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Interpretation and Fracture Characterization of Early-Cretaceous Buda Limestone Formation Using Post-Stack 3D Seismic Data in Zavala County, Texas

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Interpretation and Fracture Characterization of Early-Cretaceous Buda Limestone Formation Using Post-Stack 3D Seismic Data in Zavala County, Texas

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Geology

by

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May 2018
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This thesis is approved for recommendation to the graduate council.

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Abstract

The Buda Limestone is a naturally fractured Early Cretaceous carbonate formation in south Texas which unconformably underlies the Eagle Ford Shale. Matrix porosity of the Buda is less than 6%, therefore natural fractures improve the potential for commercial hydrocarbon production from this tight limestone formation. This presents a challenge for producers to identify these zones using well log and post stack 3D seismic data typically available to medium or small exploration companies. This project provides a workflow based on well log analysis tied to seismic acoustic impedance (AI) inversion to locate areas of probable natural fractures.

Acoustic impedance inversion was performed across a 42 square mile 3D seismic survey. The AI data shows low AI shadow zones on the down thrown side of faults. Post stack geometric seismic attributes such as coherence, maximum and minimum curvature were analyzed in the anomalous AI areas, along with physical seismic attributes such as instantaneous amplitude and instantaneous frequency. This study indicates that a combination of acoustic impedance inversion and seismic attributes can identify areas of enhanced natural fracturing within the Buda Limestone interval.
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CHAPTER 1:
INTRODUCTION

Introduction

One of the requirements for commercial oil production from Buda Limestone is presence of natural fractures which are unevenly distributed throughout the formation. Natural fractures in carbonate reservoirs can be characterized by utilizing prestack or wide azimuth seismic data, however this research focuses on utilizing post stack seismic data for fracture characterization. It is proposed, that naturally fractured zones can be predicted by utilizing acoustic impedance inversion with a combination of physical (instantaneous amplitude, instantaneous frequency) and geometric (curvature, coherency) seismic attributes.

Previous Investigations

Zavala County has been an oil producing region since the 1920s when producers were targeting Late Cretaceous Olmos and Escondido Formations. In this research we will focus on the Mid Cretaceous Buda Limestone Formation in the Pedernales 3D seismic data. The outline of Pedernales 3D seismic survey is shown in figure 1. The early literature about Buda Limestone as oil reservoir goes back as far as 1990s when two vertical wells were drilled in Frio County, TX with intention to run logs, but resulted in production of 5,317 bbl of oil in first 7 days (Petzet, 1990). However, due to the peculiar geology of Buda Limestone, both of these wells declined quickly and interest in Buda Limestone diminished until 2012, when Hughes Company established a commercial horizontal well making 120,950 bbl of oil and 194,689 mcf of gas in the first 12 months of production. It’s generally assumed that Buda Limestone must be naturally fractured for successful oil production; this creates a challenge to predict fractured zones,
especially from 3D seismic data. It has been established elsewhere that naturally fractured zones can be characterized using prestack, wide azimuth 3D seismic data to estimate azimuthal anisotropy (Far et al., 2013). The current study is limited to the use of post-stack data and well control, a situation common in medium to small exploration companies.

The Buda Limestone play is very similar to the Austin Chalk play as both of these formations have low matrix porosity and permeability, and both feature fracture porosity and associated permeability. Therefore successful production from these formations is based on predicting “sweet spots” or areas of concentrated fractures. In fact, more than 60% of the world reservoirs are fractured and the distribution of natural fractures is not random but can be associated with structural setting, lithology, faults and folds (Ouenes, 2010). Faulting and folding are the most important fracture creators and geometric attributes (coherence, curvature) are useful to identify them. Acoustic Impedance is a powerful attribute for fracture characterization as it provides a direct estimate of rock “hardness” which has the potential to distinguish fractured and unfractured rock (Ouenes, 2010). The literature is silent on fracture characterization of Buda Limestone using post stack 3D seismic data, however there have been studies on other carbonate formations establishing that it is possible to predict highly fractured zones by application of post stack seismic attributes. In particular, a combination of geometrical attributes which reveal seismic discontinuity and instantaneous Hilbert attributes that may provide important rock and fluid information (Holman, 2014). Holman studied Mississippian Limestone in Oklahoma which is oil-producing and naturally fractured, similar to Buda Limestone except the Mississippian Limestone has interbedded chert layers which Buda lacks. Holman (2014) showed that Mississippian Limestone, naturally fractured reservoir zones can be predicted by a combination of geometric (coherence, curvature) and instantaneous (amplitude, instantaneous frequency)
attributes. Coherency is the most commonly used geometrical attribute as it represents low trace-to-trace continuity which reveals faulting. Curvature (Roberts, 2001) measures local event shape in 3D and is defined as the inverse of radius of curvature; it has the effect of decomposing a surface into a series of synclines and anticlines. Instantaneous Amplitude is an attribute in fracture prediction since it often decreases rapidly indicating changes in relative acoustic impedance. Low instantaneous frequencies combined with high negative curvature near a fault can suggests that the footwall has more fracturing relative to the hanging wall (Holman, 2014).

