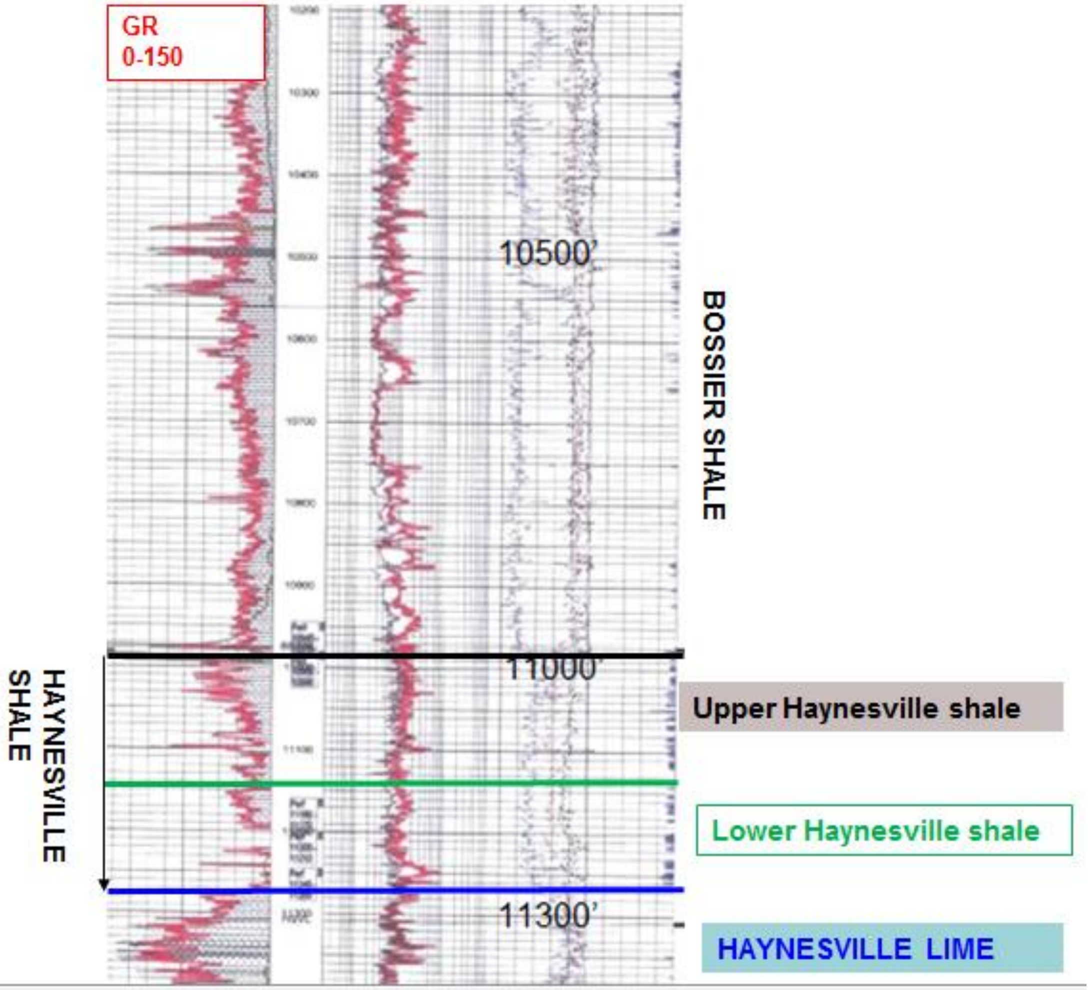


Figure 7: Modified log image from a well in Harrison Co., Texas, showing interpreted divisions between upper and lower Haynesville shale, with lower Haynesville showing very high GR "hot shale" readings

Chapter 3

DATA AND METHODS

3.1 Data Used

The well data used in completing this project was donated by companies operating within the area of interest. This data includes vertical wells that penetrated the Haynesville formation and offset horizontal wells that were drilled within the same formation. Numerous wireline logs were examined and tops were picked to create a structural subsurface map of the Haynesville (Figure 4.) to highlight the depths and overall dipping trend of the formation. A gross isopach map was also created to show the thickness of the Haynesville shale across the region (Figure 8).

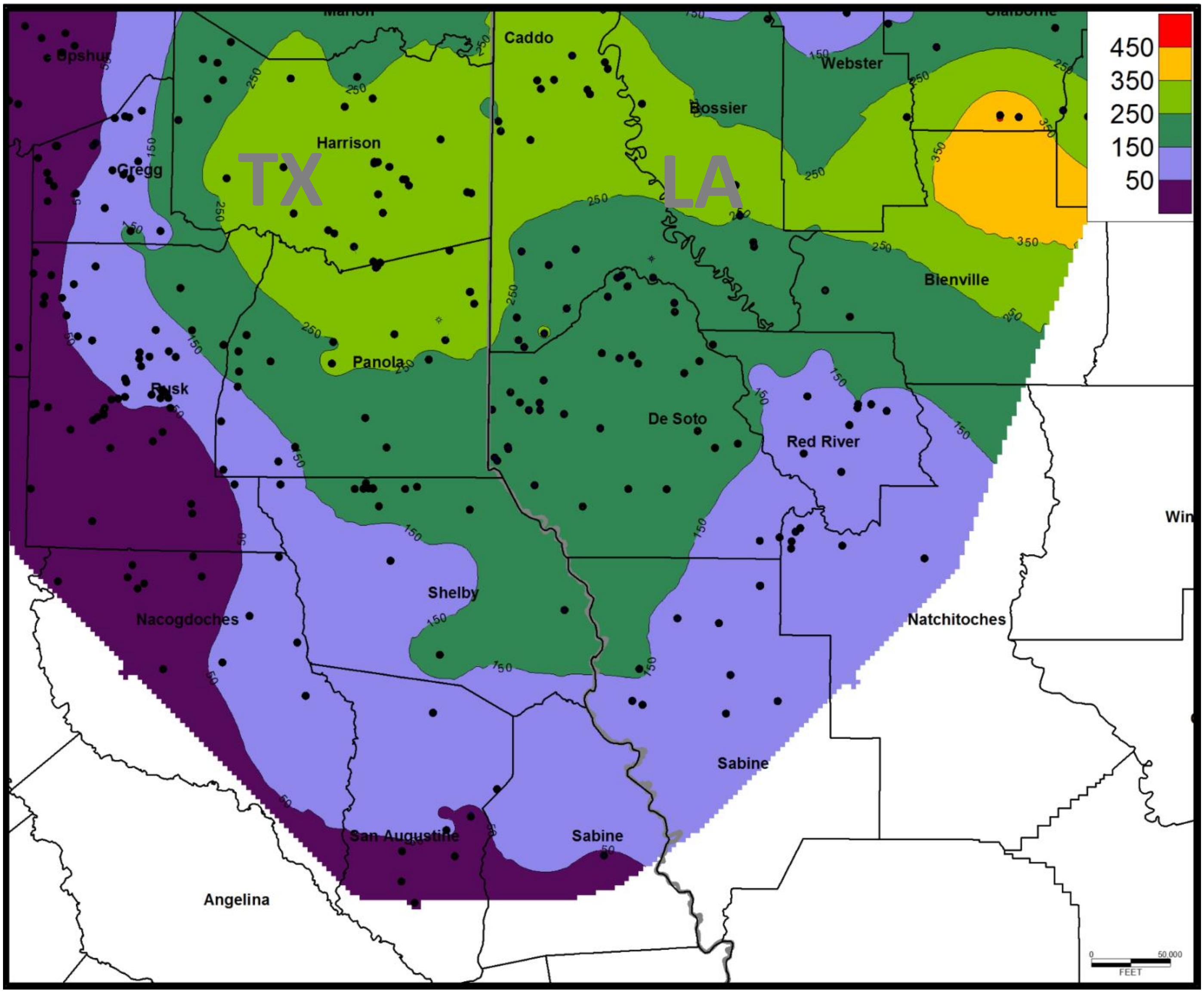


Figure 8: Gross Isopach map of the Haynesville shale

Six typelogs were selected to be used as a case study (Figure 9). Four of these typelogs were located in Texas and labelled thus: **T1** and **T2** in Panola County, **T3** in Shelby County and **T4** in San Augustine County. Two others were located in

Louisiana: **L5** and **L6** in De Soto Parish. These typelogs were selected based on the availability of complete sets of quad combo log suites (gamma ray, resistivity, porosity, and sonic logs), core data, and a cluster of lateral wells drilled to offset them. Some horizontal wells drilled around each typelog were incorporated to examine their landing points, completions and production profiles. These horizontal wells were “reverse-geosteered” to determine their original landing points and trajectory and compare against the determined preferred target intervals from the petrophysical analysis of the typelogs.

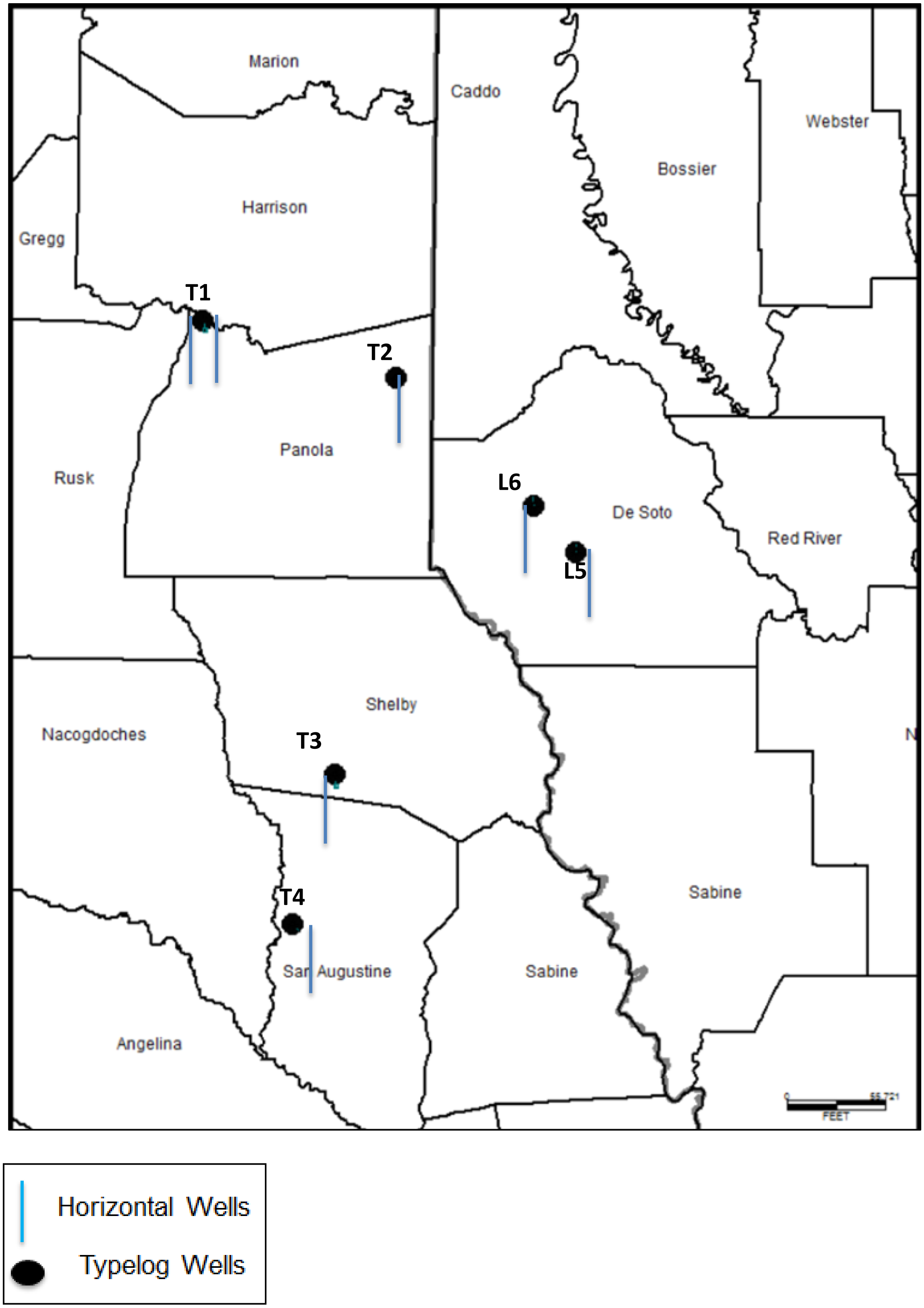


Figure 9: Map showing location of Typelogs and horizontal wells

3.2. Methods

As mentioned earlier, the Haynesville shale is easily distinguished from the overlying Bossier shale and the underlying Smackover limestone due to its high gamma ray signature. Observations from well logs also indicate a slight increase in resistivity averaging 10 ohms or greater, with porosities of around 9-14%.

The primary focus is to examine the geomechanical properties within the Haynesville to determine the best possible zones for landing laterals (i.e. the most brittle intervals) within the shale. Rickman et al (2008), postulate that the key factors to consider before designing a successful hydraulic fracturing treatment of any shale play are both geomechanical and geochemical. The primary geomechanical consideration is the shale brittleness which can be determined from petrophysical evaluation. The primary geochemical consideration is the mineral composition of the shale, which can be determined from laboratory analysis of core data in addition to petrophysical evaluation. When taken into account, these factors can influence well planning and placement, thereby ultimately impacting productivity.

3.3. Mechanical Properties

The Key to determining rock brittleness lies in the combination of Young's Modulus (YM) and Poisson's Ratio (PR). The Poisson's Ratio is the ratio of lateral strain (perpendicular to an applied stress) to the longitudinal strain (parallel to applied stress). It measures the geometric change of shape under uniaxial stress. The Young's Modulus, also known as the elastic modulus, is the ratio of uniaxial compressive stress (force applied per unit area) to the resultant strain (proportional distortion brought on by the applied force). (*Rickman et al, 2008*).

In order to calculate the Young's Modulus and Poisson's Ratio, it is necessary to have sonic log curves; Delta T-Compressional (DTCO) and Delta T-Shear (DTSM) throughout the formation. It is also essential to have a bulk density curve (RHOB). These curves were all present in the typelog wells analyzed.

Accessory data from core analysis, specifically X-ray diffraction (XRD) data, was incorporated to provide actual mineralogical compositions of the formation.

The data from XRD shows the primary mineral composition for the Haynesville shale to be silica (quartz), calcite and clays. The clays consist mainly of illite and smectite, with virtually no kaolinite present (Quirein et al, 2010; core XRD data from typelogs). In some cases, pyrolysis data was available showing TOC and kerogen volume estimates across the cored intervals in the Haynesville.

Successful reservoir optimization of the Haynesville would require horizontal drilling in order to connect fractures thereby enhancing productivity. The typical lateral lengths of wells in the Haynesville vary from 3000 – 8000 ft. Owing to data constraints such as limited number of deep well logs, proximity to nearby wells with complete log sets, or unavailability of cores and well logs due to cost saving measures, it is useful to have a template of geomechanical and geochemical properties that could serve as a guide for the operators to identify the best interval to land the laterals in order to maximize stimulation treatments. Calculations were computed from equations established in multiple research papers for mechanical properties, with certain parameters customized for the local geology. The major calculations included Poisson's Ratio (PR), Young's Modulus (YM), Brittleness (BRIT); Mineral Volumes such as Clay (Vclay), Calcite (Vcalc.), Silica (Vquartz), Kerogen (Vker.), Total Porosity, and Shale Volume (Vshale). These calculated parameters were then compared to their core derived counterparts to see how closely they match in an effort to make a deterministic template.

To compute the Poisson's Ratio (PR) and Young's Modulus (YM), the following equations were deployed:

Poisson's Ratio (PR) =

υ	Poisson's Ratio	$\frac{\text{Lateral strain}}{\text{Longitudinal strain}}$	$\frac{\frac{1}{2}[(DTS/DTC)]^2-1}{(DTS/DTC)^2-1}$

--*(Equation 1)*

Where,

DTS= Delta T-Shear in us/ft. (from Sonic Log)

DTC= Delta T-Compressional in us/ft. (from sonic log).

Young's Modulus (YM) =

E	Young's Modulus	$\frac{\text{Applied uni-axial stress}}{\text{Normal strain}}$	$2G(1+\upsilon)$

-- *(Equation 2)*

Where,

G= shear modulus, derived by $\frac{\rho_b}{DTS^2} \times a$

ρ_b is Bulk Density in g/cm3 from the well log, often characterized as RHOB, RHOZ, etc. depending on the logging company,

a is a constant of 1.34×10^{10}, provided bulk density is in g/cm3 and DTS is in us/ft.

DTS is Delta T-Shear from sonic log

υ is Poisson's Ratio (PR).

