

# Eagle Ford Shale Basin Study

April 19, 2019  
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## ACRONYMS AND ABBREVIATIONS

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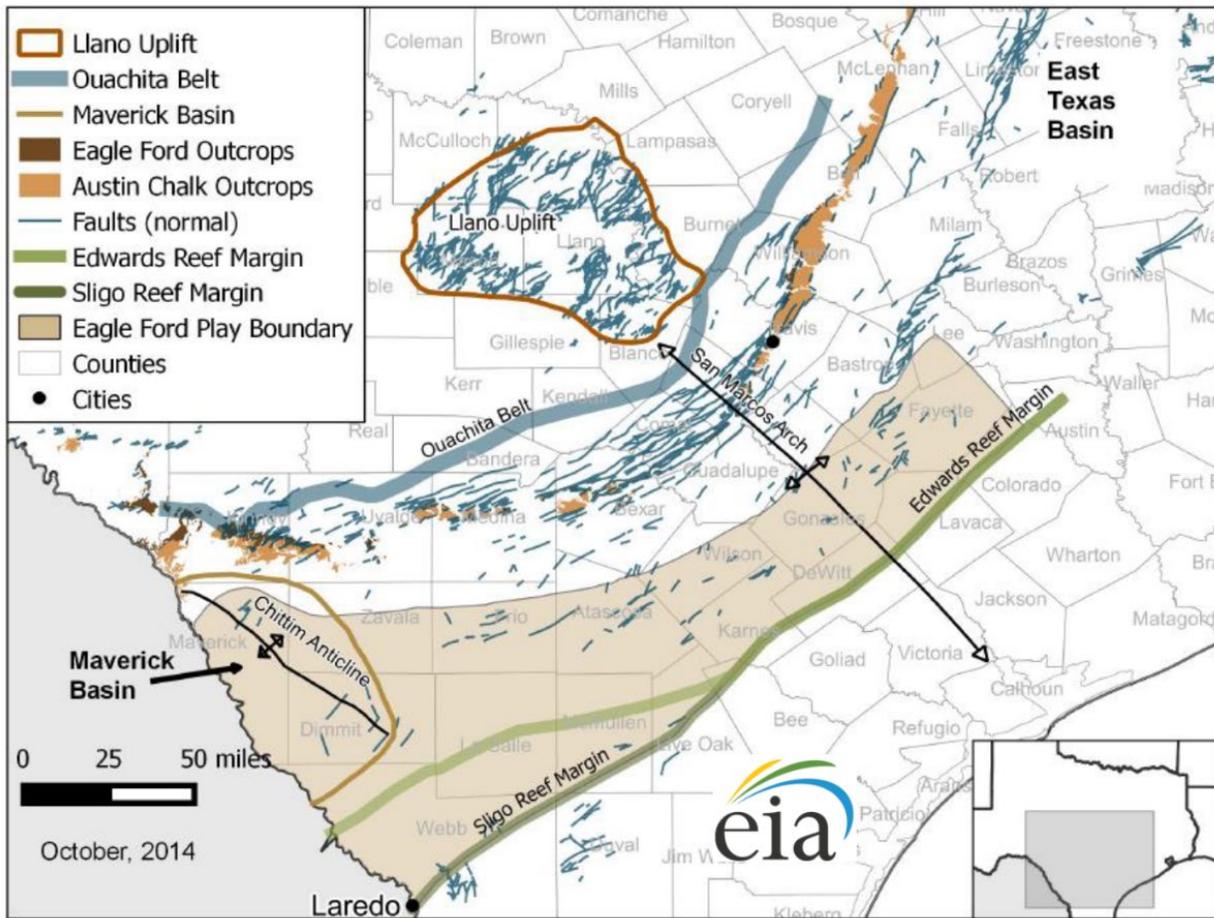
API	American Petroleum Institute
ARI	Advanced Resources International
B	Barrel
bbl	Barrel
BOE	Barrel of oil equivalent
BOED	Barrels of Oil Equivalent per Day
bpd	Barrels per day
CCS	Carbon capture and sequestration
CO <sub>2</sub>	Carbon dioxide
D&C	Drilling and Completion
DOE	Department of Energy
EIA	Energy Information Administration
EOR	Enhanced oil recovery
EPA	Environmental Protection Agency
EUR	Estimated ultimate recovery
FE	Fossil energy
ft	Foot, Feet
GOR	Gas-oil ratio
Hz	Horizontal
IOR	Improved oil recovery
MBbl	Thousand barrels
MBOED	Thousand Barrels Oil Equivalent per Day
Mcf	Thousand cubic feet
MESA	Mission Execution and Strategic Analysis
MM	Million
MMB/D	Million barrels per day
MMcfd	Million Cubic Feet per Day
MMscf	Million standard cubic feet
MMscfd	Million standard cubic feet per day
N <sub>2</sub>	Nitrogen
NETL	National Energy Technology Laboratory
NGL	Natural gas liquids
O&M	Operation and maintenance
OOIP	Original oil in-place
psi	Pounds per square inch
R&D	Research and development
RB/STB	Reservoir barrels/stock tank barrels
Ro	Vitrinite reflectance
TOC	Total Organic Carbon
U.S.	United States
°C	Degrees Celsius
°F	Degrees Fahrenheit

