FACIES AND STRATIGRAPHIC INTERPRETATION OF THE UPPER CRETACEOUS WOODBINE-EAGLE FORD INTERVAL IN LEON, MADISON, GRIMES AND BRAZOS COUNTIES, TEXAS

A Thesis

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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May 2016

Major Subject: Geology

ABSTRACT

The Upper Cretaceous in Texas is a proven prolific hydrocarbon system. The "Eaglebine" in Central Texas, which includes both the Eagle Ford and Woodbine intervals, is an emerging play with promising results. However, stratigraphic architecture in this region is poorly understood when compared to that of the Maverick Basin and East Texas Basin. The objective of this research is to narrow the stratigraphic uncertainties of Woodbine-Eagle Ford correlation between the East Texas and Maverick Basins and to predict the distribution of sand bodies in the active "Eaglebine" interval in Leon, Madison, Grimes and Brazos Counties by integrating information from available wireline logs and cores. A new stratigraphic interpretation of this region is proposed, and estimates of the petrophysical properties for the potential hydrocarbon-bearing intervals in the study area are presented.

The Buda Limestone-Austin Chalk succession in this study area, which brackets the "Eaglebine", thins westward due to uplift associated with the San Marcos Arch and erosion at the Base Austin Chalk (BAC) Unconformity. Wireline log interpretation suggests that Woodbine Group sediments, which are dominantly siliciclastic, are a little over 500 feet (152.5) thick updip in Leon County and thin dramatically to fifty feet (15.25 m) thick downdip in Brazos County. This transition records the Woodbine shelf break in Leon-Madison County area. The unconformably overlying Lower Eagle Ford Formation is relatively thick in Brazos and Grimes Counties. The lower part of the Lower Eagle Ford Formation is carbonate-rich shale with high gamma ray and formation resistivity. This unit has the potential to be a prolific play in Brazos and Madison Counties. The Upper Eagle Ford Formation in this region is a mixture of siliciclastic and carbonate sediments. The proportion of carbonate sediments gradually increases upwards to the Base Austin Chalk Unconformity. The sandstones of Upper Eagle Ford Formation have good hydrocarbon reservoir potential based on their non-shale porosity values and high sand percentage. This study resolves the stratigraphic architecture of the Upper Cretaceous Woodbine-Eagle Ford interval in the study area and will be helpful in understanding the regional stratigraphy from the East Texas Basin to the Maverick Basin when integrated with seismic data.

DEDICATION

This thesis is dedicated to my parents Ravi Kumar Vallabhaneni and Padma Vallabhaneni.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Thomas Olszewski, without his help and commitment this project could have never been accomplished. I am extremely thankful to my co-advisor Dr. Michael Pope for his guidance throughout my stay at Texas A&M University. I would also like to thank my committee member Dr. Zoya Heidari, for her time, guidance and support throughout the course of this research.

I am thankful to the director of Berg-Hughes Center, Dr. Carlos Dengo, for his generous support to cover my expenses involved in visiting the core facility in Houston. My sincere thanks to Mark Nibbelink from Drillinginfo for generous donation of the bulk of the data used for this study. I would also like to thank Dr. Art Donovan and Matthew Wehner for their insights and knowledge sharing.

Finally, my deepest love and thanks to my father Ravi Kumar, mother Padma and sister Sriharshini for their encouragement and support in pursuing my graduate degree and to my fiancé Sai for her patience and love.

NOMENCLATURE

TOC	Total Organic Carbon
GR	Gamma Ray
DT	Compressional Slowness
ResS	Shallow Resistivity
ResD	Deep Resistivity
PEF	Photo Electric Factor
DPHI	Density Porosity
NPHI	Neutron Porosity
PHIT_ND	Porosity from neutron and density logs
Vclay/Vsh/VShale	Volumetric concentration of Shale from GR using linear method
UEF	Upper Eagle Ford Formation
LEF	Lower Eagle Ford
m	Meters
in	Inches
ft	Feet
km	Kilometers
mi	Miles
Non_Sh_Por	Non-Shale Porosity
Swt_Dual	Water Saturation from Archie's "dual-water" method
a	Archie's parameter: Tortuosity factor

m	Archie's parameter: Cementation exponent
n	Archie's parameter: Saturation exponent
Rw	Resistivity of water
I.I.	Ichnofabric Index
MFS	Maximum Flooding Surface
SB	Sequence Boundary
TST	Transgressive System Tract
HST	Highstand Systems Tract

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

Page

1. INTRODUCTION

The Upper Cretaceous succession between the Buda Limestone and the Austin Chalk in Texas has contributed significantly to hydrocarbon production in the United States since 1930. The giant oil field in the East Texas Basin, which has had a cumulative production of over 5.42 billion barrels, (Ambrose et al., 2009) and the Eagle Ford Group in South Texas (one of the most actively producing shale-gas plays in the United States) are proven prolific hydrocarbon plays. The area in between these two basins (Figure 1) is an emerging play informally referred as the “Eaglebine” (Eagle Ford and Woodbine) by operators. Despite being a proven hydrocarbon reserve, the stratigraphic architecture of the interval between the Buda Limestone and Austin Chalk is still uncertain, primarily due to high siliciclastic sediment supply from the northeast and erosional unconformities which truncate the strata. The sandstone units pinch out into shale units as facies change laterally and are truncated by the unconformities.

Numerous studies have examined the stratigraphy of the Upper Cretaceous Buda Limestone-Austin Chalk interval. However, most of them were focused on either the prolific Eagle Ford play of the Maverick Basin or the East Texas Basin. Very limited research has been carried out in the Eaglebine play region, and a majority of the studies were either outcrop based or regional studies with widely spaced data that presented conflicting interpretations (Hentz and Ruppel 2010; Hentz et al., 2014; Donovan et al., 2015; Adam and Carr; 2010, 2014; Hudson, 2014). These interpretations often differ in terms of stratigraphic nomenclature, environments of deposition and correlation framework. In addition, the Upper Cretaceous Eagle Ford and Woodbine Groups are themselves stratigraphically complex both vertically and laterally. Equivalent chronostratigraphic units often vary in lithology, well log response and mineral composition from the East Texas Basin to the Maverick Basin. These lithological variations over both local and field scales make exploration challenging in the Eaglebine play area. Utilizing subsurface data to refine stratigraphic correlations within the Eaglebine interval will reduce uncertainty in hydrocarbon exploration.

1.1 Objective

The primary objective of this study is to understand the stratigraphic architecture of the active Eaglebine region by integrating closely spaced well log correlations with facies models interpreted from core. This understanding will help in resolving the uncertainty about which, if any, geologic units are time equivalent between the East Texas Basin and the Maverick Basin, which is of much interest because of the potential for prolific hydrocarbon exploration and production linked to stratigraphic understanding (Hentz et al., 2014). This study also helps in identifying the time equivalent strata in the East Texas and Maverick Basins.

Lithologies are determined using information from both well log responses and core; these descriptions give insight into the relative sea level changes and source of sediment supply during the time of deposition. The facies models generated from the descriptions of the core aid in defining the depositional environments and paleo-environmental conditions during the time of deposition for individual stratigraphic packages identified on the well logs. The facies models aid in identifying and predicting vertical and lateral lithologic variations due to facies transitions when data are scarce. Moreover, an attempt to estimate the average porosity for the potential reservoir facies and petrophysical property descriptions was made with the available data to provide preliminary reservoir characterization, thereby aiding in future hydrocarbon exploration and resource estimation.

1.2 Study Area

The study area is located in Leon, Madison, Grimes and Brazos Counties in the state of Texas (Figures 1 and 2) and is considered as the southwest extension of the East Texas Basin in the direction of the San Marcos Arch. Historically several operators have successfully produced hydrocarbons from the Austin Chalk, Buda Limestone and Upper Eagle Ford Formation siliciclastics (Sub-Clarksville Sandstone) in this region (Hentz and Ruppel, 2010). Some huge discoveries such as Kurten, Aggieland and Halliday fields, are proven examples for these reservoirs (Hudson, 2014). Current exploration in the study area primarily targets in the Upper Eagle Ford Formation (UEF) siliciclastic units, Woodbine units and the unconventional Maness/Lower Eagle Ford shale (Hudson, 2014). Several exploration wells targeted and tested the potential of the Lower Eagle Ford/Maness Shale by Apache Corporation in Brazos and Burleson Counties; their preliminary results are promising in terms of the potential unconventional play (Hudson, 2014).

The Buda Limestone through Austin Chalk interval in the study area varies significantly between the East Texas and Maverick Basins (Hentz and Ruppel, 2010) in terms of both stratigraphy and lithology. The East Texas Basin is dominated by

Woodbine siliciclastics of the Woodbine Delta, whereas the entire succession in the Maverick Basin is composed of the carbonate-rich Eagle Ford Group. This transition between the lithologies in these two basins makes this study area stratigraphically challenging and thus requires a high density of wireline logs to make reliable interpretations. Three cores from these counties also were used in defining the sedimentary facies.

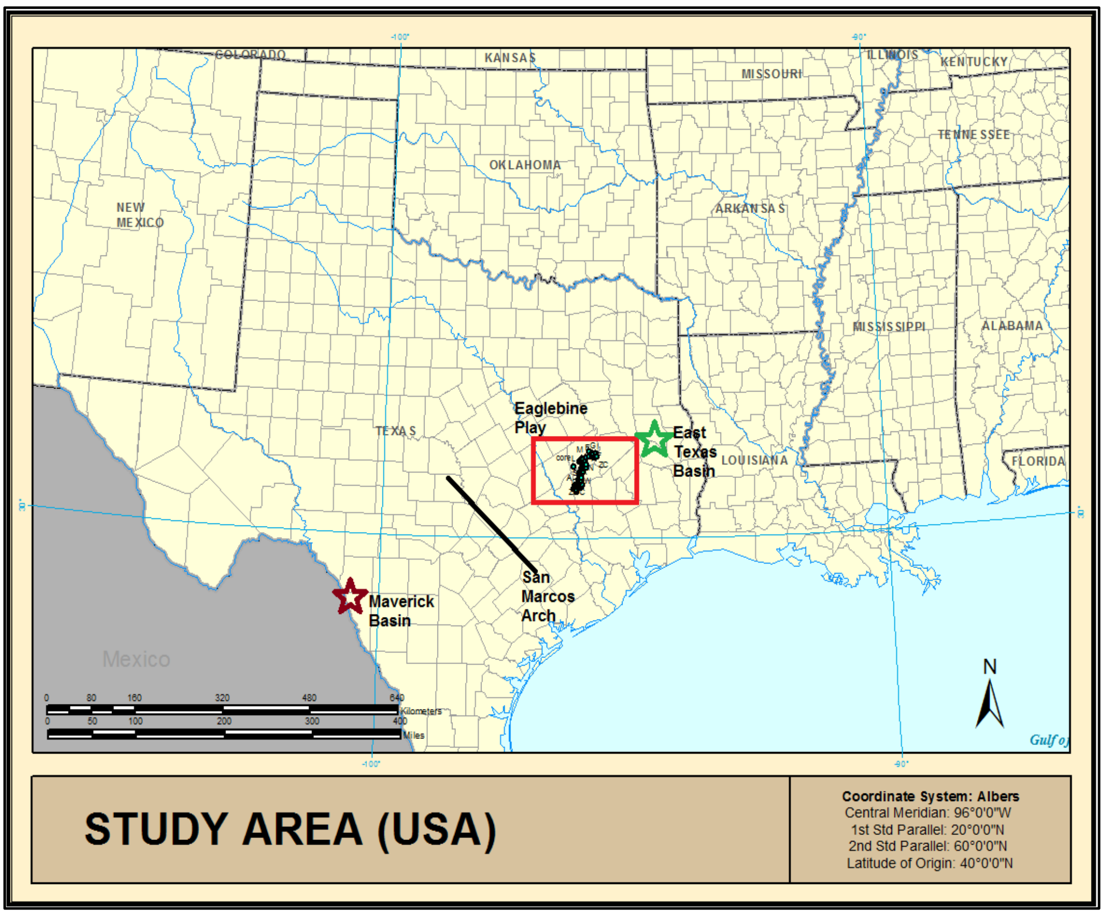

Figure 1: Map of the study area (red rectangle). East Texas and Maverick Basins indicated.

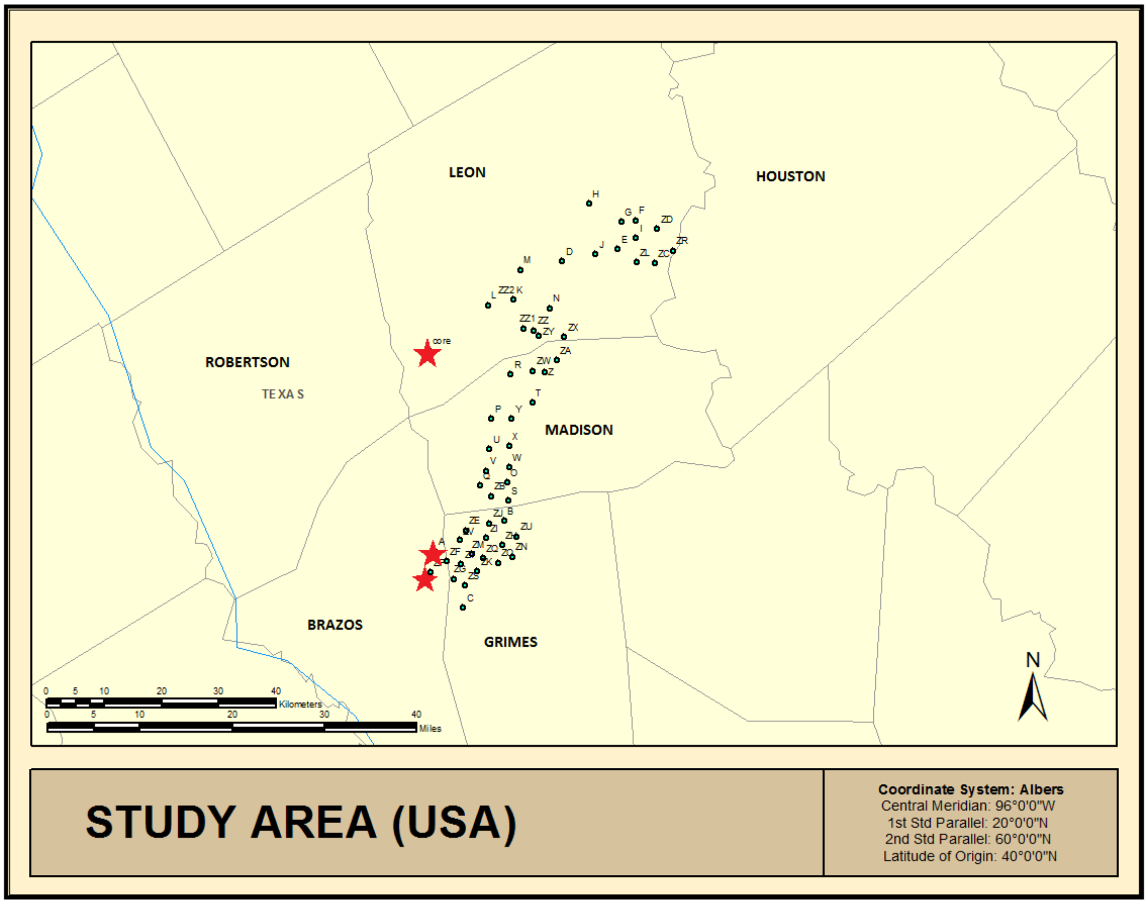

Figure 2: Study area highlighted in Figure 1. Black dots indicate locations of wells and red stars indicate locations of cores used in this study. List of wells and cores are described in Table 1 and Table 2 respectively.

1.3 Geologic Background

1.3.1 Structural Setting and Basin Evolution

The East Texas Basin, the Maverick Basin and the San Marcos Arch formed as a result of differential subsidence. The East Texas Basin is an extensional basin formed during Cretaceous rifting along the Gulf coast (Mancini and Puckett, 2005). It is bounded by the Sabine Uplift to the east, where Woodbine strata are truncated (Figure 3) (Ambrose et al., 2009). The Sabine Uplift is syntectonic with the deposition of the

Woodbine Group, which significantly affected the stratigraphic framework of the region (Ambrose et al., 2009). The East Texas Basin is bounded on the north and west by the Mexia-Talco Fault Zone. Towards the southwest, the East Texas Basin is bounded by the San Marcos Arch. The San Marcos Arch is interpreted to be a basement uplift created by late Mesozoic-Cenozoic intra-plate folding (Hentz et al., 2014). At the depocenter of the East Texas Basin, the thickness of the sedimentary fill exceeds more than 13,000 feet (3960 m) (Hentz et al., 2014). These sediments were deformed by salt tectonics and diapirism of the Middle Jurassic Louann Salt throughout the Cretaceous and early Cenozoic. The evacuation of salt coupled with the high rate of Woodbine sediment supply increased subsidence, thereby creating accommodation for the sediments in the East Texas Basin (Seni and Jackson, 1984). Other tectonic events during the deposition of the Woodbine and Eagle Ford Groups include growth faulting along the Mexia-Talco Fault Zone and faulting associated with the Mount Enterprise Fault Zone.