Yenugu and Marfurt (2011) developed a relationship between most positive curvature and fracture density in Mississippian play showing that curvature generally predicts higher fracture intensity in the crest-forelimb region of a fold and supported this with outcrop examination as well as a horizontal well fracture log.

Najmuddin (2003) studied frequency attenuation in Austin Chalk as an indicator of fractured media. Fractured rock attenuates higher frequencies resulting in a downward shift of the dominant frequency, compared to frequency spectra from above the fractured formation. Najmuddin (2003) developed a new method to represent frequency attenuation by a post-stack 3D seismic attribute called t* and validated results by a comparison with production data in Burleson County, TX. The results appeared to be consistent with fracture orientation and trend across the survey area and Najmuddin (2003) proposed undrilled sweet spots.

Bello et al. (2013) have studied correlation of high density fracture zones in Austin chalk and Eagle Ford Shale derived from image logs with seismic curvature and coherence attributes generated from post stack seismic data. They conclude that wells with the highest calculated fracture density (>12%) coincide with curvature and wells in low coherency areas had lower fracture density.
Bennet (2015) focused on seismic interpretation of Cretaceous volcanic mounds of the Rio Grande Embayment and surrounding Gulfian series formations using the same Pedernales 3D seismic survey as the present research. Her research structurally characterized this specific area and included time structure mapping of all the Gulfian series formations including Buda Limestone. The current study differs from all previous work by utilizing post stack seismic attributes plus impedance inversion to indicate areas of probable natural fracturing of the Buda in south east Zavala County, TX.

Geologic Setting

Buda limestone in the study area (figure 1) was deposited on the wide shallow Comanche shelf during Early Cretaceous (Albian-Cenomanian) time within the Maverick basin (figure 2), when much of south Texas was dominated by carbonate deposition with a few transgressive shales (figure 3). During the Albian stage, the southeastern Comanche shelf bordered the Gulf of Mexico, marked by a narrow carbonate belt – the Stuart City reef (Rose, 2016). Seaward from the Stuart City reef, water depth increased steadily, however on the Comanche shelf water depth remained shallow. The Comanche shelf featured structurally controlled depressions, with the Maverick basin being one of them. The Maverick basin is believed to be a Jurassic rift valley with a NW-SE fault system. During Aptian time, when Buda was deposited, the Silgo shelf margin bridged the Rio Grande Embayment, adding a depositional aspect to the Maverick Basin (Rose, 2016).

Bennet (2015) outlined that faulting and folding caused by extension and subsidence of the Gulf of Mexico basin, dominate the structural architecture of South Texas; however only two fault zones (the Balcones and Luling) may influence the Maverick basin. The Balcones fault zone parallels the Ouachita thrust belt and is dominated by normal faults that can exceed 1600
feet of throw and extends from Williamson County, TX southwest into Uvalde County. The Luling fault zone is parallel to the Balcones fault zone and extends from Williamson County south into northern Medina County. Luling is characterized as a normal fault zone that can extend into Paleozoic basement rocks. These two fault systems also feature the Balcones igneous belt which consist of more than 200 volcanic mounds clustered within the Zavala County. Two of the volcanic mounds are imaged by the Pedernales 3D seismic survey (figure 4) with distinct radial faults above them caused by collapsing of overlying deposits due to overburden load. Distribution of volcanic mounds suggest that their accumulation is a result of magma intrusions through faults that penetrate Paleozoic and Pre-Cambrian rocks, moving up along fracture zones related to the Balcones fault zone (Bennet 2015).

**Stratigraphic setting**

The Buda Limestone in the study area was deposited in a shallow water below fair-weather wave base as indicated by abundance of fossils and variable fossil content (Oya, 2015). It overlies the Del Rio Formation and unconformably underlies Eagle Ford Shale (figure 3). The unconformity between the Buda Limestone and Eagle Ford Shale is a subject to subaerial exposure caused by a drop in relative sea level. The contact between Buda Limestone and Eagle Ford Shale is easily recognized in both outcrop and subsurface logs. In outcrop, Buda Limestone appears as a gray wackestone and Eagle Ford Shale is an organic rich mudrock. On gamma ray, the contact between Buda Limestone and Eagle Ford appears as a very sharp spike (figure 5). Snyder and Craft (1977) evaluated Buda Limestone from core and fracture analysis, they conclude that the matrix permeability of the Buda and the Austin formations are very similar (less than 0.5md). Natural fractures within the Buda are mostly vertical, ranging in width from 0.1 to 0.4mm with fracture density ranging from 1 fracture per foot up to 25 fractures per foot.
Oil saturation within Buda varies from 0% to 60% and is unevenly distributed through the formation. Snyder and Craft (1977) gave three requirements for successful oil production from Buda Limestone without hydraulic fracturing: 1) the fracture density must be more than 1 fracture per foot, 2) residual oil saturation in the matrix must be more than 10%, and 3) there must be an indication of matrix permeability, normally 0.01 md.

