CHEMOSTRATIGRAPHY AND PALEOENVIRONMENT
OF THE HAYNESVILLE FORMATION,
HARRISON COUNTY, TEXAS

by

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ABSTRACT

DEPOSITIONAL ENVIRONMENT OF THE HAYNESVILLE FORMATION WITH A FOCUS ON CHEMOSTRATIGRAPHY, HARRISON COUNTY, TEXAS

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The Late Jurassic (Kimmeridgian) Haynesville formation consist of post rift siliciclastics, carbonate, and evaporite deposits that accumulated in continental to deeper marine environments on an asymmetrical basin where topography was modified by salt and basement tectonics. The Haynesville stretches from East Texas to West Louisiana, deposited on the Smackover lime and overlaid by the slightly coarser grained Bossier Formation and the inter-bedded sands of the Cotton Valley Formation in some places. Complex basin morphology and later stage salt tectonics have played an important role in the development of the sediment fill. The evacuation of salt from overburden increased accommodation space. The basin's architecture had affects on water movement, which allowed for a restricted basin and created ideal conditions for anoxic bottom waters. The influx of sediments and nutrients along with anoxic bottom waters conditions contributed to the creation of an organic rich

mudstone. However, cyclical changes in water levels, onshore erosional variations, upwellings, and regional environmental factors contributed to the complexity of the entire Haynesville formation.

A better understanding of the Haynesville shale on all scales will help in differentiating geological variations and anomalies. This study will focus on micro core analysis but give an overall regional description of Harrison County. Research of geochemical proxies and subsurface analysis of this basin will help in categorizing the basin evolution and sediment fill. The geochemical study will use high definition (HD) bulk chemical analysis obtained from a core scanned at 2 inch intervals. The subsurface analysis will use well logs, top structure maps, initial production maps as a basis for defining hydrocarbon concentrations and migration. The top structure maps will reveal migration pathways and any possible faulting. The geochemical study will be compared to the more conventional well logs to illustrate the lack in resolution. The subsurface database will provide information relating to paleobathymetric deposition and lateral variations related to deeper structural components. Additionally, it will help in understanding sediment and nutrient supply routes. Top structure maps of the Bossier Formation and Haynesville Formation will be created using Gamma well logs and resistivity logs. Initial production (IP) maps will help in correlating geochemical signatures with hydrocarbon rich strata. Furthermore, bulk chemical elements will be analyzed and compared to provide insight into the depositional environment. The study will focus on the interactions of sediment influx, organic variations, paleotopography, and paleoclimate. The geochemical analysis was used to compare high definition measurements against broader interval measurements. Furthermore, total organic carbon (TOC) and total inorganic carbon (TIC) was analyzed to highlight the sediment sources and organic content. IHS PETRA was used to create the subsurface database. The Costech Element analyzer, UIC Coulometer and ED-XRF was used to create the geochemical analysis.

Results from the bulk data have been plotted to show variations in signatures that will help categorize and interpret depositional condition. Overall results indicate that we are working with anoxic bottom waters with a moderate detrital input and periodic oscillating blooms of organics. The detrital input is a result of previous uplift, erosion and transportation from the surrounding environment, both terrestrial and marine. The two major detrital inputs are illite and quartz. The combination of synthesized calcium carbon from the surrounding marine and terrestrial sources; along with the input from in place organics with low oxygen levels provided the building blocks for a source rock. Average TOC values for the base of the Bossier and the Haynesville are 2.51%. Secondly, the average TIC was 2.09%.

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CHAPTER 1

INTRODUCTION

1.1 Project Outline And Study Area

Regionally, the Late Jurassic provided excellent conditions for the formation of organically rich marine mudstone. During this time a global oceanic event included stratified water columns and anoxic bottom waters prime for the preservation of the high influx of organic matter (Langrock, 2004). Late Jurassic (Kimmeridgian) mudstones found in the United Kingdom contained mineralogical similar clays deposited in low oxygenated waters (Newton and Wignall, 2001). High sea levels were reported, using C-O isotopes, to deposit restricted lime mudstone in Croatia (Husinec and Read, 2010). The anoxic bottom waters of the Gulf Coast preserved the organic matter that would eventually become a source of hydrocarbons, later known as the Haynesville Formation. Mudstones are highly complex and have a great degree of heterogeneity. The heterogeneity can be hard to assort through conventional methods. Additionally, predictions made strictly on petrophysical observation can be difficult. It is with great importance academically and industrially to create a working model of the complex depositional forces of mudstones. The dissection of mudstones gives an insight into the paleoenvironment, including ancient water chemistry, sedimentation variations and organic carbon cycles. Categorically defining these environments will help focus hydrocarbon exploration.

In the past decade, hydrocarbon exploration in North America has significantly increased domestic production. Advances in drilling have opened the door to unconventional hydrocarbon plays, such as the Haynesville Formation. Upper Jurassic and Cretaceous formations have been discovered and described as prolific source rock around the world (Klemme, 1994). Geologic factors driving richness of total organic carbon (TOC), mineralogical composition need to be understood in geologic context to predict area of highest gas content (Steinhoff, 2011). Baker (1996) states that TOC less than 1% is the lower limit for an effective source rock. Technological advances have made it necessary in categorizing once forgotten source rocks.

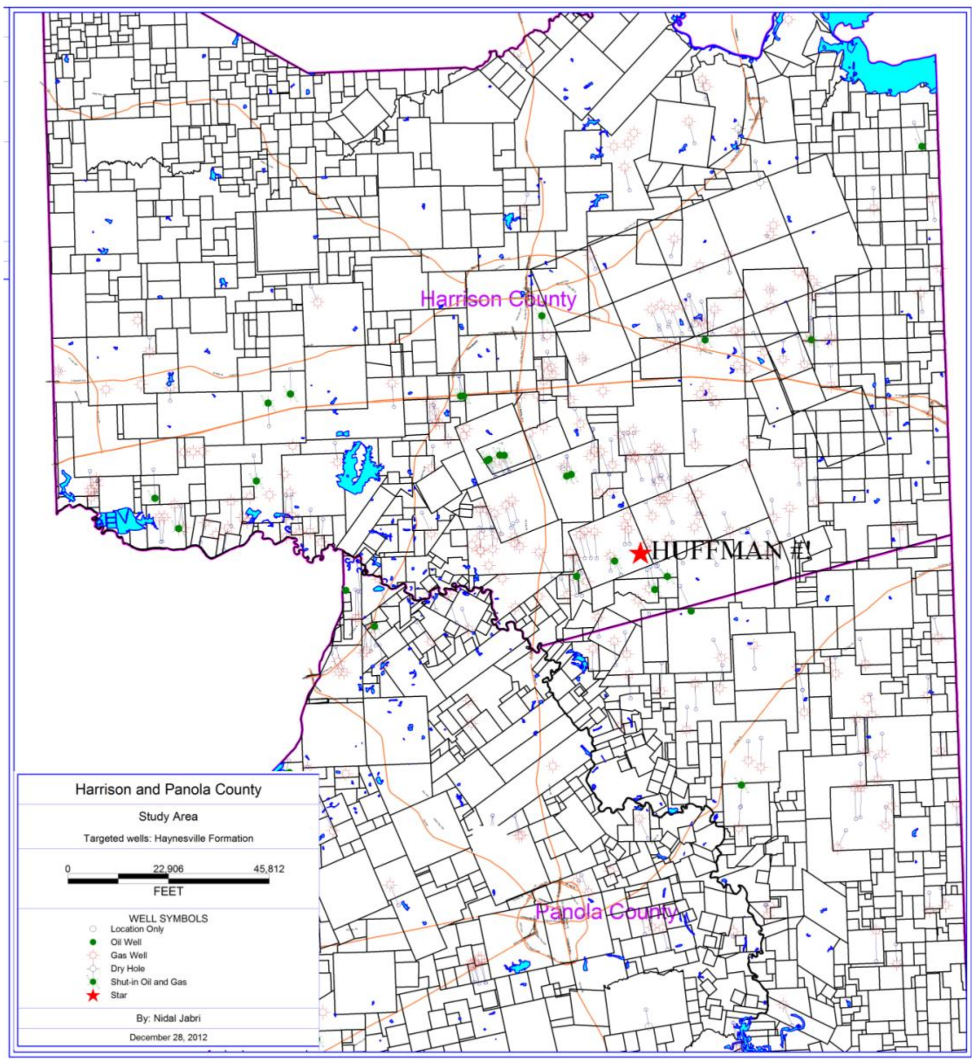

Figure 1.1 Study area showing the Huffman #1 core location.

Specifically, the study focuses in Harrison County, East Texas, USA (Fig 1.1). Concentrating on the Haynesville Formation of the Late Jurassic (Kimmeridgian). The Haynesville Formation is a fine grained, black to gray, mudstone deposited in a deep water environment on the margins of the Gulf of Mexico. It sits atop of the Smackover carbonates and overlain by the Bossier Formation (Fig 1.2). Industrially, the Haynesville Formation is referred to incorrectly as shale.

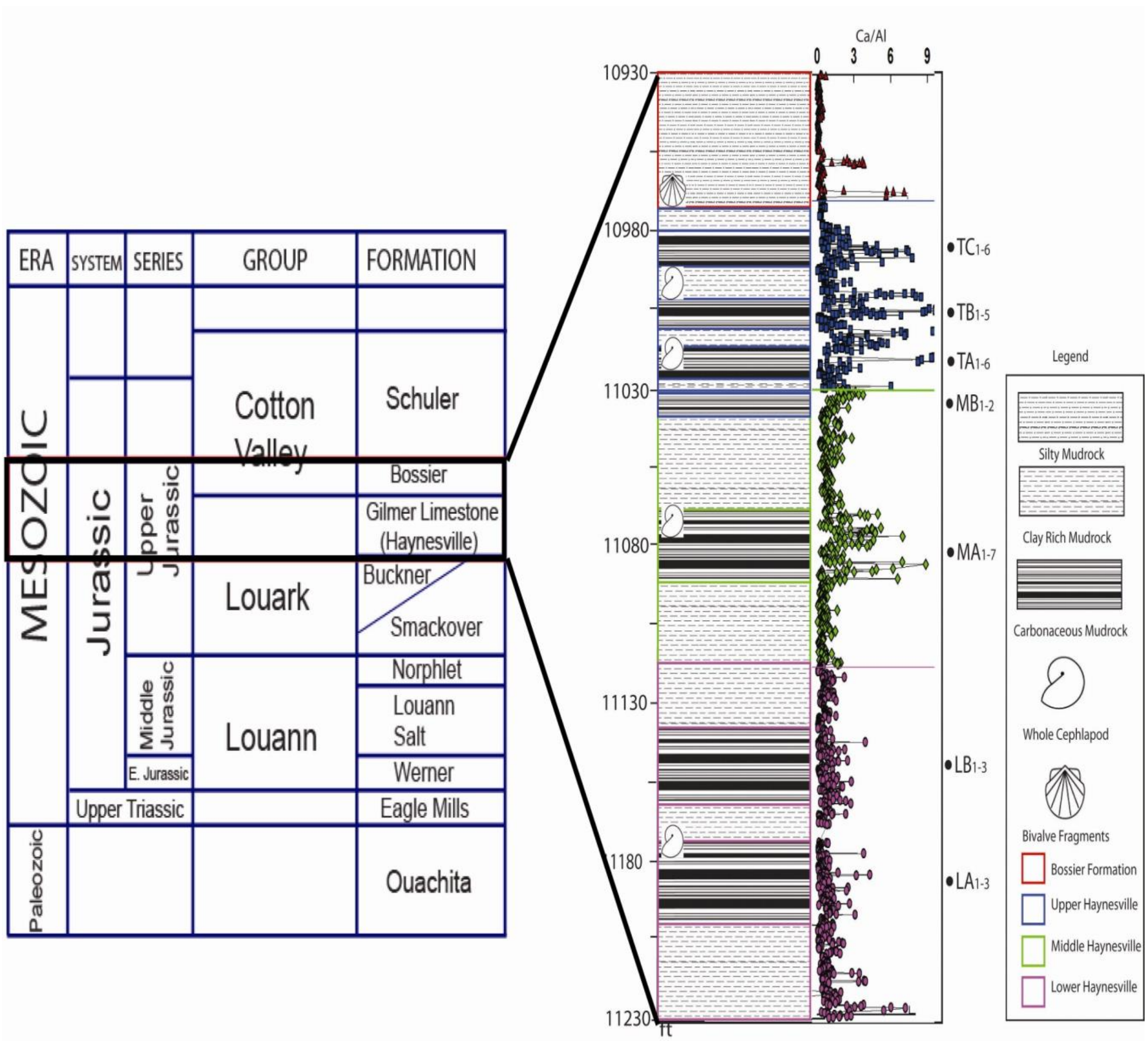

Figure 1.2 Stratigraphic column illustrating lithology of study core Huffman #1 and geochemical proxy, Ca/Al.

However, shale is a descriptive term for its fissile cleavage planes rather than a rock classification. In this case, The Haynesville Formation does contain sections of fissile mudstone but not throughout.

In this study, a micro-localized geochemical analysis will be related to a larger local basin topography and depositional system. Paleotopography affects sediment and biological distribution (Mancini, 2010). The study will include a high definition geochemical analysis of a core from Harrison County (Huffman #1). Additionally, well logs will be used to create a top structure map over Harrison County. Lastly, an initial production fairway map will be used to tie the bathymetric settings and the migration accumulation with the geochemical deposition.

1.2 Geological Setting and Stratigraphy

The Haynesville formation was deposited in a deep marine setting on Jurassic age strata. It was deposited on the flank of the East Texas Salt Basin and west of North Louisiana Salt Basin, constrained in the north by subsidence and rifting faults, and truncated in the south by a structurally high island complex (Hammes et al., 2011). An orogenic event during the Pennsylvanian, known as the Ouachita thrust front set the stage for later salt tectonics and the younger extensional event (Fig 1.3).