The entire succession between the Buda Limestone and Austin Chalk was deposited in an outer-shelf environment as a part of the Upper Cretaceous lower Gulfian Series based on previously interpreted regional studies (Bukowski, 1984) (Hentz et al., 2014). Given the conflicting stratigraphic nomenclature in this region, the important and most commonly used stratigraphic units in this study are: the Buda Limestone, the Woodbine Group, the Eagle Ford Group and the Austin Chalk.

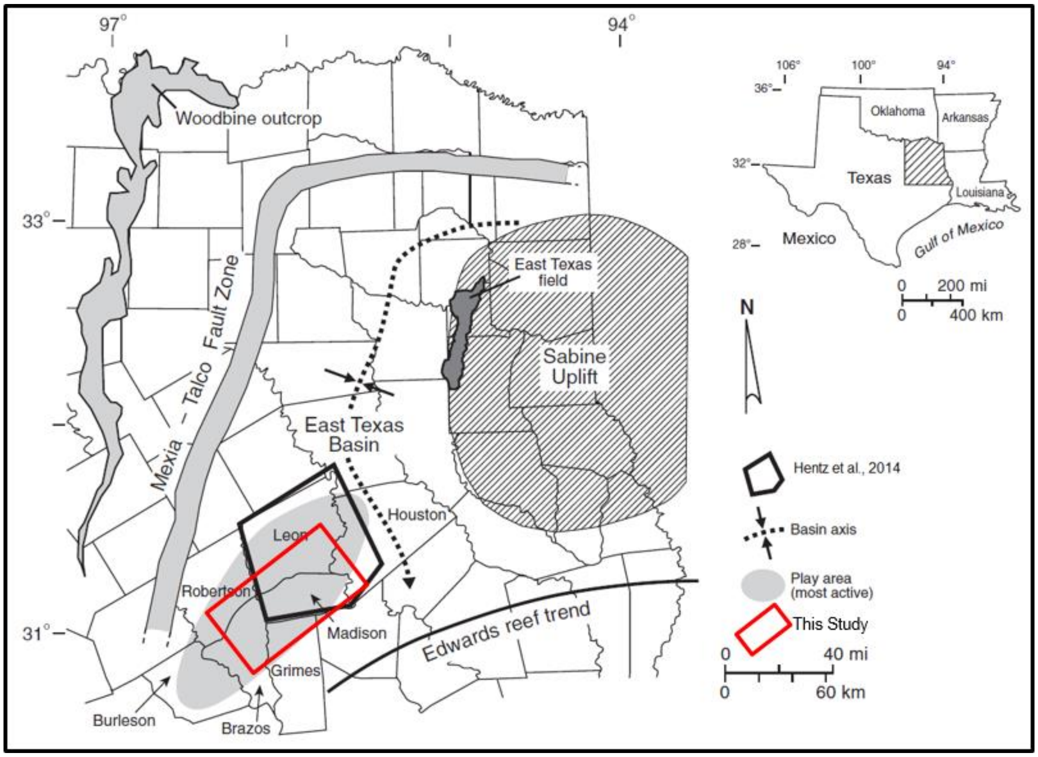

Figure 3: Regional structure map highlighting the study area in red and major structures. Modified from Hentz et al. (2014).

The Woodbine Group is the dominant Upper Cretaceous siliciclastic sedimentary fill in the East Texas Basin (Ambrose et al., 2009). The downdip part of the succession marks the approximate Woodbine Shelf Margin (Hentz and Ruppel, 2010). The Woodbine Group thins from a maximum of 1100 feet (335 m) at the depocenter or basin axis to less than fifty feet (15.25 m) near the San Marcos Arch. It also is truncated eastward by an erosional unconformity toward the Sabine Uplift and thins westward into the outcrop belt (Hentz et al., 2014). The Woodbine Group sandstone units are interpreted to be fluvial-deltaic and occur between the Eagle Ford Group and the Buda

Limestone. Depositional systems of the Woodbine Group vary significantly from the stratigraphically adjacent units.

In contrast to the Maverick Basin, the Eagle Ford Group in the study area is composed of Mixed Sandstone and Wackestone strata. The sandstone units in the top part, commonly known as Sub-Clarksville Sandstone, are often good drilling targets. Nevertheless, the thin fluvial-deltaic sands of the Woodbine Group, which regionally pinch out to form stratigraphic traps, also were being explored and produced through horizontal drilling and hydraulic fracturing (Hentz and Ruppel 2010).

The San Marcos Arch is a northwest-southeast trending extension of the Llano Uplift that separates the Maverick Basin on its western flank from the East Texas Basin on its eastern flank (Dravis, 1980; Harbor, 2011). Low subsidence led to high relief of the San Marcos Arch, which resulted in limited accommodation for sediments even during eustatic sea level highs.

Tectonic activity played the primary role in the evolution of the Maverick Basin, which was formed by the movement of basement structures developed during the failed Rio Grande Rift (Donovan and Staerker, 2010). Similar to the East Texas Basin, salt mobilization helped in continuously creating accommodation in the Maverick Basin.

1.3.2 Lithostratigraphy and Chronostratigraphy

Several stratigraphic models were proposed for the Upper Cretaceous Buda Limestone-Austin Chalk interval. The regional stratigraphy can be further subdivided into three sub-regional stratigraphies corresponding to the East Texas Basin, the San Marcos Arch and the Maverick Basin, due to the lack of lateral continuity and the sharp facies transitions. In all three sub-regions, the entire study interval unconformably overlies the Buda Limestone and unconformably underlies the Austin Chalk.

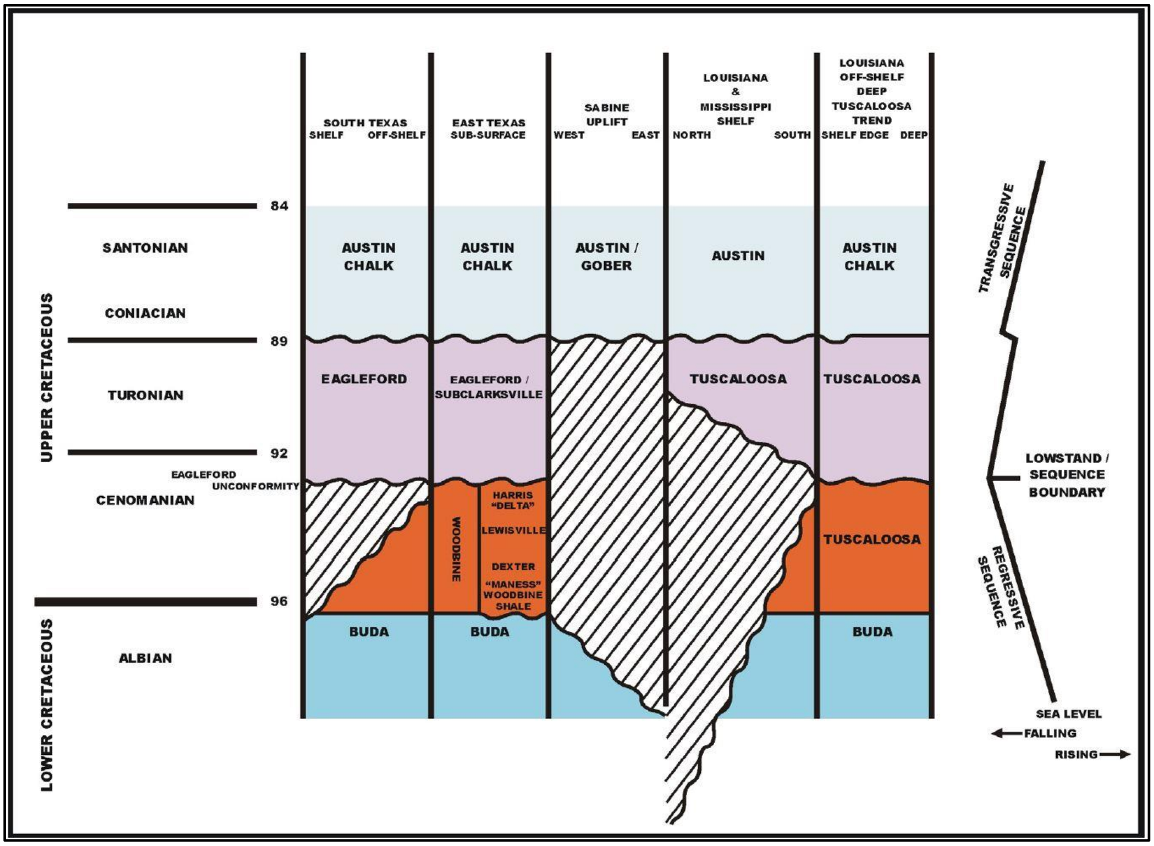

Figure 4: Regional stratigraphy of the Upper Cretaceous interval from South Texas to Louisiana, taken from Adam and Carr (2010).

East Texas Basin

In the East Texas Basin, the Woodbine Group overlies the upper part of the Upper Albian to middle Cenomanian Washita Group. There is 50-75 feet (15.25-22.88 m) thick shale termed the Maness Shale between the Buda Limestone of the Washita Group and the Woodbine Group sandstone units. It is unclear whether the Maness Shale should be assigned to the top unit of the Washita Group or the bottom unit of the

Woodbine Group (Bailey et al., 1945). The Woodbine Group was deposited as a fluvial deltaic system sourced from the Ouchita front in southern Oklahoma and Arkansas during the major middle and late Cenomanian regression (Adams and Carr, 2010). The drop in relative sea level just before Woodbine deposition exposed most of the Gulf Coast Basin. However, the East Texas Basin remained submerged during this event due to high subsidence as a result of salt mobilization relative to other parts of the Gulf Coast Basin. During relative sea level rise, the Maness Shale was conformably deposited over the Buda Limestone in the East Texas Basin (Salvador, 1991). Away from the axis of the East Texas Basin, the top of the Buda Limestone is an erosional unconformity, whereas it is described as a transgressive surface of erosion (TSE) in the basin (Ambrose et al., 2009). The entire Woodbine Group is considered to be a third-order sequence, with a maximum of fourteen fourth-order sequences at the basin center (Ambrose et al., 2009). The upper Woodbine fourth-order sequences gradually thin and pinch out westward as facies transition into the Pepper Shale. The Woodbine Group sub-divided into the Dexter and Lewisville formations primarily based on the proportion of sand to mud with the younger being sand dominated (Ambrose et al., 2009).

The Eagle Ford Group in the East Texas Basin consists predominantly inter fingering sandstone and shale beds. The upper portion of the Eagle Ford Group (Sub-Clarksville Sandstone) consists of sandstone units that are a prolific hydrocarbon carbon reservoir. The Eagle Ford Group is around 100-300 feet (30.5-91.5 m) thick in the East Texas Basin (Surles, 1987), but is absent towards the south (Hentz and Ruppel, 2010). The top of the Eagle Ford Group is truncated by the Basal Austin Chalk Unconformity

(BAC). By the end of Eagle Ford deposition, the tectonic activity of the Sabine Uplift had ceased (Ambrose et al., 2009).

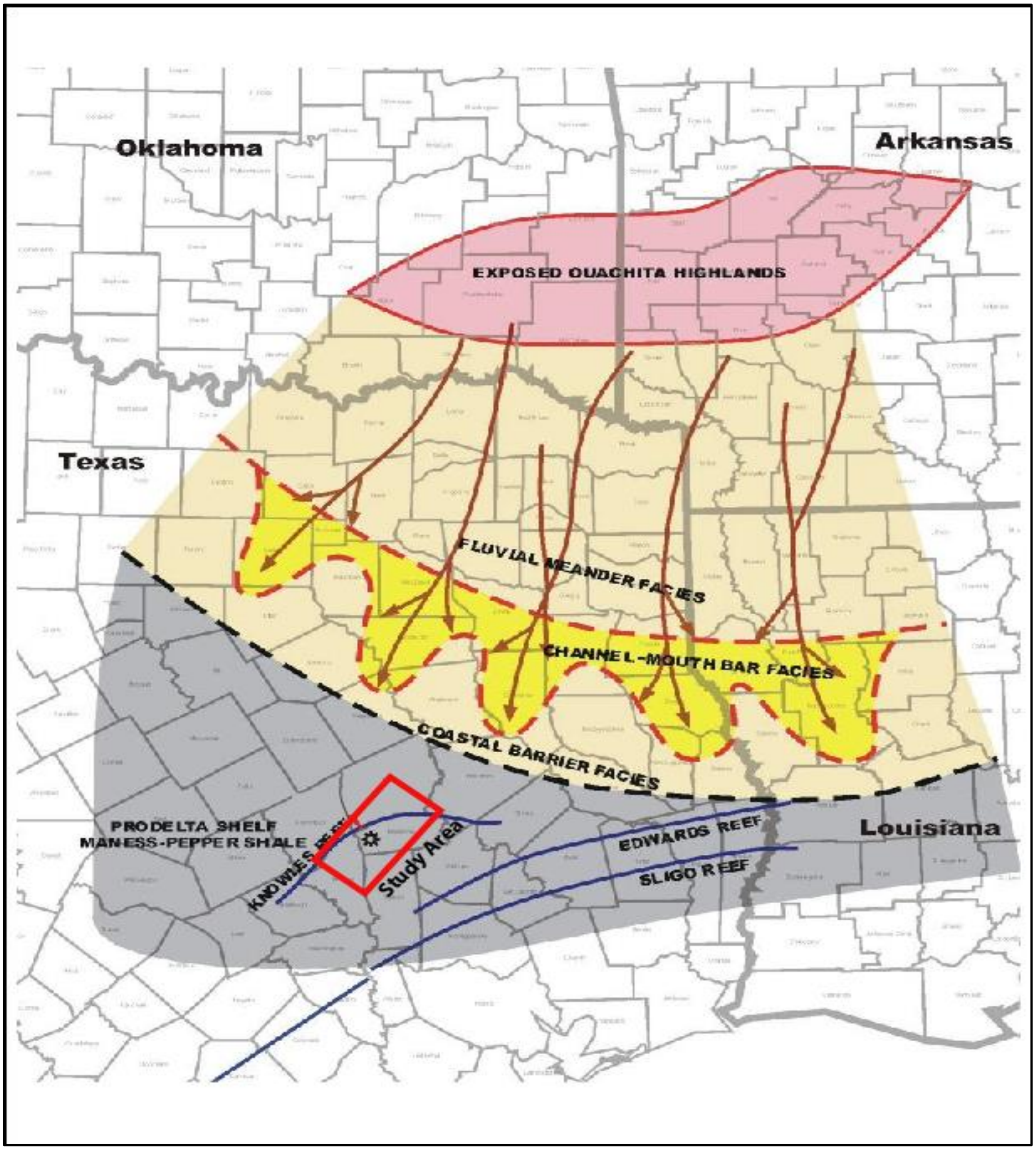

Figure 5: Woodbine depositional facies, after Oliver (1971), taken from Adam and Carr (2010).

San Marcos Arch

Along the exposures of San Marcos Arch, the overall thickness of the interval between the Buda Limestone and the Austin Chalk is less than 100 feet (30.5 m) and the Woodbine Group is completely absent. The only units at the San Marcos Arch are dark grey mudstone above the Buda Limestone, which is equivalent to the Lower Eagle Ford shale of the Maverick Basin and a carbonate-rich, low-GR shale unit equivalent to the Upper Eagle Ford Formation shale of the Maverick Basin. This shale-rich unit is often erosionally truncated by the Basal Austin Chalk unconformity (Hentz and Ruppel, 2010). The lithostratigraphy of the Lower and Upper Eagle Ford Formations is discussed in detail in the section on the Maverick Basin.

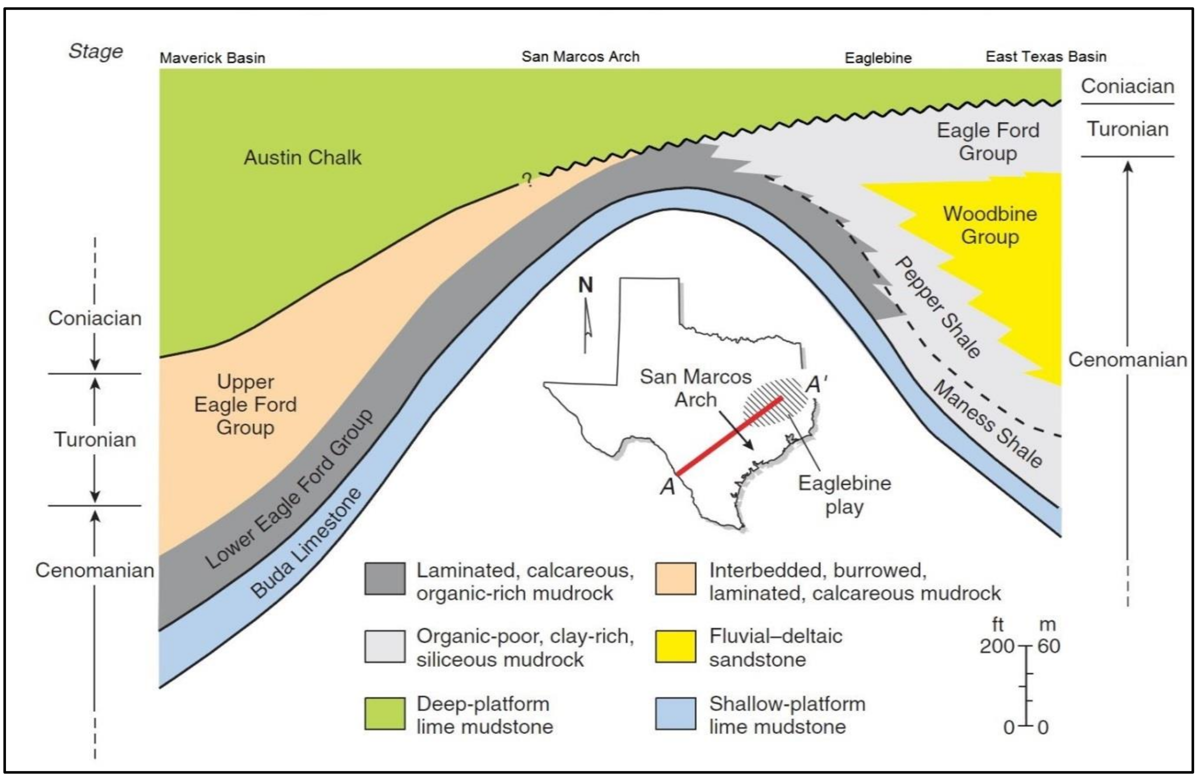

Figure 6: Regional cross section A-A' from the Maverick Basin to the East Texas Basin. Modified from Hentz et al. (2014).