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# 1 INTRODUCTION

The Eagle Ford Shale is located in the South Texas Shelf and extends across a 20,000 square mile area of the Western Gulf Coast Basin. The more actively developed 10,000 square mile central portion of the Eagle Ford Shale is bounded on the east by the San Marcos Arch, on the west by the Chittim Anticline, on the south by the Sligo Reef Margin, and on the north by the shallower productive limits of the light oil play area before reaching the shale outcrop near the Ouachita Belt, Exhibit 1-1.

*Exhibit 1-1 Eagle Ford Shale Location Map*



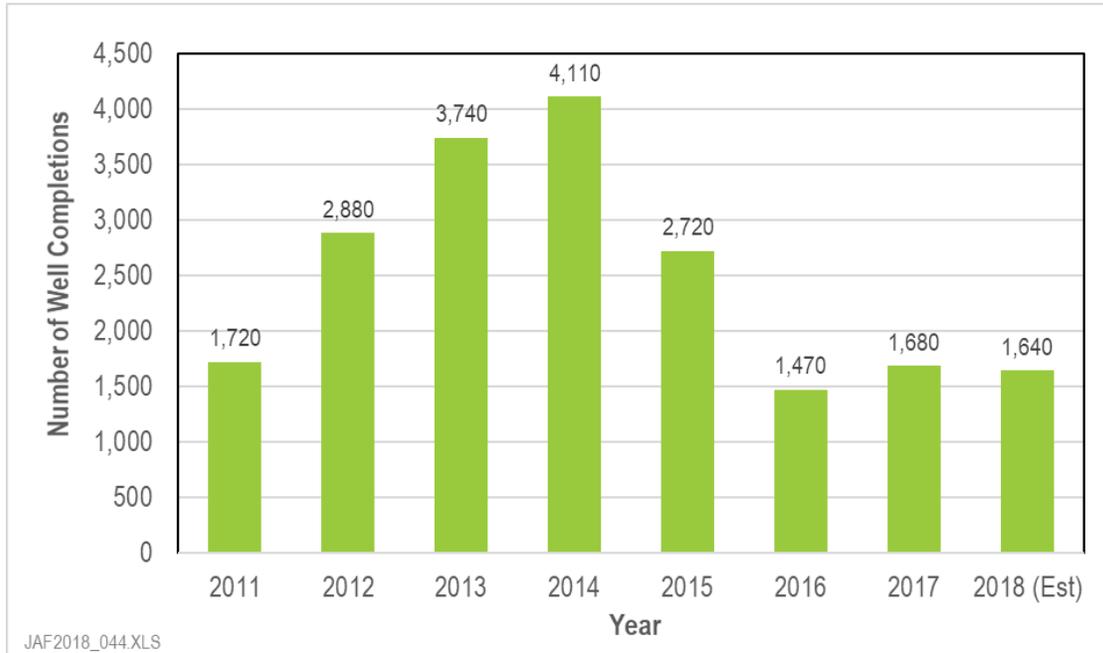
*Source: U.S. Energy Information Administration, 2014*

Much of the initial development of the Eagle Ford Shale was in the eastern, oil dominant area of the shale, in DeWitt and Karnes counties. More recently, the development of the Eagle Ford Shale has progressed to the central and western portions of the shale area, in McMullen, LaSalle and Dimmit counties. As of the end of 2018, a total of nearly 20,000 horizontal (Hz) wells have been drilled and completed in the Eagle Ford Shale, with the great bulk in the oil dominant area in the central and northern portions of the shale deposition.

## 2 DEVELOPMENT ACTIVITY

Following the drilling of a handful of shale characterization wells, significant development of the Eagle Ford Shale started in 2009 with drilling and completion of 74 Hz wells. With increasing deployment of rigs, Hz well completions reached a peak of 4,110 in 2014. Well completions declined to 1,470 two years later, following the sharp drop in oil prices. With the recent increase in oil prices, well completions have rebounded to 1,680 in 2017, with similar activity expected in 2018, Exhibit 2-1.