Buda Limestone is known to be a tight formation with typical matrix porosity of 3 to 4 percent. As a result of Buda Limestone’s low matrix porosity, the reservoir quality is mainly determined by fracture porosity, since improved oil production is related to the fracture network. Buda Limestone also features thin (3-10 feet) layers with high total porosity (up to 15%) which is achieved by combination of intercrystalline matrix porosity and fracture porosity. These high porosity zones, which can be identified by density-porosity petrophysical log, are likely due to diagenetic changes and are considered as the best oil producing zones.

**Data Description**

This thesis will use a 3D Seismic Survey where primary data type is post stack time migration (PSTM) with 4 ms time sample rate. Acquired in Zavala County, Texas the survey covers an area of 42 square miles with a bin size of 110 by 110 feet. Frequency spectra indicate signal in the range 9.9 – 63.5 Hz with a dominant frequency of 36.7 Hz (figure 6). Average P-wave speed through 125 feet thick interval of Buda Limestone is 18887 ft/s which suggests that horizontal resolution of Pedernales 3D survey within the Buda Limestone interval is 266 ft and vertical resolution is 133 ft. Also available are geophysical well logs from Holdsworth-Nelson (see table 1) well which will be used in interpretation process.
CHAPTER 2:

METHODS

Synthetic Seismogram

The purpose of synthetic seismogram is to create a zero offset seismic trace that theoretically would have been recorded at a well location (Liner, 2016). It is a primary way of establishing a connection between borehole geology and geophysics. The Holdsworth-Nelson well was chosen for this process as it has both sonic and density logs measured on 2551.5-6348.0 ft and 2523.0-6328.5 ft intervals respectfully, as well as check shots necessary for creating a proper time-depth relationship.

Synthetic generation was done using Schlumberger Petrel software. It starts from calculating travel times associated with each depth level in the sonic log and calculating reflection coefficients from sonic and density log value. The mathematics and assumptions related to synthetic seismogram generation are itemized in Liner (2016). Each reflection coefficient is then placed at its appropriate time to create reflection coefficient time series. In this study, an Ormsby zero-phase wavelet (Figure 7) was chosen for use in synthetic generation and using corner frequencies determined by analysis of Fourier amplitude spectra of nearby seismic traces over a 2 second window centered on Buda Limestone (Figure 6). The convolutional model (Liner, 2016) assigns this wavelet to each RC and scales it by that RC. The resulting synthetic seismogram (figure 8) is a summation of all such scaled wavelets (Liner, 2016). The displayed columns with assigned to them letter in Figure 8 are (A) measured depth in ft and two-way time in milliseconds, (B) calibrated sonic and density log, (C) Reflection coefficient time series, (D) wavelet parameters, (E) seismic trace, (F) synthetic trace, (G) interval velocity, (H) output/input
interval velocity, (I) drift, (J) formation well tops. The visual fit between Buda Limestone top and synthetic seismogram is very good (Petrel does not compute a quantitative goodness of fit measure) as well as for Del Rio and George Town. Formations above the Buda such as Eagle Ford, Austin Chalk don’t show very good fit which is probably due to poor surface coverage at this location that caused lower fold. It was possible to obtain a good fit in formations above by using Deterministic Wavelet and manipulating the phase, however it resulted in Buda and surrounding formations to be out of phase, thus the wavelet was not used in the thesis. The synthetic seismogram based on the analytical Ormsby wavelet (figure 8) did not require any squeezing or stretching to obtain a good fit of Buda Limestone top with synthetic, thus preserving the velocity field. After synthetic generation, the Holdsworth-Nelson well was tied to the seismic data at the well location (figure 9) and formation tops were brought from the well depth-domain to the seismic time-domain and associated events were identified. These included the top of the Buda Limestone and Del Rio Formation. The Buda is represented by a very distinct peak which results in a smooth, continuous tracked horizon (figure 10). Seismic horizon representing the top of the Buda Limestone was shifted 3ms up to correlate with the well top.

