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Evaluation of the depositional environment of the Eagle Ford Formation using well log, seismic, and core data in the Hawkville Trough, LaSalle and McMullen counties, south Texas

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EVALUATION OF THE DEPOSITIONAL ENVIRONMENT OF THE EAGLE FORD FORMATION USING WELL LOG, SEISMIC, AND CORE DATA IN THE HAWKVILLE TROUGH, LASALLE AND MCMULLEN COUNTIES, SOUTH TEXAS

A Thesis

Submitted to the Graduate Faculty of the
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Zachary Paul Hendershott
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ABSTRACT

The Upper Cretaceous Eagle Ford Formation of South Texas records a mixed siliciclastic/carbonate depositional environment across the Late Cretaceous Platform of the Gulf of Mexico. During the Late Cretaceous, LaSalle and McMullen Counties was part of the Hawkville Trough, a wedged shaped region between the Edwards and Sligo carbonate reefs. Well logs from 21 wells and seismic data were used to construct structure and isopach maps of the Eagle Ford Formation throughout the Hawkville Trough. Only the unconformable bottom (Buda-Eagle Ford) and top (Eagle Ford-Austin Chalk) boundaries plus the conformable boundary between the upper and lower Eagle Ford can be consistently correlated in the area. The Eagle Ford-Austin Chalk boundary is variable/gradational due to variable erosion of the Eagle Ford prior to deposition of the Austin Chalk. This variability is also observed in core data. The Lower and Upper Eagle Ford are trough shaped deposits that strike northeast roughly parallel with the Edwards reef. Maximum thickness of the Lower Eagle Ford is more than 180 ft in LaSalle County and 140 ft in McMullen County. The Upper Eagle Ford has a maximum thickness of 160 ft along the LaSalle-McMullen County Border. Both the Lower and Upper Eagle Ford thin to half their maximum thickness within 5-6 miles of the axis. Depth to the top of the Eagle Ford varies from 9600 ft to 15000 ft and strikes parallel to the Edwards and Sligo reefs. Numerous faults are visible. Most faults are post-depositional with modest offsets. Few faults are syn-depositional growth faults and the Eagle Ford is thicker on the down thrown side. Well and seismic data document dramatic decreases in thickness of the Upper Eagle Ford over a few miles. In the most extreme case in southwest LaSalle County, the Upper Eagle Ford is entirely missing in 2 wells and has been replaced by a sand unit not previously reported. A seismic cross section, or time slice, just above the top of the Eagle Ford
shows a channel structure running west to east along southern LaSalle County. This channel is likely the cause of observed erosion and sand deposition.
INTRODUCTION

The Eagle Ford Formation is an Upper Cretaceous organic-rich calcareous-rich mudstone that occupies a northeast-southwest band across South Texas (Figure 1). The Eagle Ford Formation is an unconventional shale oil and gas play and is stratigraphically variable in terms of thickness, organic content, and composition (Lock et al, 2010). Although the Eagle Ford Formation has been extensively drilled for oil and gas production, the regional depositional and diagenetic history are still poorly understood. In particular, the Hawkville Trough in LaSalle and McMullen Counties contains a stratigraphically variable section of the Eagle Ford Formation ranging in thickness from 50-317 feet (this study). A notable difference in the Eagle Ford within the Hawkville Trough is that the Turonian portion of the section is incomplete or in some cores completely missing (Figure 2). The presence of only the Cenomanian aged section of the Eagle Ford is unique to the Hawkville Trough and is beneficial to the reservoir due to the overlying Austin Chalk and Anacacho formations having a high clay content, low resistivity, and high ductility that creates an effective seal for the Eagle Ford. The upper unconformity acts as an effective top seal due to an absence of extensive natural fracturing, allowing a successful trap for hydrocarbons.

In the fall of 2008, Petrohawk Energy Corporation acquired the first acreage specifically targeting the Eagle Ford Formation. Only a few pilot holes had been drilled in the area through the Eagle Ford, but were targeting the Edwards Limestone or Austin Chalk. That first year there were only 3 wells permitted and drilled targeting the Eagle Ford Formation in South Texas (DrillingInfo, 2012). Four years later, there are over 120 pilot holes over 24 counties, and just under 6000 horizontal wells drilled, making it one of the most active fields in the United States (DrillingInfo, 2012).
Figure 1: Map of the regional extent of the Eagle Ford Shale in Texas. The Hawkville Trough (black box) lies between the Edwards and Sligo reef margins (modified from Hentz and Ruppel, 2010).
Figure 2: Stratigraphic column specific to study area, showing the Eagle Ford Formation unconformably bound by Austin Chalk (above) and Buda Limestone (below). Thick wave lines indicate hiatuses that are not well constrained in the subsurface (See Donovan and Staerker, 2010)
Recent studies have focused on defining a lithostratigraphic framework for the Eagle Ford Formation by separating it into a number of depositional parasequences (e.g., Lock et al., 2010; Donovan and Staerker, 2010; Hentz and Ruppel, 2010; Adams and Carr, 2010) (Figure 3). Lock (2010) used subsurface data from the Hawkville Trough to conclude that the unstable slope sediments making up the lower member identified in outcrop are absent because they are a localized facies confined to the marginal slope. Donovan and Staerker (2010) evaluated the same outcrop in Lozier Canyon along with subsurface data within the study area and referred to it as the Rio Grande Submarine Plateau. They proposed that this submarine plateau consisted of submerged portions of the (older) Sligo Platform between the Edwards and Sligo margins that formed a physiographic bench on the inner portions of the continental slope (Donovan and Staerker, 2010). Donovan and Staerker’s (2010) work correlated multiple parasequence packages from outcrop to subsurface, and noted that it is generally accepted to separate the subsurface into upper and lower members according to work done by Grabowski (1995). Finally, Donovan and Staerker (2010) further cited an additional (Langtry) member as a transition from upper Eagle Ford to Austin Chalk lithologies. The Langtry member is a 40-90 ft thick depositional sequence that records a subtle upward gradation from the underlying Eagle Ford to the overlying Austin Chalk (Donovan and Staerker, 2010). The correlations by Grabowski identify the division between the upper and lower Eagle Ford as the division between the Cenomanian and Turonian sections.