*Exhibit 2-1 Eagle Ford Shale Hz Well Completions, 2011- 2018*



*Source: Advanced Resources International's Tight Oil Database, 2018; Drilling Info, 2018*

Today, the Eagle Ford Shale is an increasingly mature tight oil play, with over 16,000 Hz oil wells and 3,000 Hz gas wells drilled and placed on production. As such, some of the more productive areas of the Eagle Ford Shale have become highly developed. For example, the geologically attractive Karnes Trough area, in the eastern portion of the Eagle Ford Shale oil “window”, now has nearly 4,000 well completions, consuming three-quarters of the potentially available well locations.

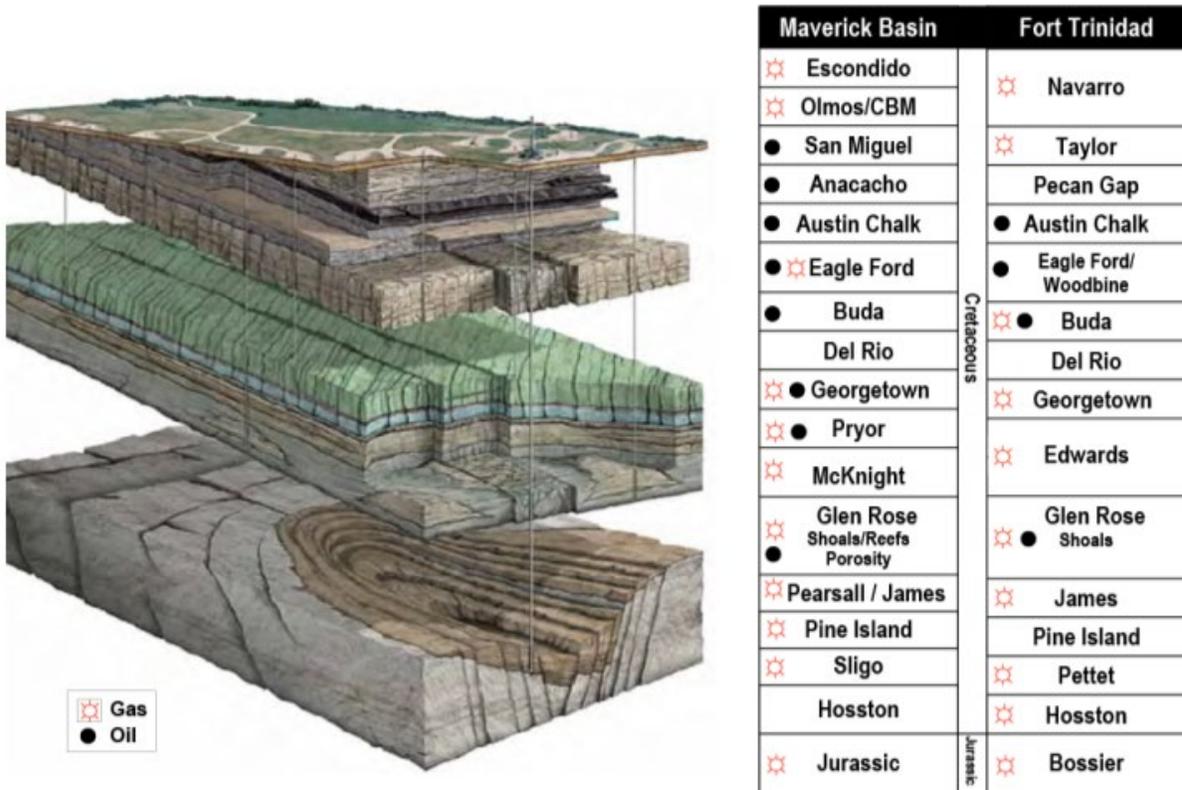
As such, other portions of the Eagle Ford Shale play, such as the less developed central and western areas, will become the focus of new well drilling. In addition, following numerous cyclic gas injection pilot projects, industry is examining the potential of using gas injection as a process for increasing oil recovery efficiency from the Eagle Ford Shale.

### 3 GEOLOGIC SETTING

#### 3.1 STRATIGRAPHIC COLUMN

The Upper Cretaceous Eagle Ford Shale lies above the Buda Limestone and is overlain by the Austin Chalk, as shown on Exhibit 3-1 for the Maverick Basin. This area contains a stack of oil and gas producing formations, ranging from the Escondido Formation at the top of the Cretaceous section to the Sligo Formation at the base of the Cretaceous section. Considerable activity is also currently underway in the overlying Austin Chalk Formation.