Maverick Basin

The Maverick Basin is on the southwestern flank of the San Marcos Arch. Lithostratigraphic units of interest in this basin are: the Buda Limestone, Lower and Upper Eagle Ford Formations in between the Buda Limestone and the Austin Chalk. The Lower Eagle Ford (LEF) was deposited unconformably over the Buda Limestone, is a high gamma ray (GR), high resistivity (ResD) formation and often termed a "hot shale" due to its high organic content. The LEF is a world-class source rock which charged the Buda Limestone and Austin Chalk intervals and is currently being exploited as an unconventional shale play. The lithologic composition of the LEF is primarily dark grey mudstone, marl and limestone. Several subsurface and outcrop studies have much detailed stratigraphic and lithologic description of the Lower Eagle Ford shale (Dawson, 2000, Donovan and Staerker, 2010). Depositional strike of the Lower Eagle Ford is northeast-southwest and the unit is thickest (210 feet/64 m)) in the Maverick Basin. It gradually thins towards the San Marcos Arch. The presence or absence of the Lower Eagle Ford shale or its chronostratigraphic equivalent units northeast of the San Marcos Arch and the East Texas Basin remains unresolved in the literature and is one of the objectives of this study.

The Upper Eagle Ford Formation (UEF) has relatively low GR values is organic poor and its resistivity is low when compared to the LEF. Lithologically, it is composed of interbedded dark grey and light grey mudstone (Hentz and Ruppel, 2010). The UEF has a gradational contact with the Austin Chalk and is often difficult to distinguish in the GR log and on seismic data. The UEF interval in the Maverick Basin attains a maximum thickness of around 500 feet (152.5 m) and thins downdip and towards the San Marcos Arch. Again, this unit or its chronostratigraphic equivalent northeast of the San Marcos Arch is poorly understood (Hentz et al., 2014).

2. DATA AND METHODS

2.1 Data

The data used in this study consists of wireline logs from more than sixty wells, publicly available through Drillinginfo, and three cores. A majority of the well logs are modern LAS files and contain information about the gamma ray, sonic, resistivity and density logs. The wells have an average spacing of 2.5 km. In order to identify the wells containing the study interval, contour maps of the top of Buda Limestone (i.e., the base of the study interval) by Hentz and Ruppel (2010) were used. The location, API number and the log curves associated with these wells are summarized in table 1.

Three cores used in this study are: Hilltop Resort 2 (HR-2), Amalgamated Bonanza Petroleum 2 - Smith (AB-2) and Buttess Resources 2 - Wilson (BW-2). AB-2 and BW-2 cores are from the downdip Kurten Field in Brazos County in the Robert R. Berg core collection at Texas A&M University and the HR-2 core from updip Leon County at the Texas Bureau of Economic Geology's Houston core repository. The well logs corresponding to these cores are not available publicly. Nevertheless, the nearest wells available from Drillinginfo.com were taken for comparison. The locations and details about the cores and nearby well logs are summarized in table 2.

Table 1: List of wells with API and location.

Well Name	API	Latitude	Longitude	County
A	42-041-31728	30.7769	-96.191	Brazos
B	42-185-30042	30.822088	-96.05936	Grimes
C	42-185-30046	30.690844	-96.13792	Grimes
D	42-289-30618	31.214249	-95.94913	Leon
E	42-289-30729	31.233091	-95.84161	Leon
F	42-289-30796	31.276047	-95.80838	Leon

Table 1 contd.

Well Name	API	Latitude	Longitude	County
G	42-289-30829	31.273203	-95.83424	Leon
H	42-289-30830	31.301523	-95.89742	Leon
I	42-289-30870	31.249426	-95.80759	Leon
J	42-289-30985	31.225342	-95.88524	Leon
K	42-289-31023	31.156252	-96.04236	Leon
L	42-289-31049	31.148209	-96.08975	Leon
M	42-289-31851	31.20141	-96.02807	Leon
N	42-289-80174	31.143461	-95.97282	Leon
O	42-313-30076	30.880098	-96.0523	Madison
P	42-313-30299	30.976099	-96.083435	Madison
Q	42-313-30313	30.876192	-96.10532	Madison
R	42-313-30329	31.043749	-96.04745	Madison
S	42-313-30355	30.85269	-96.05131	Madison
T	42-313-30506	31.001205	-96.0054	Madison
U	42-313-30627	30.931023	-96.088196	Madison
V	42-313-30692	30.898148	-96.09324	Madison
W	42-313-30706	30.903166	-96.049706	Madison
X	42-313-30710	30.934973	-96.02976	Madison
Y	42-313-30713	30.976126	-96.04496	Madison
Z	42-313-30751	31.046568	-95.98184	Madison
ZA	42-313-30756	31.064611	-95.95936	Madison
ZB	42-313-30907	30.859972	-96.08413	Madison
ZC	42-289-30719	31.210712	-95.77178	Leon
ZD	42-289-30884	31.263601	-95.76622	Leon
ZE	42-185-30069	30.80798	-96.13292	Grimes
ZF	42-041-31048	30.76145	-96.1684	Brazos
ZG	42-185-30337	30.73476	-96.155846	Grimes
ZH	42-185-30218	30.785902	-96.06342	Grimes
ZI	42-185-30515	30.796762	-96.09293	Grimes
ZJ	42-185-30519	30.818775	-96.08768	Grimes
ZK	42-185-30572	30.745731	-96.11003	Grimes
ZL	42-289-30821	31.21289	-95.80541	Leon

Table 1 contd.

Well Name	API	Latitude	Longitude	County
ZM	42-185-30498	30.7725	-96.12139	Grimes
ZN	42-185-30199	30.768213	-96.0444	Grimes
ZO	42-185-30221	30.759306	-96.07093	Grimes
ZP	42-041-30344	30.744766	-96.200195	Brazos
ZQ	42-185-30240	30.765917	-96.09896	Grimes
ZR	42-289-30562	31.230122	-95.73701	Leon
ZS	42-185-30198	30.724989	-96.134705	Grimes
ZT	42-185-30303	30.756557	-96.14069	Grimes
ZU	42-185-30510	30.79896	-96.03493	Grimes
ZV	42-185-30205	30.79319	-96.14386	Leon
ZW	42-289-30543	31.100742	-95.94446	Leon
ZX	42-313-30306	31.049011	-96.004906	Madison
ZY	42-289-31211	31.10995	-96.0022	Leon
ZZ	42-289-31200	31.101154	-95.992645	Leon
Core_Leon	42-289-31909	31.079601	-96.20381	Leon

Table 2: List of cores and nearby well logs.

Core	County	Nearby Well	Well API
Hilltop Resort 2	Leon	Core_Leon	42-289-31909
Amalgamated Bonanza Petroleum 2 - Smith	Brazos	A	42-041-31728
Buttess Resources 2 - Wilson	Brazos	ZF	42-041-31048

2.2 Processing and Interpretation Methods

2.2.1 Well Logs

All the well log data was loaded into TechLog 2014, a well logging and petrophysical software package. Each individual log curve was calibrated to a uniform scale and units within the software package. The study interval was identified across all the well logs by the sharp contacts with the overlying Austin Chalk and underlying Buda Limestone units based on gamma ray, density and sonic log signatures. Austin Chalk and Buda Limestone are carbonate-rich and clay poor, hence characterized by very low GR, high density (RHOB) and low compressional slowness (DT) values when compared to the study interval (Figure 7). Logs were correlated to generate several cross sections in the direction of depositional strike and dip and the direction of regional sediment supply (Hentz and Ruppel, 2010; Hentz et al., 2014; Adams et al., 2014).

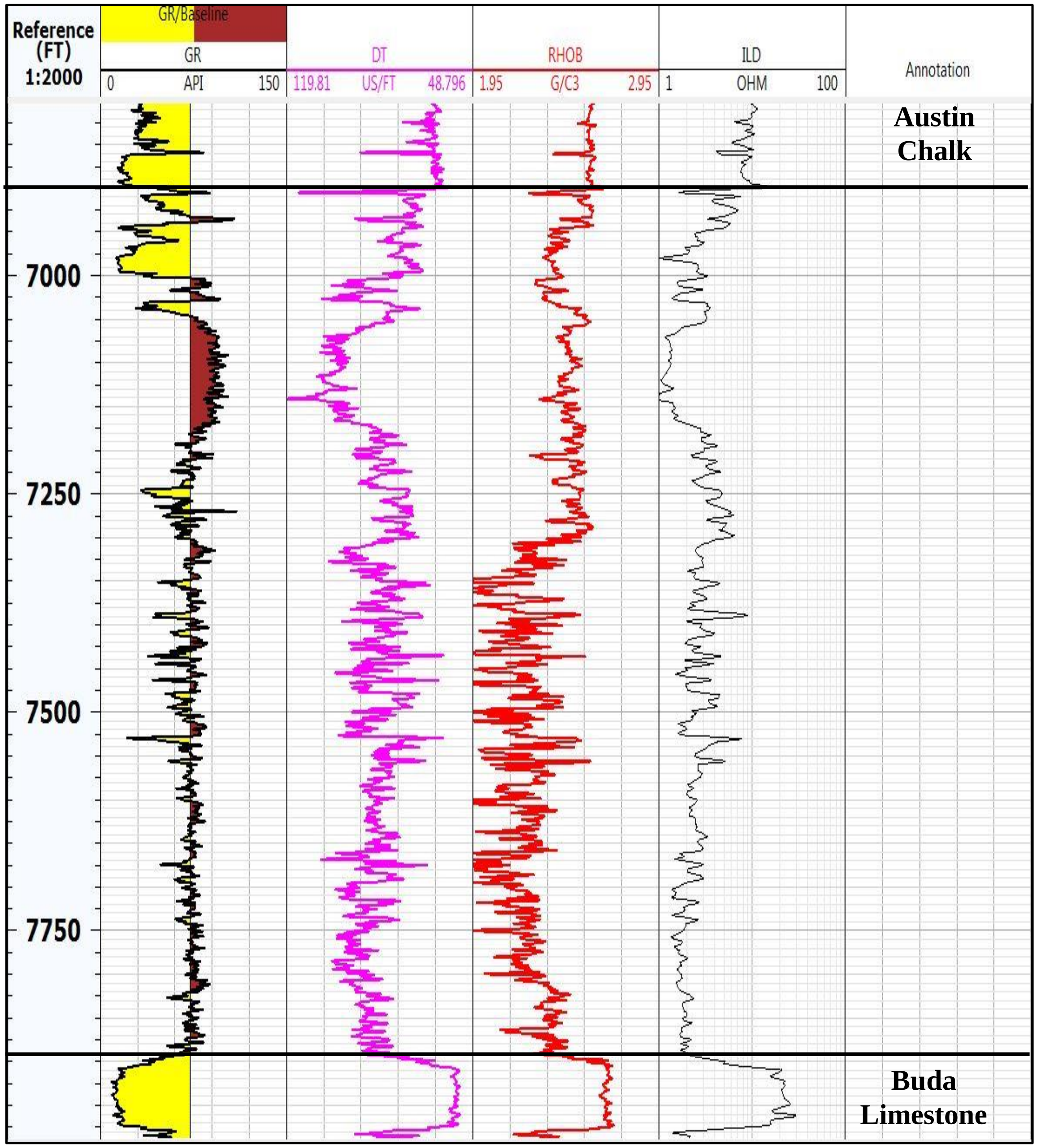

Figure 7: Gamma Ray (GR), Compressional Slowness (DT), Bulk Density (RHOB) and Deep Resistivity (ILD) log responses of well ZD.

Once the study interval was identified in all the wells, it was sub-divided into parasequences. In general, parasequence boundaries are characterized by a sharp increase in the gamma ray values due to an increase in clay content; these are interpreted as flooding surfaces recording sharp increase in water depth (Figure 8). Flooding surfaces were used to correlate all nearby wells. Parasequences can be grouped together based on their stacking patterns. For example, in figure 8, the smaller scale parasequences 1, 2 and 3 (red arrows) can be stacked into an overall prograding upward parasequence set (blue arrow) based on the decreasing shale to sandstone ratio in each successive parasequence. Most of the LAS log files are modern and have good depth resolution, which helped in picking and correlating the flooding surfaces with confidence.

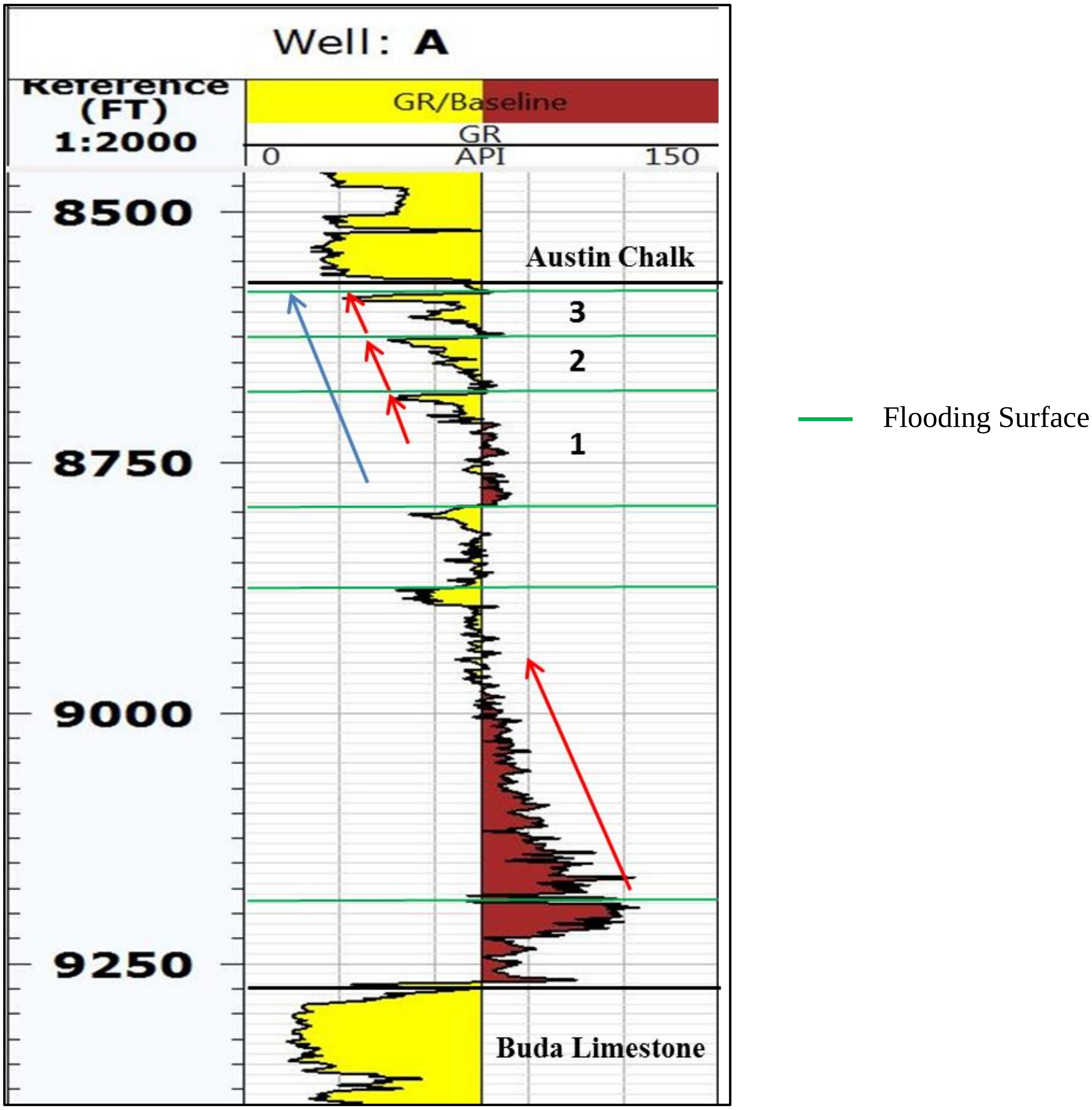

Figure 8: Flooding surfaces (in green) from GR log response of well A.