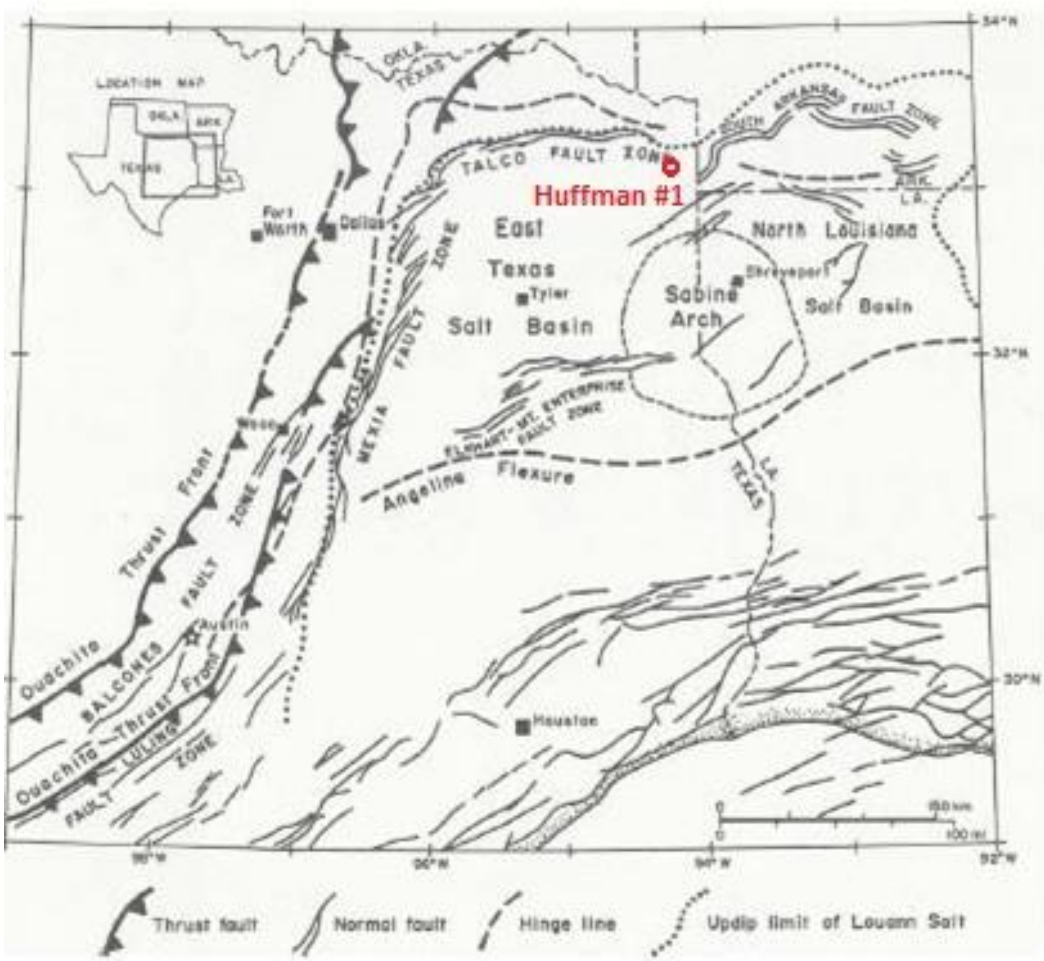

Figure 1.3 Illustration showing the structural setting (Jackson, 1982)

The uplift from the Ouachita event increased the sub-aerial exposure; which resulted in sediment overburden favorable to salt deformation and acted as a source for detrital material. Erosional forces for an ancient Mississippi river delta would be a large contributor of detrital material to the future basin. The Ouachita event was the tip of a larger event known as the Appalachian Orogeny. In Texas, these thrust fronts ran North-South under cover and as they extended into Oklahoma and Arkansas they outcrop running East-West. The Mesozoic was characterized by a rifting event of grabens and half grabens creating varying topography and running parallel with the thrust event (Jackson ,1982). Further subsidence allowed for slight marine intrusions which deposited the Louann Salt (Jackson,1982). The Louanna Salt was deposited approximately 5,000 feet thick. It was removed through dissolution and post depositional halokinesis (Maione, 2001). The northern deposition of the Louann Salt is parallel to the Ouachita trends, which indicates that during the Jurassic the Ouachita area was subject to sub-aerial exposure north of the East Texas Salt Basin (Jackson, 1982). This event is the main contributor to the detrital flux in the Haynesville. Additionally, the post thrust period of reduced tectonics allowed for subsidence which created faults dipping marine ward and striking parallel with the thrust faults. The final result of the rifting was the creation of the Gulf of Mexico Basin. The same processes that formed the Gulf of Mexico formed the Sabine Uplift (Adams, 2009) which is another important detrital source. During the Triassic, basement involved faults and thermal doming from mantle up-well resulted in the creation of the Sabine Uplift (Ewing et al., 2009). The uplift effectively separated the East Texas Basin and North Louisiana into two mini-basins. The basement is up to 10,000 feet shallower than in the middle of the East Texas Basin (Adams, 2009). As a result, the uplift disturbed water currents and increased the stratification of the water column.

In the low areas created by the faulting, the Louann salt was deposited and capped by an erosional surface during the Middle Jurassic. The Middle Jurassic to the Paleocene was characterized by eustatic cycles of deposition (Fig 1.4). Consequently, the deposits created overburden which deformed the layer of salt. The salt traveled through the propagated extensional and thrust faults as diapirs and pillows (Fig 1.5). The salt flow and further subsidence created turtle structures, Salt free asymmetrical anticlines and mini basins. (Jackson, 1982) Overall, it set the stage for complex basin morphology.

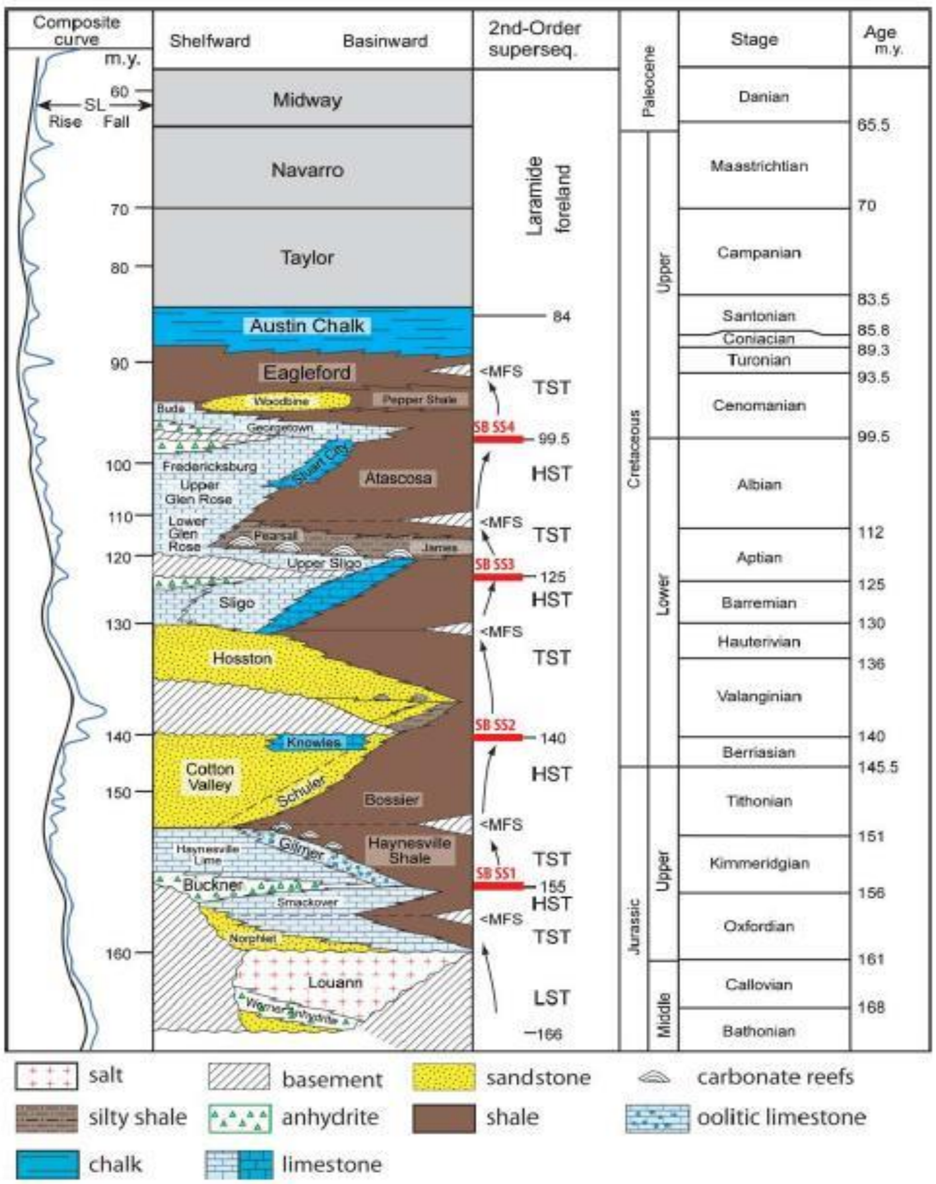

Figure 1.4 Stratigraphy column illustrating the cyclical sea level changes during the Cretaceous and Paleocene. (Goldhammer, 1998)

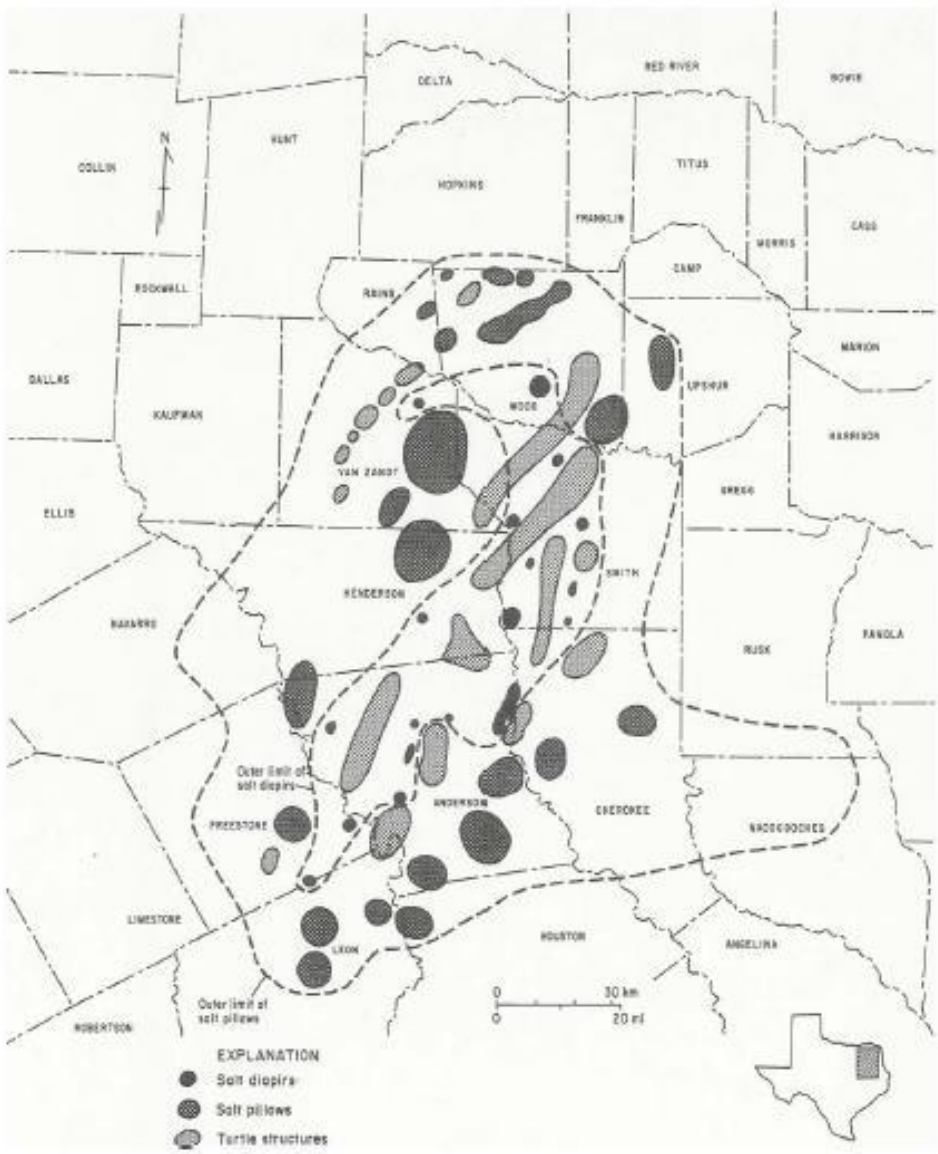

Figure 1.5 Illustration showing the salt diapirs and pillows of the East Texas basin. (Jackson, 1982)

1.2.1 Stratigraphy

Early nomenclature describes the Haynesville as the Lower Bossier as noted by the Texas Railroad Commission (TRRC). However, subsequent studies have determined two different stratigraphic units. The Bossier and Haynesville Formations can be distinguished by a particle size, color and a lack of calcium carbonate. The Bossier Formation has larger grains and a more grayish black color. As you transition from the older into the Haynesville, the grains become fine, and the color deepens to a rich organic black. The Haynesville Formation is underlain by a carbonate rich section deposited on the ramp and margins of the Gulf of Mexico (Hammes et al., 2011). The Haynesville is characterized by anoxic bottom waters and a restricted type basin (Fig 1.6; Scotese, PALEOMAP Project). Both detrital and marine influences play a role in the formation of the Haynesville. The top of the Haynesville is the most landward extent of that transgression cycle and as we enter the Cretaceous period sea level was decreasing. The early cretaceous was dominated by Hosston sands. Deposition of sediments occurred until the Paleocene when sea level retreated enough to create sub-aerial exposure that we observe today. Currently, the Haynesville Formation ranges from 9000-14000 feet with an average thickness of 200 to 300 feet (Hammes et al., 2011).

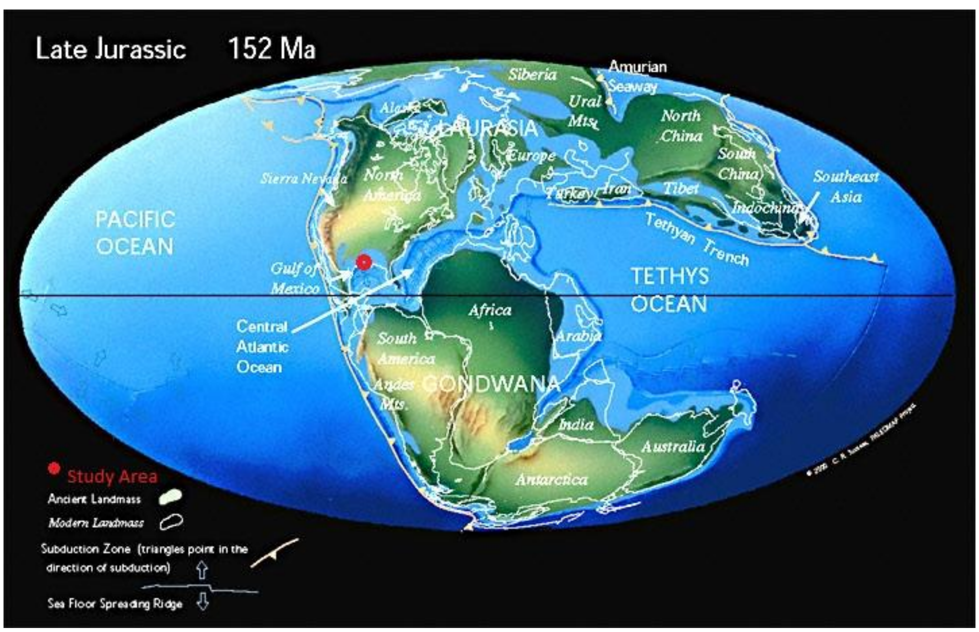

Figure 1.6 Paleogeographic map of 152Ma showing the study area as a red circle.