This study uses gamma ray, resistivity, and density logs from twenty-one wells that penetrate the entire stratigraphic section of the Eagle Ford across the Hawkville Trough in LaSalle and McMullen Counties to map variations in thickness and preservation of the Eagle Ford.
Ford. Core photos are used to identify the nature of the log response along the bounding unconformities.

Figure 3: Summary of previous studies of the Eagle Ford Formation in outcrop and in the subsurface (from Donovan and Staerker, 2010).

An amplitude map made from a 3D seismic cross section is used to show an erosional feature affecting total thickness along the upper Eagle Ford/Austin Chalk boundary. Additionally, this amplitude map and other seismic cross sections show a complex network of faults spanning the entire study area.
GEOLOGIC BACKGROUND / STUDY AREA

The Eagle Ford Formation in southwest Texas records an Upper Cretaceous (Cenomanian to Turonian) mixed siliciclastic/carbonate depositional system. The Eagle Ford Formation was deposited during a transgressive cycle in a shallow epeiric seaway that covered the southern margin of North America (e.g., Liro and Dawson, 1994). Across the Cretaceous Platform, the Eagle Ford Formation trends from southwest to northeast roughly subparallel to the present day strike of the Gulf Coast. The Eagle Ford Formation crops out along a broad band extending from El Paso, Texas, eastward to San Antonio, Texas, where it then follows the margin of the East Texas Basin northward to the Oklahoma State line (Figure 1)(e.g., Liro and Dawson, 1994). The Eagle Ford Formation in south Texas dips south-southeast towards the Gulf of Mexico (Martin, 2011). The Eagle Ford Formation is correlative to the Boquillas Formation in the Maverick Basin, northwest Texas, and the Tuscaloosa Formation in Louisiana and Mississippi (Lock and Peschier, 2006).

The youngest and easternmost deformation of the Laramide Orogeny (post Eagle Ford deposition) was a structural influence on the Cretaceous Platform (e.g., Scott, 2010). During a transgressive cycle in the Cenomanian to late Turonian, the Sabine Uplift, located east of the study area (Figure 4), was a positive salient feature and the Ouachita Mountain chain, to the north, was a primary siliciclastic sedimentary source (Scott, 2010). Sediments were also shed into the Maverick Basin from the northwest Western Interior Seaway and then into the restricted basin of the Hawkville Trough (Figure 4). The Eagle Ford Formation and the stratigraphic units above were heavily influenced by basement faults and basin topography. Late Cretaceous sediments display thickness variations across the area. This suggests that
basement control plays a major role in the depositional and post-depositional accommodation patterns for all these units (Donovan and Staerker, 2010).

Figure 4: Paleogeographic map of the Gulf Coast region during the Late Cenomanian showing the major topographic features and relative distance from sediment sources (Image modified from Bailey [2007] by Salvador [1991], Sageman & Arthur [1994], and Donovan and Staerker [2010]).

In ascending order, the major lithostratigraphic units across the Upper Cretaceous Platform are the Del Rio, Buda, Eagle Ford, and Austin Chalk (Figure 2). Within the Hawkville Trough, the Eagle Ford is unconformably bound by the overlying Austin Chalk and the underlying early Cenomanian Buda Formation (Figure 2). The Eagle Ford Formation was
deposited during a global transgression and highstand of sea level following the Middle Cretaceous Unconformity at 96 Ma (MCU of Winker and Buffler, 1988) in the Gulf of Mexico Basin (Haq et al., 1988; Jiang, 1989). The preceding lowstand is represented by the underlying carbonate horizon, the Buda limestone (e.g., Treadgold, 2010). The internal carbonate marker of the Eagle Ford Formation, the Kamp Ranch Member, is the stratigraphic marker between the upper and lower Eagle Ford in the region (e.g., Donovan, 2010). The Kamp Ranch Member separates the lower, organic rich shale member from the upper more calcareous member. The Coniacian to Santonian Austin Chalk stratigraphically overlies the Eagle Ford with a major unconformity separating the two formations. Donovan and Staerker (2010) place the K69 Maximum Flooding Surface (MFS) as a possible contact between the Austin Chalk and the top of the Eagle Ford Formation, citing a transition zone reaching 40 feet thick in the subsurface (also called the Langtry Member)(Donovan and Staerker, 2010). In some wells the contact is abrupt, and others it is more gradational, thus making it difficult to resolve. For this study there is particular interest in the upper contact between the Eagle Ford and the Austin Chalk because of fluctuating amounts of missing section. A drop in base level and subsequent subaerial exposure, as well as channel incision post Eagle Ford deposition is the main source of missing section along this surface, and will be discussed in greater detail below (Scott, 2009).

Regional lithofacies patterns and fossil assemblages indicate a marginal to open marginal marine depositional environment for the Eagle Ford Formation (Passagno, 1969; Surles, 1987). These studies conclude that southwestward prograding deltas supplied bioclastic-siliciclastic sediments near and below storm wave-base (Dawson and Almon, 2010). Sediments deposited on the shallow shelf represent the proximal deltaic facies; sediments
deposited further south and southwest are interpreted as the distal deltaic facies basinward of the shallow shelf (Figure 4).