Before estimating any petrophysical properties, the dominant siliciclastic lithology in the study interval was determined using the log curves. Both density and neutron logs were calibrated to sandstone matrix across all the well logs. In an ideal case, the porosity values from density and neutron logs should exactly match for a 100%

water saturated sandstone interval. However, the porosity values have to be considered carefully in the case of formations with carbonate cement or content. GR logs for all the wells were normalized before estimating clay content. Normalizing the GR values accounts for uncertainties associated with the different tools and calibration methods used while recording the data. For the stratigraphic units with interbedded shales, V-clay (volumetric concentration of shale) is estimated from the GR log using the linear extrapolation method after defining the Shale and Clean baselines. Later, the porosity for these formations is calculated using "Shaly-Sand Analysis". The basic concept behind this method is that the matrix density of shale differs from the matrix density of sandstone, which makes V-clay an important parameter in estimating the total porosity of the unit (Figure 9). It is evident how the neutron and density porosity values deviate with increase in shale volume (Vsh) (Figure 9). "Shaly-Sand Analysis" accounts for the presence of shale and helps in estimating both the total porosity of the formation and the porosity of the non-shale part of the unit.

Shales contain chemically bound water along with the fluids in the pore space. These two types of water differ in physical properties such as resistivity and salinity. To differentiate the water saturation in the pore space with the water molecules bounded to the shale, Archie's 'dual-water' saturation model is used to estimate the water saturation in the formations. Archie's parameters *a*, *m* and *n* are obtained from picket plots (Figure 10) between formation resistivity and porosity calculated from neutron and density logs. The shale porosity is estimated as an average between the neutron and density porosity in a fully water saturated shale and shale resistivity is the deep resistivity for a fully water saturated shale (Figure 9). A fully water saturated zone typically has low resistivity (Figure 9) and is often equal to the shallow resistivity in the case of water based mud (WBM).

Archie's equation is written as

(Sw)^n= Rw*a/((Phi^m)*ResD)

log ResD = -m * log PHI + log (a * Rw) - n * log Sw

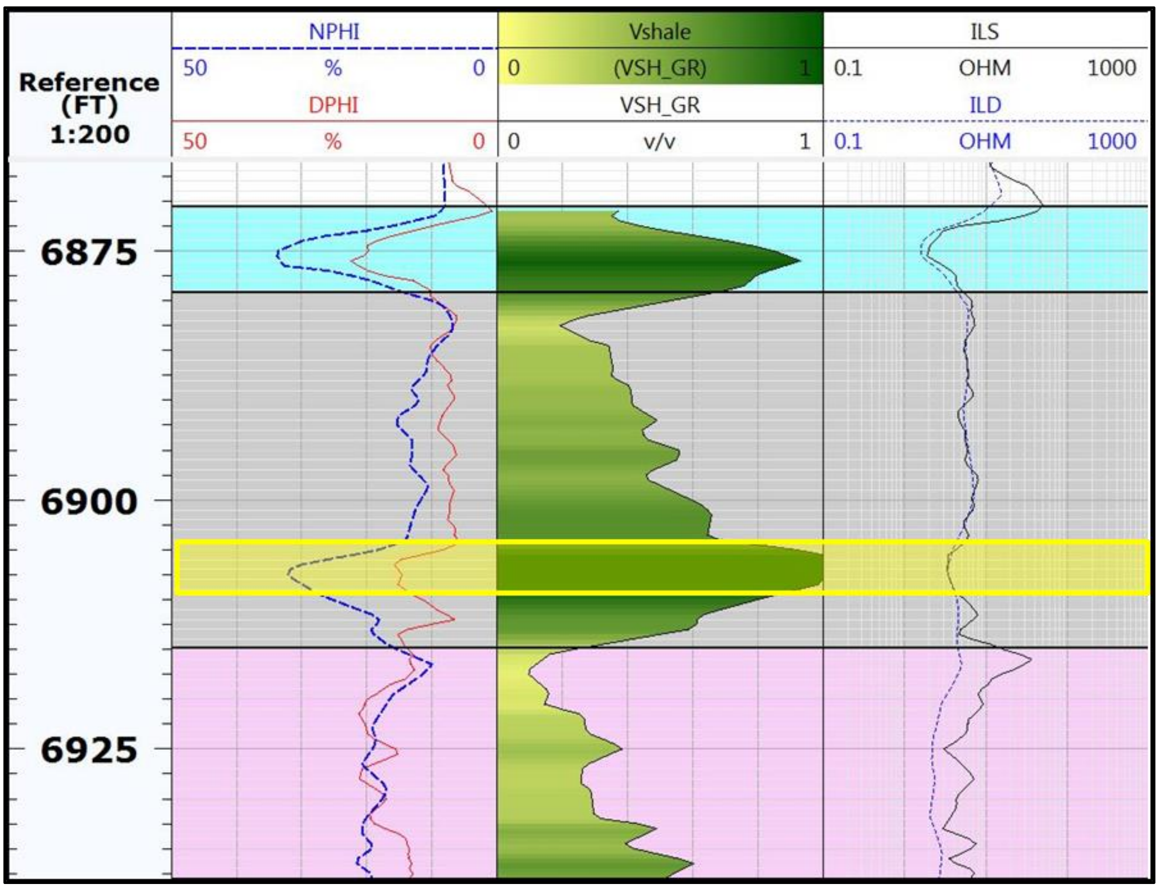

Figure 9: Neutron (NPHI) and Density (DPHI) porosity, V-clay (Vshale), shallow (ILS) and deep resistivity (ILD) log response in well I. Area highlighted in yellow represents a fully water saturated shale.

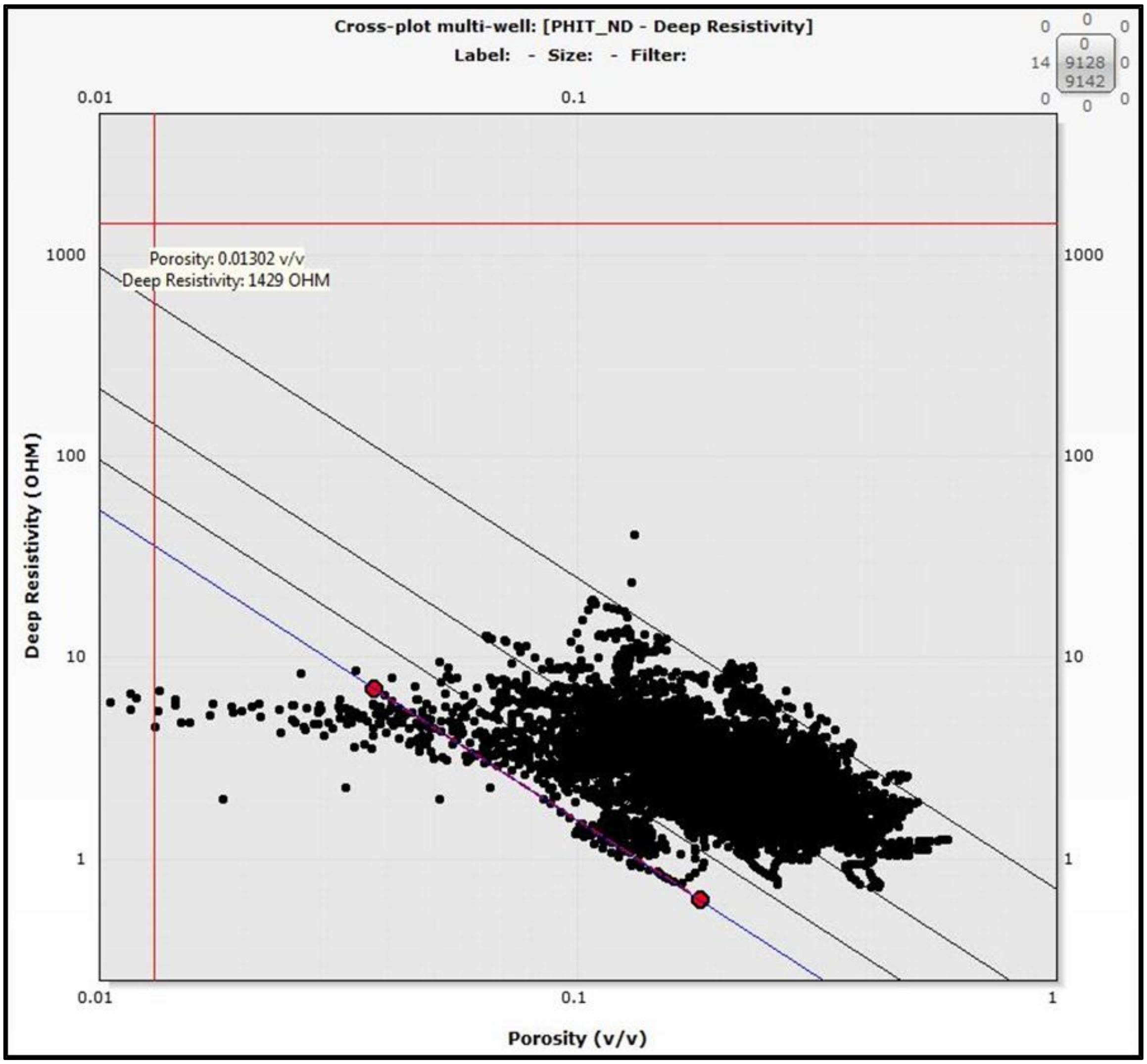

Figure 10: Picket plot of formation resistivity vs porosity for all the wells. Blue line represents 100% water saturation i.e. Sw=1.

Property	Value
a	1
m	1.54333
n	2
Rw	0.0441817

Figure 11: Archie's parameters *a*, *m*, *n* and *Rw* obtained from picket plot above.

The petrophysical properties V-clay, water saturation and porosity are used to calculate the Gross thickness, Net thickness, Net-to-Gross sandstone ratio and Avg V-clay for individual stratigraphic units in all the wells. This data is imported into subsurface mapping and contouring software (Surfer). Gross thickness and Net to Gross maps are generated for all the units to observe the thickness and facies variations and trends in the study area. These maps also help in reserve estimation for hydrocarbons.

2.2.2 Core

Measured sections of cores were based on direct observation with 10x magnification. Description includes grain size, grain sorting, mineral composition, fossils, carbonate cementation, physical sedimentary structures, biogenic sedimentary structures and any other features that were noticed. Using the observed sedimentary features, a facies classification was developed and used to infer depositional environments. Ichno-fabric Index (I.I.) is also provided with the measured sections as most of the core is bioturbated.

3. RESULTS

3.1 Core Descriptions

3.1.1 Measured Sections

Amalgamated Bonanza Petroleum 2 - Smith

This core is located in the Kurten Field of Brazos County. The dominant lithology for the cored interval is interbedded sandstone and shale, which is consistent with the well log response of the nearby well. Three facies were identified in this core, which are primarily differentiated based on the percentage of sand and the intensity of bioturbation (Figure 12) and (Table 3). Most of the cored interval is moderate to heavily bioturbated, which indicates bottom-water oxygenation. A total of three parasequences each bounded by a sharp transition from sandstone to shale were observed, but these are not resolvable at the scale of the nearby wire line log. The thickness of each parasequence and the percentage of sand content gradually increase upward in the core, indicating an overall prograding upward parasequence set. The thickness of the parasequence set from the core is equivalent to the thickness of a parasequence in the wireline log.

Hiltop Resort 2

The Hilltop Resort 2 core is located in the western part of Leon County. The core is available as two separate intervals with a missing section in between them. The first part of the core is detailed in measured section B1 (Figure 13) and the second part in measured section B2 (Figure 14). Measured section B2 represents a dark, carbonate-rich shale. It also contains planar laminations of relatively coarse grained and light colored sediments. The occurrence of undisturbed planar laminations indicates that there is very limited or no bioturbation and suggests that this shale was deposited under an anoxic to sub-anoxic water column. The bottom part of measured section B1 is primarily siliciclastic and is composed of facies that are similar to those observed in Amalgamated Bonanza Petroleum 2 - Smith, showing a gradual increase in sand content upward. However, in this core, shale content and bioturbation is very high and the clean sandstone facies is absent. In the top part of the core, a mixture of carbonate and siliciclastic rocks is observed; in this interval, the carbonate content gradually increases upward. Shell fragments occur in this facies.

Buttess Resources 2 - Wilson

This core is located in the Kurten field of Brazos County and very close to Amalgamated Bonanza Petroleum 2 - Smith and consists of the same three facies. The bottom part of the core is dominantly comprised of silty mudstone and interbedded sandstone and shale (Figure 15). The interbedded sandstone is heavily bioturbated. However, the size of the burrows in the lower part is smaller than the size of burrows observed in the upper half of the section. Also, the percentage of sand gradually increases upward. This suggests that the bottom part was deposited in relatively deeper water, which suggests an overall shallowing upward succession in the core.

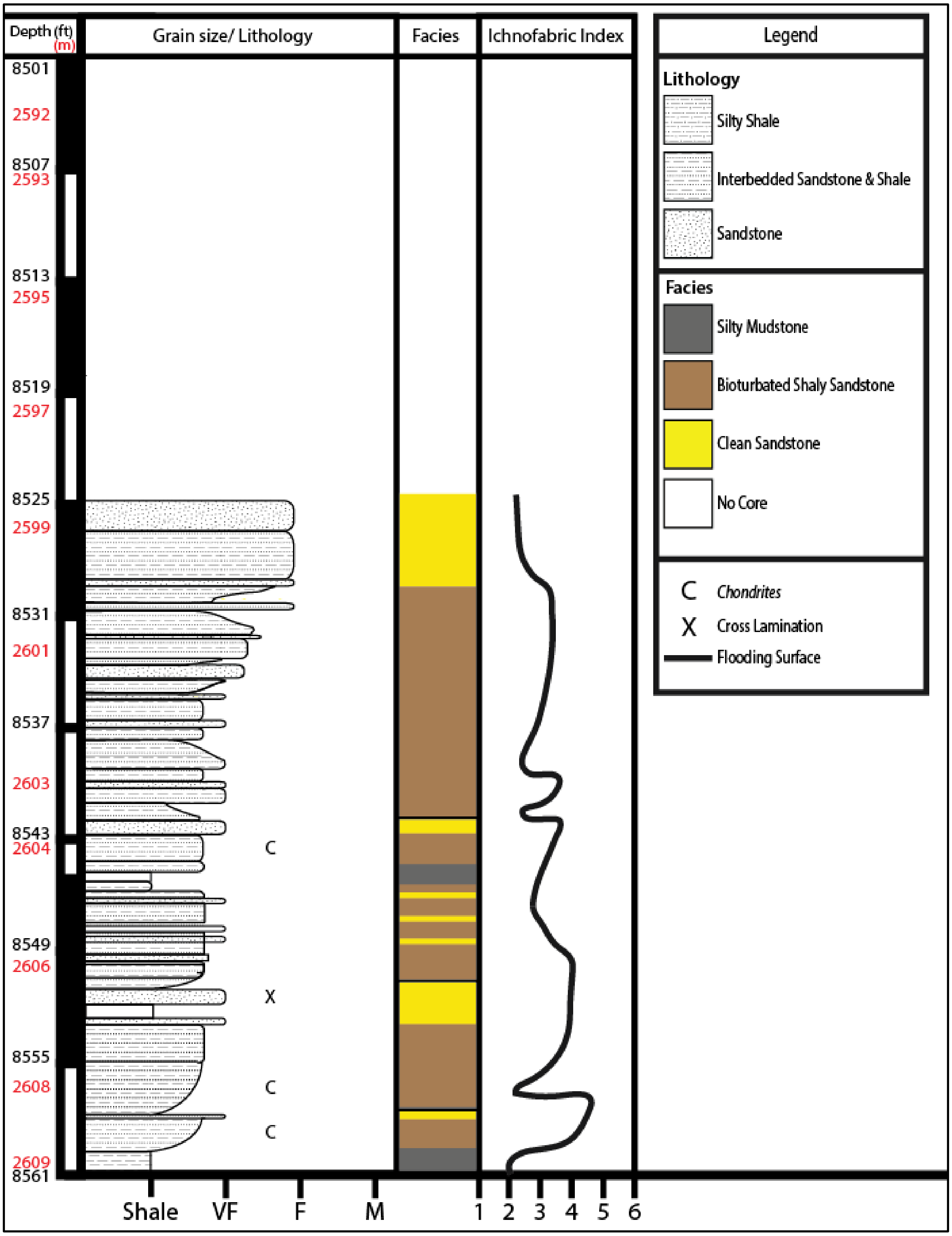

Figure 12: Measure Section A: Amalgamated Bonanza Petroleum 2 - Smith.