CHAPTER 2

METHODS

2.1 Subsurface Database

A large subsurface database in IHS Petra was compiled using wells in Panola and Harrison County (Figure 1.1) provided by the TRRC. The database was used to create top structure maps of the Haynesville and Bossier Formations. Additionally, the database will be used to create initial production map, cross sections, field maps and for well logs illustrations.

The database was narrowed down based on wells with available well logs and wells that penetrated the Haynesville formation. Well logs will be provided free of charge from the Texas Railroad Commission. Top Structure maps will be created by calling tops from well logs. If well logs are unavailable and the well penetrated the Haynesville, the top will be recorded off the Texas Railroad Commission's completion report with an uncertain level of error. Using the kelly bushing subsea, values were derived to normalize differences in surface elevation. The initial production map will be created by recording the first 24 hours of gas production. Those values will then be normalized by the length of the well lateral. Then, the values for the initial production will be plotted and contoured. Cross sections will be generated from the IHS Petra Cross Section Module. The cross section will be composed of raster image logs that have all been depth calibrated with each other. The field maps were composed of the shape files compiled in ARCGIS. The shape files were provided by the Texas General Land Office and Tigerline. The shape files included survey outlines, water sources, and county outlines. The shape files were all converted to NAD 1927 using ARCGIS.

2.2 Well Core Information

One drill core, Huffman was recovered from Harrison County in the East Texas Basin. The drill core is composed of the entire Haynesville formation and the overlain formation, Bossier formation (Table 2.1). The drill core, Huffman #1 is currently being housed in the core repository of the Bureau of Economic Geology (BEG) at the JJ Pickle Research Facility in Austin, Texas. Permission to scan the cores was given by Senior Research Scientist for the BEG, Dr. Stephen Ruppel. The Huffman #1 core was drilled by NFR energy, currently known as Sabine Oil and Gas, as a horizontal gas well.

Table 2.1 Core specifics

Core Name	Huffman #1
Operator	NFR Energy
API	4220334529
Location	South Central Harrison County
Units	Imperial
Core Interval (Length)	10930-11230' (300')
Sample Interval for ED-XRF (TOC, N, $\delta^{13}C$, $\delta^{15}N$)	2' (1')
Number of Samples for XRF (TOC, N, $\delta^{13}C$, $\delta^{15}N$)	1800

2.3 Energy-Dispersive X-Ray Fluorescence (ED-XRF)

The Huffman #1 core was analyzed for major inorganic elemental chemistry using a Brüker Tracer III/V handheld energy-dispersive x-ray fluorescence (ED-XRF) instrument. An Approximately two-inch interval was used with a sampling time of 30 seconds. The instrument was kept stable using a using a stand. The sample would sit on top of a platform to keep the sample flush with 3x4 mm elliptical beam area (Fig 2.1). The sample must lie closely and flush with the elliptical beam area because the accuracy decreases by the inverse square of the distance away from the silicon detector (SiPIN)(Hughes, 2011).

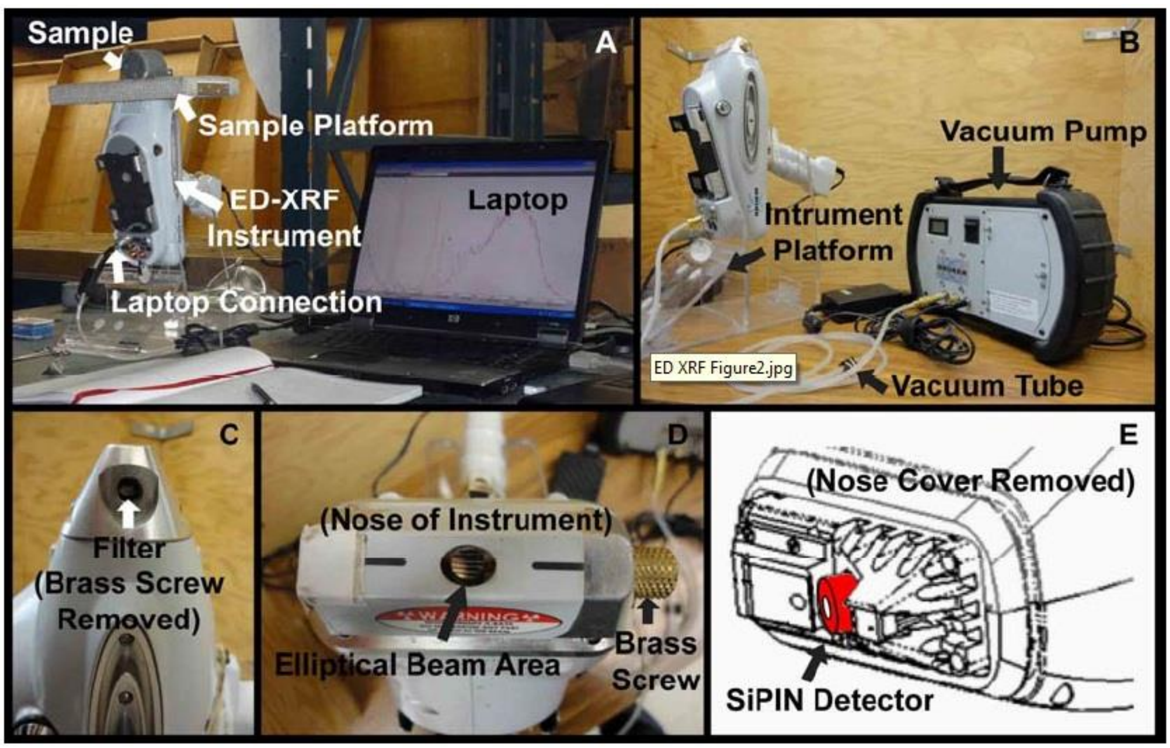

Figure 2.1 Instrument setup (A) Showing the general setup
(B) illustrating the the vacuum pump and platform (C) filter loading area
(D) 3x4 mm beam area (E) SiPin Detector (Hughes, 2011).

The Huffman #1 core was analyzed on the smoothest possible surface to insure an accurate reading. The inorganic elemental chemistry analysis was generated using a low energy, vacuum pump setting on the instrument. The low energy spectrum acquisition includes elements that emit characteristic x-rays between 1.25 to 7.06 kV. The voltage was set to 15 kV to collect the elements in this range and allow for backscatter that does not conflict with the peaks of interest (Hughes, 2011). The instrument current was set to 42 μA. Accuracy of the instrument, when analyzing lighter elements (below and including Ca), was increased using a vacuum pump operating <3 torr attached directly to the Tracer III-V. The vacuum pump removes air between the sampling window and the detector. Resulting in raw data later expressed in weight percent (wt%) for elements such as magnesium (Mg), aluminum (Al), silicon (Si), phosphorus (P), calcium (Ca), titanium, (Ti), manganese (Mn), and iron (Fe); and, where applicable, parts-per-million (ppm) of vanadium (V), and potassium (K).

2.3.1 ED-XRF Mudrock Calibration

The raw data gathered by the Tracer III-V requires calibration by comparing the qualitative values to other mudrock reference suits to create quantified weight percentages. The calibration includes the following 90 mudrock standards: 5 international, 7 Devonian-Mississippian Ohio Shale, 20 Pennsylvanian Smithwick Formation of Central Texas, 27 Devonian-Mississippian Woodford Formation of West Texas, 15 Late Cretaceous Eagleford Formation of South Texas, and 16 Mississippian Barnett Formation of North Central Texas (Hughes, 2011).

Each of the 90 reference materials were pulverized in a TM Engineering Pulverizer with trace-metal grade grinding barrels to 200 mesh. Eight grams of each of the powdered standards with a boric acid backing were pressed using a Carver press to 40 tons with a 40mm die. The finished reference pellet was analyzed for major elements using wavelength-dispersive x-ray fluorescence (WD-XRF) and inductively-coupled plasma mass spectrometry (ICP-MS) (Hughes, 2011).

The standard pellet was analyzed on the Bruker Tracer III-V in various locations under low energy settings. The raw x-ray spectra data was loaded into Bruker's CalProcess software along with the accepted (WD-XRF & ICP-MS) elemental concentrations for all standards. Certain standards were omitted after the implementation of the inter-element corrections using statistical analysis for each element to determine the outliers with a critical value greater than 3.0 standard deviations from the mean. The standard pellet used for this study was the Barnett Formation.

2.4 TIC, TOC, TN, δ13C, and δ15N Analyses

Samples were collected and pulverized from the Huffman #1 core in approximately one-foot intervals. The samples were stored in 120 mL specimen containers (VWR part# 82030-366). Total inorganic carbon (TIC) analyses were performed using a UIC, Inc. coulometer equipped with a CM5230 acidification module (Engleman et al., 1985), with average unknown standard deviations of <0.5%. The TIC samples were weighed between 5 to 80 mg and acidified at 70°C with 10% phosphoric acid (H3PO4). Total organic carbon (TOC), total nitrogen (TN), and stable isotopic compositions of TOC (δ13C) and TN (δ15N) were performed on powdered samples that were weighed into silver capsules (Costech

Analytical, Inc. #41067) and subsequently acidified repeatedly with 6% sulfurous acid (H_2SO_3) in order to remove carbonate phases (Verardo et al., 1990; Rowe et al., 2001). Samples were analyzed at the University of Texas at Arlington using a Costech 4010 elemental analyzer interfaced with a Thermo Finnigan Conflo IV device to a Thermo Finnigan Delta V isotopic ratio mass spectrometer. Isotopic results are reported in per mil (‰) relative to V-PDB for $\delta^{13}C$ and air for $\delta^{15}N$ (Hughes, 2011).

CHAPTER 3

RESULTS

3.1 Subsurface Database Results

The subsurface database started out with 16682 wells that were drilled in Harrison and Panola Counties. The wells were narrowed down 326 wells based on Haynesville penetration (Study Area). The main focus was on wells that had usable well logs. There were 141 well logs that were depth calibrated, but only 26 well logs were un-correlatable (Fig 3.1). 115 wells logs were correlated for Bossier Top. Of those 115 well logs only 74 wells logs actually recorded the Haynesville top. The rest of the tops data was recorded from completion reports. The contoured top structure maps have well control highlighted in purple. The total data points for the Bossier Formation were 126 and Haynesville were 88. The Bossier Formation was consistently conformable to the Haynesville Formation (Fig 3.2). Both formations had approximately 43 feet/mile gradient dip to the west (Fig 3.3). The top structure of the Haynesville has varying topography creating ridges and valleys. The initial production maps were composed of 301 data points. The Initial production ranges from zero to 2.8 mmcf and had a mean value of 1.9 mmcf and median value of 1.7 mmcf (Fig 3.4).