As stated earlier, the main focus of this work is to determine the brittleness factor of the shale interval and highlight the best possible zones for placing laterals. This is because a brittle interval will respond positively to hydraulic fracturing treatments since it is most likely already naturally fractured, in comparison to ductile shale which tends to heal any natural or hydraulic fractures (Rickman et al, 2008). The brittleness factor computed from petrophysical evaluation takes into account the rock mechanical properties (YM and PR) and is intended to serve as a possible alternative/guide to actual rock measurements derived from core, considering that in present day practical industry operations, cores and complete log suites are rare to find due to the high cost of obtaining them. Many operators do not drill pilot holes or run open-hole logs; they proceed to drilling the laterals as offset to the nearest well with complete log information which in some cases could be several miles away. This is based on the assumption of lateral continuity of relevant reservoir properties. The equations used to calculate the brittleness factor (BRIT) from the Young's Modulus and Poisson's Ratio are derived from work previously done by *Rickman et al, 2008 and Mullen et al, 2007*:

$YM\_BRIT = [(YM - 1) / (8 - 1)] * 100$………………………….. *(Equation 3)*

$PR\_BRIT = [(PR - 0.4) / (0.15 - 0.4)] * 100$ ……………………… *(Equation 4)*

$BRIT = (YM\_BRIT + PR\_BRIT) / 2$ ---------------------- *(Equation 5)*

Furthermore, additional computations for Rock Mineral properties (Vclay, Vcal, Vker, Total Porosity, and VQuartz) were modeled and compared to actual nearby core measurements to see how closely they matched in an effort to make a model that can be used to further strengthen confidence in selection of subsequent lateral landing zones for reservoir optimization. This was done for all typelog wells using simultaneous equations modified after *Asquith*, *2010* with certain adjustments (correction factors) made to fit local geologic conditions of the Haynesville.

Volume of Kerogen

$VKer = (TOC * Kvr * \rho B) / \rho Kerogen$ …………………. (*Equation 6)*

$TOCLog = (156.956/\rho B) - 58.271$ ----- (Schmoker Equation) ……. (*Equation 6.1)*

Constants* ***156.956* *and* ***58.271*** *adjusted to match measurements from nearby core TOC Pyrolysis data. Values used are* ***95.524*** *and* ***35.093*** *respectively. Correction factor of* 1.6 *applied*

Total Porosity

$$Total\ \Phi = \{[NPHI-\Phi nCl) + [(\Phi nCl - \Phi nQtz) / (\rho Qtz-\rho Cl) * [(\rho B-\rho Cl) + Vker * (\rho Cl-\rho Qtz)]] + [Vker *(\Phi nCl - \Phi nKer)]\} / \{(\Phi nf-\Phi nCL) - [(\rho Cl-\rho f)*((\Phi nCL - \Phi nQtz) / (\rho Qtz - \rho Cl)]\}$$

………. …… (*Equation 7)*

Volume of Quartz

$$VQtz = \{(\rho B- \rho Cl) + [VKer*(\rho Cl- \rho Qtz)]+[\mathbf{Total\ \Phi*(}\ \rho Cl- \rho f)]\} / (\rho Qtz- \rho Cl)$$

………. …… (*Equation 8)*

Volume of Clay

$Vclay = Vsh * 0.60$ …………………. …… (*Equation 9)*

Vsh (Shale Volume) = $[GRlog - GRsand] / [GRshale - GRsand]$ …. (*Equation 9.1)*

Where:

GR log (variable) = GR value at a particular point on the log,
GR Sand (constant) = lowest GR (preferably from a clean sand up-hole)
GR Shale (constant) = highest GR value from the shale formation

Assumption that most shales are composed of 50-70% clay, hence cut-off of 60% for calculating VClay is applied, per *Bhuyan and Passey, 1994*.

Volume of Calcite

Vcal= 1- [Vclay + VQtz + Vker + Total Φ] ………………… …… (*Equation 10)*

Default Values/Constants

ρCl = 2.71 g/cm3

ρQtz = 2.65 g/cm3

ρf =0.3g/cm3

ρKer =1.2g/cm3

ρgas=0.1g/cm3

ρwater=1.1g/cm3

KVr= 1.2

ΦnCl=0.35

Φnf= 0.52

ΦnKer= 0.40

ΦnQtz= -0.05

Φngas=0.4

Φnwater=1

3.4 Well Log Analysis

Typelog #T1 (Panola County, Texas)

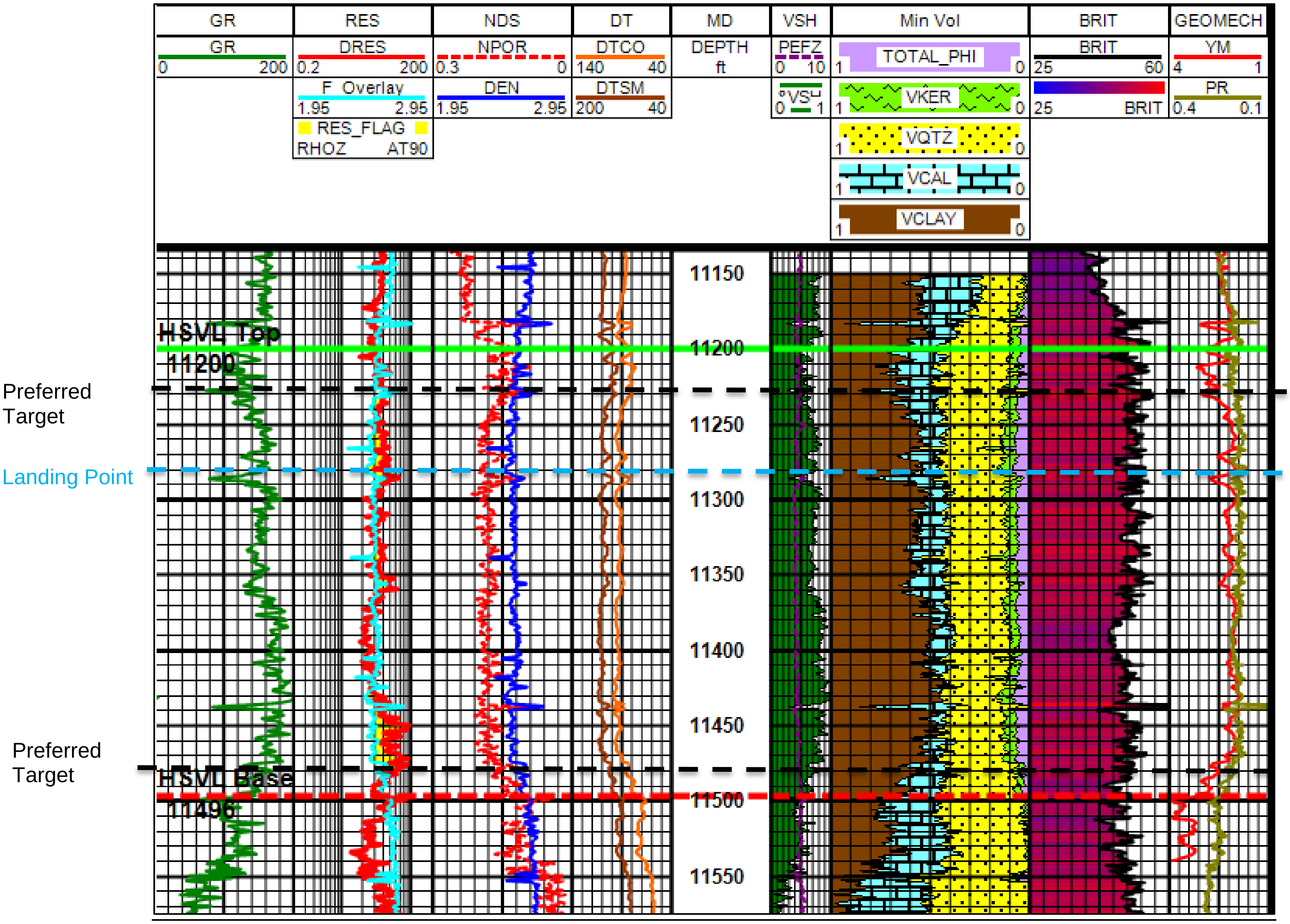


Figure 10. Log Analysis showing the Haynesville section in the T1 typelog, Panola County, Texas

Figure 10 shows an analyzed quad combo log over the Haynesville interval, with the top of the Haynesville (solid green line) and the base (dotted red line). The depth track is in the middle. The log curves on the left are raw digital curves: Gamma Ray (GR), Resistivity (DRES), Neutron/Density Porosity curves (NPOR/DEN), and acoustic curves- delta shear and delta compressional (DTSM/DTCO). The resistivity flag is highlighted based on an overlay of the bulk density (RHOB) curve to show areas with a resistivity cutoff greater than 10 ohms. The top of the Haynesville was picked where the Neutron and Density curves converge because this is a very consistent indicator across the Haynesville area. The base of the Haynesville was picked where the Gamma begins to decrease significantly as this indicates a transition in facies from shale to limestone (the Smackover/Haynesville limestone). The curves on the right of the depth track are mostly interpretive, showing the calculated Shale Volume (Vsh), Mineral Volume: Volumes of Calcite, Quartz and Clay (Vcal, Vclay, Vqtz,), Volume of Kerogen (Vker), and Total Porosity (Total Phi). These were derived from the Simultaneous equations above *(Equations 6, 7, 8, 9, 10)*. Also shown are the Brittleness (BRIT) curve, Poisson's ratio (PR) and the Young's Modulus (YM: 1 x 10^6). The PR and YM were derived from *Equations 1 and 2* respectively, using the DTCO, DTSM and RHOB log curves. The BRIT was derived simultaneously from *Equations 3, 4 and 5*. The areas of high brittleness are brightly colored (red-pink) while the less brittle/ductile areas consist of darker colors (blue-purple).

Based on the brittleness and geomechanical properties of the typelog T1, it appears that the upper and middle parts of the Haynesville interval: 11210-40’ 11260-90’ and 11310-60’ are the most brittle areas. These depth intervals selected are hereafter referred to as target zones. Additionally, an increase in resistivity also lends credence to the selection of these zones as the best areas to place a lateral wellbore; higher resistivity is widely understood to be an indicator of hydrocarbons present. This idea is further bolstered by the assumption of Passey’s (1990) method of estimating organic richness in shales by overlying density with the resistivity curve and highlighting their separation as possible indication of high TOC. The XRD from core in this well shows the following *average* mineral values over these intervals: 35%clay, 17% calcite, 31%quartz, 5.6% Kerogen. These values are a close match to the log calculated mineral volumes from equations 6-10 above: 43%clay, 14%calcite, 31%qtz, and 5.4%kerogen. Two horizontal wells (laterals) were drilled on the east and west sides of the typelog and landed within the interval of 11270-11285’ (Fig. 11). Geosteering profiles were re-created to confirm the landing points of the laterals. Additionally, alternative completions profiles were developed for the laterals. These profiles were modeled on the brittleness curve from the typelog, to ascertain which parts along the laterals are the most brittle and will respond most favorably to hydraulic fracturing.

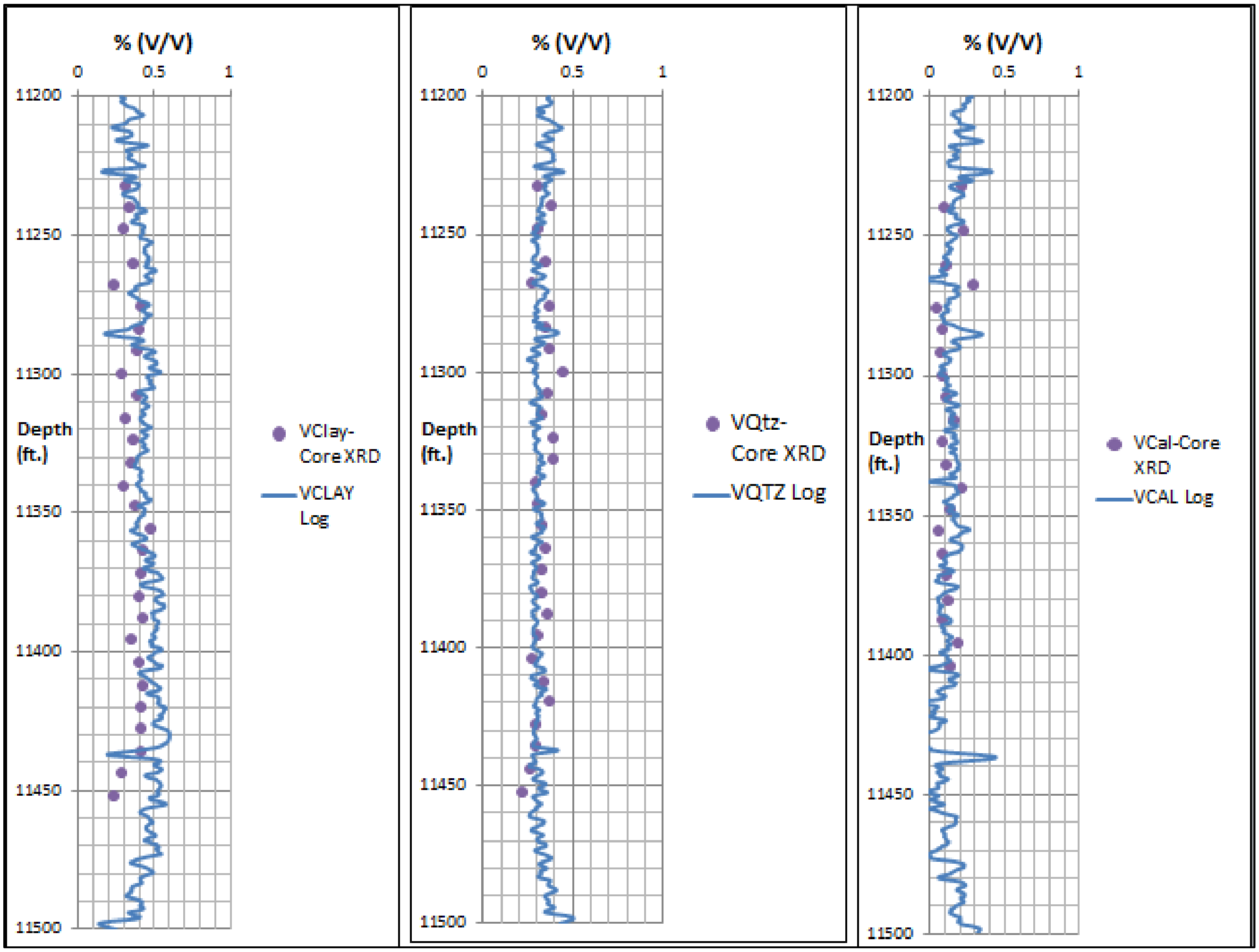


Figure 10a. Graph plots over Haynesville interval showing comparison of core XRD volumes (Purple dots) to calculated log volumes (Blue lines). Note: XRD volumes obtained from sidewall cores.

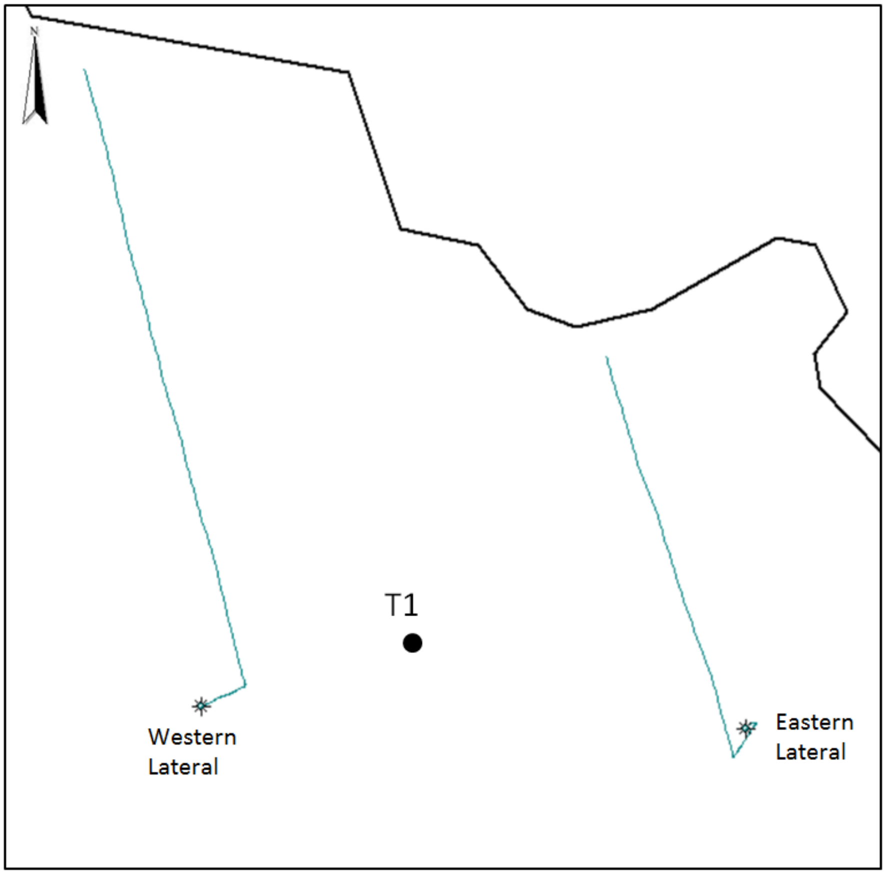


Figure 10b. Map showing position of typelog T1 and surrounding laterals (Distance from Western lateral to T1=0.5 Mile; from Eastern lateral to T1=1 Mile)