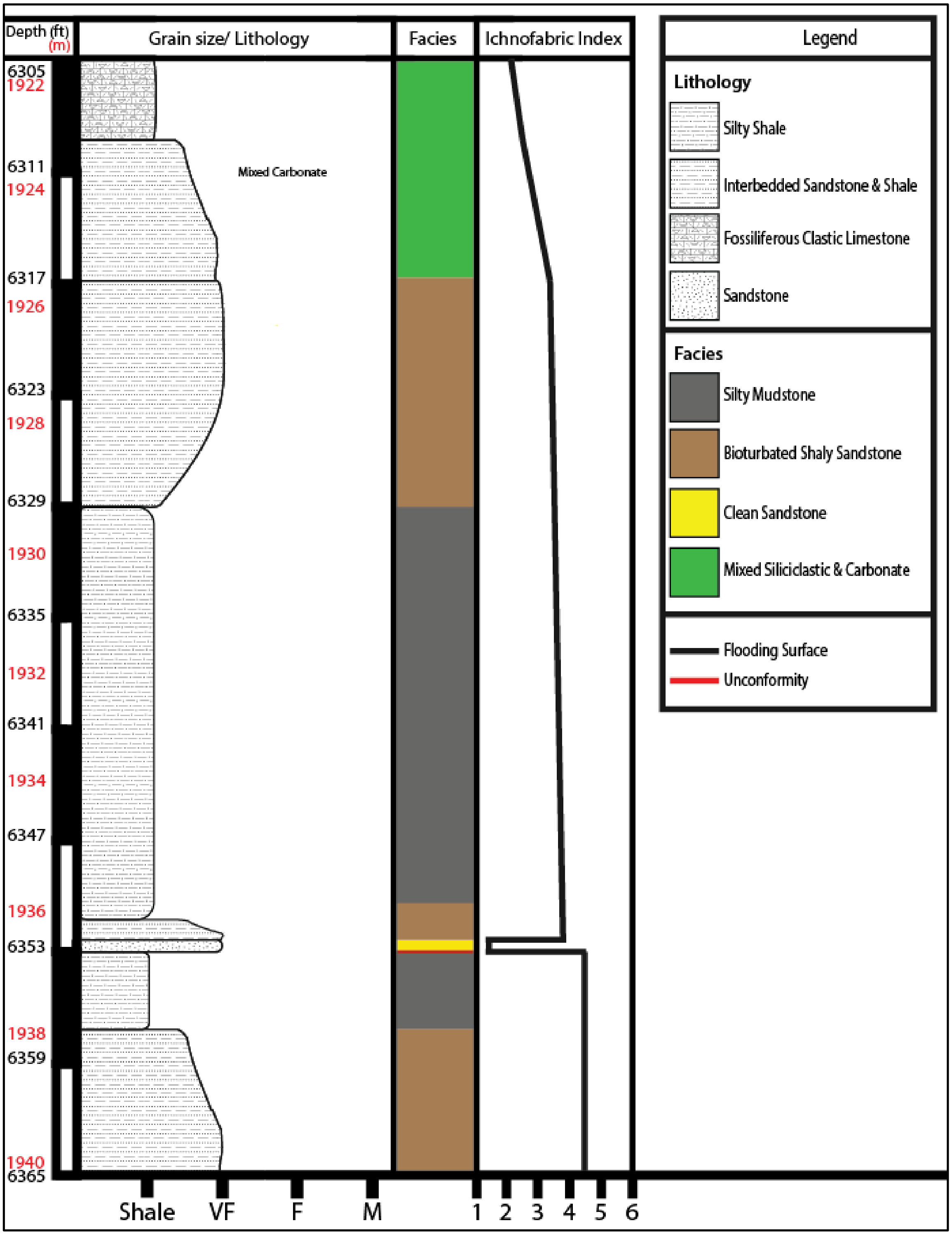

Figure 13: Measured Section B1: Hilltop Resort 2 (1).

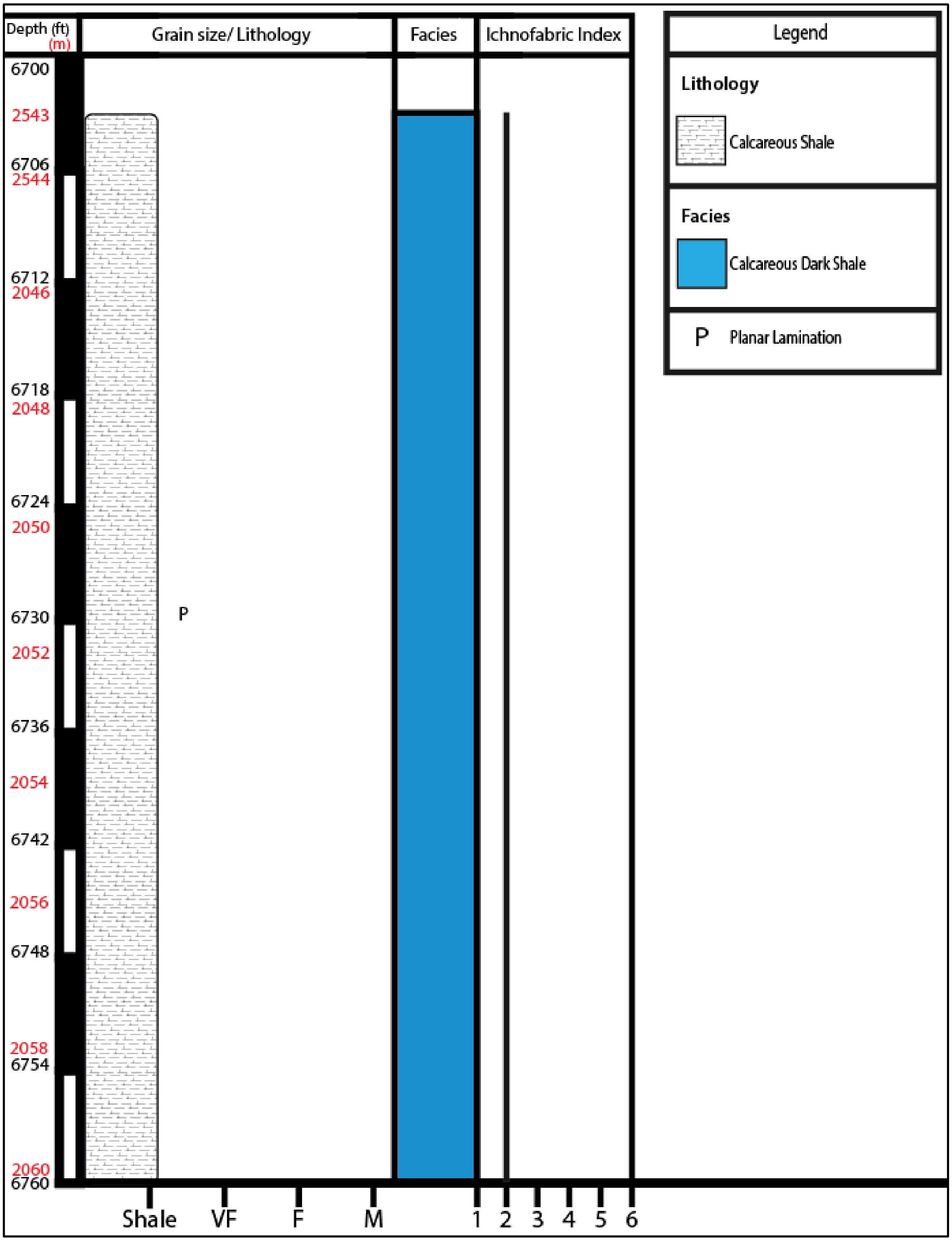

Figure 14: Measure Section B2: Hilltop Resort 2 (2).

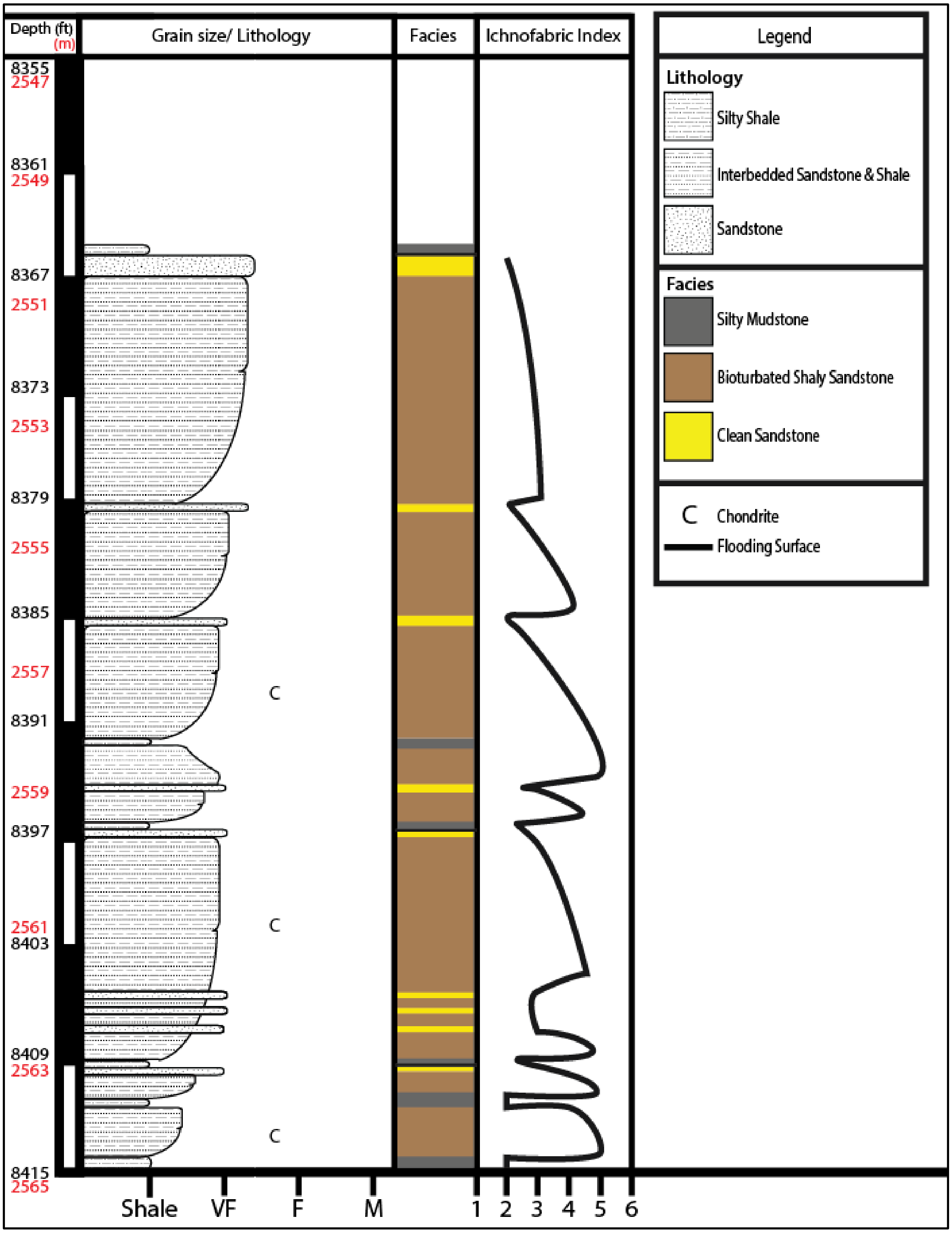

Figure 15: Measured Section C: Buttess Resources 2 - Wilson.

3.1.2 Facies Descriptions

The facies observed from all the available cores are summarized with descriptions and interpreted environment of deposition in the table below (Table 3). Siliciclastic facies are heavily bioturbated and have a good potential to bear the hydrocarbons.

Table 3: Facies descriptions and interpretations.

Facies	**% Sand**	**Facies Description**	**Inferred Environment of Deposition**
Calcareous Dark Shale	0-5%	Dark shale with little to no bioturbation. Carbonate-rich and contains planar laminations of sand or calcite cement. This facies often has high resistivity and high gamma ray on well logs	Deep marine anoxic environment
Silty Mudstone	0-25%	Dominantly shale, sometimes interbedded with fine sandstone or siltstone layers, which are less than three centimeters in thickness. The extent of bioturbation is high in the sandstone and invisible in the shale.	Distal Prodelta-Basinal Muds
Bioturbated Shaly Sandstone	25-70%	The most common facies observed in core. Fine grained sandstone interbedded with shale and often heavily bioturbated. Burrows include *Chondrites*	Prodelta
Clean Sandstone	> 70%	Fine to very fine grained sandstone with very few laminations; some beds coarsen upward from very fine to fine grain size. Cross lamination is observed in one of the cores. Bioturbation is very limited.	Delta Front-Distal Delta front
Mixed Sandstone and Wackestone	30%	Contains both siliciclastic (both sandstone and shale) and carbonate sediments including shells and fossils. The source of sediment for this facies could be different from the siliciclastic facies mentioned above.	Marine

Figure 16: A: Calcareous Dark Shale facies in Core from Hilltop Resort 2. B: Silty Mudstone facies from Hilltop Resort 2. C: Transition from Silty Mudstone Facies to Bioturbated Shaly Sandstone facies in Hilltop Resort 2. Burrow cross-section highlighted in yellow. D: Mixed Sandstone and Wackestone facies from Hilltop Resort 2. Shell fragment highlighted in yellow.

3.2 Wireline Logs

3.2.1 Wireline Log Facies and Petrophysical Properties

Seventeen wireline parasequences were defined between the top of the Buda Limestone and the base of the Austin Chalk. The first stratigraphic unit is “false Buda”. This unit belongs to the Washita Group and has a blocky pattern with a sharp top and base in the GR log (Figure 17). The density (RHOB) and PEF values of the “false Buda” are higher than the overlying Woodbine Group. Though “false Buda” has been picked across all the well logs, its significance for the stratigraphy of the Woodbine and Eagle Ford Groups is very limited. “False Buda” often is eroded either completely or partially in most of the well logs due to the top Buda erosional unconformity in the Eaglebine play area.

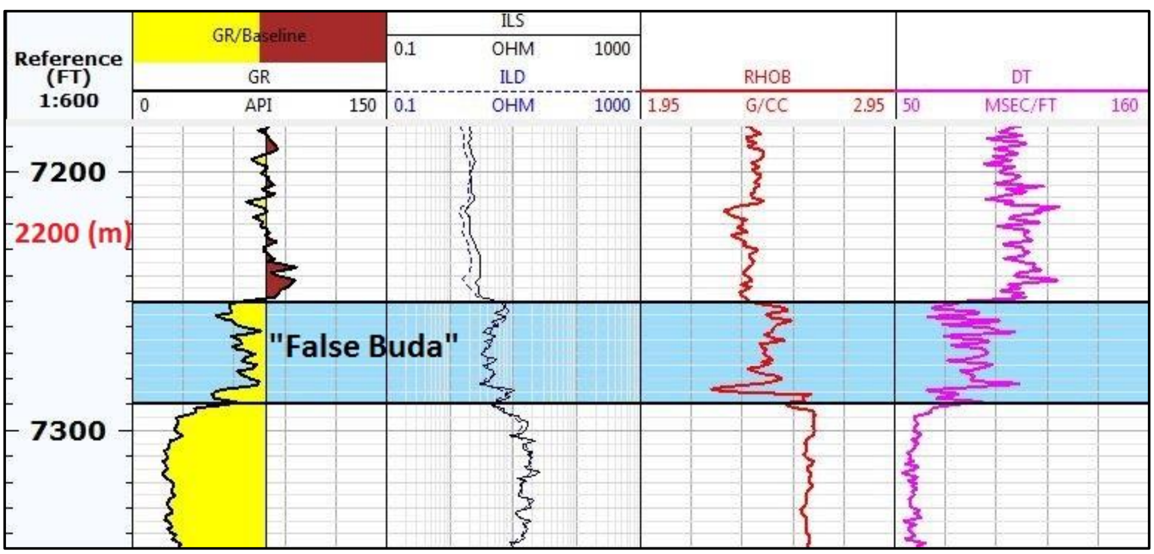

Figure 17: Gamma Ray (GR), Shallow resistivity (ILS), Deep resistivity (ILD), Bulk density (RHOB) and Compressional slowness (DT) log response for "false Buda" in well L.

Units S1A-S2B are interpreted to be shaly sandstone based on their well log response. The resistivity of sandstone often is high, suggesting the presence of hydrocarbons in the pore fluids. There is no core data available for this interval. The unit S1A is separated from "false Buda" by an unconformity. The percentage of sandstone and the thickness increases upward from S1A to S2B implying an overall progradational succession (Figure 18). These units have an average non-shale porosity of 8% and water saturation of 62%. The hydrocarbon saturation, which is 100-water saturation, porosity and percentage of sand gradually increase upward from 6%, 25% in S1A to 12%, 40% in S2B suggesting that the upper units of this parasequence set has better reservoir potential.