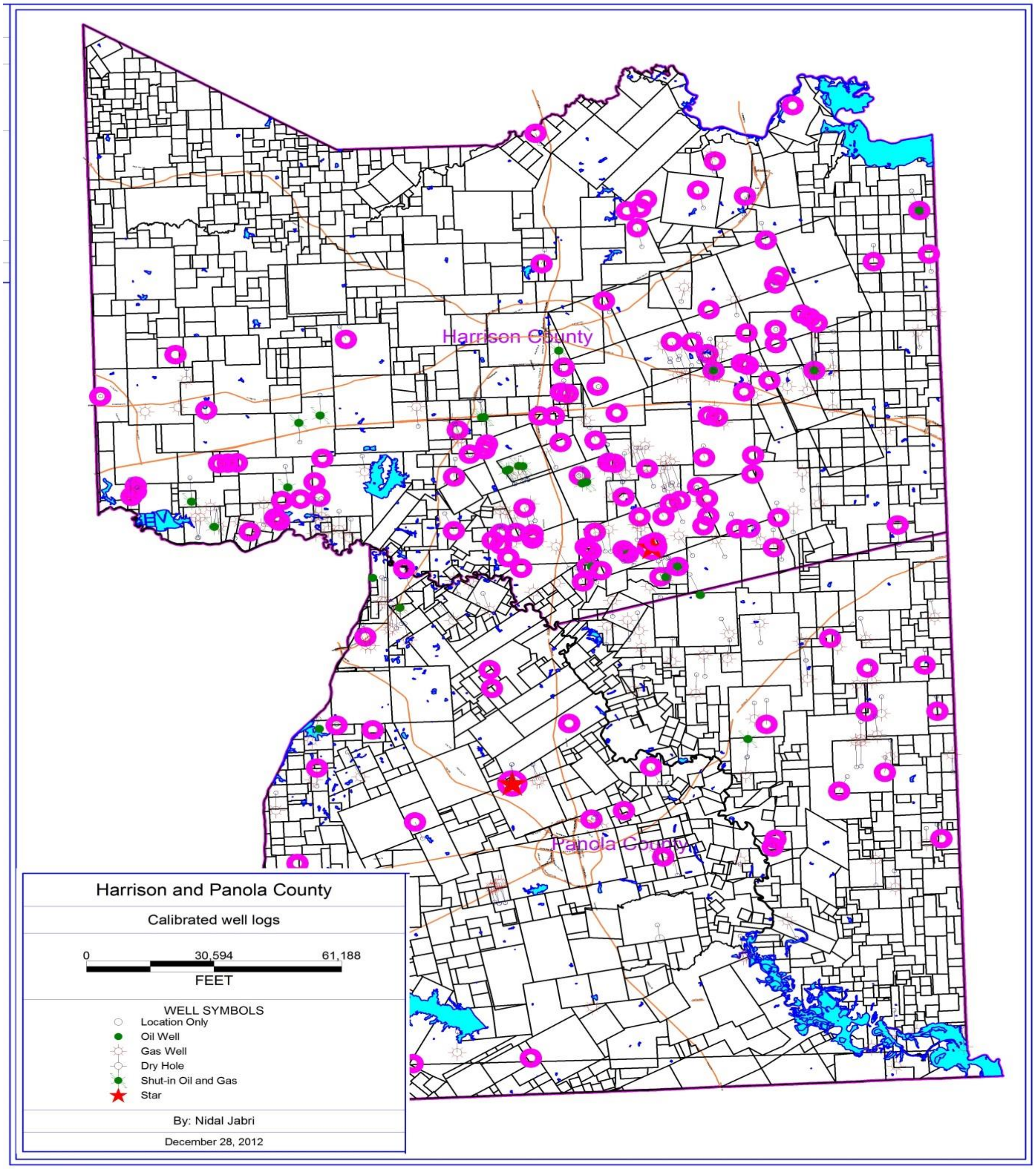

Figure 3.1 Calibrated well logs highlighted in purple

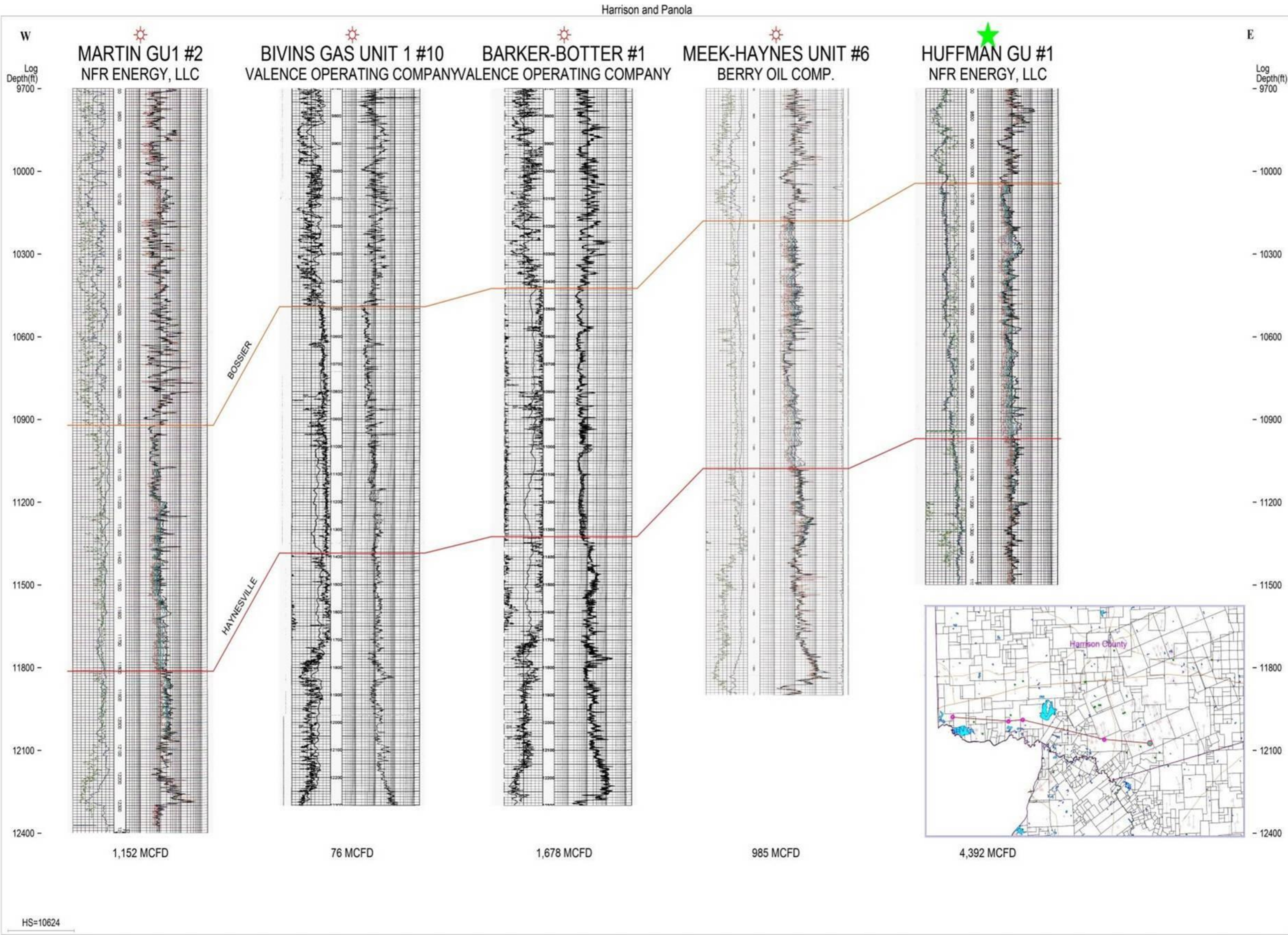

Figure 3.2 Cross Section Running West to East showing local dip direction.

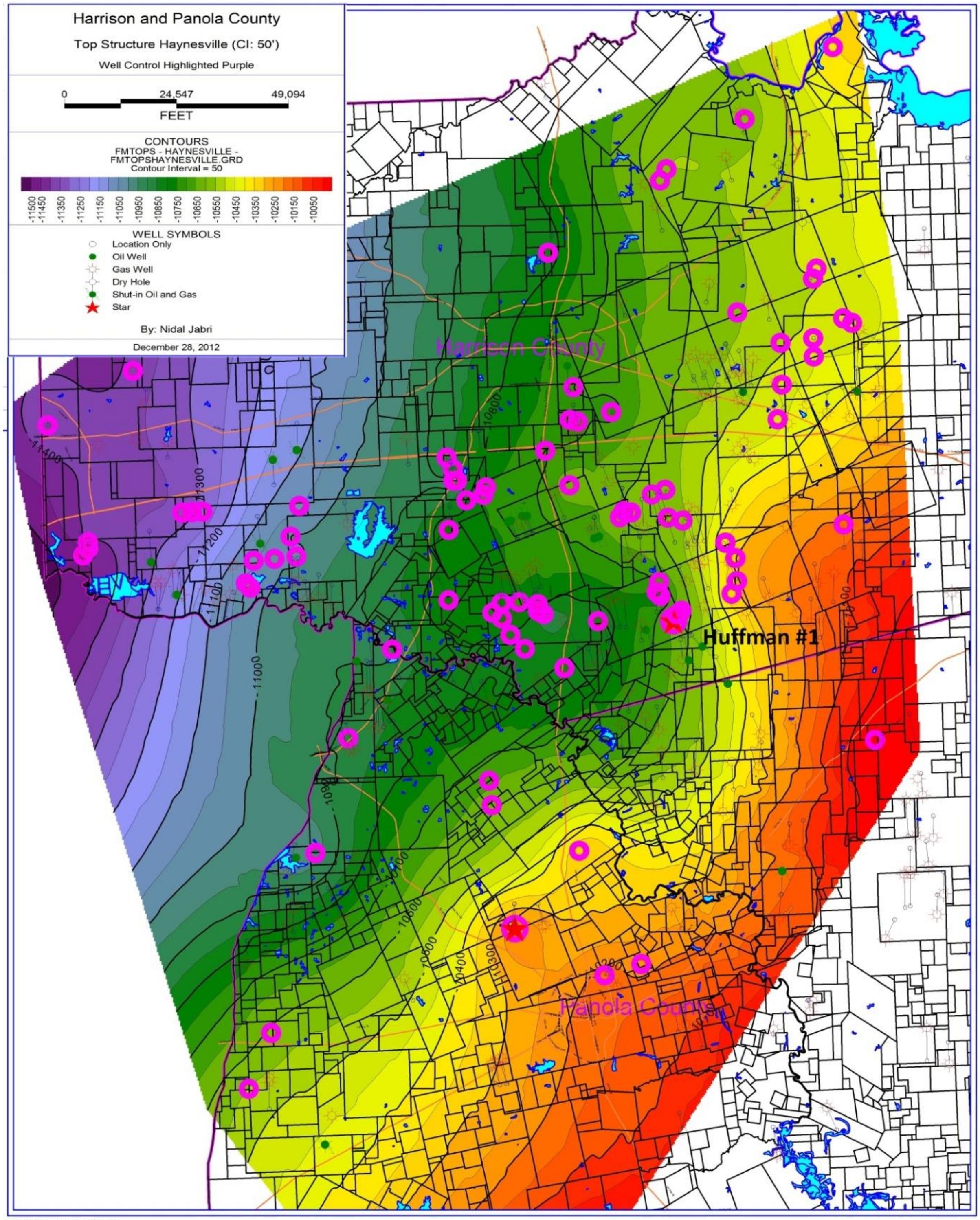

Figure 3.3 Top Structure map of the Haynesville. Highlighted control points (CI:50')

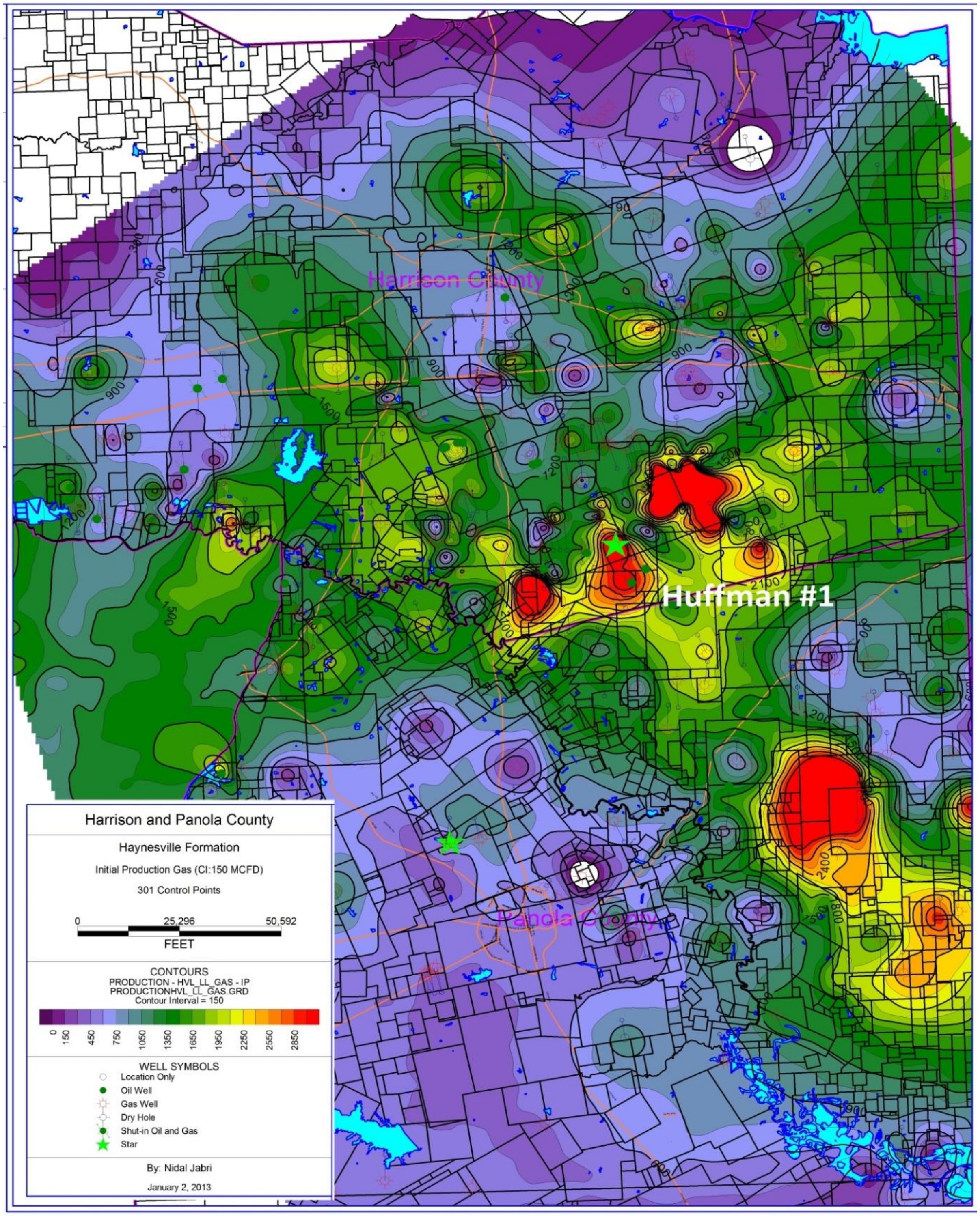

Figure 3.4 Initial Production Map (CI: 150 mcf/d)

3.2 Core Characterization

The Huffman #1 core contained the lower part of the Bossier Formation and the entire Haynesville Formation. The visual inspection of the core resulted in near homogenous properties. The only distinctive traits that were observed were calcite stringers, pyrite fragments, and the occasional Ammonites (Fig 3.5). Lastly, there was a visual darkening from the Bossier Formation transcending to the Haynesville Formation. For a better understanding of the core, a high definition analysis was performed. Other studies, Pukar 2011, have analyzed the geochemical framework but lack the resolution to get an in depth dissection of the core. Also, standard gamma ray logs do not have the resolution that is provided by scanning at 2 inch intervals (Fig 3.6). The Huffman #1 core had 1800 sample points scanned at 2 inch intervals. A previous study was conducted on a Haynesville core, the Carthage #16-19, by Pukar that had one foot intervals which resulted in approximately 280 sample points. The previous study missed the high variability of the Kimmeridgian mudstone.