Mudstones in the Eagle Ford Formation vary from slightly to very silty, calcareous, phosphatic, pyritic, glauconitic, bentonitic and carbonaceous facies, ranging from massive to well-laminated and slightly to abundantly fossiliferous (Dawson and Almon, 2010). Six microfacies were identified by Dawson (2000) in a core sample from LaSalle County within the study area: 1) pyritic shales; 2) phosphatic shales; 3) bentonitic shales; 4) fossiliferous shales; 5) silty (quartzose) shales; and 6) bituminous claystone and shales. The transgressive (lower) Eagle Ford shales consisted of microfacies 1, 4, and 6; the condensed interval consisted of 1, 2, and 3, and highstand (upper) Eagle Ford microfacies exhibit microfacies 4 and 5 (Dawson, 2000). Core images illustrate the nature of the upper and lower Eagle Ford (Figure 5). Black, thinly laminated shales dominate the Lower Eagle Ford, and the upper Eagle Ford contains more abundant calcareous and mixed siliciclastic (quartzose) beds (light-gray). Upward-finising trend dominates the lower member as gamma ray decreases, while upward-coarsening trend characterizes the upper member with gamma values increasing (Dawson, 2000). The lower Eagle Ford is characterized by high gamma-ray values (90 to 135 API units) and an upward-coarsening trend (Figure 5). The lower member is dominated by dark, well-laminated organic-rich shale (Figure 5) with subordinate light-gray calcareous mudstone, marl, and traceable amounts of limestone (i.e., Hentz and Ruppel, 2010). There is a condensed section, representing a period of sediment starvation during a maximum flooding event separating the transgressive and early highstand systems tracts (Loutit et al., 1988). This condensed section occurs between the upper and lower Eagle Ford Formation and tends to fluctuate in thickness across the regional extent of the Eagle Ford (Donovan and Staerker, 2010). The condensed
interval developed during cycle 2.5 of the Upper Zuni A-2 (UZA-2) supercycle (Haq et al., 1988; Ulicny et al., 1993). The upper Eagle Ford Formation, interpreted as part of the highstand systems tract, is characterized by generally low gamma-ray values (45 to 75 API units) and an upward-finining trend. The upper member consists of interbedded dark- and light-gray mudstones as well as thinly stratified shale, limestone, and carbonaceous quartzose siltstone (Figure 6; Hentz and Ruppel, 2010).

Figure 5: “Core” type log from McMullen County, Texas (McM-1). From left-right curves present are gamma ray, resistivity, and density porosity. Core image is from the same well, and used to highlight nature of the contact between upper and lower Eagle Ford (Petrohawk Energy, 2009).
The Late Cenomanian-Early Turonian is marked by a major anoxic extinction event (Fan et al., 2011). This boundary is characterized by a worldwide deposition of hydrocarbon-rich shale lithofacies like the Eagle Ford Formation. Other notable occurrences of organic-rich Cretaceous shale deposits include the Mowry and Pierre Shales of the Western Interior Seaway and mudstone-rich formations in Morocco, Venezuela, Tunisia, Nigeria, Western Australia, and the Polish Carpathians (Jenkyns, 2010; Hallam, 1987). Warm, shallow seas were prevalent during this global greenhouse event. The greenhouse effect caused a significant increase in CO₂ levels and thus organic productivity. Regressive periods, or periods of relative sea level fall, turned the Hawkville Trough into a restricted basin (Figure 6). The organic productivity continued until sediment and oxygen supply was depleted, resulting in an anoxic environment, which in turn preserved the organic material (Martin and Baihly, 2011).

The deep (200-400 ft) and restricted setting of the Hawkville Trough as well as cyclic sediment influx allowed for an anomalously thick section of organic rich material to accumulate between the Edwards and Sligo Reef margins (Figure 6)(Lock, 2010). The Edwards and Sligo reef complexes were formed during periods of rapid sea level transgression. Subsequent regressive periods resulted in anoxic conditions in the restricted basins due to a lack of nutrient-rich sediment supply (Figure 6). The lower section of the Eagle Ford Formation has a higher total organic carbon (TOC) value as a result of high organic productivity. Following an increase of sediment influx there were subsequent periods of hypoxia, or times of local dysoxic (oxygen-poor) conditions (Adams and Carr, 2010). Generally, this describes periods of partially oxygenated water. As a result there was water column stratification and depletion of oxygen below the pycnocline. The pycnocline describes the boundary separating changes in density (in this case salinity) between two liquid “layers”. The depletion of oxygen below this boundary
allows for the organic matter to be preserved at the bottom of the basin. A cyclic depositional model in these conditions can be used to illustrate the thick and organic-rich section of Eagle Ford: 1) relative sea level rise, 2) terrigenous sediment influx, 3) organic productivity, 4) organic sedimentation, 5) relative sea level fall, 6) local dysoxic and subsequent anoxic environment, and 7) organic preservation (personal communication with Scotty Tuttle-Petrohawk Geologist, 2011). The Upper Eagle Ford is more carbonate rich, implying a shelf/slope depositional setting. The Upper member displays a progradational log pattern of fining upward (Figure 5). This unit has lower TOC values across the area and represents the mid to inner-shelf deposits with highly laminated carbonate-rich marls and skeletal limestones. The lower TOC of the upper member corresponds to more proximal facies with higher energy, less productivity, and more interaction with the bottom of the ocean (rip-up clasts).