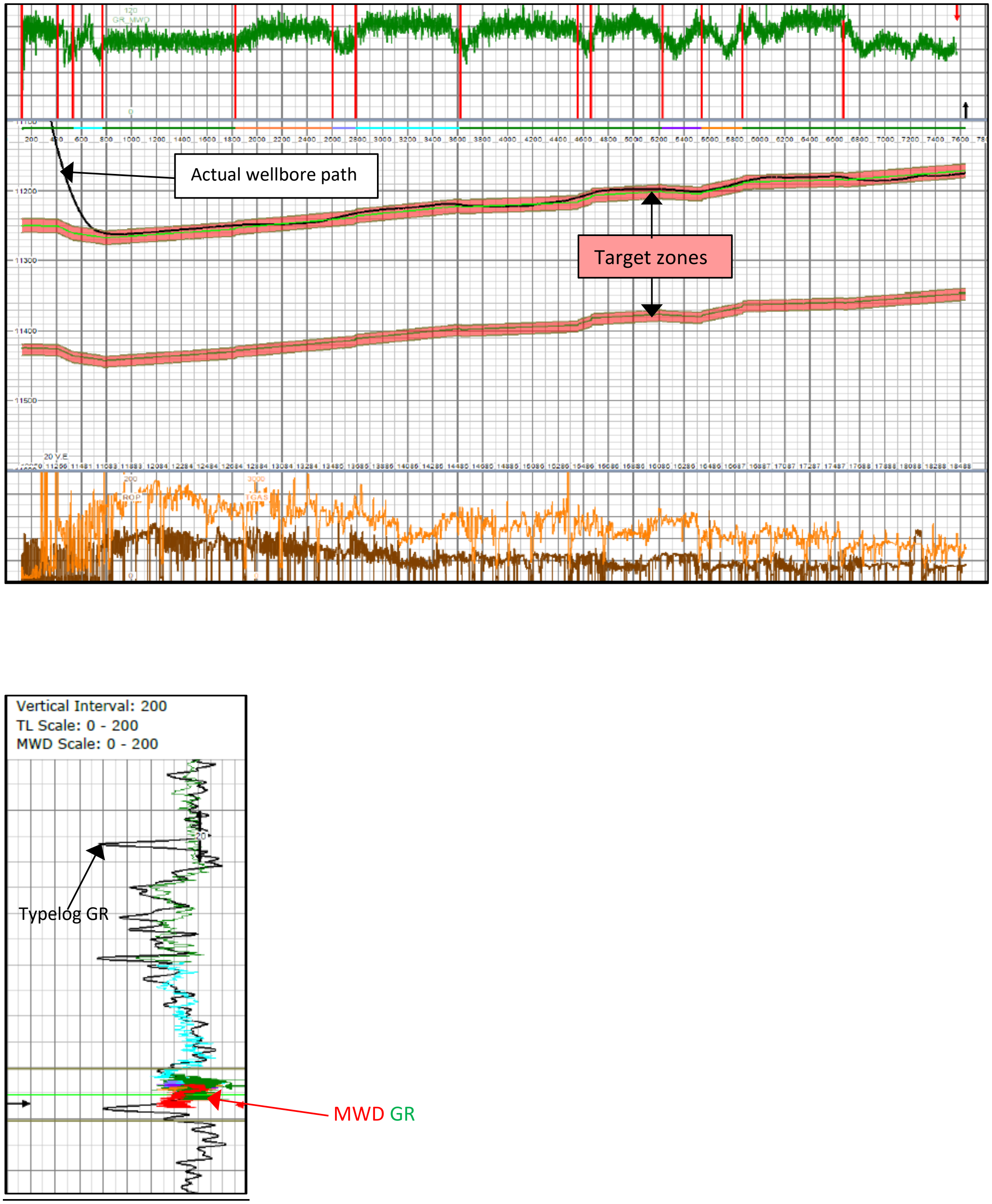


Figure 10c. ***Top image****- Geosteering interpretation window for Western lateral showing the target zones;* ***Bottom image****- Correlation window showing correlation of the mwd gamma (multi-colored curves) to the typelog gamma (solid black curve)*

Figure 10c is a lateral drilled to the West of the typelog T1 and was recreated by tying the MWD gamma ray to the typelog gamma ray. This shows the landing point to be 11275’ on the typelog (Figure 10). The lateral stayed mostly within the selected target zone shaded in red. A completion profile was modeled based on extrapolating the typelog brittleness (BRIT) curve along the lateral with the assumption that major reservoir properties remain relatively unchanged along the lateral length. In this case, the lateral length was approximately 6922’. The reason for doing this is to achieve fracture design optimization by highlighting brittle areas along the lateral that will be most amenable to hydraulic fracture treatment.

The available data reveals this well was fractured in 34 stages. The stage length was calculated by dividing the lateral length by the number of stages which in this case is 203’. The model is also based on the assumption that there were 6 clusters per stage and a cluster spacing of 30’. These assumptions are based on general industry practice given the unavailability of detailed completions information for the lateral. The cluster spacing is important to note because a smaller number (tighter spacing) signifies greater contact with the reservoir hence the potential for increased fracture propagation.

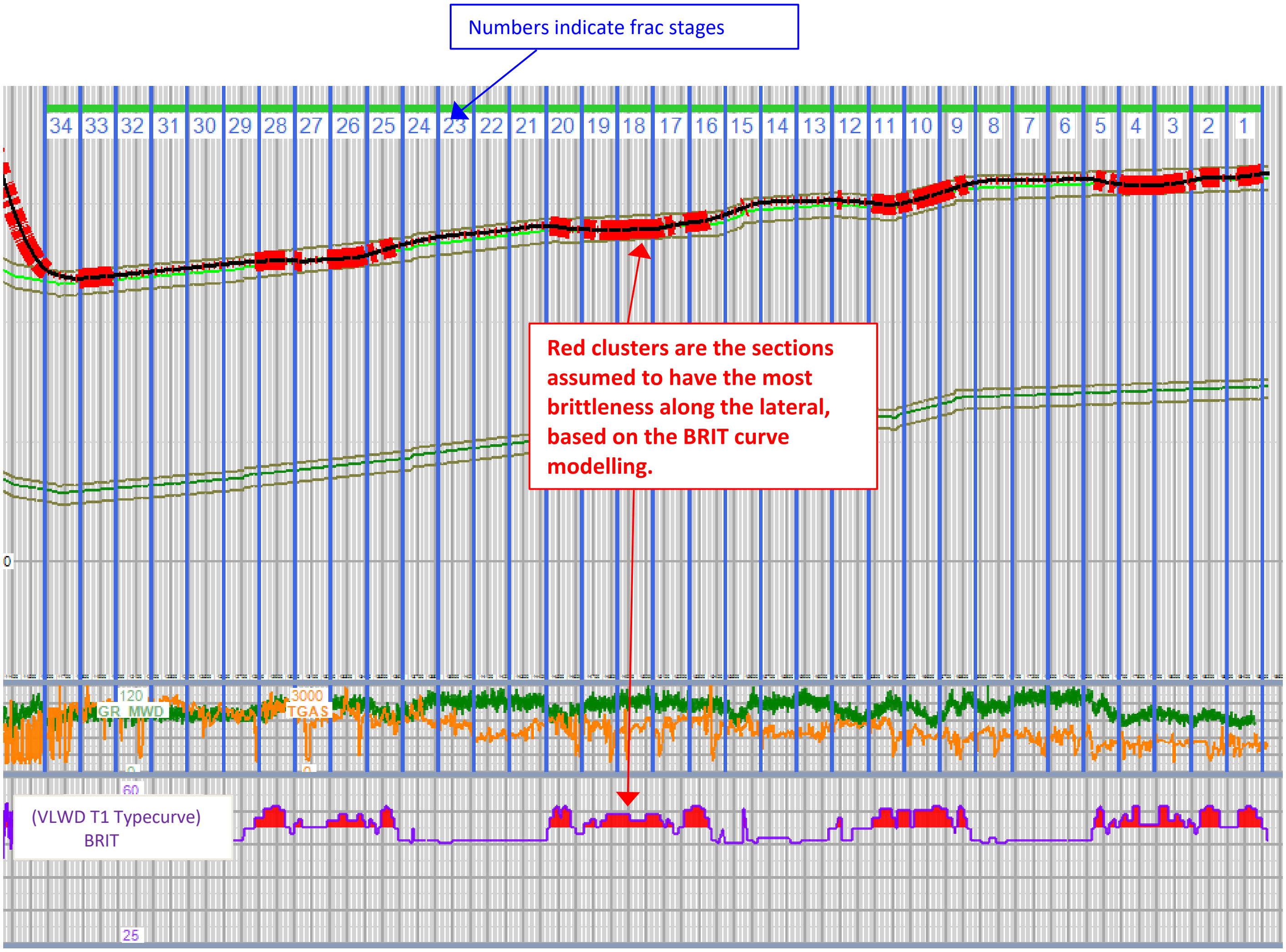


Figure 10d. Completion profile simulation for Western lateral of typelog T1 based on rock brittleness (BRIT) curve from typelog showing the proposed frac stages (Simulated with BHL Boresight completions module software)

In an ideal situation, after a well has been drilled, Fig. 10d could serve as a guide to select the most brittle areas to perforate and initiate fracture treatments. Multiple stages along the lateral can be treated selectively in terms of volume pumped, proppant concentrations, fluid types (i.e. gel, slick water or foam, etc.). Alternatively, since this lateral has been completed, this model could also aid in selecting zones for recompletion/re-fracturing operations to boost production and counter natural decline. This would be necessary upon determination by the operator that there are sufficient reserves in portions of the lateral that were untapped during the initial completion. The production data from the well was also analyzed. The well began producing in March 2013 and the peak 30-day rate (IP-30) was 9Mmcf. So far the Cumulative production is 4.3Bcf as of February 2018.

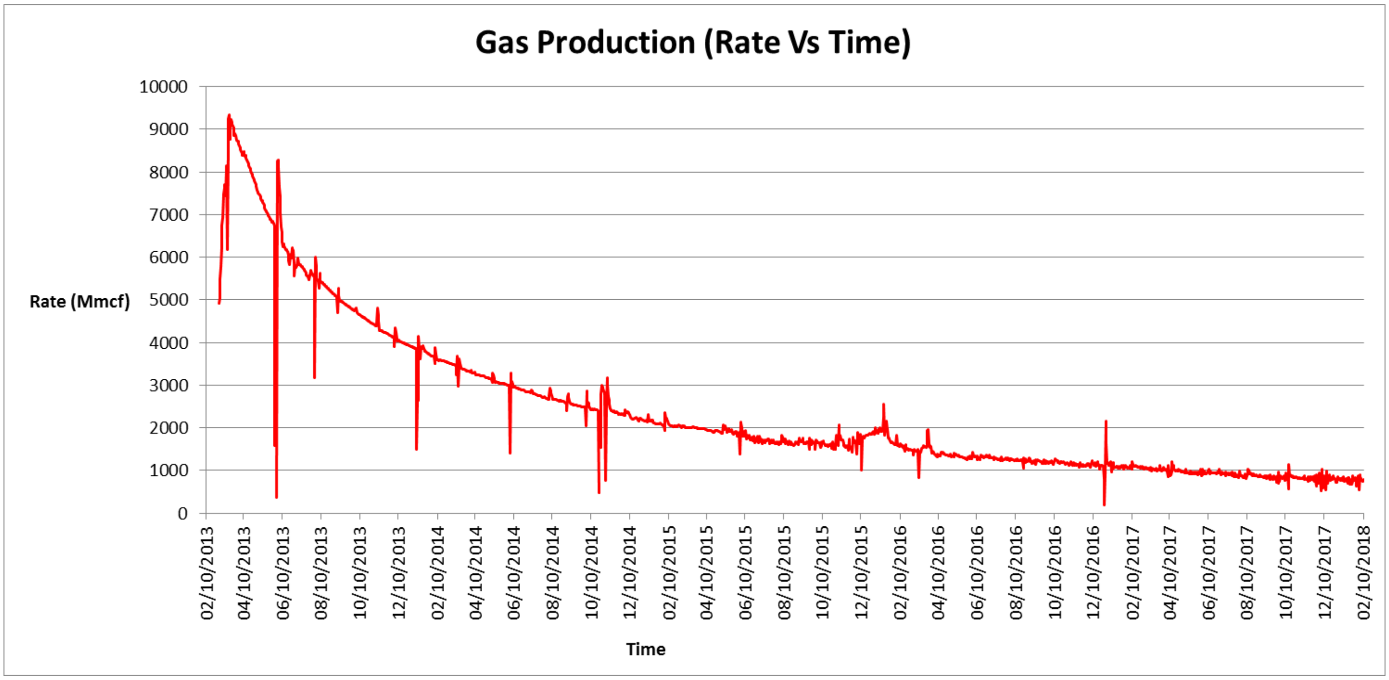


Figure 10e. Gas production from Western lateral offset of typelog T1.

Another lateral offset drilled to the East of typelog T1 was evaluated and a geosteering profile created to confirm its landing point. The brittleness curve from the typelog was also extrapolated to model the completions along the lateral.

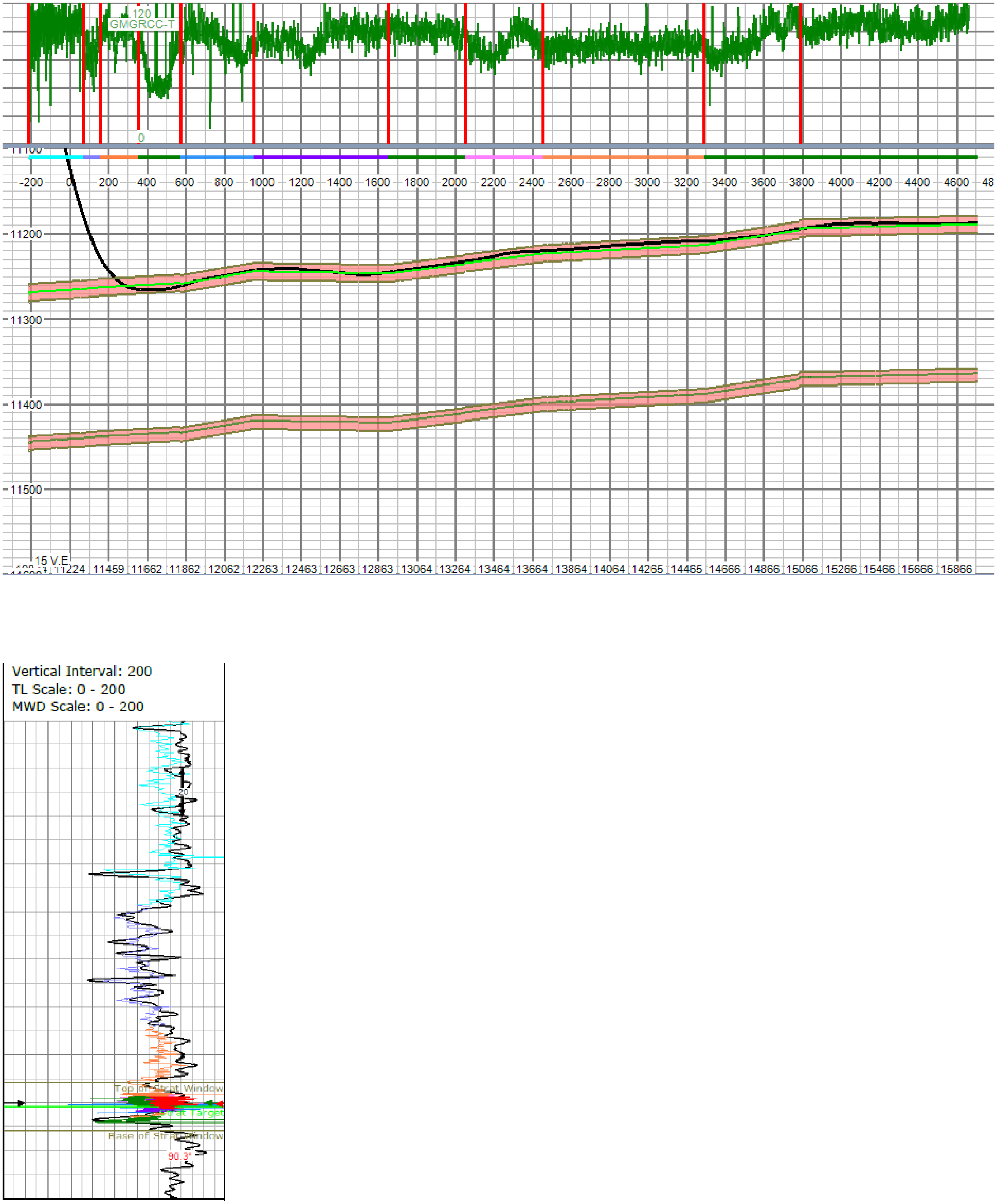
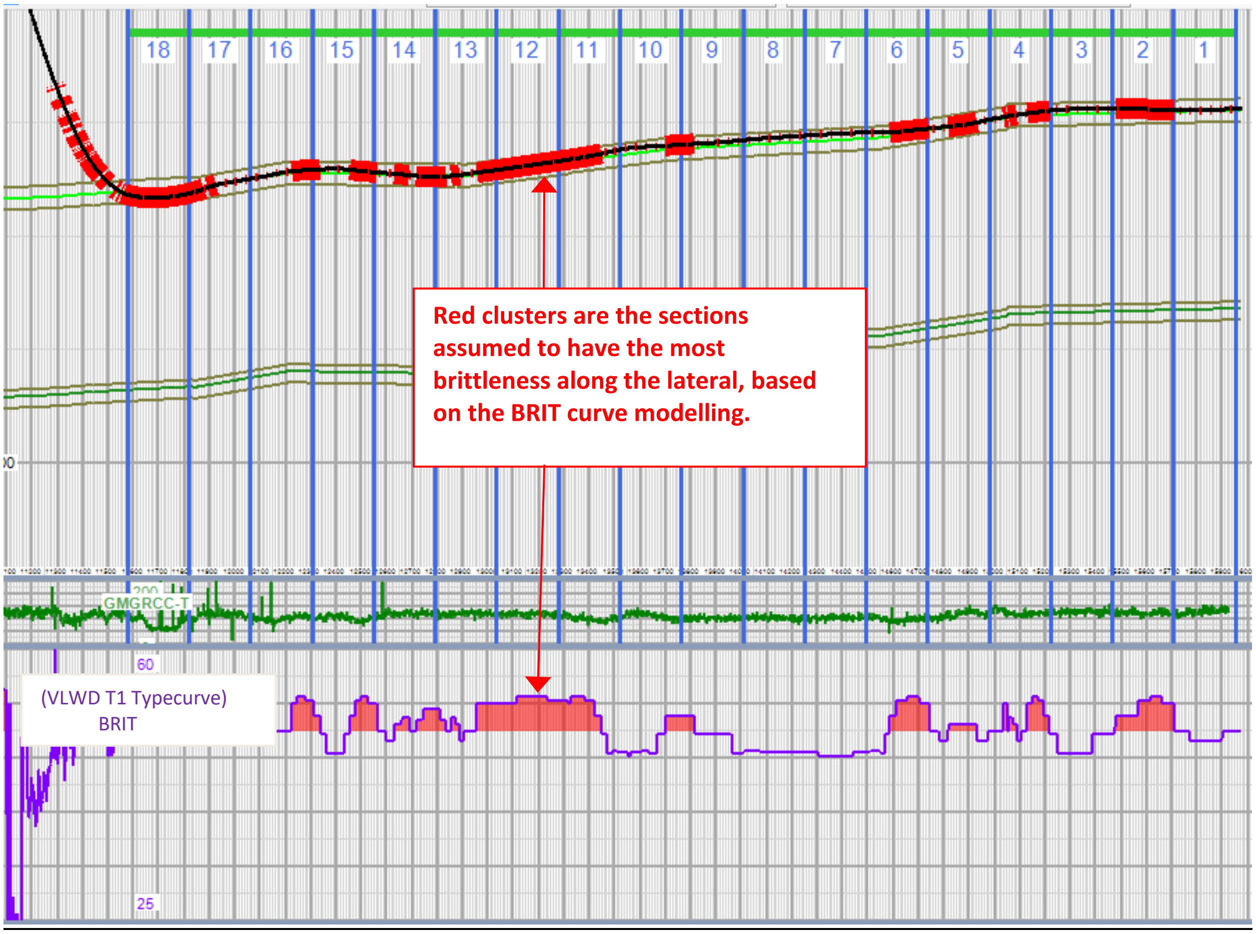