Figure 3.5 Image of a whole Cephalopod cast in the Huffman #1 Core

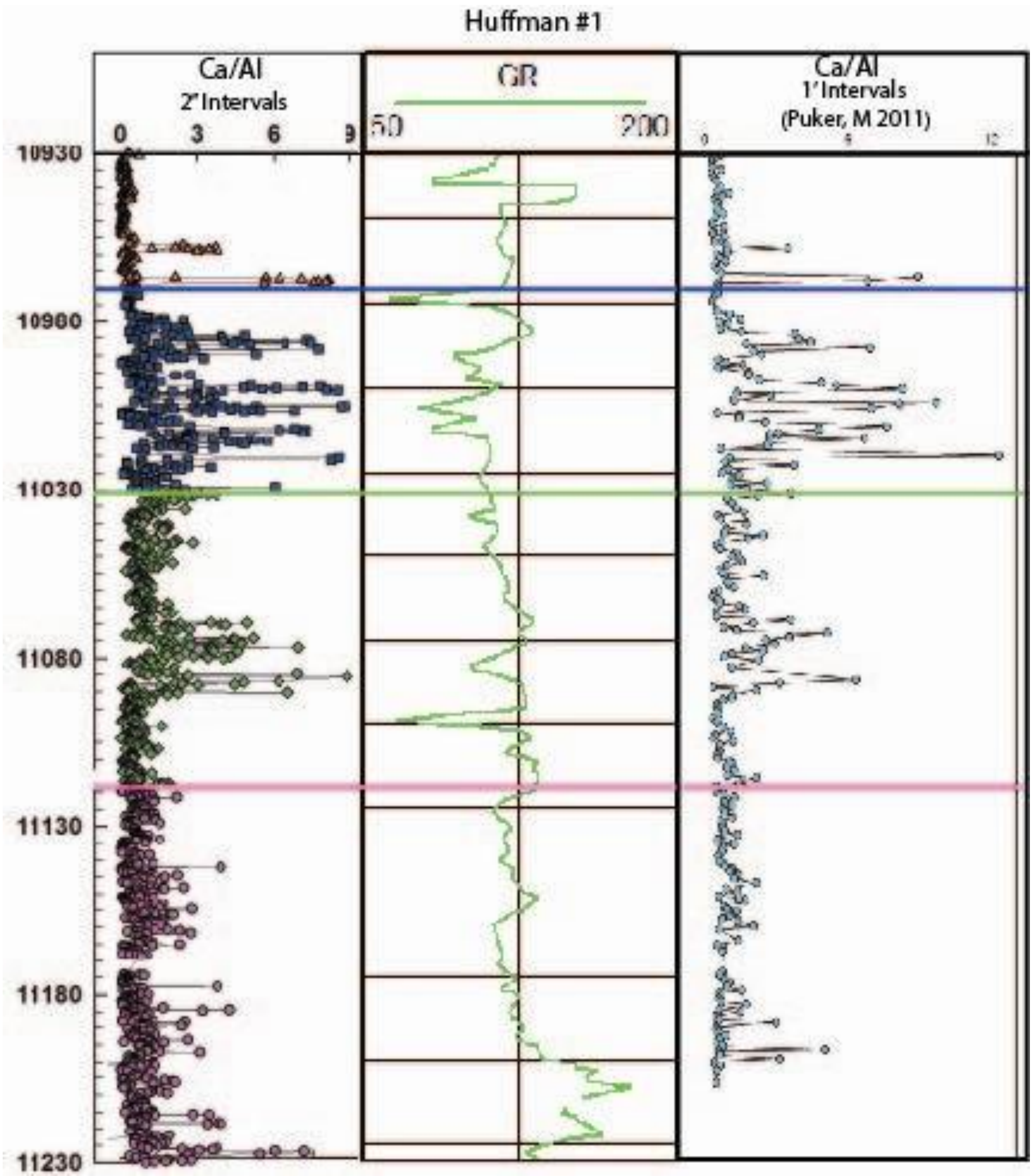

Figure 3.6 Illustrating the variations in resolution between 2" on the left, Gamma in the Middle ½' and 1' done by Pukar, 2011,

3.2.1 ED-XRF and UIC COULOMETER

The main proxies for mineralogical classification are the comparison between %Al, %Ca and %Si. Figure # (Fig 3.7) illustrates the normalized weight percentages between SiO_2, Al_2O_3●5, and CaO●2. The SiO_2 end member represents the Quartz mineralogy; the Al_2O_3●5 represents the clay, illite, components and the CaO●2 represents the Carbonate rich organics. The Huffman #1 has a background amount of silica and was either enriched by carbonate or illite. The ternary diagrams were broken into the Bossier Formation, Upper Haynesville, Middle Haynesville and Lower Haynesville. The Bossier formation had the most concentrations of silica with low values of carbonate (Table 3.1). In reference to the concentration of silica, The Bossier and the lower Haynesville are closely related. The upper Haynesville and middle Hayneville had the lowest values of silica. The relationship between other major elemental components was cross plotted against %Al. They include: %Si, %Ca, %Fe, %Mg, %Ti, and %K (Fig 3.8 & 3.9). The % Si showed a linear correlation with % Al, indicating that the Si was part of the clay fraction rather than detrital quartz. This was also the case with %K, %Ti, %Mg, and %Fe. This is an indication that they reside within the clay structure, or are intimately related with the clay structure (Rowe, 2010). Titanium is often believed to reside in Rutile phase (TiO_2) which is highly resistant heavy metal (Morton and Hallsworth, 1999). Since the titanium is not used by a biogenic process and has a linear correlation with aluminum it either acts as a clay mineral grain or is associated with the illite (Rowe et al, 2012). %Ti is also indirectly related to the size of the grain. The % Ca when plotted against % Al showed an inverse relationship indicating that the % Ca wasn't associated with the clay but rather biogenic calcite. The % TIC indicates the presence of a carbonate phase, siderite, ankerite, or pure calcium carbonate. However, low values indicate that the phase is

more associated with biogenics (Fig 3.10). Identifying the biogenetic component poses some issues due to different grain association such as silica, calcareous, or other organic material. Using TIC predominates of siliceous and/or organic material in anoxic environments (Rainswell et al, 2001)

Table 3.1 Showing average concentrations of mineralogical components in the Huffman #1

	Bossier	Upper Haynesville	Middle Haynesville	Lower Haynesville
Avg %Si	19.23	17.50	18.50	19.15
Avg %Ti	0.36	0.30	0.36	0.38
Avg %Fe	3.95	2.67	3.07	3.33
Avg % Ca	3.02	8.36	5.95	4.59

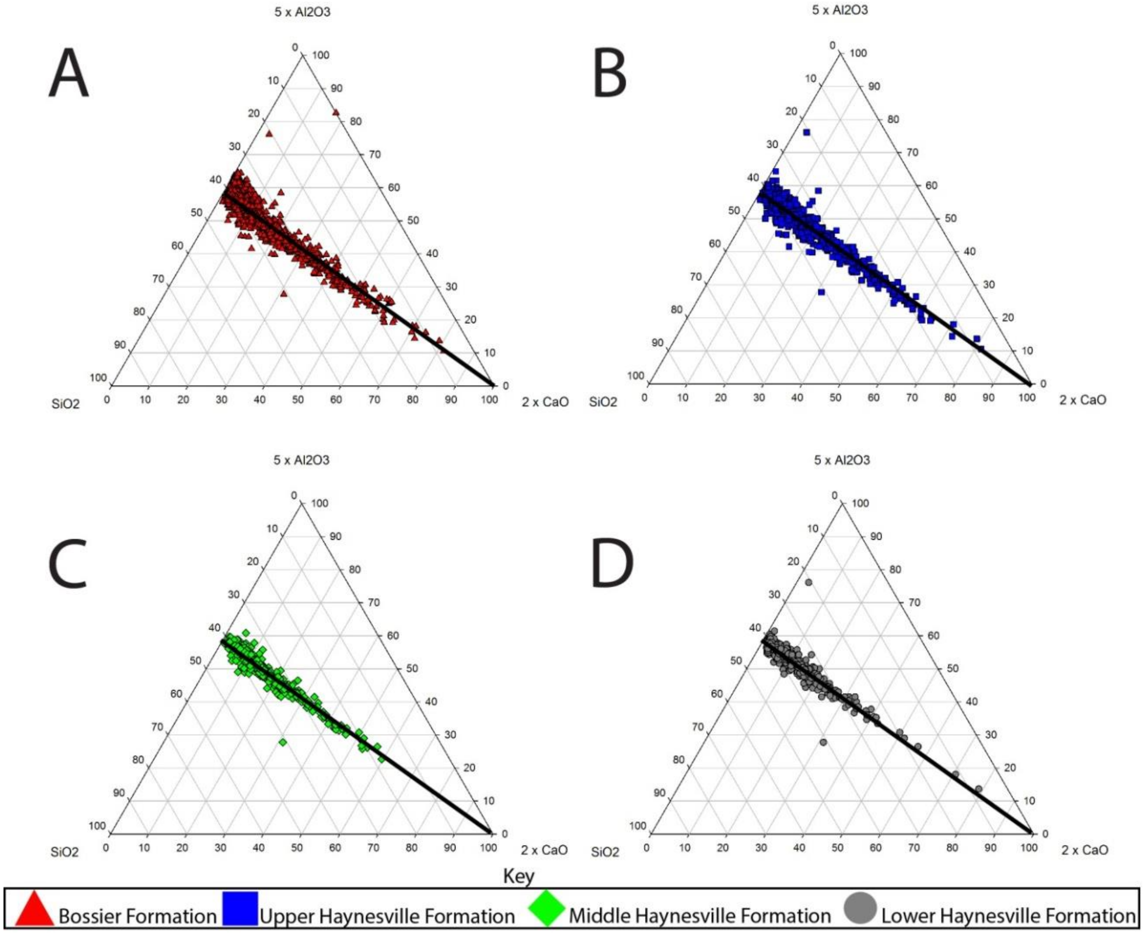

Figure 3.7 Ternary diagrams illustrating the major constituents of the Haynesville and Bossier. (A) Bossier, (B) Upper Haynesville, (C) Middle Haynesville, (D) Lower Haynesville.

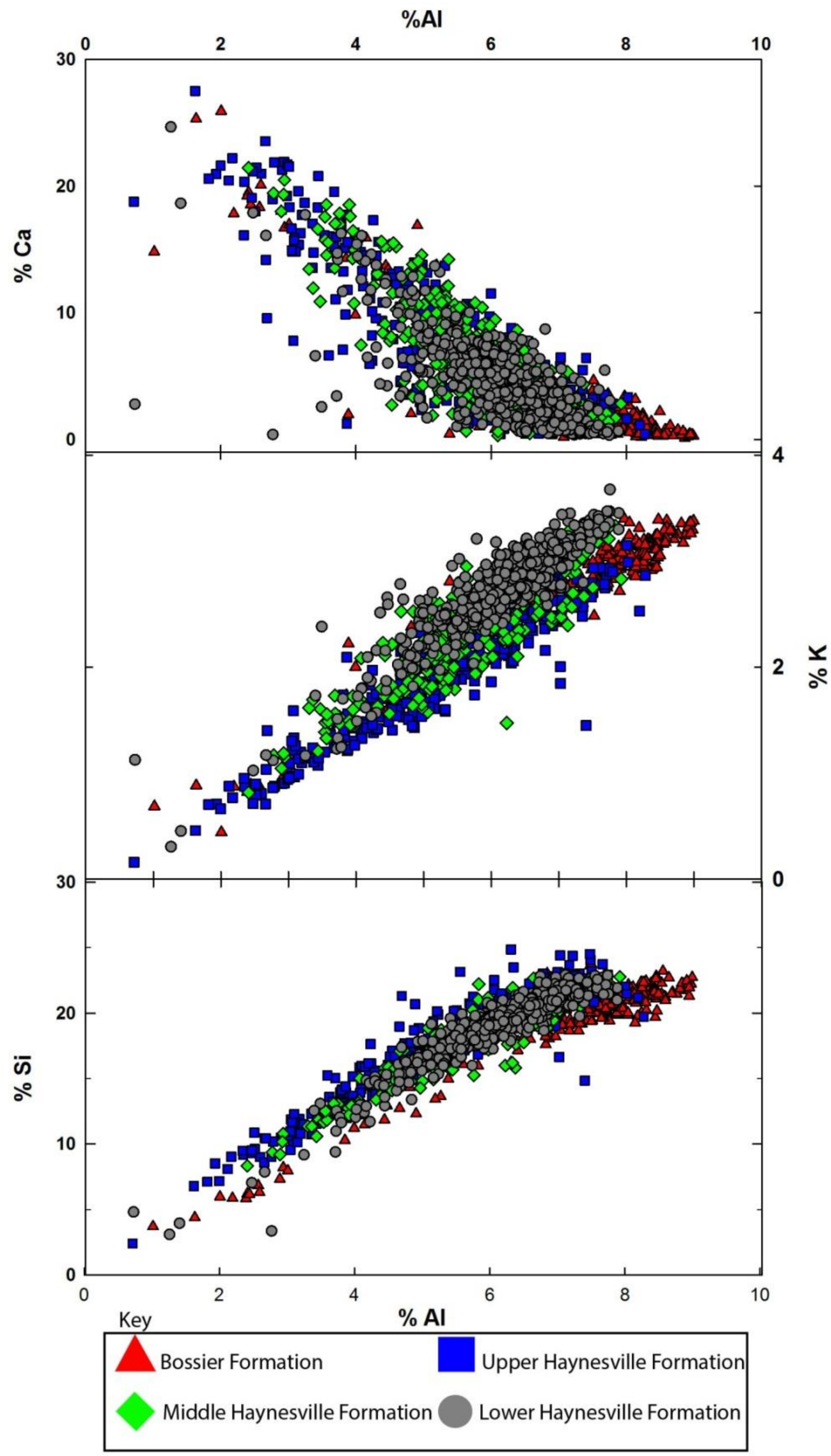

Figure 3.8 Cross Plot of %Si, % K, %Ca, Versus % Al to illustrate the phase each component resides

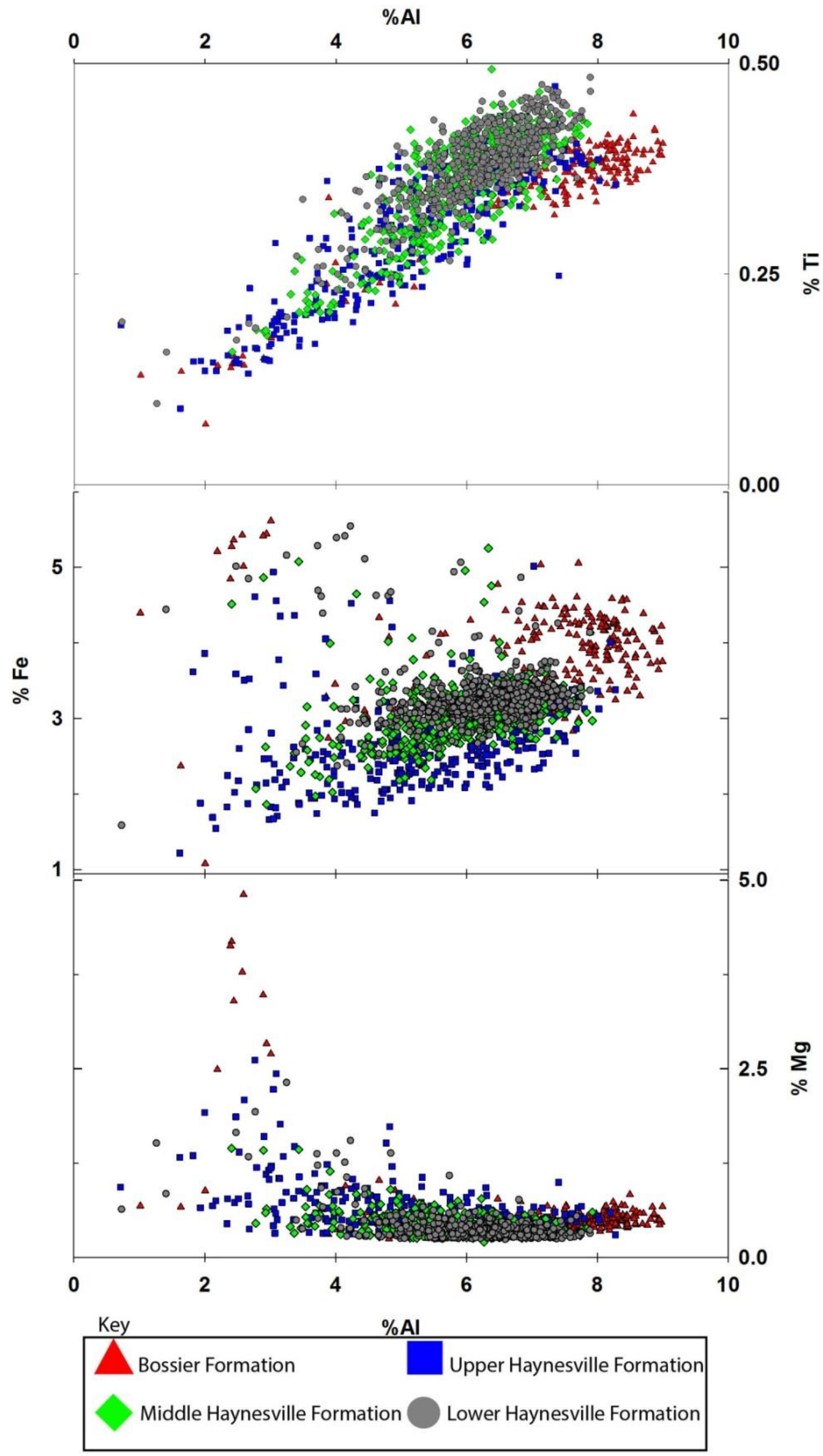

Figure 3.9 Cross Plot of %Mg, %Fe, %Ti, Versus % Al to illustrate the phase each component resides