Figure 6: Schematic cross-section from northwest Texas through the Hawkville Trough depicting estimated approximate water depth during Eagle Ford deposition. A-A’ from figure 3 modified from Donovan and Staerker, 2010.
METHODS

Gamma ray, resistivity, and density log curves were used to evaluate the thickness variation in the Eagle Ford Formation in the Hawkville Trough. Twenty-one wells spanning 72 miles across LaSalle and McMullen counties, Texas, were used to understand the Cenomanian depositional environment in the study area (Figure 7). These wells vertically penetrated the entire section of the Eagle Ford Formation into the underlying Buda Formation. Most horizontal wells were excluded because of an incomplete vertical stratigraphic succession through the Eagle Ford section. Wells with bottom hole locations used in this study were drilled into the Buda and corrected to TVD by using known bed dips, length of lateral, and penetration points in order to calculate the true stratigraphic thickness (TST). Formation tops were principally interpreted using the gamma ray log; however, resistivity and density-porosity curves were used to support correlation of wells in close proximity to one another. Isopach maps were generated by log data compiled to show the shape of the total section, as well as upper and lower Eagle Ford. Due to proprietary obligations, the wells were listed by county (LaS = LaSalle; McM = McMullen), and numbered increasing from West to East per request of Petrohawk Energy.
Figure 7: Map of studied wells in the Hawkville Trough in LaSalle and McMullen Counties, TX. Well names are posted (LaS - LaSalle wells; McM- McMullen Wells). LaS-4 and McM-1 are the type logs for the area. Regional, strike, and dip oriented cross section lines are provided. Those wells with a bottom hole location (labeled horizontal above) were drilled vertically into the Buda Limestone and corrected for true vertical depth (TVD) (Image created in SMT).
FORMATIONS AND UNIT DISTINCTIONS

The marker at the top of the Eagle Ford Formation is characterized by a distinct, high gamma ray response (120-145 API) and sharp increase in resistivity (from 1-3 ohms to 10-15 ohms) immediately below the base of the Austin Chalk Formation (~76 API)(Figure 8). The Austin Chalk lies unconformably above the lower section of the Eagle Ford Formation in the Hawkville Trough. As a whole, the upper section of the Eagle Ford is represented by a generally lower (45-75 API) gamma ray response (Figure 8). An examination of the Langtry Member, as described by Donovan and Staerker (2010) as a distinctly different stratigraphic unit between the Eagle Ford and Austin Chalk, was explored in well logs in the study area and remains indistinguishable.

The upper and lower units are divided by the K72 sequence boundary (Donovan and Staerker, 2010). This division is noted by a significant increase in the gamma ray response, and a decrease in resistivity. The lower Eagle Ford has a higher (90-135 API) gamma response (Figure 8). This unit ranges from 72-186 feet thick and is dominated by interbedded marls and limestones. These unit distinctions, tops, and bases rely primarily on pattern recognition in the well logs. Images of core from a well in the Hawkville Trough are used to demonstrate the nature of unit change, the unconformable contacts at the top and base of the Eagle Ford, and to explore a possible correlation to log signatures (Figure 8 and 9). These images can be used to either support or disprove the nature of the unconformable contacts and are also used for visual inspection internal unit distinctions. An attempt was made to identify and correlate additional internal units based on log response to corroborate with outcrop studies done by Donovan and Staerker (2010) and Lock and Peschier (2010).
Figure 8: LaS-4 type log from LaSalle County, Texas. From left to right the most important log curves to this study were the gamma ray, resistivity, and density-porosity curves (color of scale bar indicates color of curve used).
Figure 9: Core Image from McM-1 displays the nature of the abrupt contact between the Austin Chalk and Eagle Ford formations. Skeletal lag and rip up clasts are common features along this contact (Image courtesy of Petrohawk Energy Eagle Ford Consortium).

Cross sections based on gamma ray tops through the Hawkville Trough were constructed to highlight the thickness variations in both strike (northeast-southwest) and dip orientation (southeast). Logs analyses were done with the IHS - PETRA software package. PETRA is an integrated application with a common database and interface for project and data management; well log analysis, mapping, cross-sections, seismic integration, production and reservoir analysis, and 3D visualization.
Spatial analysis of three-dimensional (3D) seismic data across the Hawkville trough demonstrates the stratigraphic and structural aspects affecting section thickness variations. Seismic horizons, interpreted by geophysicists at Petrohawk Energy Corporation, were used to evaluate the relationships between log depths and their equivalent time-depth relationships. Formation markers picked from wireline logs were correlated to a time-equivalent horizon by making time-depth charts using average velocities to the top of the Eagle Ford Formation. Seismic lines oriented in strike and dip direction of the Eagle Ford Formation were generated. These lines highlight the erosional and structural attributes immediately above and below the Eagle Ford Formation effecting thickness variation. An amplitude map of a horizon directly above the Eagle Ford Formation was generated from 3D seismic. This was used to support observations made in 3D seismic, as well as well log data in southwest LaSalle County. Due to proprietary obligations, exact locations of 3D seismic lines are withheld, and only general geographic orientation and scales within the county are described.
RESULTS

WELL LOG

Gamma Ray, resistivity, and density-porosity logs were used to identify three important stratigraphic markers. The most regionally consistent marker for the Eagle Ford Formation is the basal unconformity between the Eagle Ford Formation and the underlying Buda Limestone. The transition between the Eagle Ford and Buda Limestone is indicated by abrupt changes in rock properties, which made this surface easily correlatable across the region. The calcium carbonate percentage goes from 15-25% (EFS) to 90% (Buda), gamma ray values drop from 125-130 API (EFS) to less than 15 API (Buda), resistivity increases from less than 10 (EFS) to over 50 Ohms (Buda), and the density-porosity values drops from 10-15% (EFS) to less than 5% (Buda).

The conformable contact between the lower and the upper members of the Eagle Ford Formation is reliably based on a drastic increase in the gamma ray (120-140 API) (Figure 8). Across the Hawkville trough, this marker is one of the few that can be consistently correlated. The character of the gamma increase differs from well to well, but occurs roughly in the middle of the formation. The resistivity and density-porosity logs proved less helpful for correlation purposes because of the variation of fluids present and porosity values. There was no distinct change in formation resistivity and porosity between the upper and lower units.

The top of Eagle Ford is the third correlative marker across the Hawkville trough that can be recognized with confidence based on gamma ray and resistivity response. However, the section at the top of the Eagle Ford was removed post-deposition in parts of the field, causing some uncertainty. Donovan and Staerker (2010) identified a transitional unit (Langtry Member) above the Eagle Ford that was not consistently identified within the study area.
Instead, this transitional unit was categorized as the Upper Eagle Ford. The transition from the overlying Austin Chalk and Eagle Ford is variably expressed in log analysis. However, the gamma ray-signature is usually a notable increase, whether abrupt or gradational, with API values respectively increasing from 50-75 API to 120-135 API from Upper Eagle Ford to Austin Chalk, respectively (Figure 5 and 8).