**Depth Conversion**

Based on the synthetic tie, key horizons were tracked throughout the Pedernales 3D seismic area to create initial amplitude and time structure maps. The Buda Limestone tracked horizon was converted to depth utilizing well top information from 3 wells. A linear velocity model was created in Petrel based on using $V=V_0$ equation (figure 11) and well tops as calibration points. The resulting velocity model (figure 12) was multiplied by the time structure map (Liner, 2016) to convert the Buda time structure map to depth (Figure 13).
In the mapped area, the Buda limestone exhibits general NW-SE dip towards Gulf of Mexico with average dip of 2 degrees. Two of the volcanic mounds appear as depressions on both time map and depth map, however these depressions are likely caused by decreased p-wave velocity through volcanic ash which increases two-way time and appears as a depression. On the vertical section, Buda limestone does not show any evidence of faulting with visible vertical displacement, however sudden dip changes occur throughout the survey. These dip changes are imaged by both time and depth map and have significant effects on seismic attributes. They also coincide with faults above Buda but with opposite displacement direction. Figure 14 shows a seismic section with typical Buda limestone structure. A fault seen in overlying formations shows throw down to the north, while the Buda exhibits a dip change that is up to the north. This unusual pattern can be recognized in many other areas of the survey and discussed in Results section of this thesis.

**Seismic attributes**

**Instantaneous attributes**

Instantaneous, or Hilbert, seismic attributes are calculated point-wise along an individual seismic trace and thus are termed simple-channel attributes (Liner, 2016) Examples include instantaneous amplitude, frequency, and phase. Hilbert attributes are often used to predict reservoir properties such as fluid type, saturation and porosity (Hardage, 2010). These attributes utilize the Hilbert transform to convert a real seismic trace into a complex seismic trace consisting of real and imaginary parts. Holman (2014) interpreted instantaneous amplitude attribute applied to Mississippian Limestone in Oklahoma and correlated low values to areas with increased porosity or “softer” lithology related to fractures developed on the footwall of a fault. Since Mississippian limestone is naturally fractured carbonate reservoir, and therefore a
possible analog for Buda Limestone, it is of interest to interpret the instantaneous amplitude attribute calculated on the Buda limestone horizon. Holman (2014) also studies an effect of instantaneous frequency variations along the Mississippian limestone and correlates lower frequency values to free gas or fault scattering. Figure 15 shows a time slice of instantaneous amplitude through the middle of Buda limestone where a similar pattern to Holman’s (2014) work can be recognized. Most of the low instantaneous amplitude values are associated with change in Buda’s dip. Values decrease rapidly (from 50 to 25) on lower side of a “step” feature and can be noted in many areas in the survey (figure 15).

**Variance (Coherency)**

The variance attribute is a multi-channel edge detection method which measures similarity of waveforms on adjacent traces over a specified window (Bahorich and Farmer, 1995). Variance is capable of imaging discontinuities in seismic data related to faulting or fracturing by evaluating local changes in seismic amplitude (Koson et al, 2014). A variance volume was created in Petrel with inline and crossline filter range (2x2) to capture smaller discontinuities such as faults that are not visible on the seismic. A dip correction algorithm was used to compute variance along a dipping plane when appropriate, instead of computing in horizontal direction only (Chopra and Marfurt, 2010). The resulting variance attribute extracted through middle of the Buda Limestone highlights dip change areas visible on seismic sections as well as on instantaneous attributes (Figure 16). Yellow areas around perimeter and data hole on the variance map of Figure 16 are edge effects unrelated to geology.
Volumetric Curvature

Curvature is structural attribute which measures the amount of deformation of the surface at a specific point. By combining such observations of structural deformation seen as flexures and folds with well control and other attributes, it is possible to predict areas favorable to natural fractures (Chopra and Marfurt, 2007). Roberts (2001) gives in depth description of the curvature attribute algorithm. In general, positive values of curvature relate to anticline features, while negative values represent a syncline form of the surface. Curvature involves second derivative calculations, which makes it sensitive to noise and acquisition artifacts (Barnes, 2016). Thus, it is common to condition the original amplitude volume to remove noise before computing curvature. Three types of noise reduction filters were used in this study: median filter (removes acquisition footprint), frequency filter (removes low frequency noise) and Gaussian filter (structurally smoothens the data).