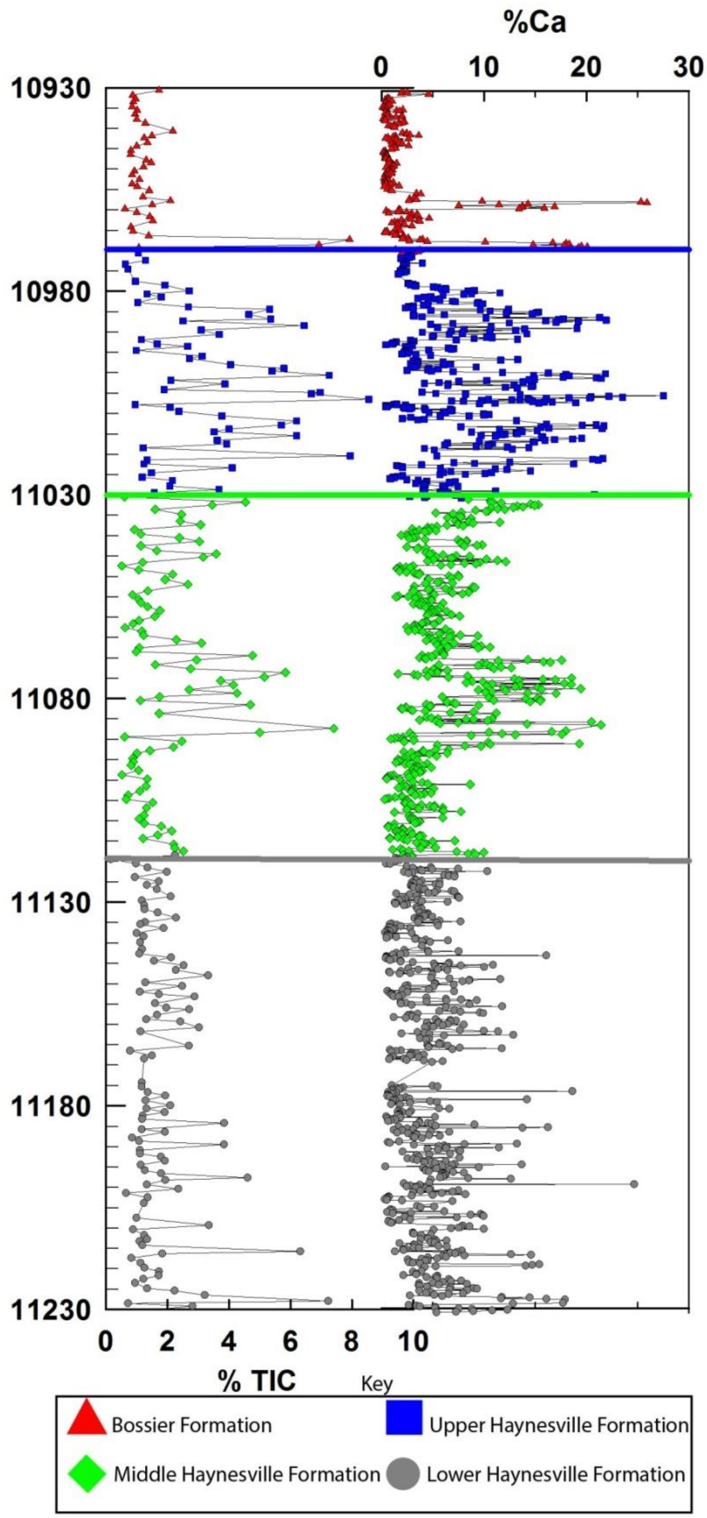

Figure 3.10 Plots of % Ca and %TIC to illustrate the similar oscillations

3.2.2 Chemostratigraphy

The core was separated based on the cyclical patterns produced by the influx of calcium carbonate (Fig 3.11). The Bossier Formation main constituent was detrital clays, quartz, and low carbonate. However, as we progress into the Haynesville, quartz becomes absent and there is an influx of carbonate (Fig 3.12). The carbonates take on a cyclical nature due to the incoming episodes of clays. The boundary between the Bossier and Haynesville Formation is denoted by gradual removal of most quartz, and a domination of illites and carbonates. The inflection point at 10970' between low %TOC and High %TOC marks the boundary between the Haynesville and Bossier Formation.

Table 3.2 dissection of the stratigraphic zonation

Formation	Series	Episodes	Interval Depths
Bossier Formation	N/A	N/A	10930-10970
Upper Haynesville	3	17	10970-11030
Middle Haynesville	2	9	11030-11118
Lower Haynesville	3	7	11118-11230

The Haynesville Formation was divided into three major units: upper, middle, and lower. Furthermore, these units were subdivided into major Carbonate series. The series were then split further into singular episodes of carbonate influxes (Table 3.2).

The Upper Haynesville Formation contains the most episodes of carbonate influxes decreasing in the Middle and Lower Haynesville Formation. As the %Ca increased a brittle petrophysical characteristic could be observed in the core. The Upper Haynesville has a thickness of 60 feet and was the thinner than the Middle and Lower. The Upper section was divided in to three series known as $T_{a,}$ the deepest, $T_{b,}$ the middle unit, and T_c, the upper most unit. Each T_a and T_c contained six subunits and T_b had five subunits. The three series were determined by overall shifts in %Ca. The subunits were defined by individual episodes of % Ca peaks exceeding 2.5%.

The Middle Haynesville is defined as having less cyclical carbonate influxes but with high intensity, having values that exceed 6 units of Ca/Al (Fig 3.13). The Middle Haynesville has a thickness of 88 feet and is divided into series known as, M_a and M_b. $M_{a,}$ the deepest series, was subdivided into seven subunits. Lastly, M_b, the uppermost series in the Middle Haynesville, was subdivided into only two subunits.

The Lower Haynesville (Fig 3.14) is characterized by having low intensity carbonate influxes. It had a thickness of 112 feet. It was divided into three series ($L_{a,}$ L_b and L_c). L_a and L_b were subdivided into three subunits. L_c only had one influx of carbonate.

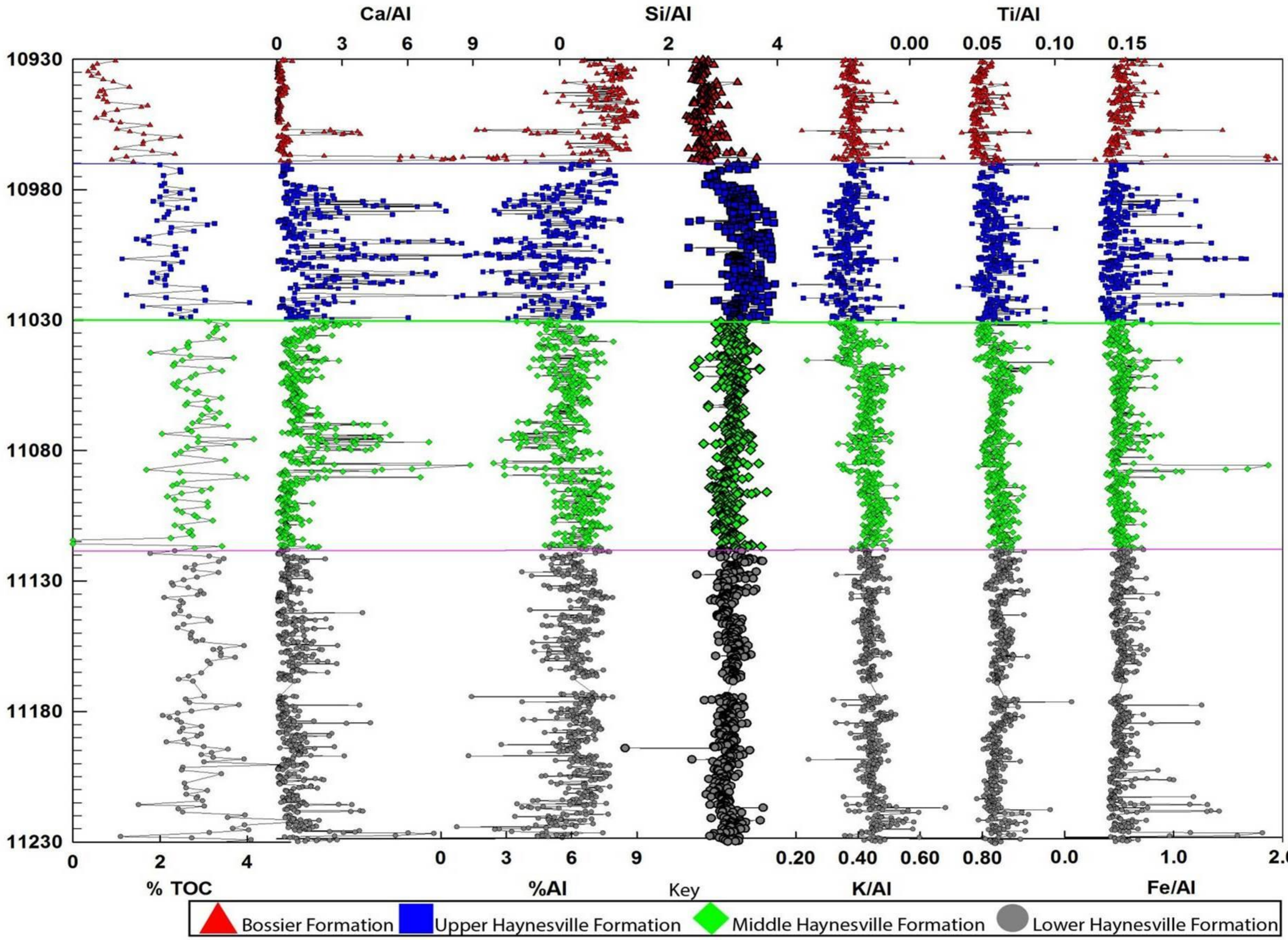

Figure 3.11 Bulk Chemical proxies of the Whole Huffman #1 Core (10930-11230’)

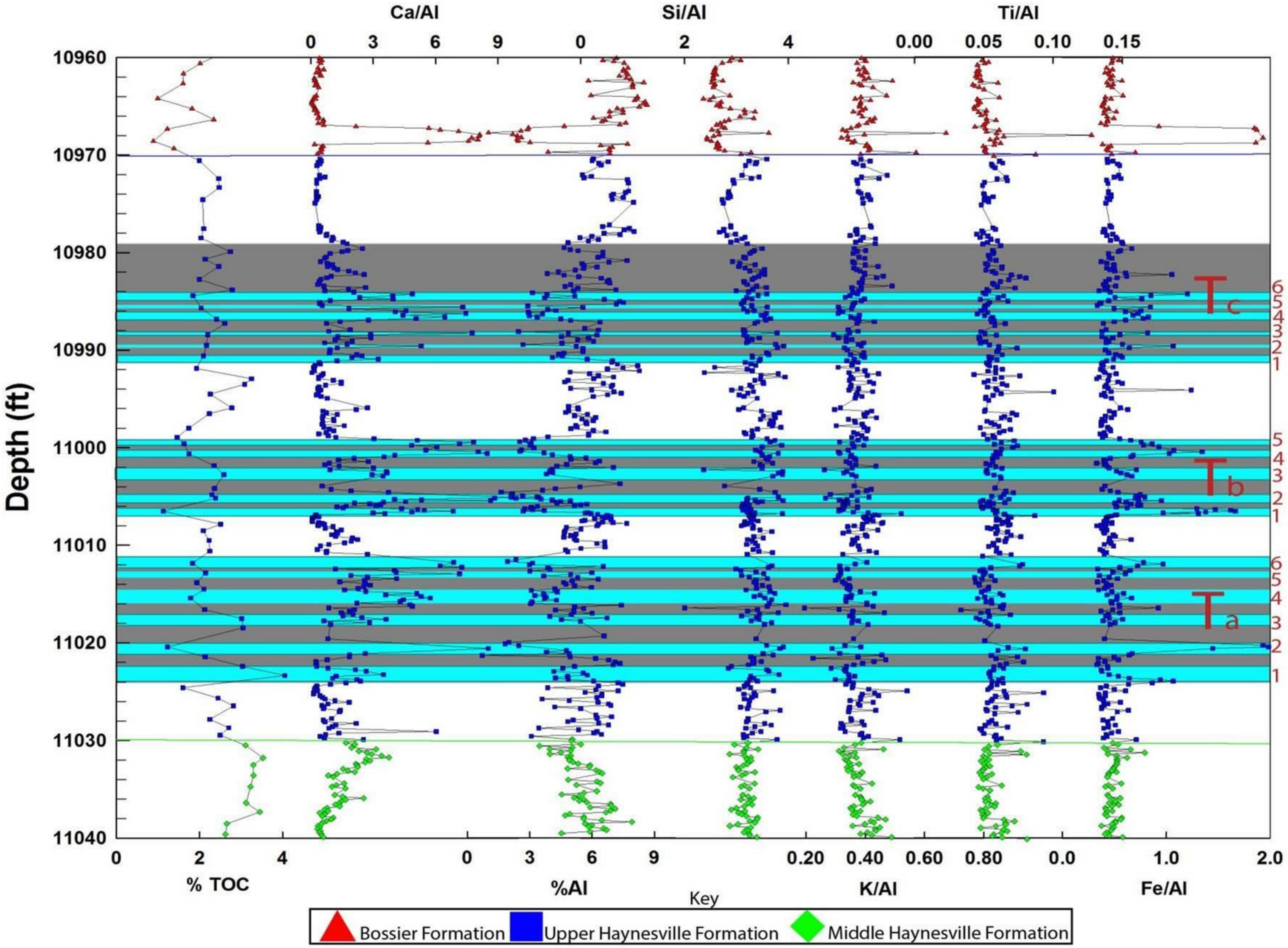

Figure 3.12 Bulk Chemical stratigraphic zonation of the Bossier and Upper Haynesville