The Hawkville Trough in LaSalle and McMullen County contains an unusually thick section of the Eagle Ford Formation situated between the Edwards and Sligo reef margins. The total Eagle Ford interval thins to the north of the Edwards reef, south of the Sligo Reef, and to the east in Bee County. However, thickness across the 72-mile long trough varies greatly over short lateral distances. Based solely on true vertical depth (TVD) well data, the total Eagle Ford thickness varies by 245’ feet (72’-317’; LaS-12-LaS-7, respectively). From LaS-9 to LaS-10 (4.4 Mi) the Eagle Ford Formation thins from 289 ft to 82 ft and contains no upper section (Figure 10).

Based on TVD well data by county, LaSalle County contains the thickest Eagle Ford section for all mapped horizons (Figures 11-13). Well data for the Eagle Ford Formation indicates that the thickest and thinnest sections are present in LaSalle County, with the thickest total section (317’; LaS-7)(Figure 11), thinnest total section (72’; LaS-12), and thickest/thinnest upper and lower sections (Table 1)(Figure 11). The total Eagle Ford Section thins to northeast into McMullen County. A structure map based off of tops gathered from well data of the Eagle Ford shows a southeasterly dip direction (Figure 14). Strike and dip oriented cross sections, as well as a regional cross section across the Hawkville Trough highlight those variations in separate units, as well as overall thickness (Figures 15-19).
Figure 10: N-S well log correlation from LaS-10 to LaS-9 (4.4 mi) illustrating that the upper Eagle Ford member is eroded out completely in LaS-9. The red line is the interface between the upper and lower Eagle Ford members. A sand body, not found anywhere else in Hawkville Trough, is found above the Eagle Ford Formation in LaS-9.
The Upper Eagle Ford (UEF) is a trough-shaped deposit that strikes northeast roughly parallel with the Edwards reef. The axis of the trough is closer to the Edwards Reef than the Sligo Reef. The UEF reaches a maximum thickness of 153 ft in LaS-6 near the LaSalle-McMullen border (Table 1). In southeast LaSalle County, the UEF has been eroded away completely in LaS-9 and LaS-12, and replaced by a sand body not previously observed in the study area (Figure 10 and Table 1). The sand body is clearly recognized in log response by a 20-45 API gamma response and 2-4 ohm resistivity, and will be discussed further in the discussion section (Booth et al., 2003).

The UEF thins rapidly to roughly half its maximum thickness moving away from the axis (Figure 12). Northward of the axis, the UEF thins approaching the Edwards Reef from LaS-4 to LaS-3 (144 ft to 74 ft, respectively) (Table 1; Figure 16). There is also thinning to the northeast in McMullen County (Figure 11).

Similar to the UEF, the Lower Eagle Ford (LEF) is a trough-shaped deposit that strikes northeast roughly parallel with the Edwards Reef (Figure 13). The axis is closer to the Edwards reef than the Sligo Reef. It reaches its maximum thickness in LaS-1 at 159 ft (Table 1). The LEF’s thinnest section is seen in LaS-12, where the UEF is removed. Thinning is drastic as you move away from the center of the axis. This thinning is due to a combination of erosion along the upper boundary, as well as additional accommodation associated with growth faults. The LEF section is not disturbed by the Edwards Reef margin with respect to the UEF, but thinning can be seen from LaS-4 to LaS-3 (124 ft and 93 ft, respectively) affecting the UEF (Table 1; Figure 16).
Table 1: TVD well data compiled from 21 wells in the Hawkville Trough. Wells with “LaS” names are from LaSalle County, and “McM” are from McMullen County. Well numbers increase from west to east by county.

<table>
<thead>
<tr>
<th>Name</th>
<th>Top EFS (TVD)</th>
<th>Middle Marker (TVD)</th>
<th>Thickness Upper</th>
<th>Top Buda</th>
<th>Thickness Lower</th>
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Figure 11: Isopach map of entire Eagle Ford Formation observed in the Hawkville Trough. The entire section is trough shaped with an axis roughly parallel to bedding strike, and shows drastic thinning within 5-6 miles of the axis. Seismic data was used to fill in areas between known values from Table 1 (Hand contoured in SMT).
Figure 12: Isopach map of the upper Eagle Ford Formation as seen in the Hawkville Trough. Values are based primarily from well data, and seismic was also used to fill in gaps between wells with known values. Note that the upper Eagle Ford Formation is absent in 2 southern LaSalle County wells (Hand-contoured in SMT).
Figure 13: Isopach map of the Lower Eagle Ford in the Hawkville Trough. Values are based primarily from well data, and seismic was also used to fill in gaps between wells with known values. It is thickest in LaSalle County in LaS-6 at 153 ft. Similar to the upper and total section, this unit is trough-shaped and the axis of the trough thins laterally from the center. This section thins dramatically towards southwest LaSalle County (Image created in SMT).
Figure 14: Regional Eagle Ford Structure map in the Hawkville Trough based on the sub-sea true vertical top (SSTVD) data gathered from logs. Faults were picked using seismic data. There is extensive faulting in McMullen County. Most of the faults post-date deposition of the Eagle Ford Formation, with the exception of a few growth faults in McMullen County that contribute to thickness and section variation over short lateral distances. (Map created in SMT)
Figure 15: Southwest-northeast cross section through the Eagle Ford Formation in the Hawkville Trough. Cross-section is hung on the top of Eagle Ford and vertical axis is shown with black line in feet. (cross section created in Petra, map created in SMT).
Figure 16: Southwest-northeast (strike-oriented) cross section, hung on the top Eagle Ford, from LaS-2 to LaS-8 in LaSalle County, TX. Black line indicates vertical axis in feet (cross section created in Petra, map image created in SMT).
Figure 17: Northwest-southeast (dip-oriented) cross section, hung on the top Eagle Ford, from LaS-3 to LaS-6 in LaSalle County, TX. Black line indicates vertical axis in feet (cross section created in Petra, map image created in SMT).
Figure 18: Southwest-northeast (strike-oriented) cross section, hung on the top Eagle Ford, from McM-3 (southwest) to McM-8 (northeast) in McMullen County, TX. Black line indicates vertical axis in feet (cross section created in Petra, map image created in SMT).
Figure 19: N-S (dip-oriented) cross section, hung on the top Eagle Ford, from McM-1 (N) to McM-3 (S) in McMullen County, TX. Black line indicates vertical axis in feet (cross section created in Petra, map image created in SMT).
SEISMIC ANALYSIS