Figure 10f. Geosteering and gamma correlation for Eastern lateral offset of typelog T1.

Figure 10f shows that the eastern lateral was landed in the same interval as its Western counterpart, at approximately 11260'TVD and stayed in the target zone for the duration of drilling.



Red clusters are the sections assumed to have the most brittleness along the lateral, based on the BRIT curve modelling.

Figure 10g. Completion profile simulation for Eastern lateral of typelog T1 based on rock brittleness (BRIT) curve from typelog showing the proposed frac stages (Simulated with BHL Boresight completions module software).

The production data for this eastern lateral was also available, and it showed the initial 30 day peak rate at 6.8Mmcf, and a cumulative production of 2.6Bcf as of February 2018. The eastern lateral began producing in May, 2014.

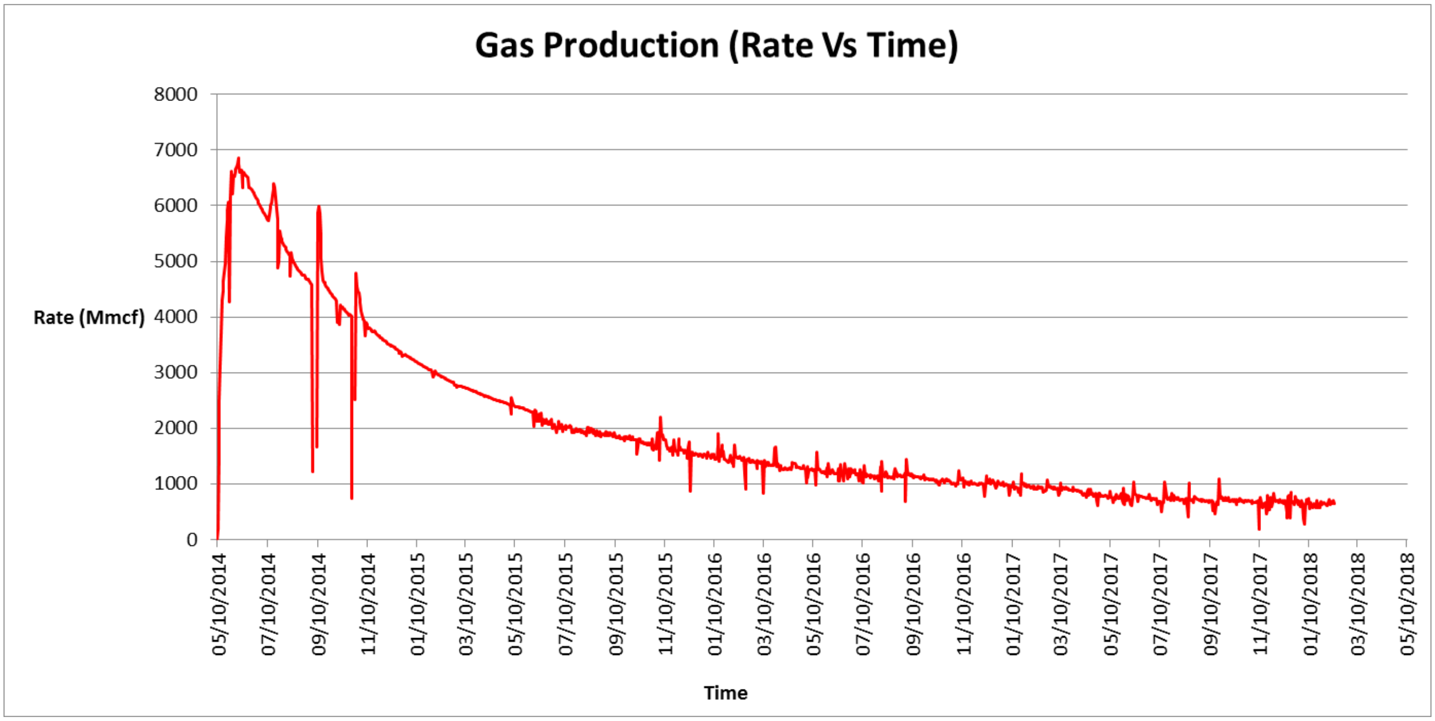


Figure 10h. Gas production from eastern lateral offset of T1.

There are several challenges that arise from a production based comparison, chief of which is the variation in completion methods, i.e. the design, amount/type of proppant used, etc. The age of the wells can also be a factor, since newer wells tend to have a more modern completions and bigger frac designs with more stages. Additionally, the choke size can control the pressures and flow rates for individual wells. The lateral length can also have an impact on production, given that a longer lateral is exposed to a larger drainage area, hence more completion stages and, potentially, more production. In the case of these two laterals, the western lateral was completed and had been producing for a whole year before the eastern lateral hence it has been able to accumulate more production volume. Furthermore, the western lateral has a longer lateral length, about 2400 feet more than the eastern lateral. Therefore it can be surmised that the western lateral produced more than the eastern lateral because it had more stages completed and had built more cumulative volume by producing for a year before the eastern lateral. This summation is made in the absence of other detailed information about the completions for each well. However, with emphasis on the geomechanical properties, the wells were drilled in the same interval hence their production trends when normalized for lateral length and other criteria are relatively similar.

Close observation of the typelog T1 (*Fig. 10*) shows that another interval in the lower Haynesville (11460-90’) could be a potential secondary target for drilling laterals in this area. The log shows high brittleness over this secondary target. This zone is also separated from the already utilized upper landing zone by 170 feet, hence minimizing the amount of depletion and potential communication between the two zones that could occur, depending on the completions design. A useful way to exploit the upper and lower Haynesville targets in this area to minimize the risk of vertical communication and depletion would be to drill the laterals utilizing the spacing technique of a “chevron” or “zigzag” or “wine rack” shape, mindful of leasing constraints, as shown below in figure 10i:

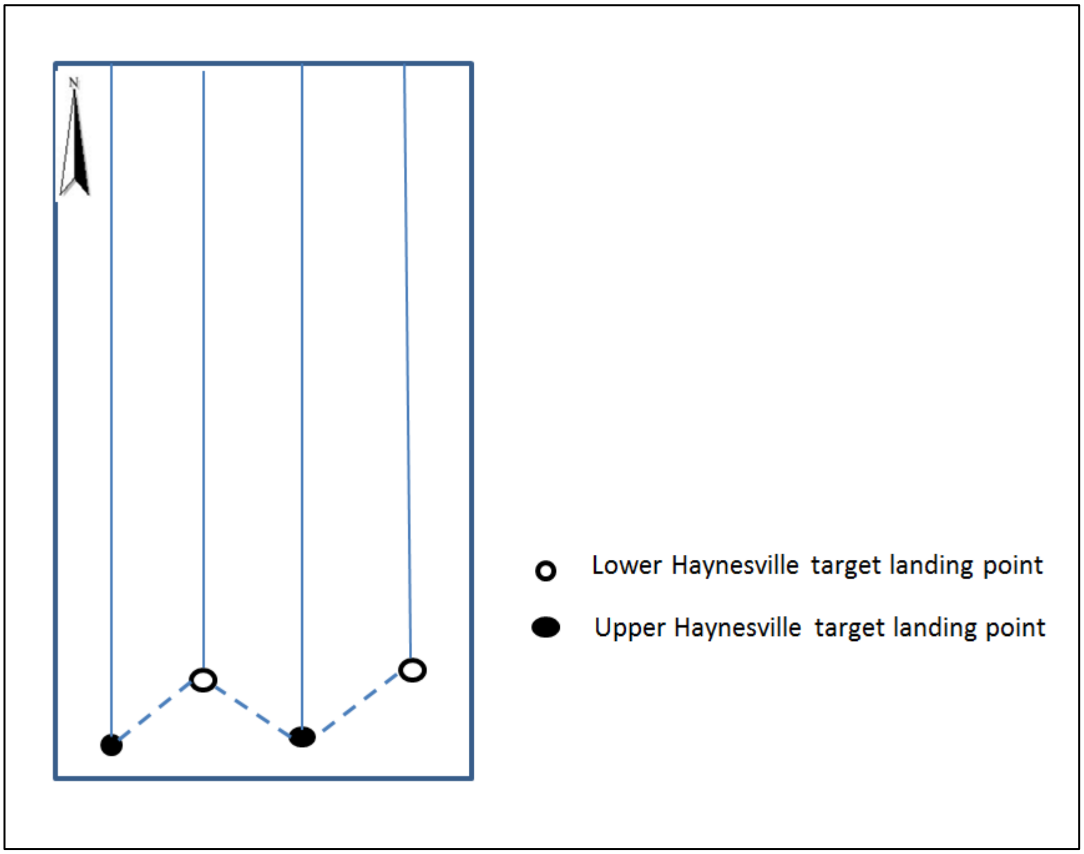


Figure 10i. Proposed “wine rack” drilling format for exploiting upper and lower Haynesville targets in typelog 1 area

Note: *The display template used for the log analysis, geosteering interpretation, and completions simulation model for typelog T1 is repeated for subsequent typelogs and laterals to maintain consistency.*

Typelog #T2 (Panola County, Texas)

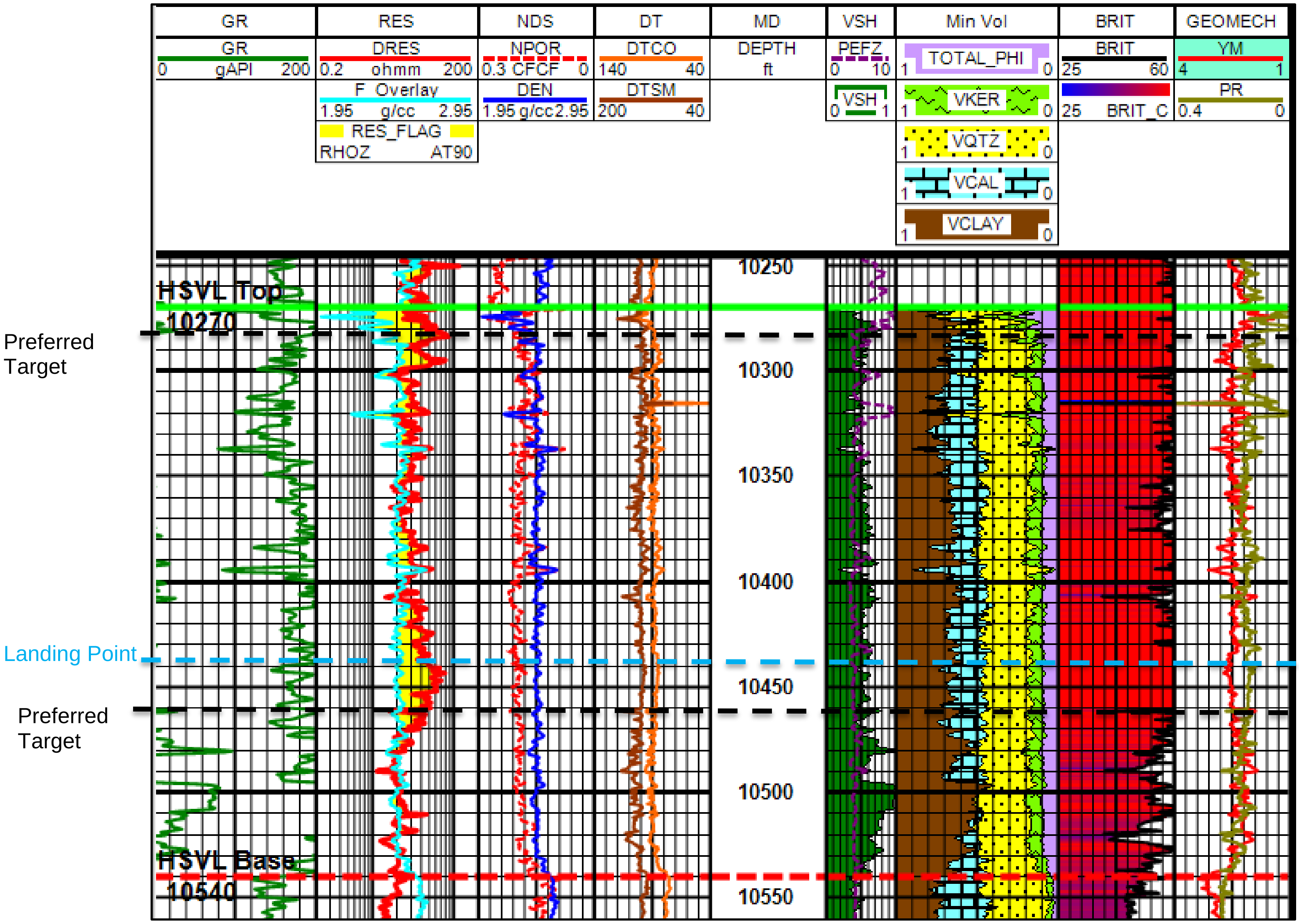


Figure 11. Log Analysis showing the Haynesville section in the T2 typelog, Panola County, Texas

An analysis of the typelog T2 in Figure 11 above indicates the presence of multiple brittle zones throughout the interval. Considering future potential to drill stacked laterals, the preferred target zones would be the upper interval: 10270’-10300’, and the middle interval: 10420’-10460’. These zones show the highest relative brittleness by coloration, with BRIT curve values above 50 and resistivity averaging 20 ohms. An offset lateral drilled to the south of this typelog landed at a corresponding depth of 10440’TVD. The lateral length for the offset well was 7000 feet. The offset lateral was completed and began production in April 2009. Its peak initial 30-day rate (IP-30) was 6.6Mmcf and the cumulative production as of February 2018 is 3Bcf. The limited completions data available indicates that this well was fractured in 17 stages.