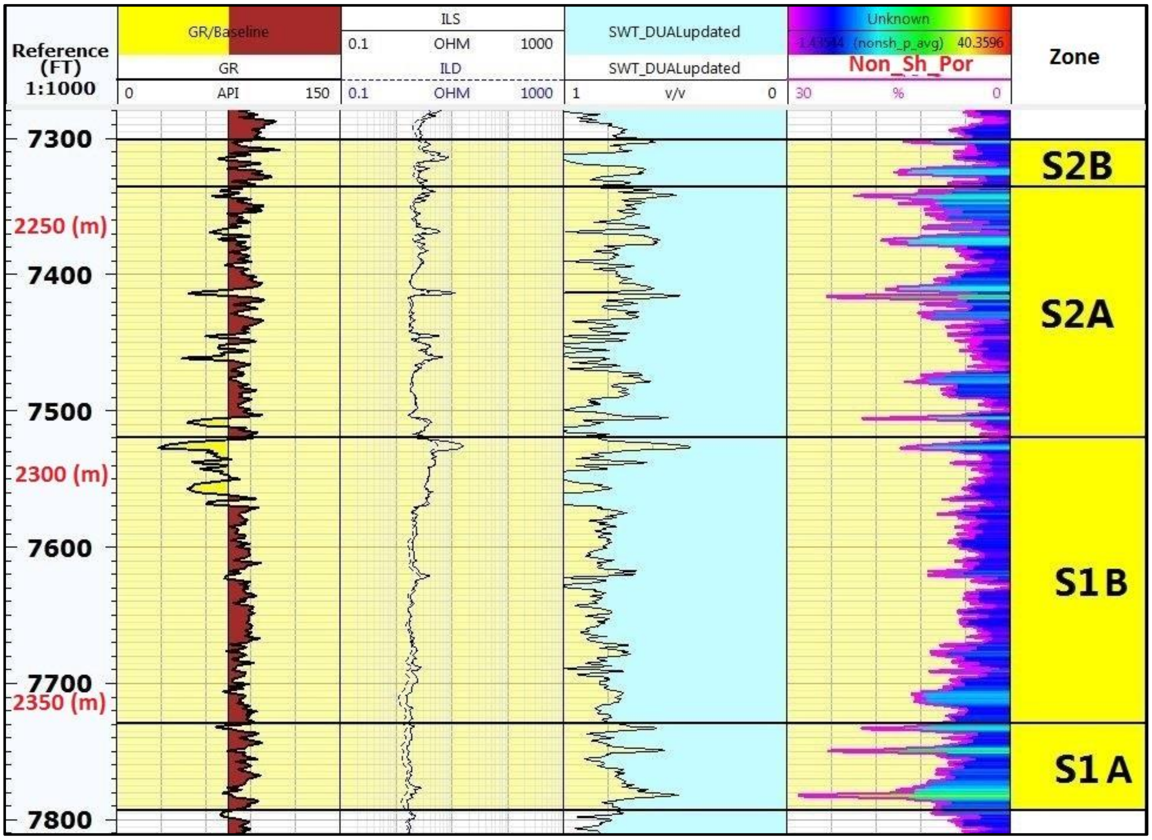

Figure 18: Gamma Ray (GR), Shallow resistivity (ILS), Deep resistivity (ILD), Bulk density (RHOB) and Compressional slowness (DT) log response and estimated water saturation (Sw) and Non shale porosity (Non_Sh_Por) for units S1, S2A and S2B in well I.

Units S3 and S4 are interpreted to be marine shales deposited during relative sea level rise. S3 represents the Calcareous Dark Shale facies identified in the Hilltop Resort 2 core (Figure 19). S4 has high GR values similar to S3 but it shows a decrease in GR upward. Also, the formation resistivity of S4 unit is lower compared to that of unit S3.

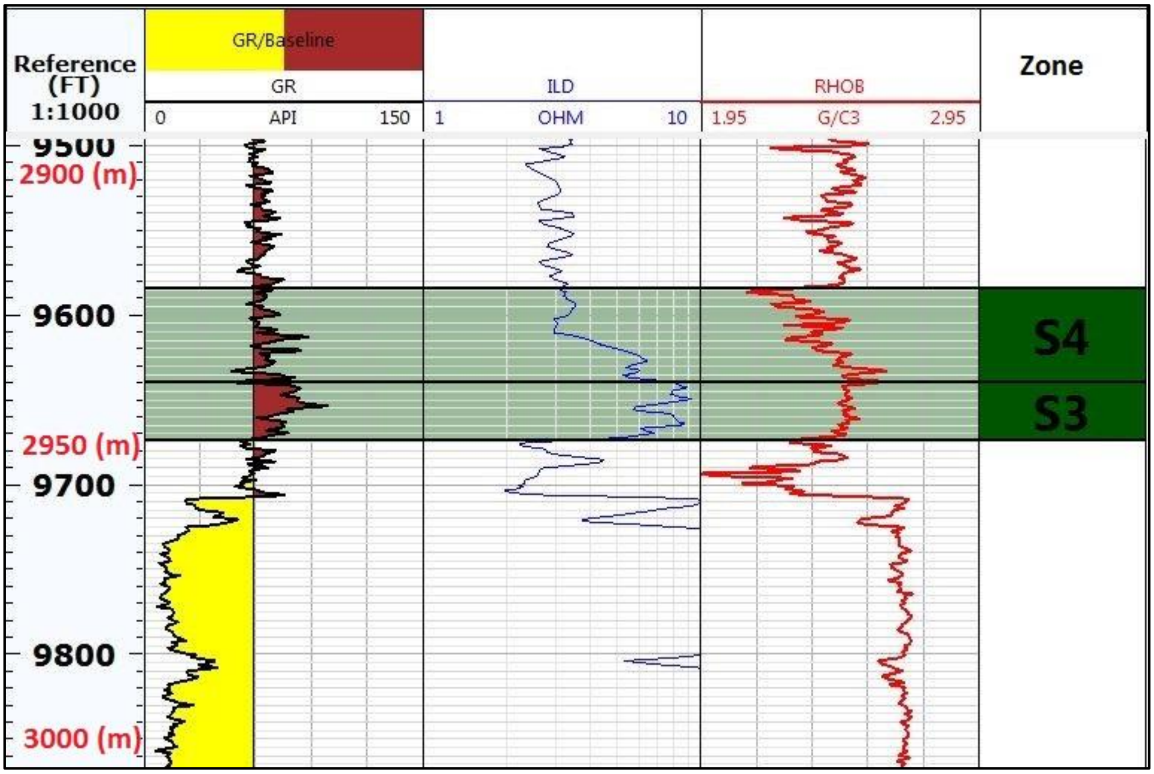

Figure 19: Gamma Ray (GR), Deep resistivity (ILD), Bulk density (RHOB) and Compressional slowness (DT) log response for units S3 and S4in well ZG.

Stratigraphic units S5A and S5B are interpreted as marine shales-basinal mudstones in most of the well logs with interbedded sands. These units are difficult to correlate across all the well logs because of the lack of consistant variations in their GR values. However, S5A typically has slightly higher resistivity values than S5B (Figure 20).

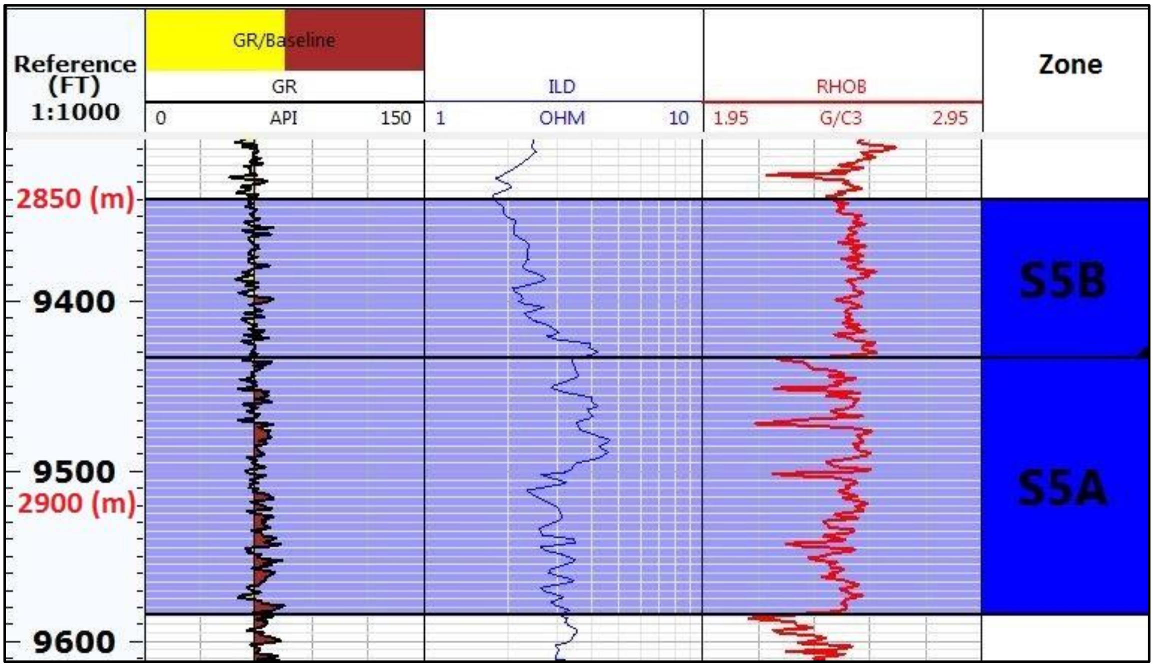

Figure 20: Gamma Ray (GR), Deep resistivity (ILD) and Bulk density (RHOB) log response for units S5A and S5B in well ZG.

Units S6-S8 each prograde upward on to a sharp flooding surface at the top (Figure 21). The lithology from the wireline logs is interpreted to be interbedded shale and sandstone at the base with sand content gradually increasing upwards. This is also consistent with the Amalgamated Bonanza Petroleum 2 - Smith and Buttess Resources 2 - Wilson cores. The average non-shale porosity and water saturation for these units are 11% and 55% respectively, with the upper units being more porous. Though S9-S13 show a similar prograding upward trend in their GR response, they are composed of mixed carbonate and siliciclastic sediments (Figure 22). The presence of carbonate is evident from the higher bulk density and low DT compared to the S6-S8. These units are interpreted as mixed carbonate and siliciclastic rock in the Hilltop Resort 2 core.

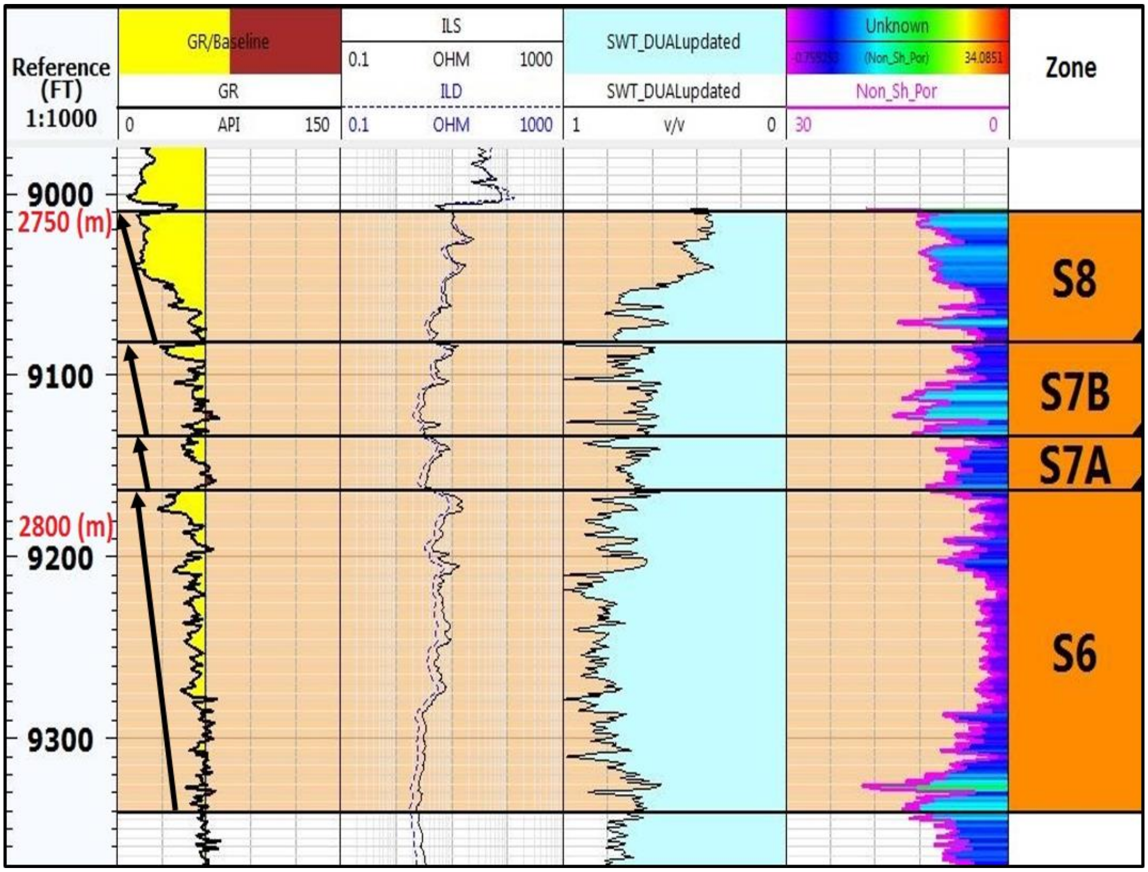

Figure 21: Gamma Ray (GR), Shallow resistivity (ILS), Deep resistivity (ILD) and Bulk density (RHOB) log response and estimated Water saturation (SWT_DUAL) and Porosity (Non_Sh_Por) for units S6-S8 in well ZG.

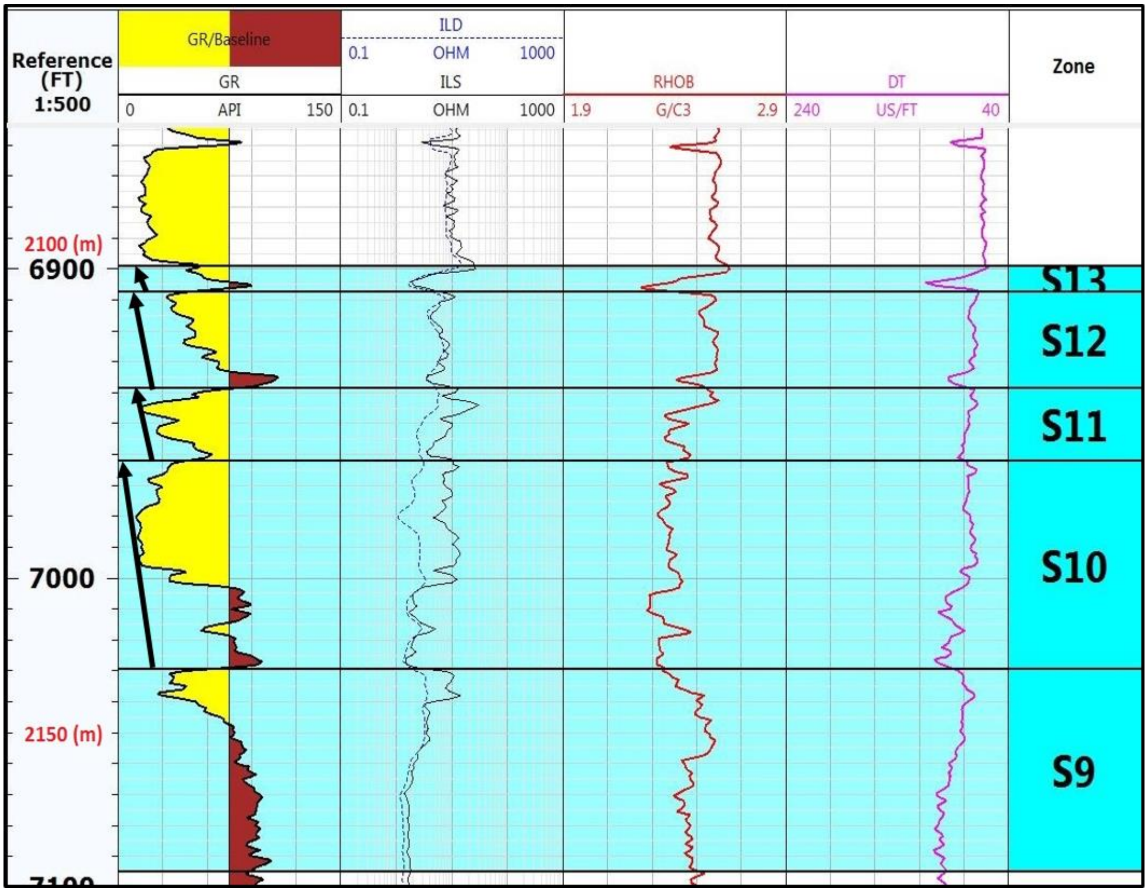

Figure 22: Gamma Ray (GR), Shallow resistivity (ILS), Deep resistivity (ILD), Bulk density (RHOB) and Compressional slowness (DT) log response for units S9-S13 in well I. RHOB increases and DT decreases gradually upward indicating an increase in carbonate content.

3.2.2 Cross-Section

Cross section A-A' trends northeast-southwest from Leon County updip to Brazos County downdip (Figure 23). The cross section covers a total length of 80 kilometers and includes 25 wireline logs with an average spacing of 2.5 km (Figure 23). The thickness of the entire study interval ranges from 1150 feet (350 m) in the northeast to 900 feet (274 m) in the southwest (Figure 24). The gradual thinning of the interval is due to erosion at the base Austin Chalk unconformity which is controlled primarily by the uplift of the San Marcos Arch in the southwest.