Chopra and Marfurt (2011) compare conventional structural curvature with short and long wavelength amplitude curvature where they concluded that amplitude based curvature provides higher resolution and thus higher level of lineament detail. They also compared short wavelength and long wavelength curvatures and established that short wavelength curvature is suitable for identification of highly localized fracture systems while long wavelength curvature enhances subtle flexures that are difficult to see on seismic amplitude data but are often related to fracture zones below seismic resolution. The interest here is fracture characterization of the Buda Limestone which likely has localized fracture systems related to abrupt dip change, thus short wavelength curvature was chosen for interpretation. A high-resolution dip model was created using preconditioned amplitude volume and then used as an input to generate short wavelength most positive and most negative curvature volumes (Figures 17 and 18 respectively). High
negative and positive values establish correlation with zones highlighted by variance and instantaneous attributes and can be associated with faulting in formations above.

**Acoustic Impedance Inversion**

As early as 1979 it was established that seismic data could be inverted to estimate acoustic impedance (Lindseth, 1979) and this process was vastly improved through use of well sonic and density data. Early inversion techniques transformed the seismic data into P-impedance from which it was possible to make predictions about lithology and porosity. But these predictions were not reliable because P-impedance is sensitive to several factors including pore fluid, lithology, porosity; it is difficult to separate the influence of each. Interval transit time and bulk density required for calculating acoustic impedance (AI) are both available from the Holdsworth-Nelson well (see table 1). This well has both neutron porosity and acoustic porosity curves calculated on limestone matrix and do not require any correction because Buda Limestone is very clean and is not known to have interbedded shales.

The relationship between acoustic impedance (AI) and sonic porosity in Buda Formation was established by cross plot (figure 19) and a trend line fitted to the data establishing a linear relationship between sonic porosity and AI with 93.2% correlation to the equation shown on the figure. Neutron porosity and AI were then cross plotted (figure 20) showing 80.9% correlation between data points and a linear fit equation. Neutron and sonic porosity were also plotted against each other (figure 21) with an equality line added to the chart in order to show anomalies where acoustic porosity and neutron differ. It is expected for neutron porosity to read higher values than sonic because it measures total porosity versus sonic porosity which measures matrix porosity. However, in carbonates neutron porosity can read lower than sonic when there is a free gas present or interbedded shales. Buda limestone is not known to have interbedded shales; thus,
this factor is not considered here. In the Holdsworth Nelson well, sonic porosity reads higher than neutron 2 feet before contact with the Eagle Ford Shale and 2.5 feet before contact with the Del Rio shale. Higher sonic values are also observed in a 2 feet thick interval in the middle of the Buda Limestone, likely caused by free gas. With the relationship established between porosity and AI from well data, post stack impedance inversion of the Pedernales seismic volume was undertaken.

In Hampson-Russel (v.10), there are three types of post-stack acoustic impedance inversion algorithms: band limited, sparse-spike and model based. Russel and Hampson (1991) compared these three algorithms and concluded that model-based inversion produced the most detailed results when applied to real data. Thus, the model-based method was chosen for acoustic impedance inversion of the Pedernales 3D survey for this study.

The Hampson-Russel acoustic impedance inversion workflow (figure 22) starts with creating a project database where all future information will be stored. Seismic SEGY data was loaded by manual override of trace header geometry. The Holdsworth-Nelson well was then imported into HR along with a LAS file containing digital well logs required for acoustic impedance generation. The well is correlated with the seismic volume to optimize goodness of fit by extracting a statistical wavelet (figure 23) at the well location and a set of picked horizons was imported to guide the interpolation of the process. The initial acoustic impedance model was created and imported horizons displayed (figure 24). Model-based inversion algorithm attempts to modify the initial model until the resulting synthetic matches the seismic trace, thus high correlation numbers between synthetic and seismic traces are desirable (Quijada, 2009).

Following a HR post stack AI inversion workflow, inversion analysis was applied to determine optimum parameters. This resulted in 0.999417 correlation between synthetic and seismic traces.
Finally, model based AI inversion was performed on the entire 3D seismic area (figure 26) and the result exported into Petrel for further interpretation.

Buda limestone natural fractures are characterized by dividing Buda interval into three segments which are formally referred as upper, middle and lower accounting for acoustic impedance variations in Lower Eagle Ford. Relative to the Buda tracked seismic event, the Buda Limestone horizon is identified here with a 0ms time shift, so that the upper, middle and lower are represented by time shifts of -1ms, -5ms and -11ms (total Buda interval is 15ms duration). Figure 27 demonstrate acoustic impedance values extracted on sample values representing upper, middle and lower sections of the Buda Limestone. Acoustic impedance values tend to decrease in areas of Buda affected by folding or faulting which can be related to natural fractures associated with local structure. Lower Eagle Ford was also divided into three formal sections (top, middle and bottom) to extract acoustic impedance values and how they change with depth (figure 28).