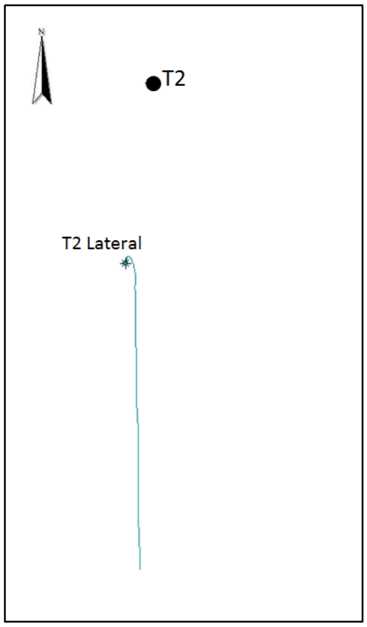


Figure 11a. Map showing T2 typelog and lateral. (Distance between T2 and lateral= 1 Mile)

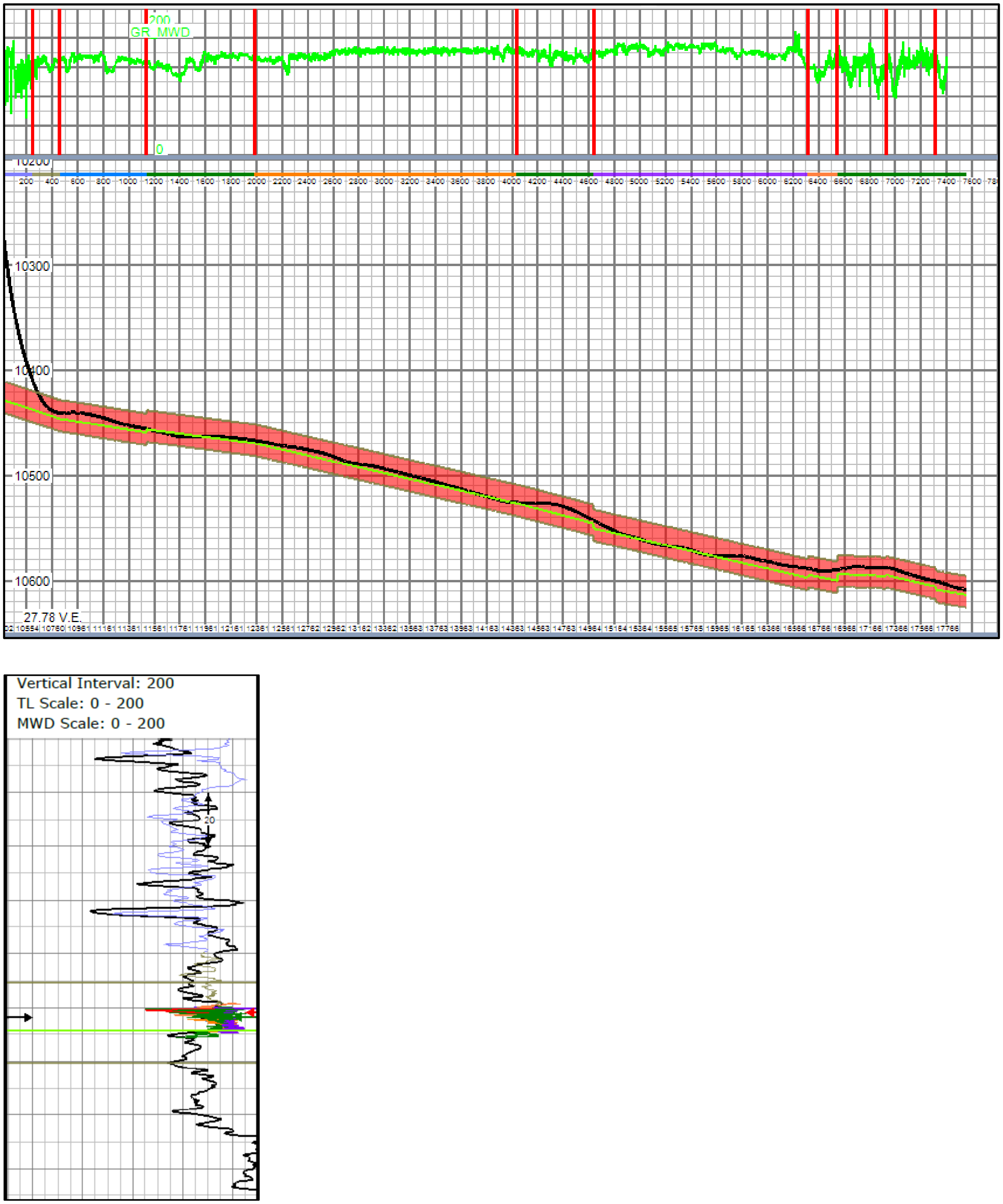


Figure 11b. Geosteering view and gamma correlation window of the T2 offset lateral

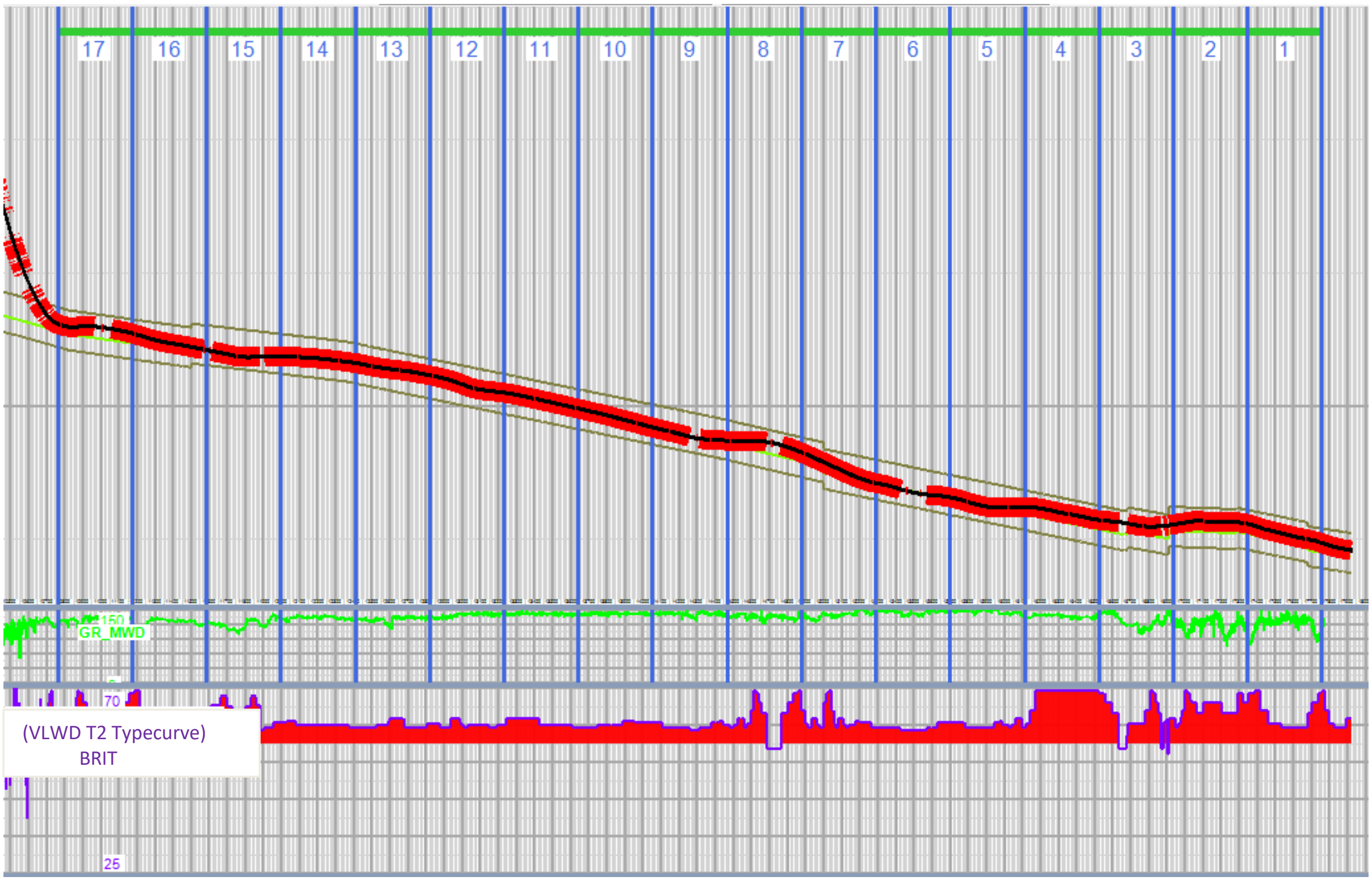


Figure 11c. Completion simulation for T2 lateral modelled with brittleness curve from T2 typelog showing the best zones to initiate hydraulic fracturing

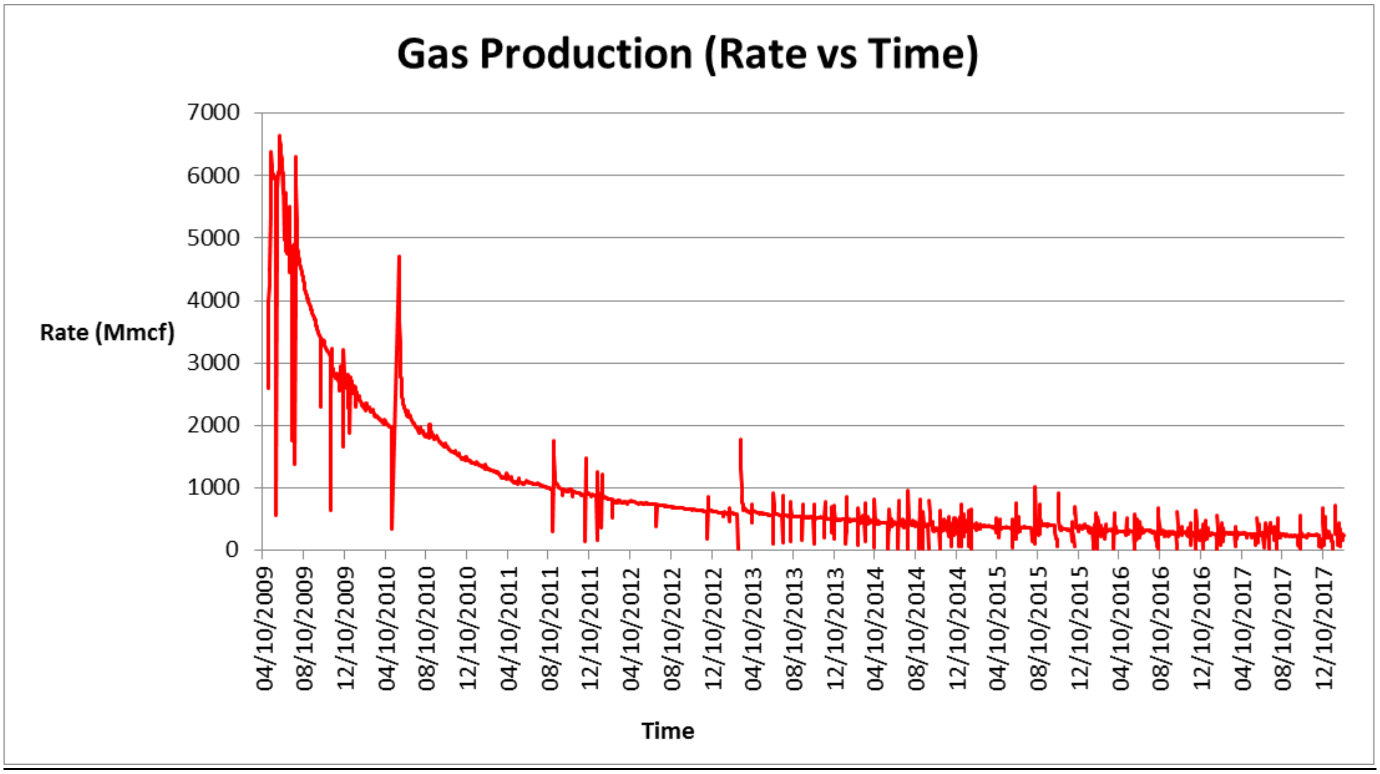


Figure 11d. Production chart for T2 offset lateral

As stated earlier, limited completions data indicates that this T2 offset lateral had a 17-stage fracture design over its 7000’ length. Its cumulative production is 3Bcf. Upon comparison with the western lateral from typelog T1 (Fig. 10c) which has an *almost similar* lateral length of 6922’, and was fractured in 34 stages with a cumulative production of 4.3 Bcf, it is evident that this T2 lateral has under-performed by about 1Bcf, despite it being on production 4 years earlier. The geomechanics of both wells indicate that they were landed in very brittle zones which should respond positively to hydraulic fracturing. Therefore the argument can be made that the newer T1 western lateral (completed 2013) probably has a more modern completion design than the older T2 lateral (completed 2009). The T1 Western lateral has 34 frac stages and a cluster spacing of 30’ while the T2 lateral had only 17 frac stages and a cluster spacing of 74’. As noted earlier, smaller/tighter cluster spacing is preferred because it leads to greater contact of the fracture agents with the reservoir hence leading to increased production. Consequently, the T2 lateral could be a candidate for re-frac operations to optimize its production by initiating tighter cluster spacing using the completions simulation model in Figure 11c above as a guide.

Typelog #T3 (Shelby County, Texas)

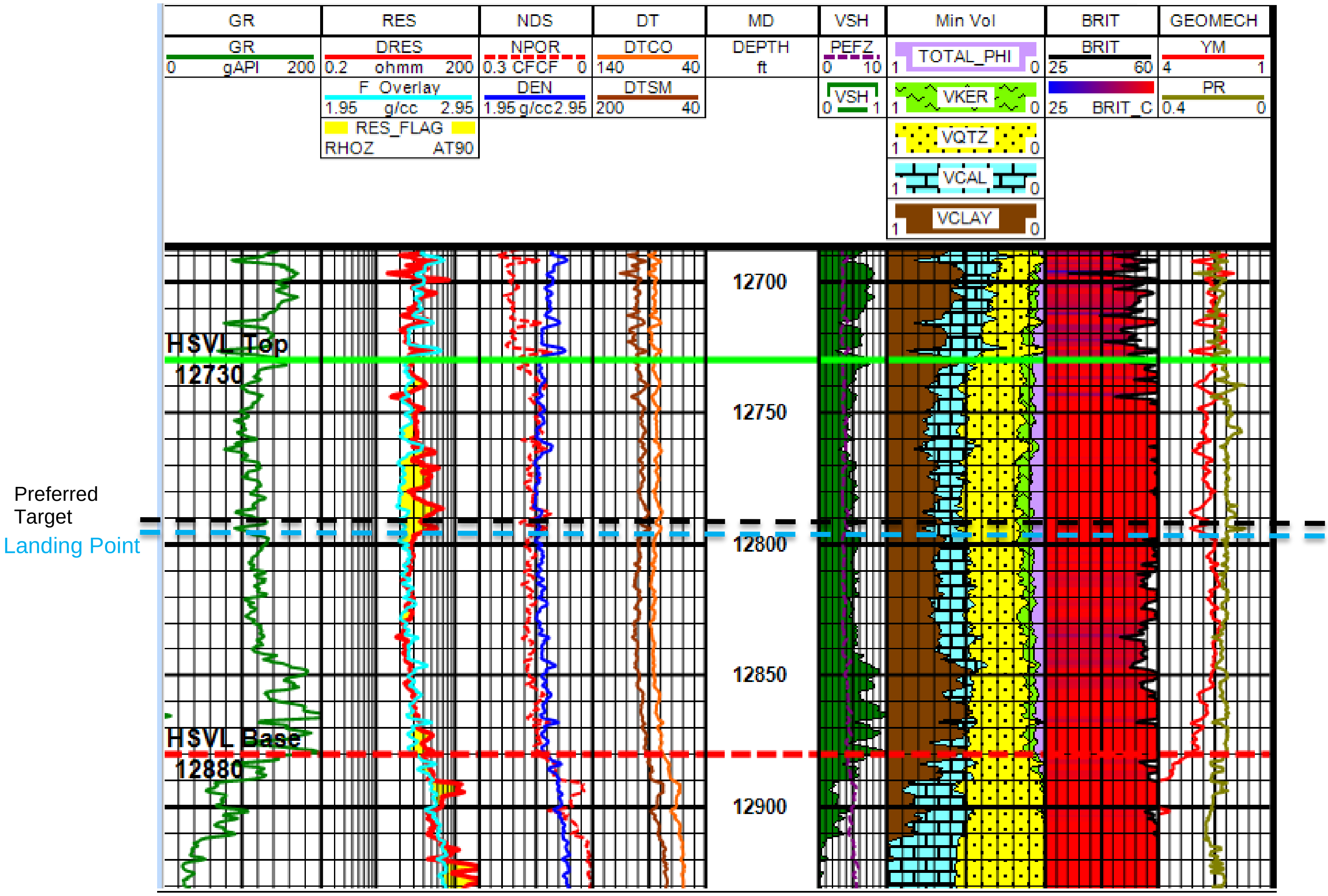


Figure 12. Log Analysis showing the Haynesville section in the T3 typelog, Shelby County, Texas

The log analysis above shows the most brittle zone, and best zone for landing a lateral is between 12750'- 12800'. This interval also shows sufficient resistivity and the clay content is only 30%.