The availability of seismic in south Texas, both two-dimensional (2D) and three-dimensional (3D), are plentiful due to the extensive continued drilling into the Eagle Ford and many other productive zones statewide. The 3D seismic in Hawkville field was shot and processed over the course of several years and broken up into phases. The Patron Grande survey covers Hawkville Field and encompasses approximately 955 square miles (www.globalgeophysical.com). The 3D data demonstrates a complex network of faults and erosional features throughout the Hawkville Tough (Figures 14, 20, and 21). The Eagle Ford and Buda Formations were picked based on tops seen while drilling, and then tied into the seismic, top for top (personal communication with Marie Henry-Geophysicist, Petrohawk 2010). The method most commonly used here is a Time Depth Chart, which is used to convert TVD values into time so the wellbore is plotted in seismic. The Buda Formation has a high velocity and density, making it the most reliable top that can be picked in the Hawkville trough; this yields high acoustic impedance. Acoustic impedance indicates how much sound pressure is generated by the vibration of molecules in a particular medium at a given frequency; locally, this shows up as a strong peak (personal communication Jarrett Pierce, Geophysicist 2012) (Figure 20 and 21). In Figure 20 (highlighted in purple), an extra peak can be seen on the left side of the figure between the top of Eagle Ford and the top of Buda. In seismic data this peak only occurs when total thickness reaches greater than 150 feet. Moving towards the right side of the figure, this strong peak disappears and the upper Eagle Ford becomes truncated. Figure 21, from McMullen County, demonstrates the additional accommodation seen on the downthrown side of growth faults. This image shows the appearance of the strong peak, discussed above, that occurs when total thickness is greater than 150 feet. This thickness continues to increase down dip as another growth fault is encountered. The total thickness
increased 95 feet over the extent of the line that is in dip orientation in central McMullen County. Figure 22 is a seismic cross section that was generated by flattening the data on the Buda Horizon and observing the horizon just above the Eagle Ford showing drastic lateral thinning across the profile. Amplitude extraction maps, or time slices, taken from 3D seismic volumes reveal high-resolution dispersal patterns and associated systems tracts on geologic time surfaces (Li, 2008). Flattening was achieved through SMT’s seismic module and subtracted the influence of regional dip in order to properly image the feature seen above (solid yellow line in Figure 22). The purpose of a structure-removed time slice is to be able to image amplitude variations in map view affecting a greater regional extent that occurred at or near a geologic time-equivalent horizon. This time slice, in map view, revealed a 6-7 mile wide channel running from southwest LaSalle across to the LaSalle/McMullen border (yellow lines in figure 25). The feature discovered corresponds to thinning of the Eagle Ford in LaSalle County from over +/- 250 feet to less than 70 feet in less than five miles.
Figure 20: Northwest-southeast Seismic dip section across LaSalle County, Texas. There is minor faulting associated with section thickness. From northwest to southeast the thickness of the Eagle Ford changes from thick to thin (as noted where the extra peak is present). The Channel Incision is evident on this section of 3D data. Field of view for figures 20-22 are approximately 7 miles. Vertical axis is recorded in time (roughly 0.5 seconds) (Image created in SMT).
Figure 21: Northwest-southeast seismic dip section through McMullen County, Texas. Note additional accommodation on downthrown side of growth faults. The complex structural framework in McMullen County is the main contributor to thickness variations within the Eagle Ford Formation. Vertical axis is recorded in time (roughly 0.5 seconds) (Image created in SMT).
Figure 22: Northwest-southeast seismic screen shot that shows flattening on the Buda Limestone (blue line) and generating the time slice through the horizon above the Eagle Ford Formation in southeast LaSalle County (yellow line). This image shows that in less than 5 miles the Eagle Ford thins by 180 feet. Vertical axis is recorded in time (roughly 0.5 seconds) (Image created in SMT).
DISCUSSION

CORE ANALYSIS

Basic core analysis illustrates the nature of the bounding unconformities, at the base of Eagle Ford/Top of Buda contact, but most notably the upper unconformity between the Eagle Ford Formation and the overlying Austin Chalk (Figure 23 and 24). In some areas of the Hawkville Trough the contact is found to be abrupt (Figure 23), and in other areas it is more gradational (Figure 24). However, it is accepted that the two formations are separated by a major unconformity and K72 sequence boundary (Petrohawk, 2009; Donovan and Staerker, 2010). The abrupt nature of this boundary consists of a thin (~.3-.5 in) layer of skeletal lag, rip-up clasts, and some soft-sediment deformation (Figure 23; Petrohawk, 2009). The rip-up clasts, skeletal limestones, and soft sediment deformation features indicates more proximal facies (Petrohawk, 2009). The proximal facies had lower TOC values and higher amounts of silica-bearing minerals. The LEF contains higher TOC, hemipelagic marls deposited in a more anoxic environment distal to sediment source (Petrohawk, 2009). The general depositional model for the Eagle Ford is a gently inclined carbonate ramp at the inner/outer shelf interface, within reach of storm-wave base (Petrohawk, 2009).