While acoustic impedance provides a good insight on relative changes in density or p-wave velocity, which may be related to fracture intensity, sonic and neutron porosity can be used to estimate secondary porosity that relates to fractures or vugs. As, established earlier in this chapter, there is a linear relationship between acoustic impedance and both sonic and neutron porosity, thus acoustic impedance volume can be converted into a sonic or neutron porosity volume using the equations presented in figures 19 and 20. The resulting porosity volume can only be used to estimate sonic/neutron porosity within the Buda interval, because porosity logs were calculated on clean limestone matrix; a good lithology match with Buda, but not elsewhere in the section where other lithologies are present. To convert the acoustic impedance volume into
a sonic porosity volume, the equation in figure 19 was used. The resulting sonic porosity values are expected to have 93% accuracy according to regression analysis presented in figure 19.

Along with the relationship between sonic porosity and acoustic impedance, neutron porosity also has a strong linear relationship with acoustic impedance within the Buda interval. This relationship is represented by the equation in figure 20 \((R^2 = 0.8089)\) which means that volume of estimated neutron porosity values within the Buda Limestone have an accuracy of 80%. After the acoustic impedance volume was converted to sonic and neutron porosity volumes, it is possible to estimate secondary porosity. Secondary porosity can be calculated by subtracting sonic (matrix) porosity from neutron (total) porosity (Asquith and Krygowski, 2004). Subtraction of the two porosity volumes was performed using the Petrel calculator function for the upper, middle and bottom Buda. Figures 29, 30 and 31 provide a comparison between neutron, sonic and secondary porosities for upper, middle and bottom Buda Limestone.

After obtaining valuable information from physical and geometric seismic attributes, it is possible to combine those observations with acoustic impedance inversion, as well as secondary porosity maps generated from sonic/neutron porosity volumes. For instance, figure 32 is a combination of 6 different figures that were discussed earlier in this chapter, (A) variance attribute, (B) instantaneous amplitude, (C) acoustic Impedance, (D) most positive curvature, (E) most negative curvature and (F) secondary porosity. Outlined with red circles are two areas that exhibit similar pattern: variance rapidly increases, instantaneous amplitude and acoustic impedance values decrease, curvature becomes higher and secondary porosity is present. Increased variance values suggest that adjacent trace waveforms differ from each other in that specific area which can be sign of faults or fractures below seismic resolution. Instantaneous amplitude decreases from 54 to 22 (down 59%) and means that the reflection strength is
decreasing which is associated with a decrease in acoustic impedance contrast and possible
presence of open pores (Sarhan, 2017). Acoustic impedance is decreasing from 54,000 to 43,000
(down 20%) supporting the previous argument regarding decrease in density and presence of
porosity. Both most positive and most negative curvatures have increased values which means
that these areas are exhibiting structural deformation such as faulting or folding and can be
related to overall decrease in AI or presence of fractures. Quantitatively, the obtained secondary
porosity changes suggest an increase of secondary porosity in these structurally affected areas
from 0.5% to 1.1%.
CHAPTER 3:

RESULTS

Synthetic Seismogram

The final synthetic seismogram has very good visual fit in the formations of interest, but poor fit in upper formations. The poor fit between seismic and synthetic traces is likely due to poor surface coverage at the well location, which caused certain formations to lack the full fold. However, Lower Eagle Ford, Buda, Del Rio and George Town obtain the full fold and thus have better fit with the synthetic seismogram. Once interpreted, seismic event corresponding to Buda was tracked and resulted horizon was shifted up 3ms to correlate exactly with the well top. This process was repeated for the seismic event corresponding to Del Rio formation. The Buda horizon time varies from 934 ms in northwest corner, down to 1146 ms in southeast corner. Time structure map (figure 10) of top Buda reveals some of the structural features across the Buda horizon that may relate to faulting. On vertical amplitude section, Buda Limestone does not show vertical displacement anywhere in the survey, but it does not mean that there are no faults penetrating Buda. The vertical resolution within Buda Limestone is 128 ft while the thickness of Buda formation is 123.5 ft, this obviously introduces a challenge when interpreting seismic attributes.

After the time structure map of Buda limestone was established, it was converted from time domain to depth domain (figure 13). At the shallowest part of the survey, Buda reaches sub-sea depth of 5358 ft in northwest and 6545 ft in south east. Abrupt dip changes can be noticed in many parts of the survey and have 30-60 ft of elevation change according to the depth map. This
explains why there is no visible vertical displacement within the Buda on amplitude seismic data with time domain.