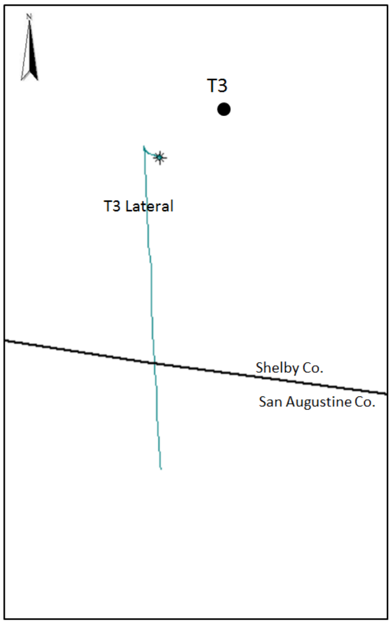


Figure 12a. Map showing T3 typelog and lateral (Distance between T3 and lateral= 1.5 Miles)

The T3 lateral landed at the equivalent depth of 12790’ on the typelog (Fig. 12) and is a very brittle interval. The lateral length is 7450’ and the well was completed with 34 frac stages. It began production in December 2012 with an IP-30 of 9.9Mmcf and a cumulative production of 8 Bcf as of February 2018, a relatively good production profile because it is in the deeper portion of the basin with higher pressure.

Figure 12b. Geosteering profile and gamma correlation of the T3 lateral

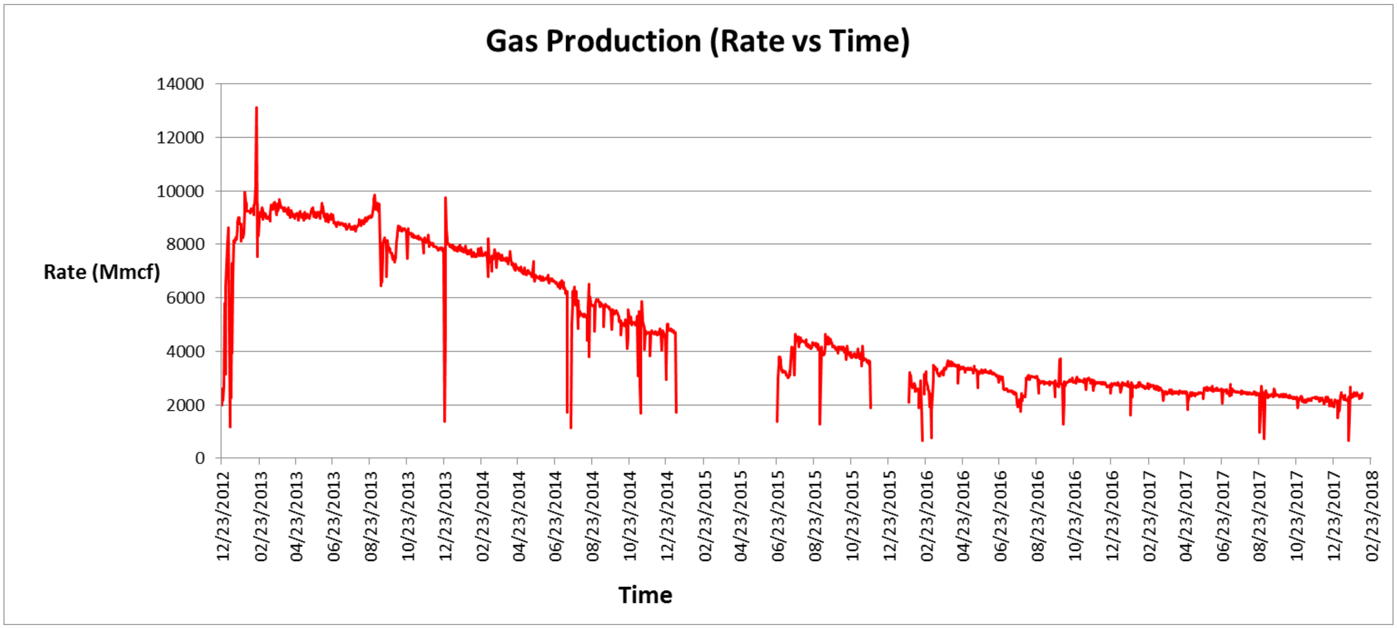


Figure 12c. Gas production for the T3 lateral

Typelog #T4 (San Augustine County, Texas)

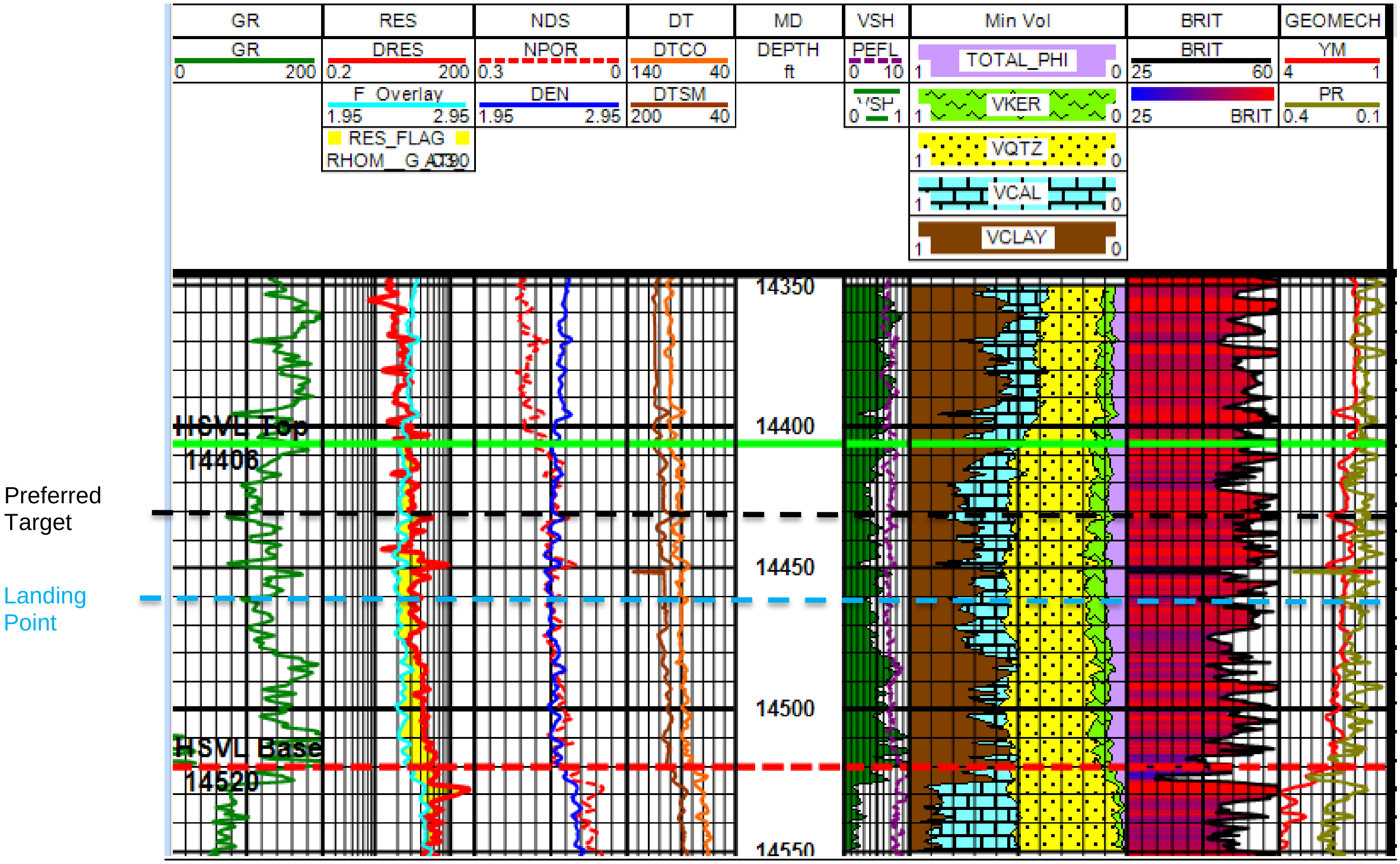


Figure 13. Log Analysis showing the Haynesville section in the T4 typelog, San Augustine County, Texas

The geomechanics of this typelog reveal the most brittle interval to be 14420 – 14470’. The clay volume in this interval is minimal, averaging 25% while the average quartz volume is 38%. YM_BRIT average is 2.2 while PR_BRIT average is 0.18. Consequently, this interval ought to respond well to fracture stimulation.

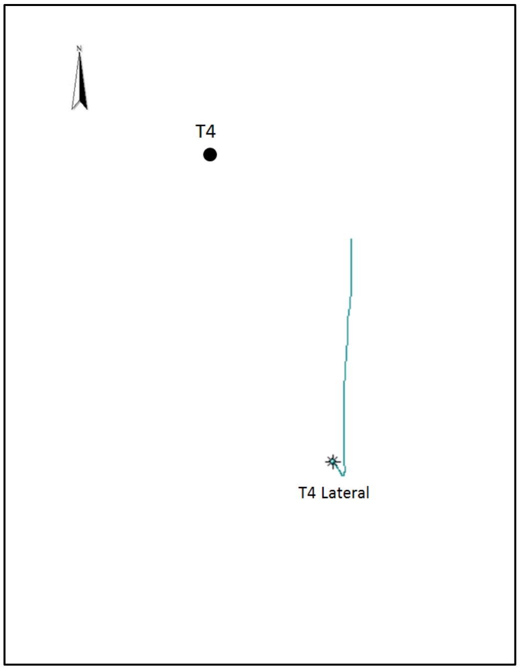


Figure 13a. Map showing T4 typelog and lateral (Distance between T4 and lateral = 2 Miles)

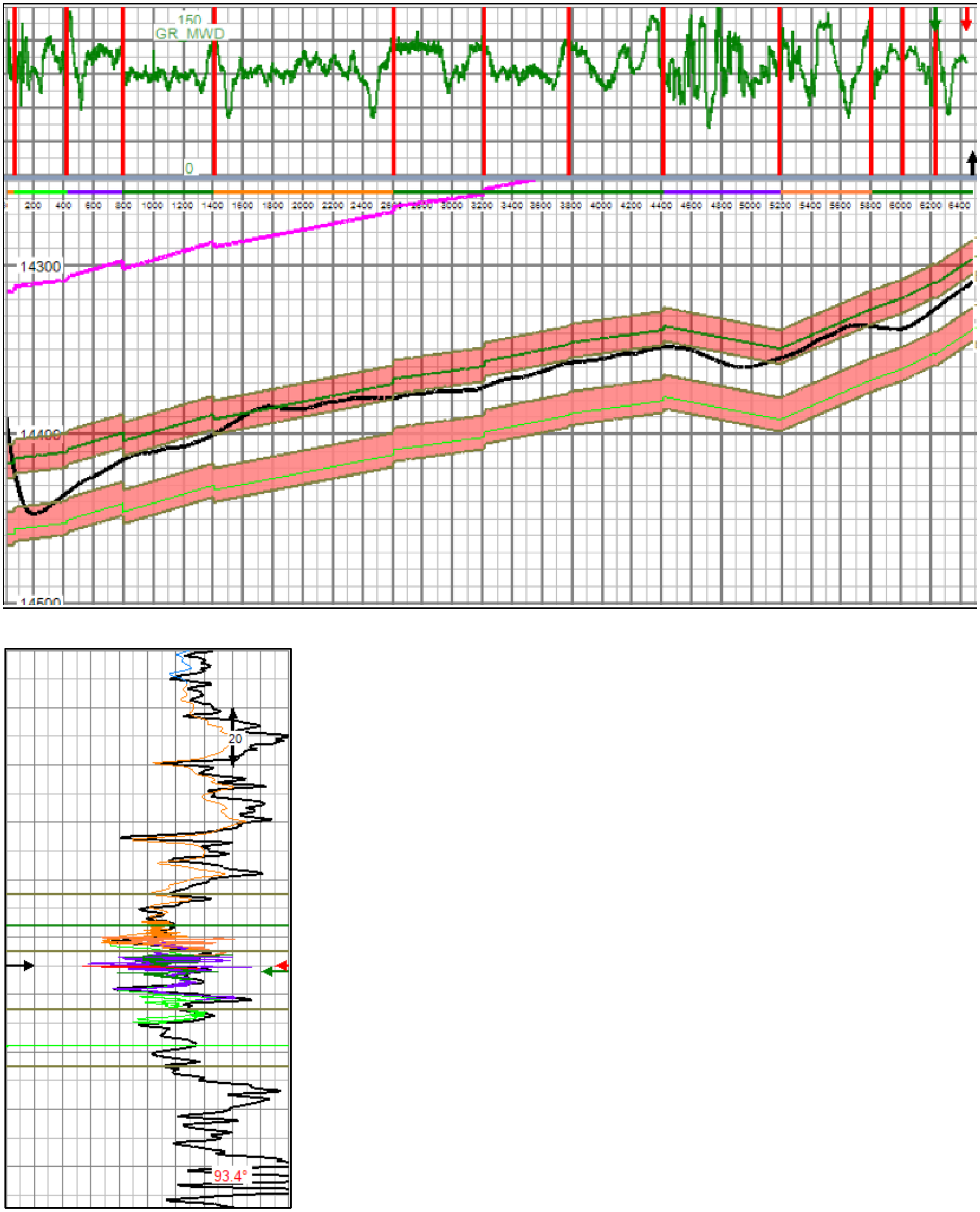


Figure 13b. Geosteering profile and gamma correlation for T4 lateral

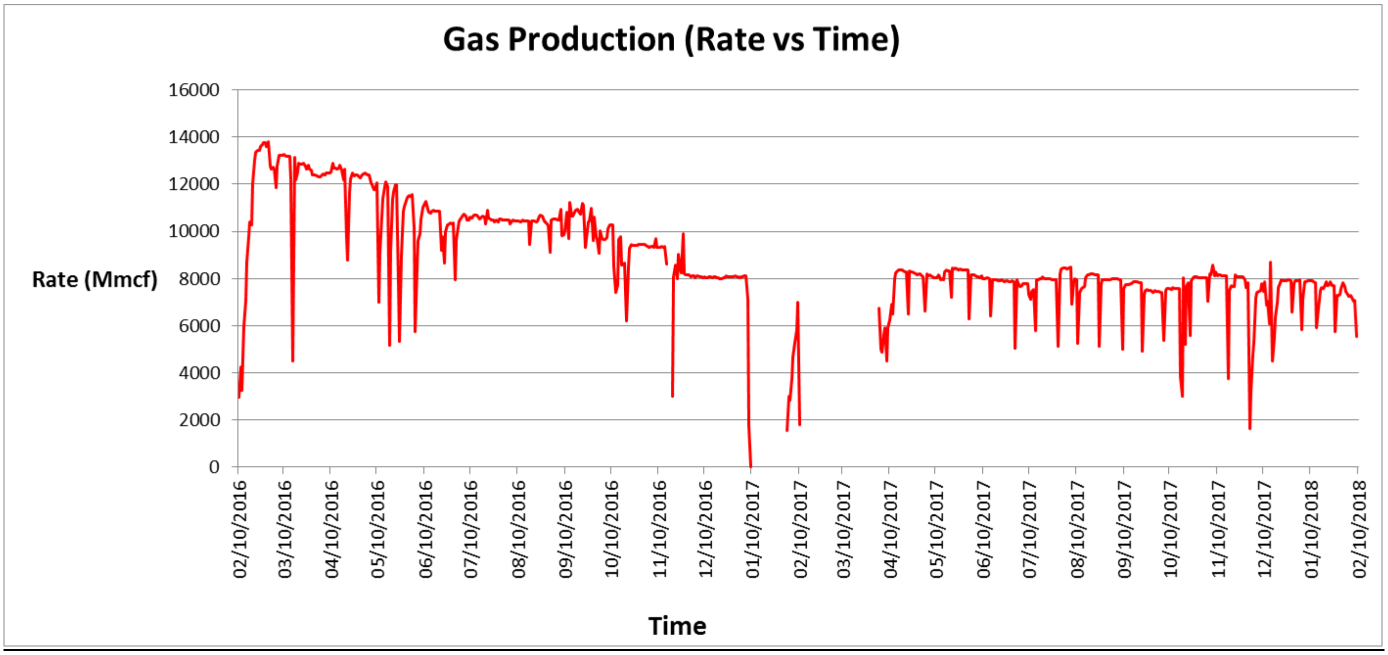


Figure 13c. Gas production for T4 lateral

The offset lateral showed the well landed at 14460' within the brittle zone, although outside the preferred targets shaded in red. It should be noted at this point that the stratigraphic targets are selected only as guides for drilling after examining the log properties. In addition to the brittleness factor, other parameters considered include resistivity, porosity, and mineral volume (lower clay, higher silica and calcite preferred). Additional considerations include the presence of considerable stratigraphic markers (carbonate streaks) to confidently tie the mwd gamma back to the typelog because this helps to define one's place in the section while geosteering.