An attempt was made to correlate the log responses at the upper and lower Eagle Ford interface, as well as internal parasequence boundaries identified by Donovan and Staerker (2010). While the sharp and gradational nature of the Austin Chalk/Eagle Ford boundary in core can be identified by the sharp and gradual increase of gamma ray seen in logs, there was no data suggesting a correlation between log response and additional individual parasequences packages. This could be caused by the inability to capture these small events in log response. The likelihood that these parasequence packages exist is high, but remain to be identified and correlated to specific log responses.
Figure 23: Core image demonstrating abrupt and unconformable nature of the Austin Chalk and Eagle Ford Formation from McM-1 well in McMullen County, TX (image courtesy of Petrohawk Energy Eagle Ford Consortium).

Figure 24: Core image illustrating the gradational nature of the unconformable contact between the Austin Chalk and Eagle Ford Formation as seen in a LaSalle County, TX well (image courtesy of Petrohawk Energy Eagle Ford Consortium).
Figure 25: Amplitude extraction projected in map view from Figure 22 in southeast LaSalle County. This projection is generated from a time-equivalent horizon just above the Eagle Ford. Yellow lines show the extent (width) of channel described in Figure 22. Faults can be seen north of the channel (dark lines). Whole image is unavailable due to proprietary obligations. (Image created in SMT).
The Eagle Ford Formation in the Hawkville Trough varies significantly in terms of thickness (shown in seismic) and internal stratigraphic framework (shown in mapping and in seismic) over short lateral distances. The paleo-water depth and basin topography situated between the structurally high features of the Edwards and Sligo Reef margins, allowed for more accommodation than distal areas. The thickness variation is due to the bowl shaped feature that formed between the two reefs (Figures 15 and 17). Based on well log and seismic data, depth to the Eagle Ford varies from 9600 ft to 15000 ft (subsea) along a roughly planar surface that strikes parallel to these reef margins (Figure 14). Post-depositional forces- such as erosion of the upper and, in extreme cases, portions of the lower Eagle Ford- were major controls on thickness variation seen in the Hawkville Trough. In the most extreme case in southwest LaSalle County, the Upper Eagle Ford is entirely missing in two wells and has been replaced by a channel sand unit not previously reported (Figure 10). This has been identified as a channel sand based on the gamma ray signatures (20-45 API) and resistivity response (2-4 ohms) using the criteria of Booth et al., 2003. The Lower Eagle Ford was also partially eroded in these two wells (Figure 10). Numerous faults are visible on seismic data (Figures 20 and 21). Most of these faults are post-depositional with modest offsets (25-200 feet)(Figure 21). A few of the faults are syn-depositional growth faults, indicated by thicker sediment accumulation in the additional accommodation on the downthrown side (Figures 18 and 20). Figure 18 shows a thicker LEF section due to a syn-depositional growth fault. Figure 20 shows the appearance and disappearance of the peak on the downthrown side of the growth fault (highlighted in purple), interpreted as the seismic expression of the UEF/LEF interface. It is only present when total thickness exceeds 150 ft.
Particularly interesting is an erosional event best captured in LaSalle County. What is interpreted as a channel, referred to herein as the Paleo-Nueces Channel, post-dating Austin Chalk and Anacacho deposition ran through southern LaSalle County (Figure 25)(this study). First described by Treadgold (2010) as a gravitational slump, further well log and seismic analysis shows that a meandering channel is another possible interpretation. When the amplitude is extracted, after flattening on the Buda horizon, from the surface just above the Eagle Ford (yellow line in Figure 22), a 6-7 mile wide channel is revealed running through the Hawkville Trough (Figure 25). Figure 20 shows high acoustic impedance above the top of Eagle Ford that cannot be correlated through the center of the feature, but is present on either side. This high acoustic impedance is interpreted in this study as the Austin Chalk formation, and allows a general time relationship to be determined. Proprietary obligations and data availability only allows this feature to be captured within the boundaries of the Hawkville Trough, primarily in LaSalle County although recent seismic analysis shows it extending into McMullen County. Figure 25 shows a horizon that was extracted from a seismic line (Figure 22 - yellow line) projecting its amplitude variations in map view. The yellow lines in Figure 25 annotate the boundaries of the channel, with the strike and dip direction (of the Eagle Ford Formation) symbol in red. The white lines to the northeast of the channel are fault systems that propagate throughout LaSalle County, but do not intersect the channel and are thus interpreted as pre-incision deformation. The Paleo-Nueces channel is first observed in southwest LaSalle County running northeast-southwest along bedding strike. Up dip, the channel is not present and the total thickness of the Eagle Ford remains between 250-270 feet (LaS-10 in Figure 10). Down dip, the channel is present, shown by the presence of sand above the Eagle Ford and the noticeably missing section of the upper Eagle Ford entirely and part of the lower Eagle Ford (LaS-9 in figure 10). When the channel meanders southeast (parallel to Eagle Ford bed dip),
the strata directly above the Eagle Ford Formation (Austin Chalk), the upper Eagle Ford, and some of the lower Eagle Ford Formation are eroded out within a matter of 4.4 miles (LaS-9 in figure 10). A distinct sand body is deposited above the Eagle Ford, and this particular sand body is unique to the area in between the boundaries of the channel (Figure 10). Most likely this is a channel and not a slump due to the fact that: 1) gravitational slumps would permeate along bed dip instead of displaying a meandering nature; 2) horizons within and above the Eagle Ford Formation would not be missing, only tilted unless the slump displaced the sediments a significant distance; 3) the strata on either side of the feature are undeformed and present in expected thicknesses; and 4) most importantly there is no explanation as to why a sand body that does not occur stratigraphically in any area of the Eagle Ford Formation is present here, solely within the boundaries of this feature.