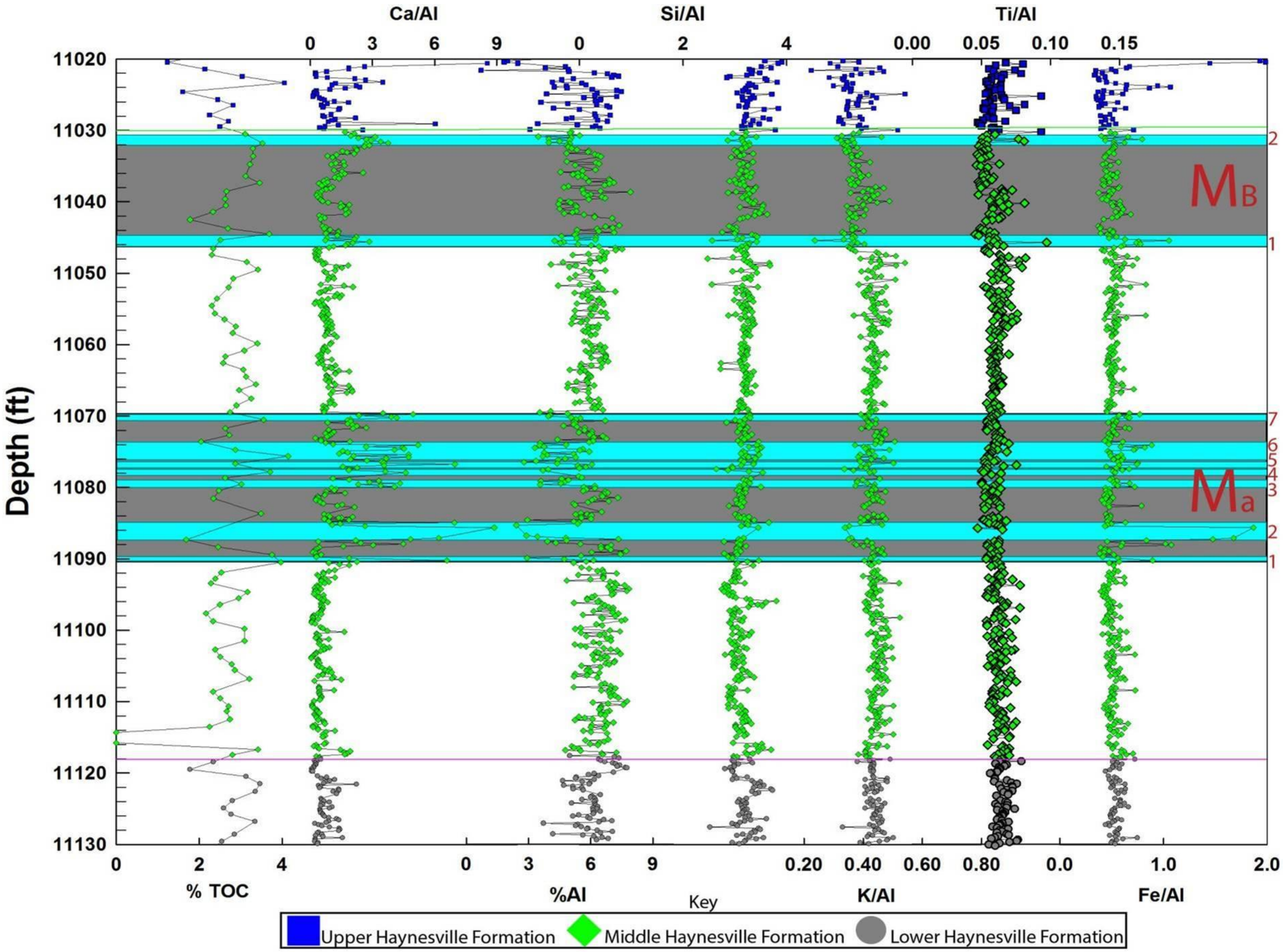

Figure 3.13Bulk Chemical stratigraphic zonation of the Middle Haynesville.

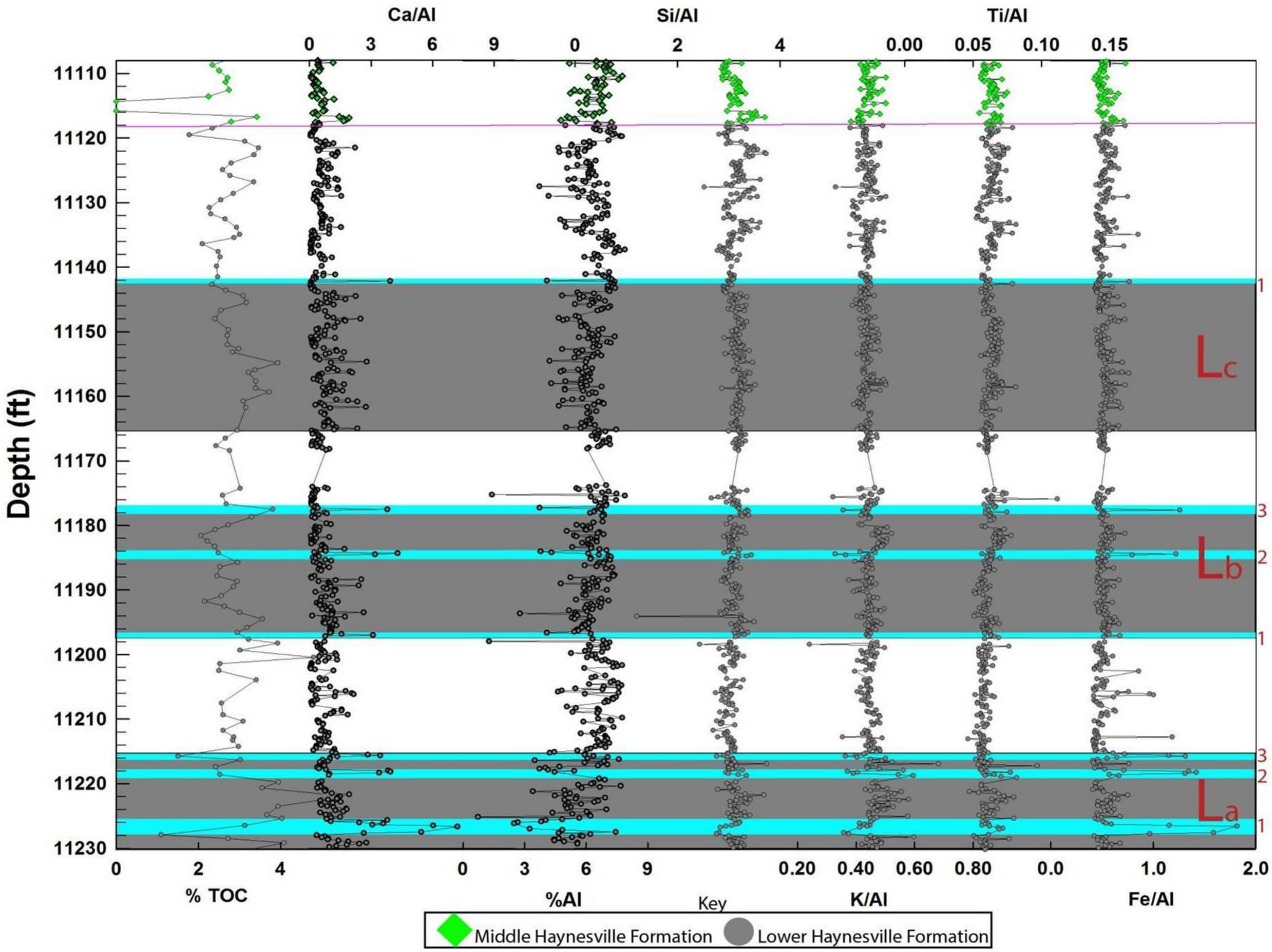

Figure 3.14 Bulk Chemical stratigraphic zonation of the Lower Haynesville.

CHAPTER 4

DISCUSSION

4.1 Subsurface Database

The discussion focuses mainly on the Haynesville formation but will discuss briefly the Bossier formation. The Lower Bossier formation lies conformably atop the Haynesville (Fig 3.2); and the high gamma ray count is mostly undistinguishable from the Haynesville. This indicates that at time of deposition that there were no major tectonic events. The discussion will provide insight into the depositional environment by the examining the relations between the paleotopographic setting, geochemistry and the production of hydrocarbons. The deposition of an organic rich mudstone requires certain geochemical parameters to preserve the kerogen. Furthermore, the paleobathymetry provides a varying topography that affects sediment fill. The Haynesville formations were deposited conformably atop of the Smackover lime.

The Haynesville formation's structural setting is composed of ridges, valleys and other varying topographies of highs and lows. The underlying formations and salt withdrawal played an important role in forming the topography that the Haynesville was deposited. Additionally, there might have been some karsted regions of the Smackover Lime. As you travel regionally down, there is an increasing accommodation which could affect thickness. However, local variations in topography affect the amount of hydrocarbons produced by trapping mechanisms and less slightly by an increase in overburden. The top structure maps show a high production fairway correlating with a valley surround by ridges (Fig 4.1 & 4.2).

Due to low permeability of mudstones, migration pathways are limited to fracture areas. The fracture areas are created either by over-pressured zones or by underlying tectonics. Therefore, structural highs play a slightly limited role in hydrocarbon accumulation. The changes in the structure of the Haynesville could have variations in subsidence increasing fractures and thusly provide a conduit for hydrocarbon migration. Moreover, the low valley areas are more productive for other reasons; it is the pathway that upwellings would follow from the deeper basin, it is less affected by storm base, and it is the route of coarser detrital material. The disturbance from the wave base could have an effect on density currents and mud plumes polluting the organic production. Lastly, it could have set the stage for stratigraphic traps to prevent expulsion of hydrocarbons from the sources rock.

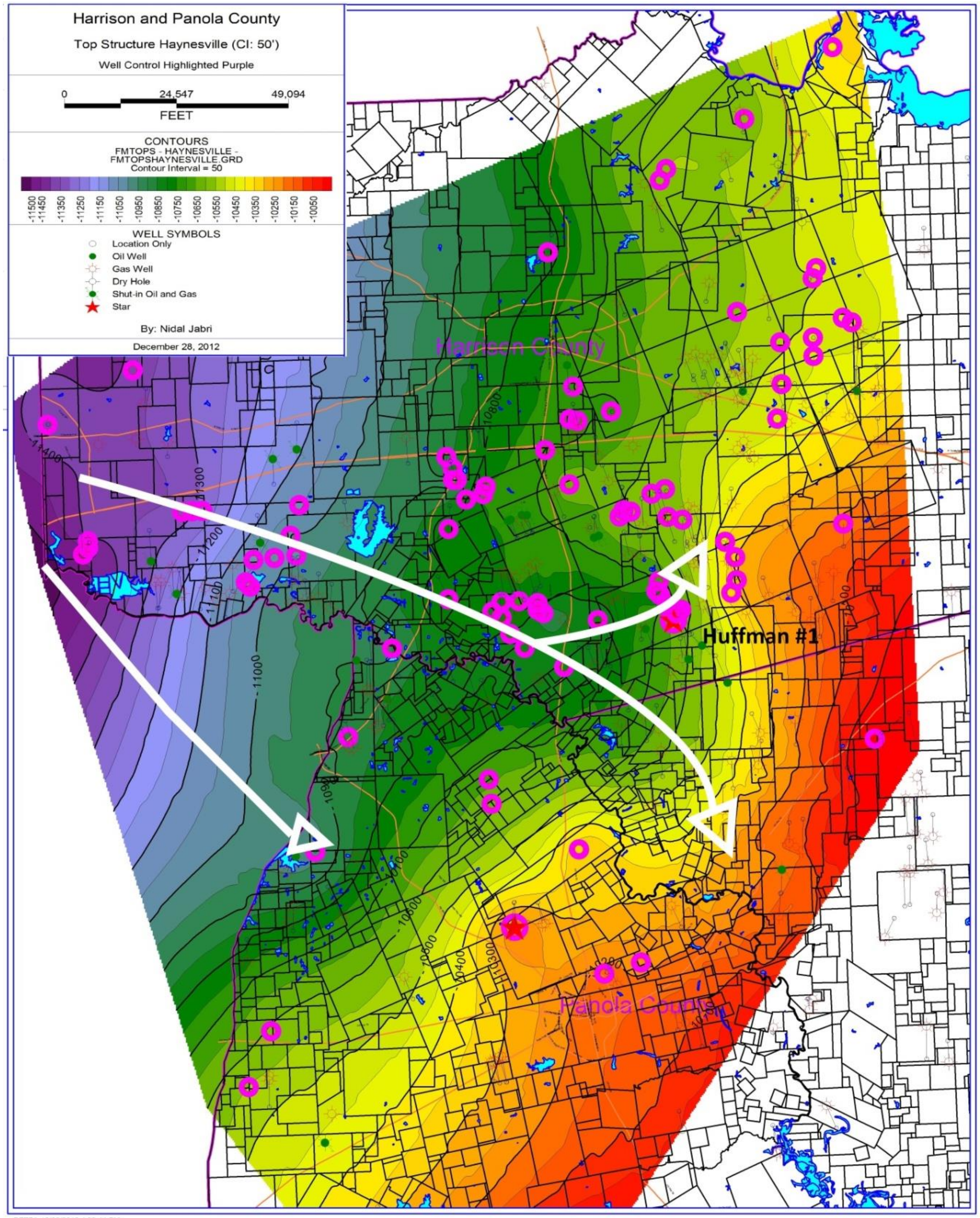

Figure 4.1 Top Structure illustrating migration and accumulation pathways (CI: 50').