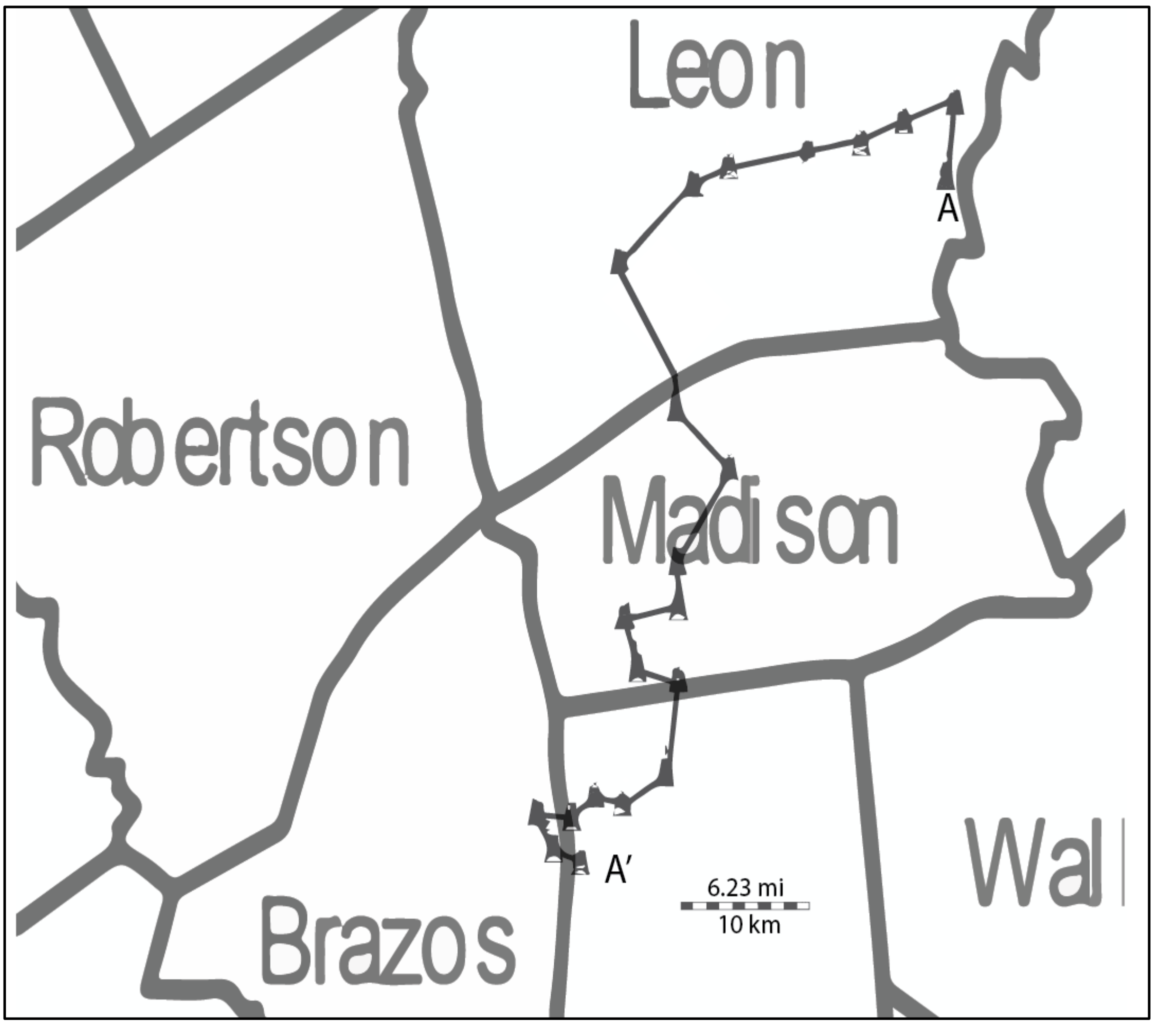

Figure 23: Base map for the cross section A-A'.

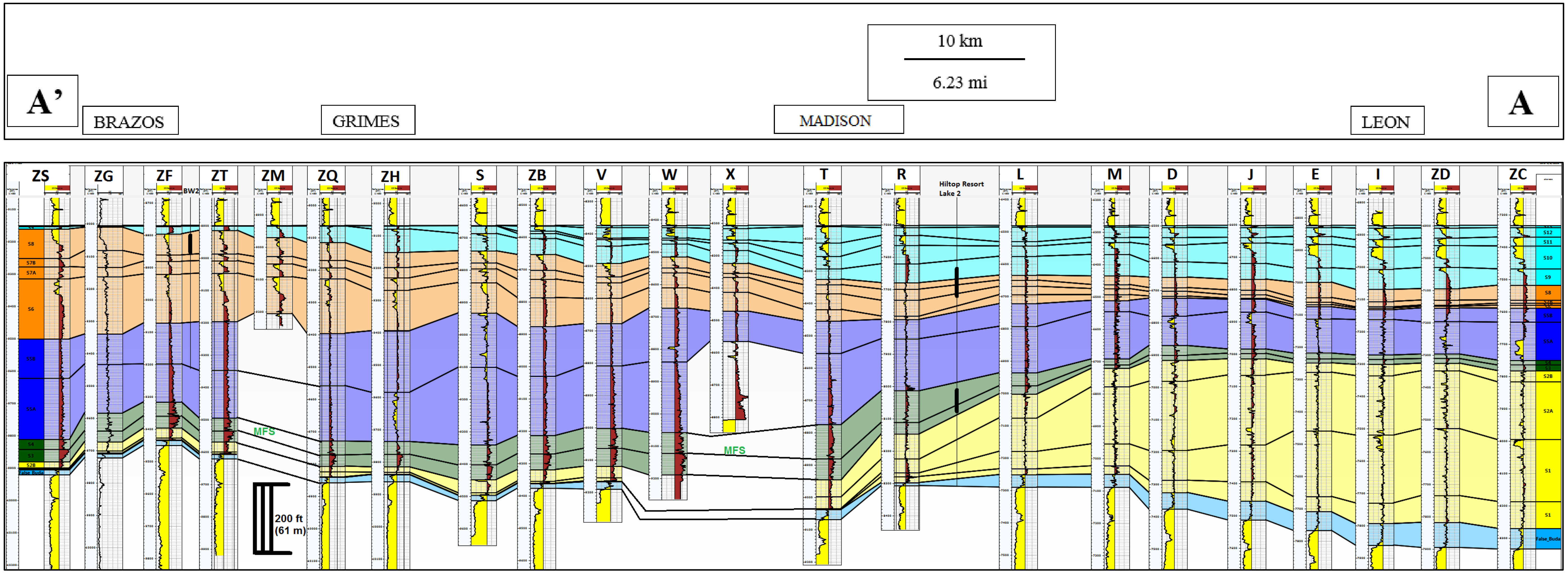

Figure 24: Cross section A-A'. Base Austin Chalk (BAC) unconformity is the datum.

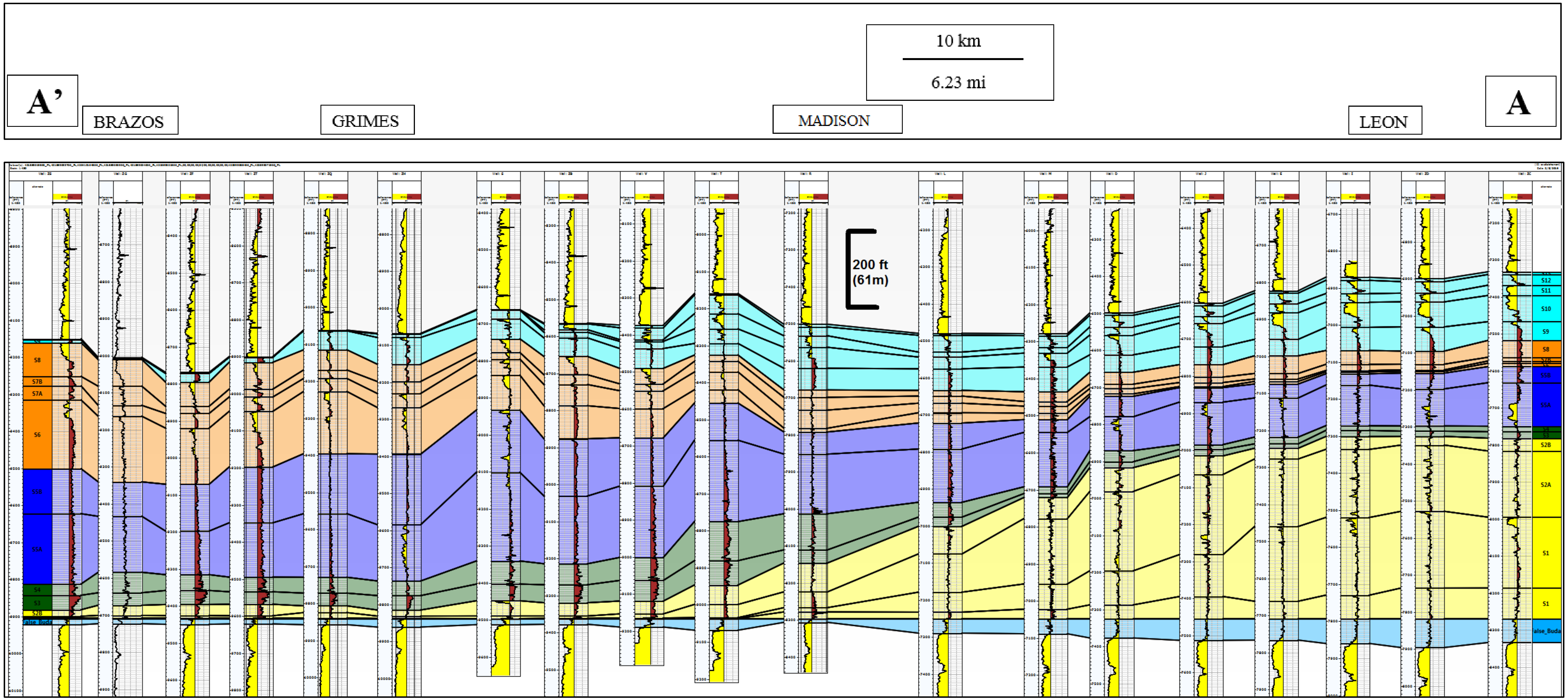

Figure 25: Cross section A-A'. Top “false Buda” is the datum. Wells ZM, X and W are excluded from this figure because these wells did not penetrate till “false Buda”.

Units S1A, S1B, S2A and S2B are interpreted to be the Woodbine Group strata based on their wireline log response. The Woodbine Group is interpreted to have d from northeast to southwest in the cross section. The thickness of the Woodbine Group changes significantly from over 490 feet (149 m) in the Leon County to less than 30 feet (9.1 m) in Brazos County (Figure 26). This transition is sharp from 310 feet (94.5 m) in well M of Leon County and 80 feet (24 m) in well T of Madison County, which are 16 km (10 mi) apart. This sudden change in the thickness is interpreted to reflect the combination of limited sediment supply and accommodation space away from the basin axis of East Texas Basin and the occurrence of the Woodbine shelf break. Lithologically, the Woodbine succession is composed of interbedded shales and sandstone beds in Leon County and transitions into primarily shale in Grimes and Brazos Counties. Based on the stacking pattern of parasequences in wireline logs and core description from Ambrose et al. (2009), the Woodbine Group gradually transitions from pro-deltaic deposits updip in Leon County to basinal muds downdip in Brazos County.

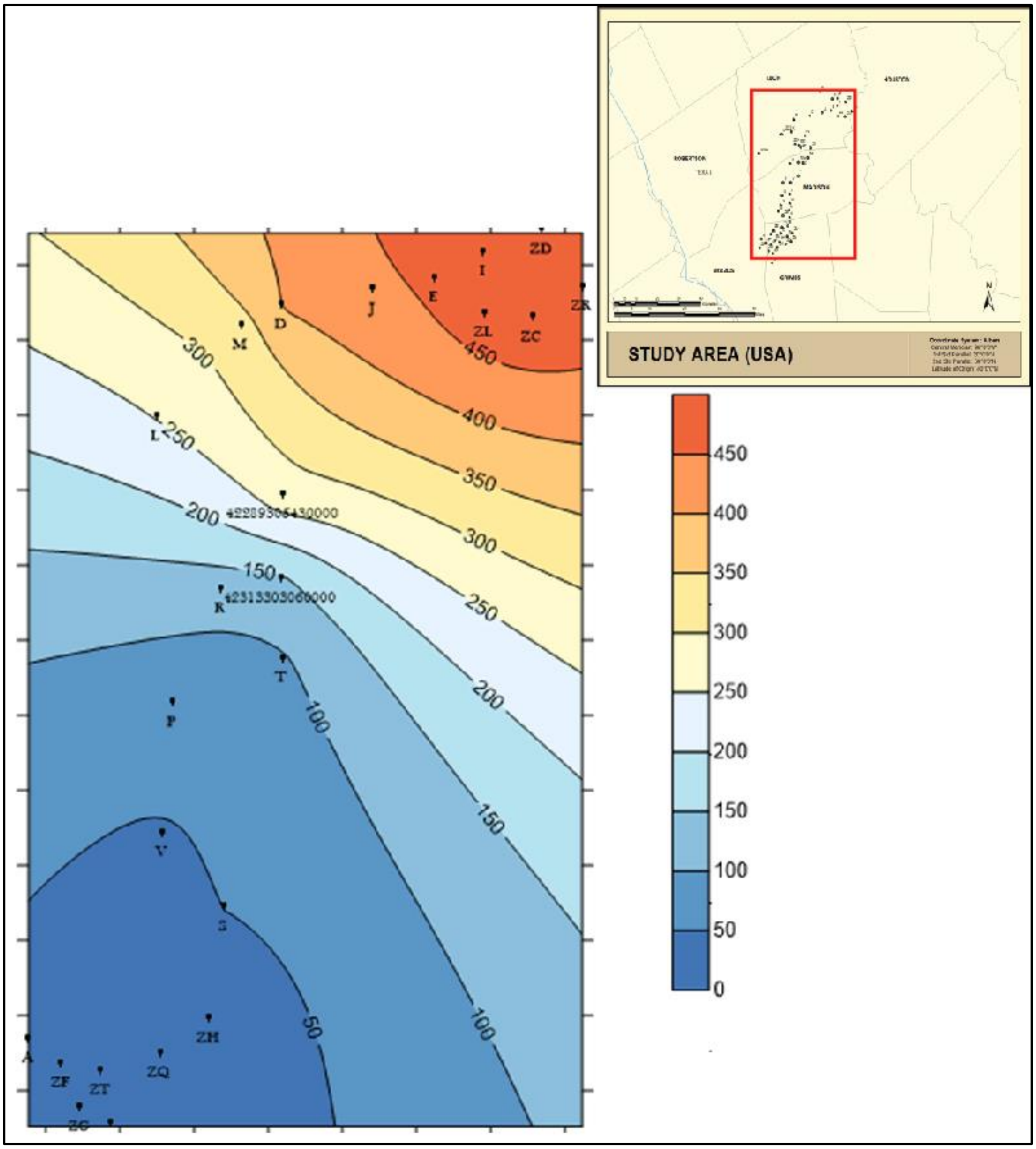

Figure 26: Isopach map of the Woodbine Group. The wells in the isopach map represents the wells, which are used to generate the isopach map.

Units S3 and S4 represent condensed marine shale deposited during a relative sea level rise. They are interpreted to be the distal expressions of transgressive and highstand system tracts, respectively, based on their well log response (Figure 19) and are interpreted to be the equivalent of the Lower Eagle Ford (LEF) of West Texas. The contact between S3 and the Woodbine Group is interpreted to be at least partly a transgressive hiatus in Leon and Madison Counties due to the absence of basinal mud transition in between the pro-deltaic Woodbine and the deep marine S3. The GR values and the formation resistivity of the S3 unit in Brazos and Grimes County is high (Figure 19) similar to the LEF of West Texas (Donovan et al., 2015), the Maness Shale of Hudson (2014) and the Lower Woodbine Organic Shale (LWOS) of Adams and Carr (2014). The overall thickness of the LEF Formation increases gradually from 30 feet (9.1 m) in Leon County to a little over 100 feet (30.5 m) in Brazos and Grimes Counties.

Units S5A and S5B are dominantly shale (Figure 20). These two units gradually thin from 300 feet (91.5 m) in Brazos County to 100 feet (30.5 m) in Leon County (Figure 24). Hydrocarbon potential for these units seems very limited due to low resistivity and sandstone percentage values from the well logs.

Units S6-S13 (Figure 21 and 22) form an overall prograding parasequence set (Figure 24). However, parasequences S6-S8 prograde eastward as opposed to the Woodbine sediments, which prograde west. This is due to the siliciclastic sediment supply delivered by the Brazos River (Figure 27) from just west of the study area (Adam and Carr, 2010). Amalgamated Bonanza Petroleum 2 - Smith core and wireline logs indicate, parasequences S7-S9 are sandstone interbedded with shale units deposited in a fluvial dominated delta with moderate-heavy bioturbation. The direction of progradation for parasequences S10-S13 cannot be determined due to their erosion at the Base Austin Unconformity in this study area. These parasequences are a mixture of carbonate and siliciclastic sediments based on their wireline log response and the interpretations from the core Hilltop Resort 2 (Figure 16). The carbonate content increases upward from S10 to S13 from the wireline log response and the shale volume decreases. Unit S13 is almost a 50-50 mixture of carbonate and siliciclastic at the base, which gradually transitions upward into the Austin Chalk (Figure 22). This progradational parasequence set is interpreted to be equivalent to the Upper Eagle Ford Formation of South Texas. There are at least two sources of sediment supply and the dominant one is to the west of this study area. Moving down dip, overall thickness of the Upper Eagle Ford Formation remains mostly uniform. However, younger parasequences truncate at the BAC because of the limited accommodation space towards the San Marcos Arch. In Brazos County, the upper units are S7, S8 and S9 (Figure 24).