Based on the isopach maps, LaSalle was most likely a site of sediment influx as seen in log analysis. Approaching the Edwards Reef Margin, dips increase from 2-4 degrees north/northwest to 7-12 degrees north/northwest. Approaching the Edwards reef, a thinner Eagle Ford section is encountered, ultimately affecting internal stratigraphic correlation (LaS-3 in Figure 17). The lower Eagle Ford is consistently higher in total organic carbon and in support of previous studies, the dark, well-laminated marls were deposited in a deep, oxygen-starved, outer-shelf/marginal marine setting during a worldwide greenhouse environment (Petrohawk Energy, 2009). An anoxic environment coupled with high organic productivity at the surface would support why there are higher total organic carbon values in this lower member. Also, the anoxic environment caused by the restricted setting between the reef boundaries would allow for a large accumulation and preservation of organic-rich sediments. During times of increased sedimentation rates and/or storm events, breaks in the reef would allow clastic-rich sediments
to flood into the Hawkville Trough. Proof for this type of sedimentation could be supported by in-depth analysis of cores.

The depositional model for the upper Eagle Ford in the Hawkville Trough is more difficult to decipher due to a more complex network of erosional features along the upper contact. The influence that the Paleo Nueces Channel had on this contact is evident through seismic and well log analysis in southern LaSalle County. Where the channel was cutting sediments above the Eagle Ford along bedding strike, the influence of its erosion on the upper Eagle Ford is largely speculative without a chronostratigraphic reconstruction of this channel. However, the erosional influence on the upper Eagle Ford is clear where it is completely missing, the unique sand body is deposited above the lower Eagle Ford, and the characteristic coarsening upward nature of the lower Eagle Ford remains intact.
CONCLUSIONS

Well log and seismic data have been used to regionally map the following Eagle Ford boundaries in the Hawkville field in LaSalle and McMullen Counties, Texas: (1) Unconformable boundary between the base of the Eagle Ford and Buda, which is characterized by 9-15 API gamma response, a transition from a strong peak (Buda) to a strong trough (LEF) in seismic, and transition from limestone to organic-rich marlstone lithology; (2) Conformable contact between the LEF and UEF characterized by a 120-140 API gamma response, transition from trough to peak (where greater than 150 ft) in seismic, and transition from marlstone to interbedded shale/limestone lithology; (3) Unconformable boundary between the UEF and Austin Chalk, which is characterized by a 120-135 API gamma response, transition from strong trough (UEF) to strong peak (Austin Chalk) in seismic, and transition from the interbedded shale/limestone lithology to the massive chalk-bearing limestone lithology.

Well log and seismic expression of the Eagle Ford-Austin Chalk boundary is variable/gradational due to laterally variable erosion of the Eagle Ford prior to deposition of the Austin Chalk. This variability is also observed in core data, where the sharp contact contains skeletal lag deposits and rip-up clasts, and the gradational contact only shows minor changes in fossil content and lighter color due to increased limestone content. Other subdivisions of the Eagle Ford suggested from outcrop studies (e.g. Lock and Peschier, 2010; Donovan and Staerker, 2010) cannot be consistently recognized in the Hawkville Trough because the contrast in properties between lithologies cannot be deciphered in the current log and seismic resolution. Both the LEF and UEF are trough shaped deposits that strike northeast roughly parallel with the Edwards Reef margin. The axis of the trough is closer to the Edwards Reef than the Sligo Reef. Maximum thickness of the LEF is more than 180 ft in LaSalle County and
approximately 140 ft in McMullen County. The UEF is thinner with a maximum thickness of 160 ft along the LaSalle-McMullen County border. Both the LEF and UEF thin rapidly to half their maximum thicknesses within 5-6 miles of the axis. The Eagle Ford also thins approaching the reef, and to the northeast into McMullen County. Well data documents dramatic decreases in thickness of the UEF over a few miles due to erosion. In the most extreme case in southwest LaSalle County, the UEF is entirely missing in 2 wells and has been replaced by a sand unit not previously reported. The LEF may have also been partially eroded in these two wells.

Based on well log and seismic data, depth to the Eagle Ford varies from 9600 ft to 15000 ft along a roughly planar surface that strikes parallel to the Edwards and Sligo Reef margins. Numerous faults are visible on seismic data. Most of these faults are post-depositional with modest offsets (25-200 ft). A few of the faults are syn-depositional growth faults and the Eagle Ford is thicker on the downthrown (Gulfward) side. Seismic data shows that the Eagle Ford in this region decreases in thickness from over 270 ft to less than 80 ft and that the reflector (strong peak in Figures 20-22) interpreted to be the boundary between the LEF and UEF disappears as the unit thins to less than 150 ft. A seismic time slice just above the top of the Eagle Ford hung on the Buda to remove efforts of basinward dip shows a channel structure running west to east along southern LaSalle County. This channel is likely the source of erosion and sand deposition observed in wells LaS-9 and LaS-12.
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VITA

Zach Hendershott was born in Houston, Texas in 1987 and attended Episcopal High School in Bellaire, Texas. After graduating in 2005, he left Houston to pursue a bachelor's degree at the University of the South in Sewanee, Tennessee. During his four years at Sewanee, Zach was a member of Sigma Alpha Epsilon Fraternity and was inducted into the Order of the Gownsman honor society in 2008. Zach worked as an exploration geology intern during the summers of 2007 and 2008 for Etoco, L.P.. After graduating from Sewanee in 2009, Zach moved to New Orleans and worked as a legal assistant while studying for his GRE and applying to Louisiana State University. Zach enrolled in the graduate program to pursue his Master's of Science degree in geology under the guidance of Dr. Jeffrey Nunn in 2010. He became the first geology intern for Petrohawk Energy Corporation during the Summer of 2011 in Houston, Texas. Zach accepted a full-time job offer with Petrohawk Energy Corporation in Houston as an Operations Geologist in their Eagle Ford Group.