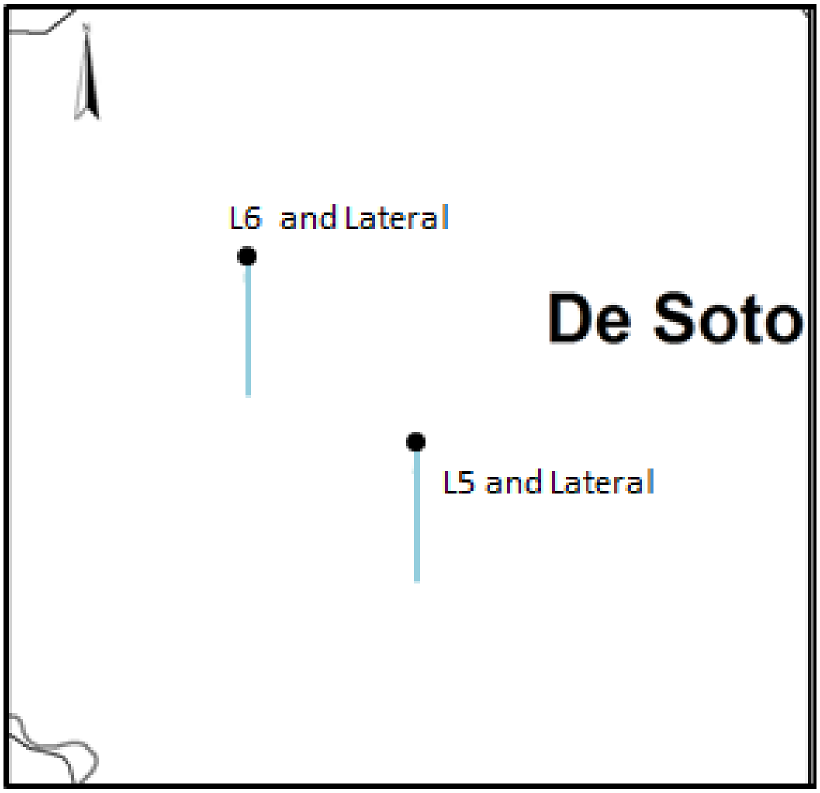
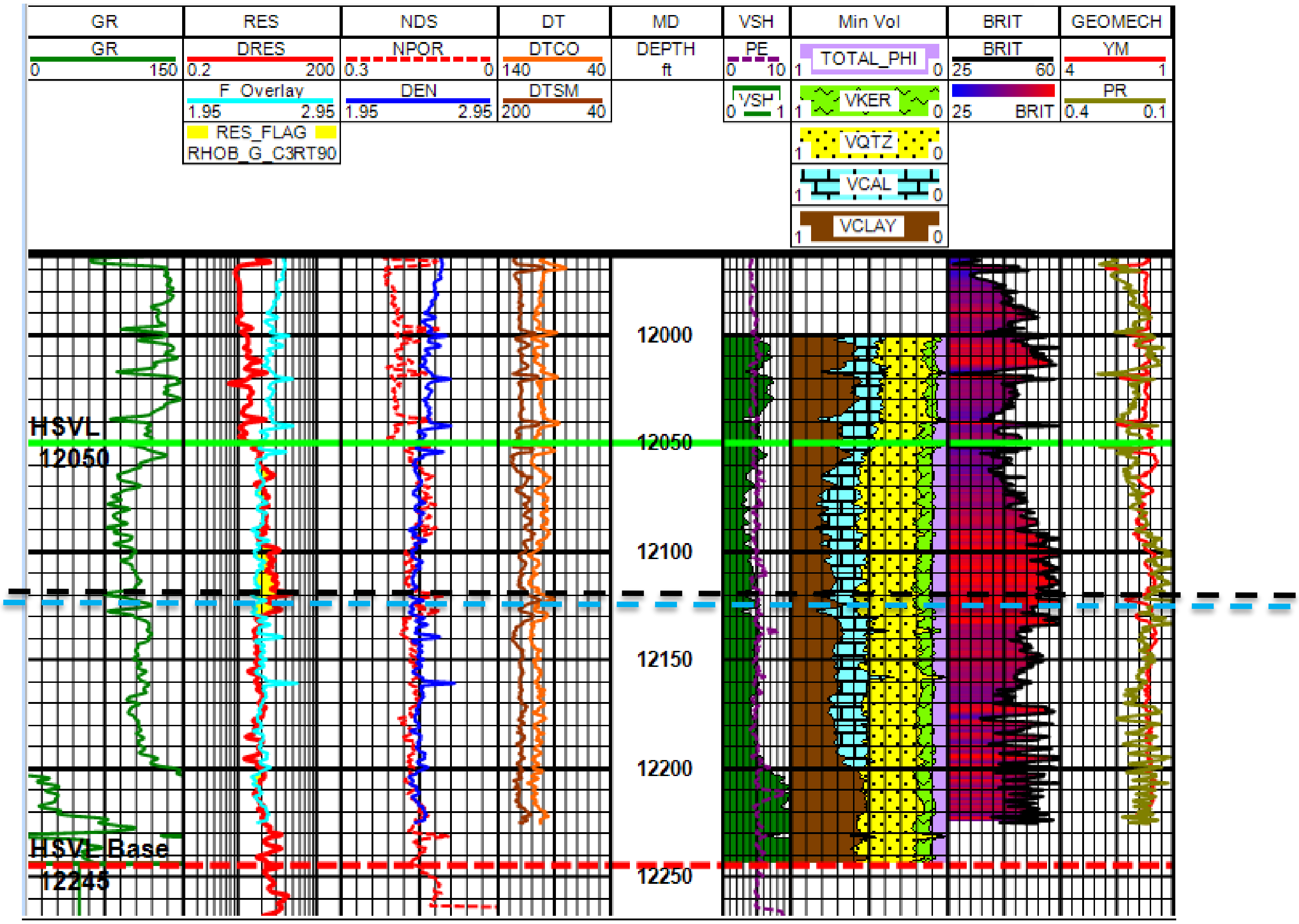


Figure 14 showing Louisiana typelogs L5 and L6 and their lateral wells. Each lateral was drilled as direct offset of its typelog. (Distance between L6 and L5 = 7 Miles)

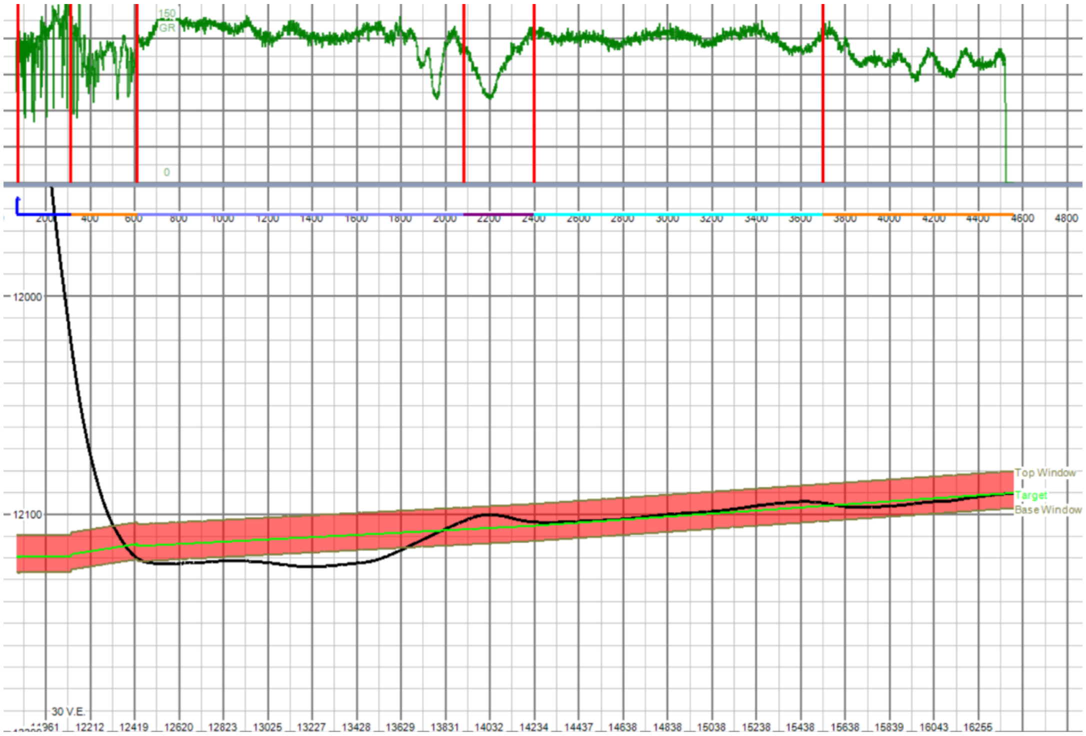
Typelog #L5 (De Soto Parish, Louisiana)



Preferred
Target
Landing
Point

Figure 14a. Log Analysis showing the Haynesville section in the L5 typelog, De Soto Parish, Louisiana

The L5 typelog shows the best zone to place a lateral is the interval between 12100 – 12130.This interval shows a relatively high brittleness by coloration, and the high silica/low clay volume lends credence to this assumption. The offset lateral drilled from this pilot hole landed at a depth equivalent to 12121’ on the typelog, which is within the preferred target zone. The well had a lateral length of 3900 feet and was completed in 13 stages. So far the cumulative production is at 2 Bcf.



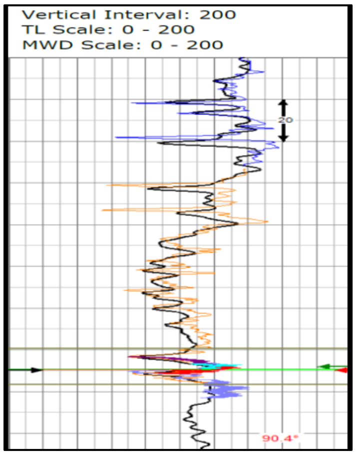


Figure 14b. Geosteering profile and correlation for L5 lateral

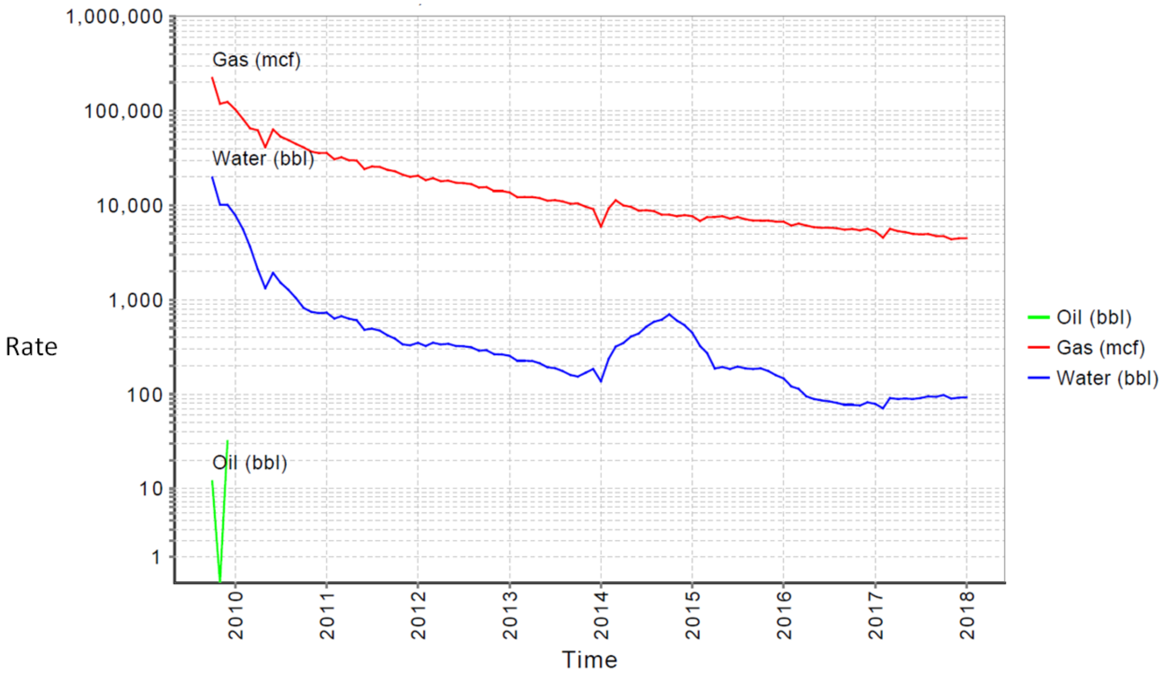


Figure 14c. Yearly production for the L5 lateral. (Culled from I.H.S. Enerdeq)

Typelog #L6 (De Soto Parish, Louisiana)

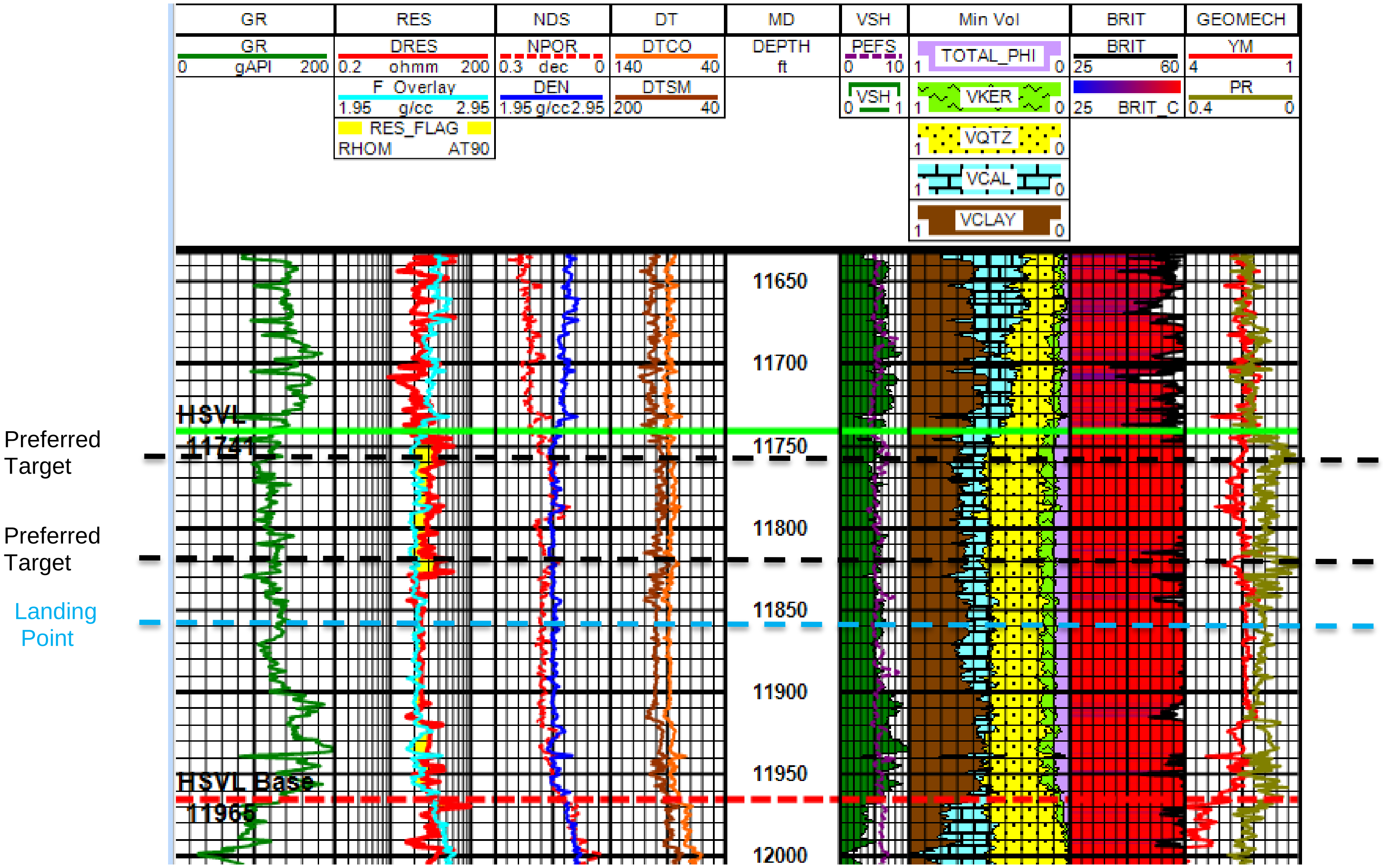
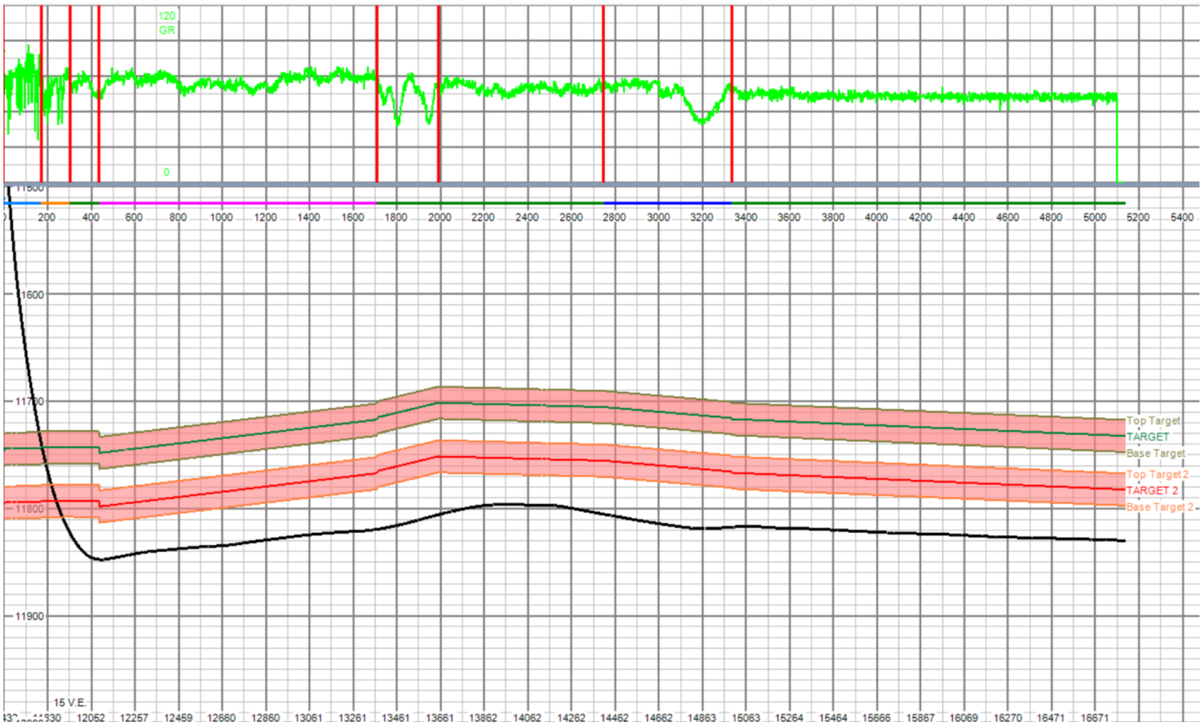