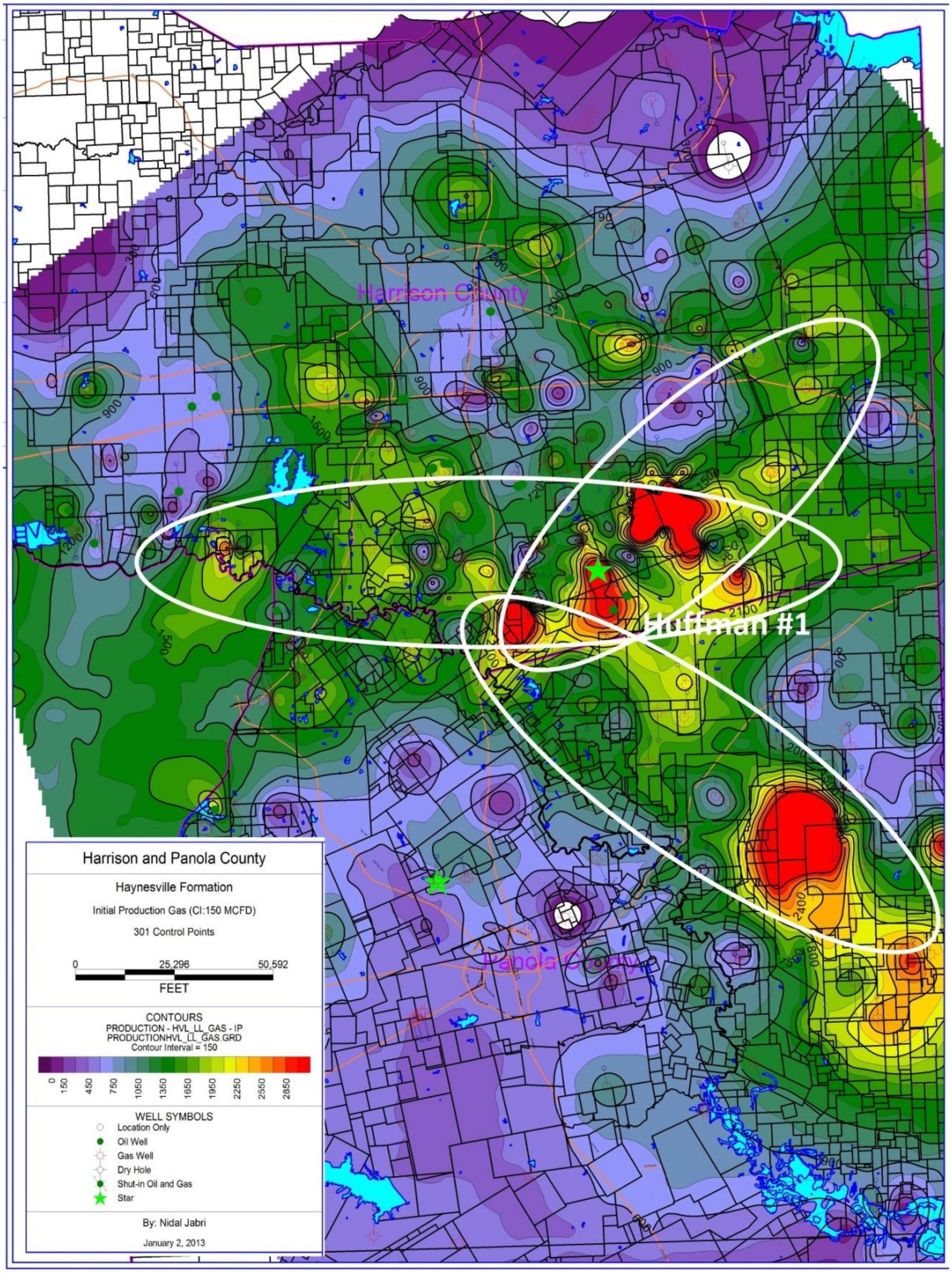

Figure 4.2 Initial Production map showing Production hotspots (CI: 150 mcf)

4.2 Major Elements and the Depositional Environment

Focusing on a more micro scale, the geochemistry could relate certain mineralogical variations to enhanced reservoir characteristics. Key drivers for a gas rich reservoir include: high TOC values, low clay concentrations, and high levels of porosity. Moreover, there is a preservation factor that is necessary in maintain the kerogen until time of maturity. Molybdenum (Mo) is used to define plaeo-redox environments, which show an above average value for the Haynesville formation (Rowe et al, 2012). Furthermore, the upwellings are associated with trace metals and give rise to seasonal plankton productivity (Brumsack 2006). The dilution of clay is important in increasing reservoir porosity. Bulk chemistry was used to identify mineralogical changes relating to key drivers. The mineralogical variations open the door to interpreting the paleodepositional environment.

4.2.1 Major Constituents

Ternary diagram (Fig 3.7) illustrates the relative changes between Quartz, Clay, and Carbonate. The Bossier, upper, middle, and lower Haynesville all plotted with average organic-rich black shale. Additionally, they plotted tightly with the Ca-dilution line. However, there is slight variation between the four divisions. The Bossier had variability resulting in more silica and clay rich constituents with minimal amounts of carbonate. The upper, middle and lower Haynesville had samples with high concentration of carbonate and clay with a background amount of silica. Fig 3.7 shows a mixed matrix mudstone transporting the depositional system out of the slope. Additionally, the grain size indicates a marine deep water environment. Lastly, the main components of input are detrital reworked sediments coming from multiple landward positions. The detrital material can be exclusively sourced to extra-basinal inputs. These extra-basinal grains originated from weathered igneous, metamorphic and older sedimentary grains from the terrestrial mainland. The grains are primarily monocrystalline and polycrystalline quartz, feldspar, micas, and diverse heavy metals such as garnets (Morad et al, 2010). The detrital rock composition is partially disintegrated by the tectonic setting of the basin (Dickison, 1985). However, it is hard to pin point the origin of the carbonates either, extra-basinal or intra-basinal. However, extra-basinal carbonate grains will be associated with a different event from the detrital clays and silica because carbonate grains are influenced chemical weathering rather than physical weathering (Morad et al, 2010). The terrestrial source would be heavily eroded by warm climatic conditions (Wright, 1988).

4.2.2 Mineralogical input

The bulk chemistry can be manipulated to reveal different variables relating to what and how sediments are deposited. X-ray Diffraction (XRD) was performed on surrounding wells, Carthage, Elm Grove, and T.W. George (Rowe et al, 2012). XRD results indicate that the Haynesville strata is mainly quartz, illite, varying concentrations of calcite, dolomite, chlorite and minor kaolinite (Rowe et al, 2012) Cross plotting the specific elements against aluminum can reveal if that element is part of or associated with clay. The cyclical patterns from the ratios form signatures that can be related to Kimmeridgian environmental factors. In order to illuminate what mineralogical phases each of the following were associated; Al, Si, Ca, K, Fe, Ti, Mg were all analyzed. Si/Al, Ti/Al are regarded as proxies of clastic influx (Rimmer et al, 2004). Most of the silica released during hydrolysis goes into solution as silica acid, colloidal or amorphous SiO_2. This component of silica is left behind and combined with clay. Therefore, the Si/Al ratio represents quartz versus clay (Tribovillard et al, 2006). Aluminum is not associated with biogenic proxies, which make it a controlling detrital proxy. The linear relationship between Si/Al indicates that the clastics are in the clay fraction. Anything that falls off of the linear trend, is not in phase with the clay fraction. The clastic influx could be contributed in many different ways, windblown, reworked sediments or carried by marine currents (Pukar, 2011). Due to the biogenic factors associated with silica, Ti is used as a verification of that clastic input. Ti has a very low concentration in seawater (Li, 1982). The high charge ratio of Ti does not allow biological participation (Piper and Calvert, 2009). Therefore, the Ti grains are erosionally resistant rutile coming from a terrestrial source. Overall, there is not a lot of variation in relation of Ti/Al. However, the Bossier and Upper Haynesville due have more oscillations than the Middle and Lower. This is an indication that the entire package is coarsening upwards. Since we have established the input of detrital material, it is important to identify which fraction the other grains reside. Potassium can be commonly found in feldspar. However, in this case, with the linear relationship with Al, most of the potassium in also found in the clay fraction. Some of the magnesium can be found as siderite, ankerite or dolomite. There is a significant amount of points that reside outside off the linear clay fraction. Pyrite was visually observed in the core which was confirmed through the geochemical study. Samples do indicate a significant amount of Fe data points not associated with the linear Al/Clay trend. Other than siderite, the Iron might be associated with Chamosite; which has a strong association with clays (Rivas-Sanchez, 2006). However, Chamosite is rarely found in nature (Rivas-Sanchez, 2006) Most likely, the iron is associated with pyrite, dolomite and siderite. Mesogenesis might have occurred to create the dolomite. The %Ca relationship to %TIC (fig 3.10) indicates a linear relationship that indicates that the majority of the calcium carbonate resides in calcite (Rowe et al, 2012). The samples that do not correspond might be in the non-carbonate phase or is supported by Ca-substituting metals (Rowe et al, 2012).

4.2.3 Depositional Environment

Taking all of the factors researched in this study and the paleoredox conditions, we can deduce that we are located in a silled, partly restricted basin. The study area had an occasional recycling of the bottom waters (Rowe et al, 2012). We were located in the deep waters of the Gulf of Mexico on the North America Craton. Restricted flow was enhanced by the Sabine uplift. Additionally, other factors such as tides or hurricanes could influence the recycling times. The Haynesville had source rock amounts of TOC which indicates that there was an organic input from planktonic snow. The most important requirement for sediments rich in TOC is a significant fraction of organic material. %TOC less than one will never generate enough hydrocarbons necessary for accumulation (Baker, 1996). Produced in the photic zone, and surviving the transit to the ocean bottom and through the bentic layer (Brumsack, 1989). After burial is it less susceptible to oxidation (Brumsack, 1989). %TOC is a proxy for organic preservation through time (Rowe et al, 2012). The organics were stored in self sourced porosity as kerogen. The accumulated organic carbon has a direct relationship with productivity and nutrients availability (Rimmer et al, 2004). The nutrients are sourced from coastal outputs and upwellings. The upwellings were the propagating force in the concentrations of TOC. Different paleoenvironmental conditions which favor TOC rich sediments are enabled by anoxic factors (Brumsack, 1989).

The calcite was reworked from inland sources or carbonate shoals. Reworking of sediments can be verified from various sedimentary features (Hammes et al, 2011). Large amounts of illite indicate high PH inland chemical weathering of K and Al rich rocks, muscovite and feldspar. The large amounts of Al indicate the lack of smectites and kaolinites. Tropical to subtropical climatic conditions played a large role in the depositional factors of the Haynesville Formation. Moreover, the major influence on the cyclical nature of the Haynesville was related to sea level change. The stratigraphic zonation can be interpreted as eustatic oscillations. Due to the equitorial climate there were immense erosional forces occurring inland. The influx of calcium was due to the sea level lowering and subaerially exposing the up dip carbonate shelf. The warm waters lead to higher productivity creating a large scale carbonate shelf during the Kimmeridgian. Once they were subaerially exposed, chemical weathering dissolved the calcium carbonate and reworked the components basinward. The stratigraphic zonation can be interpreted as fourth and fifth order lowstands occurring during a first order highstand created by global tectonic events. Figures 3.12-3.14 illustrate the fourth and fifth order cycles. The series breakout would represent the fourth order cycles and the episodes would represent the 5^{th} order cycles. Thusly, we can deduct that during times of low calcium input that the clay fraction would have dominated as the major component.

CHAPTER 5

CONCLUSION

5.1 Summary of the Haynesville

The Haynesville formation was deposited in the deep, partly euxinic and anoxic East Texas Basin during the Kimmeridgian age in the late Jurassic epoch (~150 mya). The East Texas basin was formed as a result of the European and African-South American plates colliding with the North American plate to form the Ouachita Mountains during the Mesozoic Era. As the European and southern continents continued to drift away from North America, the East Texas Basin was buried beneath thick deposits of marine salt. The faults within the East Texas basin are normal and moved syndepositionaly. They were formed by various processes associated with the gravitational induced creep of the Louann salt gliding over a salt décollment zone, then followed by crestal extension and collapse over salt pillows and turtle structures. Salt was then withdrawn from beneath down-thrown blocks (Jackson, 1982).

The basement structure and salt movement in this area influenced carbonate and siliciclastic sediments associated with the Gulf of Mexico. The Haynesville deposition is related to the 2^{nd} order transgression that deposited organic rich black shales worldwide (Hammes et al, 2011). It was deposited on a gently dipping ramp, intra-platform basin to the north and distally steepened ramp to the south. The Haynesville lies as the upper member of the Louark group between the Cotton Valley Group and the Smackover Formation. The Haynesville is considerably more calcareous than the overlying Bossier Formation and less calcareous than the underlying Smackover Formation of the mid-Jurassic age. The Haynesville is unique in that it acts as both the source rock and reservoir rock.

The key driver of a gas rich reservoir comprise of high TOC content, low clay concentration and high porosity. The average TOC of the Haynesville formation is 2.51%. High Mo (Molybdenum) concentration in our study area, represented by the Haynesville, is associated with water depth (Pukar, 2011). Therefore, the Mo vs. TOC in the western East Texas Basin forms a linear trend (Pukar, 2011). On the other hand, due to dissolution of carbonates by siliciclastics clays, % Ca vs. % Al gives an inverse linear relationship. The Haynesville is exclusive in that is contains both retrogradational and progradational facies that are contemporaneous with each other. Additionally, during a first order highstand smaller cyclical sea-level variations heavily influenced the chemical makeup of the Haynesville formation. The reducing phases of the Haynesville deposition produce pyrite from Fe, although it could possibly be components of siderite or dolomite as well. The timing of depositional aspects in relation to peloenvironmental conditions of the Haynesville Formation created a setting prime for the production of the dry gas.

5.2 Future Work

The initial research of The Haynesville Formation was just the beginning in categorizing and dissecting the complexities of this mudstone. Other cores, Carthage #16-19, need a high definition analysis to start the geochemical correlation across the basin. Additionally, other geochemical proxies, trace elements, need to be performed for a better understanding of the reducing conditions. Furthermore, a biostratigraphical study would help in creating a more constrained stratigraphic framework. A more in depth petrophysical analysis will help in identifying more porous and permeable zones. Also, more research could be done to understand any relationship, the underlying Smackover formation might have had on the development of the Haynesville Formation. More research in the variations of thickness across the Haynesville would help in resolving the architecture of the area.

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BIOGRAPHICAL INFORMATION

Nidal Radwan Jabri Graduated from the University of Texas at Arlington with his B.Sc. in Geology. He is currently working towards his Masters in Geology, proudly as a UTA Maverick. He is fortunately employed in the hydrocarbon industry. Nidal's main focus is the exploration and development of the hydrocarbons through any means necessary. Many different aspects go into successfully producing economical energy. Geochemistry, Biostratigraphy and Sedimentology were his most valued subjects. He was mostly influenced by Dr. John Holbrook, Dr. Merlynd Nestell and Dr. Harry Rowe. Additionally, he maintains a profound appreciation for all things related to science. His thirst for knowledge was well challenged by the highly competent faculty at University of Texas at Arlington.