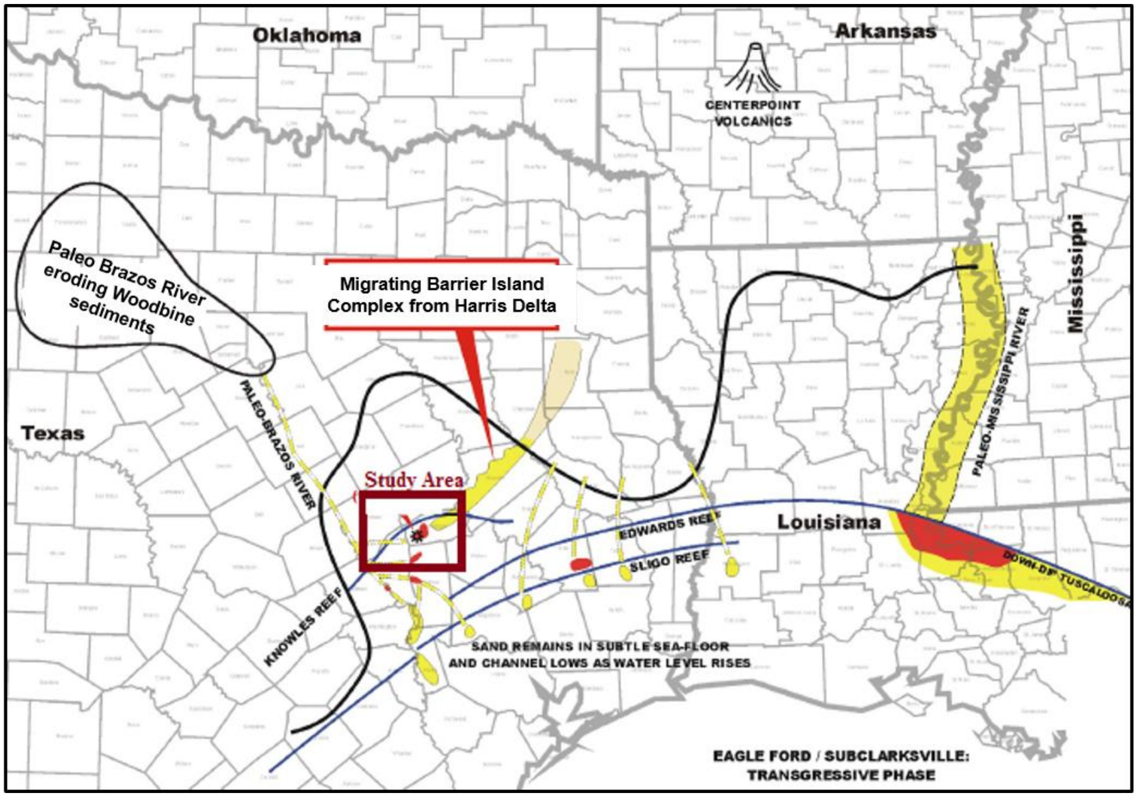

Figure 27: Paleogeographic map of the study area during the deposition of the Upper Eagle Ford Formation. Modified after Adam and Carr (2010). Taken from Oliver (1971).

4. DISCUSSION

The overall framework of stratigraphic units in the region is summarized in Figure 28. After the deposition of Buda Limestone, relative sea level dropped significantly, which exposed and eroded most of the Gulf Coast, except for the deepest parts of the East Texas Basin. When sea level began to rise, the marine Maness Shale was deposited in the axis of the East Texas Basin, which was deep enough to remain submerged even during relatively low sea level. Later, the Woodbine Group sediments were delivered from the northeast, which created additional accommodation due to subsidence. After Woodbine deposition has ceased, a sequence boundary was formed before the sea level began to rise. The contact between the Lower and Upper Eagle Ford Formation is at least partly unconformable based on numerous previous studies in South Texas (Donovan and Staerker, 2010). Finally the Upper Eagle Ford Formation siliciclastic units were sourced by the Brazos River, which eroded the Woodbine Delta sediments from North and redeposited them from the west of the study area.

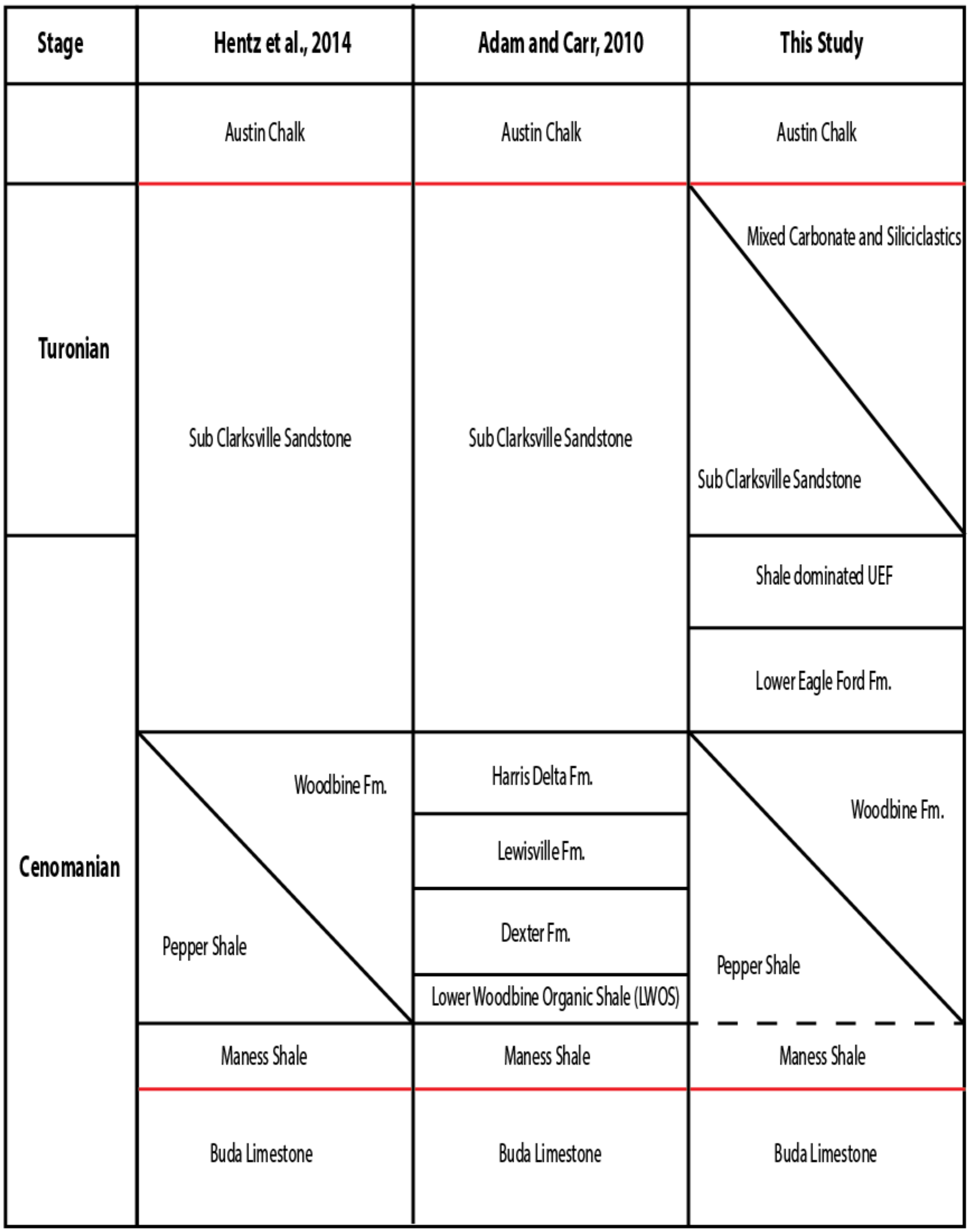

Figure 28: Stratigraphic column comparison between Hentz et al. (2014), Adam and Carr (2010) and this study.

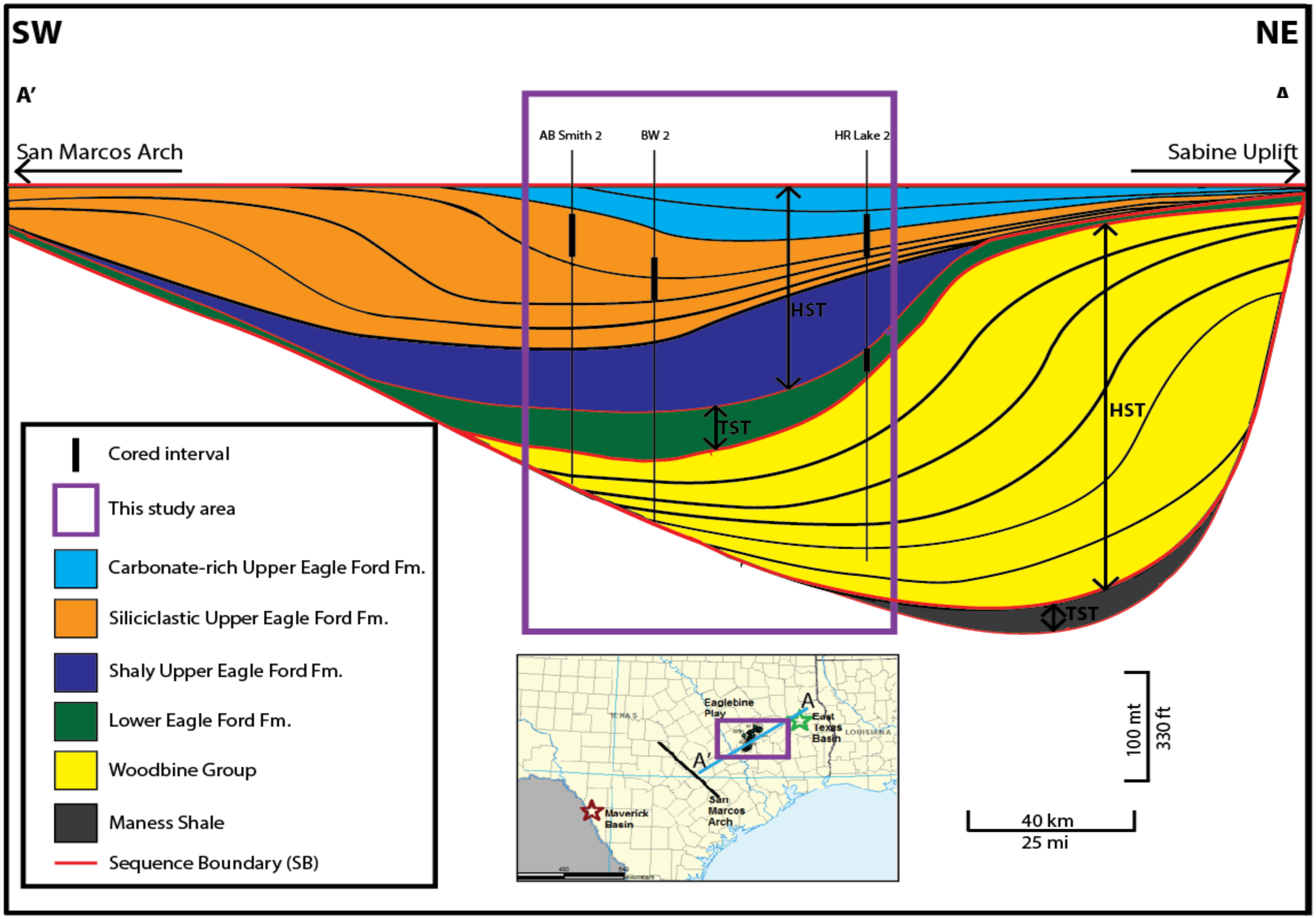

Figure 29: Schematic regional cross section from the Sabine Uplift to the San Marcos Arch.

This stratigraphic interpretation contradicts some in the literature (Hentz and Ruppel, 2010; Hudson, 2014; Adam and Carr, 2010). Firstly, the Maness Shale does not occur in Grimes and Brazos Counties. There is a thin high GR unit restricted to the updip Leon and Madison Counties. This unit could be either the Maness Shale or a transgressive Woodbine shale. In the East Texas Basin, Maness Shale was deposited during the relative sea level rise over the top of the Buda Limestone. However, most of the Gulf coast remained subaerially exposed during that period, constraining the deposition of the Maness Shale to the axis of the East Texas Basin where subsidence was very high. The Maness Shale is defined in well logs at the center of East Texas Basin as a high GR and high resistivity shale with a thickness of around 50-100 feet (15m-30m); (Ambrose et al., 2009). The Maness Shale is expected to gradually pinch out towards the flanks of the East Texas Basin. However, according to Hudson (2014) and Hentz and Ruppel (2010) the thickness of the Maness Shale in Brazos County is around 200 feet (61 m), which seems less feasible. Though the stratigraphic unit defined as Maness Shale in their studies is lithologically similar to the Maness Shale of the East Texas Basin, it is interpreted in this study as equivalent to the Lower Eagle Ford Shale of the Maverick Basin. This unit is consistently identified across all the well logs and it is younger than the underlying Woodbine Group. Geochronology of the Calcareous Dark Shale facies in the Hilltop Resort 2, the Maness Shale at center of the East Texas Basin, and the Maness Shale of Hudson (2014) further strengthens this interpretation.

The Woodbine Group is deposited over the “false Buda” above an unconformity during which the Maness Shale was being deposited in the axis of the East Texas Basin.

As described in the literature, the Woodbine Group progrades from the northeast. However, the equivalent Pepper Shale unit described in the literature i.e., distal facies transition of Woodbine sandstone beds is only few tens of feet thick in Grimes and Brazos Counties. This interpretation supports the presence of the Woodbine shelf break in Leon and Madsion Counties. Moreover, the flooding surface of the overlying Lower Eagle Ford Formation can be picked across all the well logs with confidence (Figure 24). The contact between the Woodbine Group and the overlying Lower Eagle Ford Formation is at least partly erosional at the updip Leon and Madison Counties, due to the absence of basinal/silty mudstone facies in between the prodeltaic Woodbine and Lower Eagle Ford Shale.

The basal part of the Upper Eagle Ford Formation is dominated by marine shales and basinal mudstone. This unit previously was interpreted as a lateral facies equivalent to the Woodbine Group by Hentz et al. (2014) due to its pinchout updip of the study area and the East Texas Basin (Figure 29). However, this unit is not deposited updip of this study area or near the San Marcos Arch due to the limited accommodation available in those areas. The middle unit of the Upper Eagle Ford Formation is primarily siliciclastic, deposited in a fluvial deltaic environment. This unit was sourced by the Brazos River (Figure 27) from the west of the study area (Adam and Carr, 2010). The increase in shale content and the absence of clean sandstone facies in the Hilltop Resort 2 core, supports this interpretation. Finally, the topmost unit of the Upper Eagle Ford Formation is interpreted to be deposited during a relative sea level highstand and the uppermost unit is interpreted to be an equivalent of the Langtry Member of South Texas (Donovan and Staerker, 2010).

5. CONCLUSION

The southwest extension of the East Texas Basin is an emerging play termed the "Eaglebine". Despite its proven hydrocarbon potential, the stratigraphic architecture of this region remains uncertain. In this study, wireline logs and cores were used to create a stratigraphic interpretation that resolved these stratigraphic uncertainties.

Five facies were identified from the cores. Three of them, Silty Mudstone, Bioturbated Shaly Sandstone, and Clean Sandstone were interpreted to be deposited in distal prodelta, prodelta, and shoreface environments respectively. These three facies together represent a deltaic facies succession. In addition, a deep marine Calcareous Dark Shale was identified and interpreted to reflect anoxic depositional conditions. Finally, a Mixed Sandstone and Wackestone facies has been defined which contains fossils, including shell fragments.

Seventeen wireline log units were defined based on their log response. These log facies are grouped into higher order parasequence sets based on their internal stacking patterns. Maness Shale is either eroded or not deposited in the study area. The Woodbine Group is thickest in updip Leon County and thins to less than thirty feet (9.1 m) thick in Brazos and Grimes Counties. Average non-shale porosity of the Woodbine Group is 8% and average water saturation is 62%. With advances in horizontal drilling, recompletions of the previous Woodbine Group targets could still be economic in Leon and Madison Counties.

The Eagle Ford Group is sub-divided into Lower and Upper Eagle Ford Formations. The Lower Eagle Ford is composed of the Calcareous Dark Shale facies which has high GR and high formation resistivity similar to the Lower Eagle Ford Formation of the Maverick Basin. This unit is continuous across the study area and proved to be organic rich and hydrocarbon bearing in Brazos and Burleson Counties. However, it's potential in updip Grimes, Madison and Leon Counties is yet to be evaluated. Moreover, the older Maness Shale is could be a separate unconventional shale play by itself in the axis of the East Texas Basin.

The Upper Eagle Ford Formation is further sub-divided into three units based lithology; the shaly Upper Eagle Ford unit, the siliciclastic Upper Eagle Ford and the carbonate-rich Upper Eagle Ford unit. The siliciclastic Upper Eagle Ford Formation has an average non-shale porosity of 11% and has a good hydrocarbon bearing capabilities, especially the Clean Sandstone facies. This unit was dominantly sourced by the Brazos River from the west. Finally, the carbonate-rich Upper Eagle Ford Formation is composed of Mixed Sandstone and Wackestone facies. Carbonate content gradually increases upward to the base of the Austin Chalk. The sandstone beds of these two units pinch out as shales in the Madison County indicating a poor reservoir potential in that region. This unit is interpreted to be analogous to the Langtry Member.

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