Figure 15. Log Analysis showing the Haynesville section in the L6 typelog, De Soto Parish, Louisiana

In the Haynesville section above, it can be observed that there is an excessive display of high brittleness throughout the zone. This can be attributed to a preponderance of over-pressured free gas which causes a slower than usual compressional travel time hence lowering PR values and possibly exaggerating brittleness. However, considering other attributes such as resistivity and the attendant mineral volumes (vclay and vqtz), the best interval to land a horizontal is 11750 – 11780, and 11800 – 11835. An offset lateral drilled directly from this pilot hole landed a bit lower than the selected target zones, albeit within still brittle rock with high volumes of silica and calcite as shown below. The well has a lateral length of ~4700’; it was completed in 14 stages and began producing in October 2011 with a cumulative production of 2.9 Bcf as of January 2018.



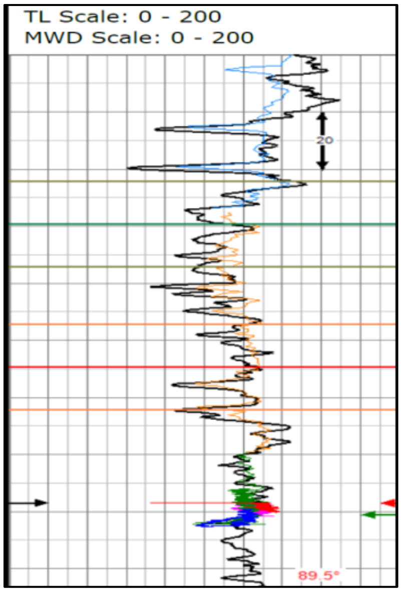


Figure 15a. Geosteering profile and correlation for offset lateral of Typelog L6

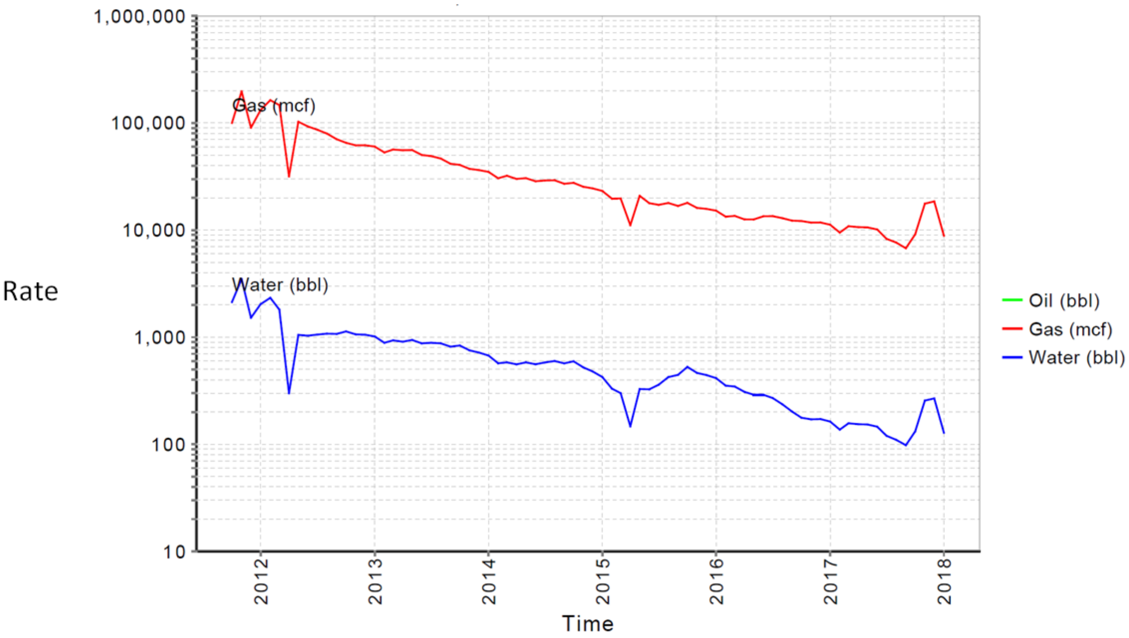


Figure 15b. Yearly production for the L6 lateral. (Culled from I.H.S. Enerdeq)

<u>Chapter 4</u>

FINDINGS AND CONCLUSION

A petrophysical and geomechanical template was developed for the Haynesville from multiple wells in the study area. This was accomplished using quad combo log sets with acoustic curves across 4 counties in Texas and Louisiana. The primary aim was to highlight zones of brittleness and ductility within the Haynesville interval in order to determine which depths would be most suitable to drill lateral well bores. This is essential because, in order to effectively exploit a tight natural gas reservoir such as the Haynesville, horizontal development accompanied by hydraulic fracturing is essential. A brittle zone would most likely respond effectively to hydraulic fracturing. Typical brittleness indicators include low - moderate clay content, relatively high levels of quartz and carbonate, higher YM_BRIT and lower PR_BRIT values (i.e. YM_BRIT and PR_BRIT should be inversely proportional to one another). The brittleness was derived by calculating a series of simultaneous equations from previously established industry research papers.

This study has shown that the geomechanical properties vary across the geographical extent of the Haynesville shale play, subject to local well bore conditions. The emphasis on developing type logs for individual areas is borne out of the knowledge that present day industry operations do not entail detailed geologic/petrophysical evaluations for every wellbore that is drilled. Primary considerations for these are the high costs associated with open-hole well logging and coring operations. Therefore, with the sparse dataset of complete wellbore information, these templates are developed to improve target selections for drilling and geosteering lateral wellbores. Additionally, the completions model developed [*Figs. 10d, 10g and 11c*] could aid in selecting stages for hydraulic fractures or for re-fracturing operations.

An attempt was made to do an outcome-based comparison of existing laterals drilled in proximity to the type logs, based on their landing points and production. This proved difficult as the data set contained wells with various parameters that could affect production. The main obstacles include the **completions method**, the **lateral length** of the well bore, and the **age of the well**. These conditions will have to be similar to do an effective well-to-well comparison. Wells with longer lateral length, in theory, ought to produce better, since they have exposure to greater drainage areas; however, this may not necessarily be the case depending on the age of the well and the completions method that was employed (e.g. number of fracture stages, type/amount of proppant, etc.). Greater number of fracture stages generally leads to better production since it would mean greater contact with the reservoir, but this requires drilling longer laterals. Geomechanical properties are useful in terms of modeling and selecting intervals to land the lateral to effectively fracture a reservoir; however, this alone cannot determine productivity as other factors have to be taken into account, especially completions.

NOTES:

Log Analysis was performed using PowerLog software. All raw digital log curves were donated by companies in operating area.

Geosteering profile and completion simulation were created in BHL Boresight software.

Production was plotted in Excel with daily production numbers provided by operating companies, except where unavailable, then production data was culled from I.H.S. Enerdeq.

Maps were created in Petra and ArcGIS.

All depth measurements are in Feet, and distance measurements are in Miles.

All petrophysical interpretation and analysis was done by the author from a beginner's/elementary knowledge level of petrophysics and the associated software. Methods and processes relied on previously established workflows in published and unpublished literature, and interactions with experienced professionals such as Petrophysicists, Completions Engineers and Geologists across the industry.

References

Asquith, G., and Krygowski, D., 2004. Basic Well Log Analysis 2nd Edition: AAPG Methods in Exploration Series, No. 16

Asquith, G., 2010. Petrophysics of gas-bearing shales. Texas Tech. University- Advanced Petrophysics Course Manual

Bhuyan, K., Passey, Q.R., 1994. Clay Estimation from Gamma Ray and Neutron-Density Porosity Logs

Buller, D., Dix, M.C., 2009. Petrophysical evaluation of the Haynesville shale in northwest Louisiana and northeast Texas. Gulf Coast Association of Geological Societies Transactions 59, 127e143.

Cicero, A.D., Steinhoff, I., McClain, T., Koepke, K.A., Dezelle, J.D., 2010. Sequence stratigraphy of the upper Jurassic mixed carbonate/siliciclastic Haynesville and Bossier shale depositional systems in east Texas and northern Louisiana. Gulf Coast Association of Geological Societies Transactions 60, 133e148.

Cicero, D., Steinhoff, I., 2013. Sequence Stratigraphy and Depositional Environments of the Haynesville and Bossier Shales, East Texas and North Louisiana

Eastwood, R.L., Hammes, U., 2011. Log model development for the Bossier and Haynesville shales. In: SPWLA 52nd Annual Logging Symposium. Colorado Springs, Co, USA May 14e18

Ewing, T.E., 2010. Pre-Pearsall geology and exploration plays in South Texas. Gulf Coast Association of Geological Societies Transactions 60, 241e260.

Foote, R.Q., Massingill, L.M., Wells, R.H., 1988. Petroleum geology and the distribution of conventional crude oil, natural gas, and natural gas liquids, East Texas Basin. USGS Report 88-450k

Frebourg, G., Ruppel, S. C., Rowe, H., 2013. Sedimentology of the Haynesville (Upper Kimmeridgian) and Bossier (Tithonian) Formations, in the Western Haynesville Basin, Texas, U.S.A.

Geology of the Haynesville Gas Shale in East Texas and West Louisiana, 2013. AAPG Memoir #105

Goldhammer, R. K., 1998, Second-order accommodation cycles and points of “stratigraphic turnaround”: Implications for carbonate buildup reservoirs in Mesozoic carbonate systems of the East Texas Salt Basin and South Texas, in W. D. DeMis and M. K. Nelis, eds., West Texas Geological Society annual field conference guidebook, West Texas Geologic Society Publication 98-105, Midland, p. 11-28.

Hammes, U., Carr, D., 2009, Sequence Stratigraphy, Depositional Environments, and Production Fairways of the Haynesville Shale-Gas Play in East Texas, no. 110084.

Hammes, Ursula, Hamlin, H.S., and Ewing, T.E., 2011, Geologic analysis of the Upper Jurassic Haynesville shale in east Texas and west Louisiana: American Association of Petroleum Geologists Bulletin, v. 95, no. 10, p. 1643–1666.

Hammes, Ursula, 2012. Depositional Environment, Stratigraphy, Geochemical, and Reservoir Characteristics of the Haynesville and Bossier Shale-Gas Plays of East Texas and Northwest Louisiana

Jiang, M., and Spikes, K.T., 2013. Estimation of reservoir properties of the Haynesville Shale by using rock-physics modelling and grid searching. Geophysics Journal International, 135, p. 315 – 329.

Male, F., Akand, W. I., Patzek, T.W., Ikonnikova, S., Browning, J., and Marder, M.P., 2015. "Analysis of gas production from hydraulically fractured wells in the Haynesville Shale using scaling methods." Journal of Unconventional Oil and Gas Resources 10 : p.11-17.

Martin, R.G., 1978. Northern and Eastern Gulf of Mexico continental margin: stratigraphic and structural framework: American Assoc. of Petroleum Geologists Studies in Geology 7, Tulsa, Oklahoma, p. 21-42

Mullen, M., Roundtree, R., Baree, B., 2007. A Composite Determination of Mechanical Rock Properties for Stimulation Design (What to Do When You Don't Have a Sonic Log) SPE #108139

Nunn, J.A., 2012. Burial and Thermal History of the Haynesville Shale: Implications for Overpressure, Gas Generation, and Natural Hydrofracture

Nunn, J.A., Scardina, A.D., Pilger, R.H., 1984. Thermal Evolution of the north-central Gulf Coast: Tectonics, v.3, p. 723-740

Parker, M., Petre, E., Dreher, D., Buller, D., 2009. Haynesville Shale: Hydraulic Fracture Stimulation Approach. SPE #0913

Parker, M., Buller, D., Petre, E., Dreher, D., 2009. Haynesville Shale-Petrophysical Evaluation. SPE #122937

Passey, Q.R., Bohacs, K.M., Esch, W.L., Klimentidis, R., Sinha, S., 2010. From oil-prone source rock to gas-producing shale reservoir – Geologic and Petrophysical Characterization of Unconventional Shale-Gas Reservoirs. SPE #131350

Penn Virginia Corporation: Haynesville Shale/ Lower Bossier Technical Presentation at Technical Conference - Gulf Coast Region (*venue unknown*), October 4-5, 2010.

Pilger, R.H., 1981. The opening of the Gulf of Mexico: Implications for the tectonic evolution of the northern Gulf Coast: Gulf Coast Association of Geological Societies Transactions, v. 31, p.377-381

Quirein, J., Witkowsky, J., Truax, J., Galford, J., Spain, D., Odumosu, T., 2010. Integrating Core Data and Wireline Geochemical Data for Formation Evaluation and Characterization of Shale Gas Reservoirs. SPE #134559

Rickman, R., Mullen, M., Petre, E., Grieser, B., Kundert, D., 2008. A Practical Use of Shale Petrophysics for Stimulation Optimization: All Shale Plays Are Not Clones of the Barnett Shale. SPE #115258

Sondergeld, C.H., Newsham, K.E., Comisky, J.T., Rice, M.C., 2010. Petrophysical Considerations in Evaluating and Producing Shale Gas Resources. SPE #131768

Torsch, W.C., 2012. Thermal and Pore Pressure History of the Haynesville Shale in North Louisiana: A Numerical Study of Hydrocarbon Generation, Overpressure, and Natural Hydraulic Fractures. Master's Thesis, Louisiana State University.

Wang, F. P., and Hammes, Ursula, 2010. Key petrophysical factors affecting fluid flow in geopressured Haynesville Shale (abs.): American Association of Petroleum Geologists Annual Convention & Exhibition, v. 19, p. 268.

Zhang, J.J., and Bentley, L.R., 2005. Factors determining Poisson's Ratio. CREWES Research Report, v.17

http://www.dnr.louisiana.gov/index.cfm?md=pagebuilder&tmp=home&pid=442 (Louisiana Dept. of Natural Resources, 1/15/2018).

https://info.drillinginfo.com/category/haynesville/ (DrillingInfo webpage 1/18/2018)

https://penerdeq.ihsenergy.com/thin2/secure/output/quickView.jsf?view=Graph&type=Production%20Allocated&key=B288861 (IHS Enerdeq Production, 4/13/2018)

https://www.eia.gov/analysis/studies/usshalegas/pdf/usshaleplays.pdf (U.S. Energy Information Administration, 11/21/2017)

https://www.ferc.gov/industries/gas/indus-act/lng/lng-approved.pdf (U.S. Federal Energy Regulatory Commission webpage, 1/28/2018)

https://www.spec2000.net/01-crainsrules.htm (Crain's Petrophysical Handbook, 3/18/2018)

http://www.rrc.state.tx.us/oil-gas/major-oil-and-gas-formations/haynesvillebossier-shale-information/ (Texas Railroad Commission webpage, 1/20/2018)

Biography

Silas O’Silas holds a Bachelor of Science degree in Geosciences from Midwestern State University in Wichita Falls, Texas. He has worked as a Geologist in the oil and gas industry in a variety of operational and development roles for both operating and service companies. He recently completed his Master’s degree in Geology from the University of Texas at Arlington, and his research focused on petrophysics, with an emphasis on unconventional oil and gas plays. He is a member of the American Association of Petroleum Geologists (AAPG).