**Variance**

Variance attribute shown in figure 16, highlights areas of structural deformation with bright yellow colors. These areas can also be seen on time structure and depth maps of Buda (figures 10 and 13). Typical increase in variance values is 0 to 0.13 in structurally deformed areas. Figure 43 demonstrates vertical section of computed variance and amplitude cube with fault cutting through formations above Buda and downthrown side to the north, while Buda has downthrown side to the south but no visible vertical displacement. However, variance attribute values increase from 0 to 0.06 at that particular spot where Buda deforms and these increased values are present in formations above and below Buda suggesting continuity. Ferrill and Morris, 2008 described in depth fault behavior of Buda limestone and concluded that typical Buda faults are vertical with 33 ft of vertical displacement on average. This is significantly below the resolution of seismic data used in this thesis, however Ogiesoba, 2014 faced the same challenge and outlined faults within Buda based on variance attribute and its continuity in vertical section. Same pattern can be noticed in the Pedernales 3D survey (figure 33). Continuous dark to bright yellow colors suggest a presence of a fault. Bright yellow colors outline faults with visible vertical displacement or stratigraphic discontinuity while dark colors suggest sub seismic faults such as vertical Buda faults. Another good example of this pattern is presented in figure 34 where there is a small fault in upper formations with downthrown side to the north. It shows up well on variance attribute as continuous stripe of bright yellow color corresponding to high variance values of 0.8 while variance values in the Buda reach a value of 0.2.
Volumetric Curvature

Increased values in short wavelength curvature tend to increase in areas with higher variance values suggesting presence of structural deformation or faulting. Values of most positive and most negative curvatures range between 0 in flat regions and up to 0.0004 in deformed areas of Buda Limestone. Figure 35 and 36 are reproduction of figures 33 and 34 but with most positive curvature instead of variance. Same pattern is present where curvature increases up to 0.002 in faulted areas above Buda and to 0.0015 within the Buda. These escalated curvature values within the Buda are continuous through formations below and are 90 degrees of dip. According to DUG Handbook (2017), maximum curvature highlights the biggest changes in dip and can be used as a good fault indicator by examining sharp, continuous changes from positive to negative curvature. Figure 37 displays such changes in Pedernales 3D survey. Left part of the figure represents cross sectional view of maximum curvature and two faults outlined by red and blue lines. Red lines indicate positive curvature which relates to the upthrown block and blue color corresponds to negative curvature which indicates downthrown side of the block. To demonstrate the relationship between faulting and secondary porosity, maximum curvature and secondary porosity maps were overlaid with 50% transparency to produce figure 38. Higher secondary porosity values can be observed in areas of faulting on downthrown side of the block.

Instantaneous Amplitude

The instantaneous amplitude values range between 25 and 55 throughout the survey, however nearly all lower values can only be observed in areas of faulting on downthrows side of the blocks. These areas of faulting are highlighted by curvature and variance attributes which are shown in figures 33-36. Instantaneous amplitude values follow the pattern and decrease from 55
to 25 on downthrown side of the block. This is only possible if downthrown side of the block is more fractured than surrounding rock, therefore has “softer” lithology.

**Acoustic Impedance Inversion**

Acoustic impedance values range from 40,000 to 56,000 ft/s\(\cdot\)g/cm\(^3\) throughout the survey. Lower values are mostly concentrated around areas of structural deformation or faults, particularly on the downthrown side of the block where they can range from 56,000 on footwall to 40,000 ft/s\(\cdot\)g/cm\(^3\) on the hanging wall. Lower acoustic impedance values on downthrown side of the block can be explained by more intense fracturing associated with stresses caused by the block movement. Increased amount of fractures concentrated within a zone can lower the overall density of that zone because of open spaces within the rock. Figure 39 displays variance overlaid by acoustic impedance at -5ms from the top of the Buda. Acoustic impedance on the footwall of the fault A has values of 55,000 ft/s\(\cdot\)g/cm\(^3\) while hanging wall acoustic impedance drops down to 45,000 ft/s\(\cdot\)g/cm\(^3\). This transition in acoustic impedance occurs as the variance values increase.

Porosity values can be estimated using the equation established in Chapter II Methods. Using this equation, sonic and neutron porosity were predicted across the Buda limestone. As expected, porosity values increase on the downthrown side of the block and follow a general trend of acoustic impedance. Because Buda formation is a clean limestone without interbedded shales and both porosity logs were ran on limestone matrix, sonic porosity can be subtracted from neutron porosity without any correction and yield secondary porosity. Secondary porosity has been calculated using Petrel calculator and displayed on figures 29, 30 and 31. Secondary porosity increases greatly on downthrown side of the block up to 1.3% through the middle of the Buda, while typical values for secondary porosity are less than 0.2%.
Figure 40 displays acoustic impedance on vertical section at the fault A without interpolation to demonstrate the effect of faulting on acoustic impedance. Time sample rate of Pedernales 3D survey is 4ms while Buda limestone is 15ms thick on average, this suggests that Buda is represented by 4 blocks, however the most upper and lower blocks of acoustic impedance have very low values across the whole Buda surface. This is likely due to the most upper and lower blocks capturing acoustic impedance from Eagle Ford and Del Rio formations. Going from footwall (north-west) to hanging wall (south-east) acoustic impedance values change from 54900 ft/s*g/cm$^3$ down to 47200 ft/s*g/cm$^3$ while secondary porosity increases from 0.67% to 1.02% (0.35% increase). Fault B (figure 41) exhibits similar pattern, going from footwall (north) to hanging wall (south) values of acoustic impedance decrease from 50,991 ft/s*g/cm$^3$ to 43,200 ft/s*g/cm$^3$ and secondary porosity increases from 0.8% to 1.15%.
CHAPTER 4:  

CONCLUSIONS

Conclusions

By studying post stack physical and geometric seismic attributes it was possible to correlate structural behavior of Buda Limestone with associated lithology and predict areas with higher fracture intensity. Geometric attributes such as coherency and curvature revealed sub seismic faults penetrating Buda Limestone that are not visible on amplitude seismic, while physical attributes such as instantaneous amplitude provided information about lithology. Acoustic impedance inversion has showed that these areas of interest have lower acoustic impedance on downthrown side of the block which suggests a decrease in overall density due to more intense fracturing. In the faulted areas, instantaneous amplitude drops from 55 to 25 suggesting a “softer” lithology. Available sonic and neutron porosity logs from Holdsworth-Nelson well, have been upscaled to the entire Buda limestone surface by establishing a linear relationship with acoustic impedance in the Holdsworth-nelson well. Resulted sonic porosity map was subtracted from neutron porosity yielding secondary porosity values. In case with Buda limestone, secondary porosity is associated with fractures and increased porosity can be observed on downthrown side of faults penetrating Buda. Secondary porosity increases by 0.3-0.4% on downthrown side of the block compared to upthrown block.

Commercial oil production from Buda limestone is possible by targeting naturally fractured zones and identifying those can be a major challenge. To reliably identify these zones prestack or wide azimuth seismic data is usually used, however these methods are more expensive and small to mid-size exploration companies often prefer to use post stack seismic
data for this task. The workflow presented in this thesis demonstrates that it is possible to predict areas of possible fracture development by utilizing post stack seismic data.

**Suggestions for future work**

Pedernales 3D survey contains a number of faults that don’t show any vertical displacement especially in tight carbonate formations such as Buda and Georgetown. There are many techniques that result in resolution improvement in post stack seismic data: from frequency filtering to spectral decomposition and it would be of interest to examine is it is possible to develop a workflow to improve vertical resolution and resolve those sub seismic faults.

Studying Eagle Ford shale communication with Buda Limestone would be another interesting topic. Hydrocarbons from Eagle Ford shale may migrate into highly fractured areas of Buda Limestone, so calculating TOC content of Eagle Ford shale would be crucial for better understanding Buda – Eagle Ford play.

Pearsall Shale formation that is found below Buda at depth 7,000 to 12,000 feet and thickness of 600 to 900 feet is known to be a gas bearing formation in Maverick Basin area and many energy companies are planning to develop it over the next years. According to Drilling Info, some wells on the border of Zavala and Dimmit Counties are producing 40,000 Mcf of natural gas monthly out of Pearsall Shale since 2013.

**Acknowledgements**

I would like to thank Christopher Liner, Robert Liner and Steve Milligan for being my committee and guiding me through the thesis. Without them this would not be possible. Big thanks to Stephens Production Company for donating 3D seismic and well data. I
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Tables and Figures

Table 1. Holdsworth-Nelson well information

<table>
<thead>
<tr>
<th>Location (TX83-SCF SIS,502274)</th>
<th>X: 1790944, Y: 355383</th>
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<tbody>
<tr>
<td>Kelly Bushing</td>
<td>684ft</td>
</tr>
<tr>
<td>Uniform Well Identifier (UWI)</td>
<td>42-507-32756</td>
</tr>
<tr>
<td>True Vertical Depth (TVD)</td>
<td>6390ft</td>
</tr>
<tr>
<td>Top Buda Limestone (MD)</td>
<td>5873ft</td>
</tr>
<tr>
<td>Base Buda Limestone (MD)</td>
<td>5997ft</td>
</tr>
<tr>
<td>Logged Sonic Interval (MD)</td>
<td>2551.5 ft – 6348 ft</td>
</tr>
<tr>
<td>Logged Density Interval (MD)</td>
<td>2523 ft – 6328.5 ft</td>
</tr>
</tbody>
</table>
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Buda Limestone Acoustic Impedance (ft/s*g/cm³)

Top (-3ms)  Middle (-7ms)  Bottom (-10ms)

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