*Exhibit 3-1 Eagle Ford Shale Stratigraphic Column*



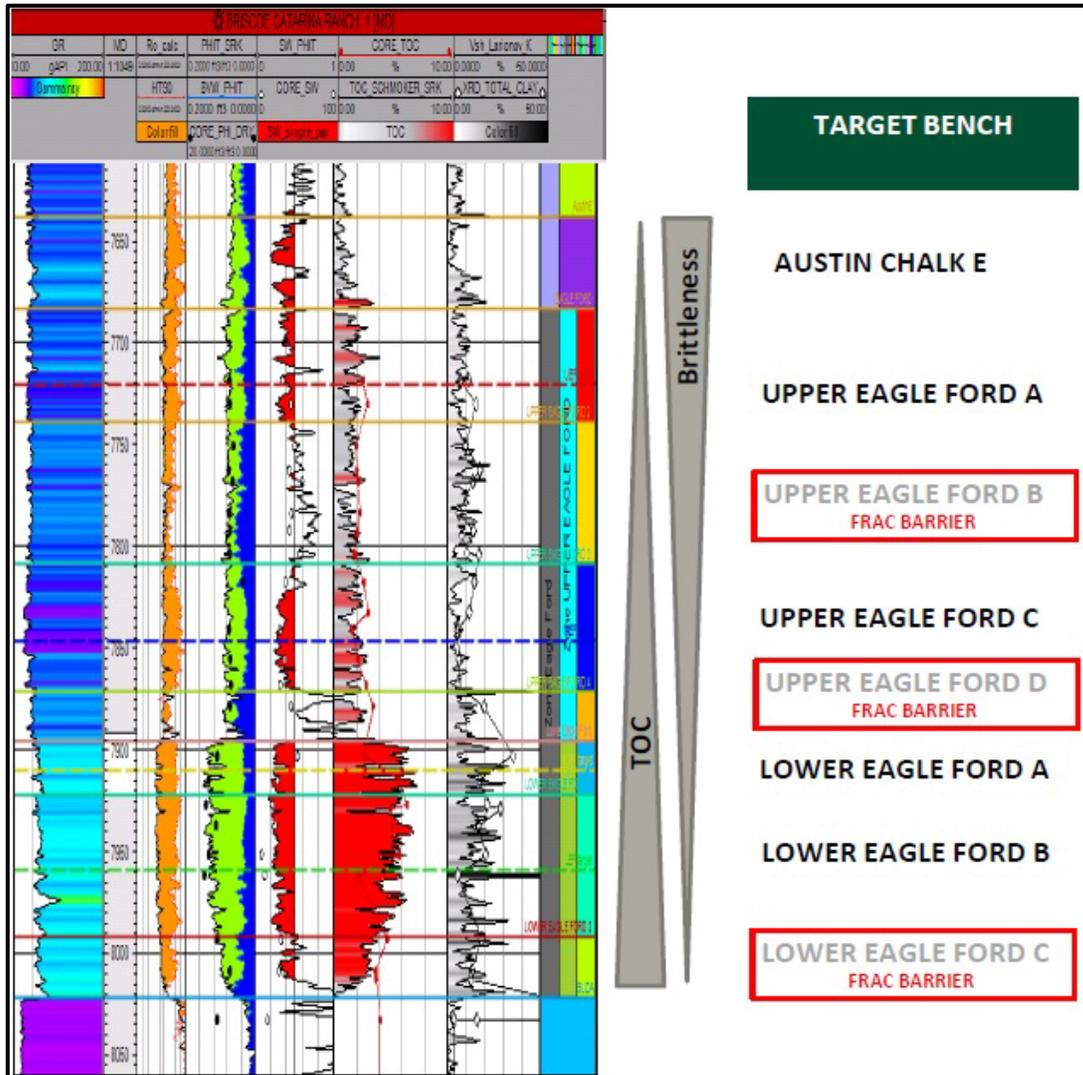
Source: TXCO Resources, 2009

The stratigraphic section labeled Fort Trinidad on Exhibit 3-1 is for the area east of the San Marco Arch where the Eagle Ford Shale interfingers with the Woodbine tight sand. This area, labeled the Eaglebine (combination of Eagle Ford and Woodbine) by industry, is not included in this Basin Study of the Eagle Ford Shale.

### 3.2 SHALE INTERVAL

The Eagle Ford Shale contains an Upper Shale Unit as well as a Lower Shale Unit, separated by a dense unit that serves as a frac barrier, Exhibit 3-2. The Upper Unit is generally thinner than the Lower Unit and has lower Total Organic Carbon (TOC). However, the Upper Unit has brittle rock properties favorable for hydraulic stimulation. The Lower Unit has higher TOC, ranging from 4 to 5 percent (by wt), but has more ductile rock properties posing challenges to optimum hydraulic stimulation.

*Exhibit 3-2 Upper, Middle and Lower Units of the Eagle Ford Shale*



Source: Modified from Sanchez Energy, 2014

Exhibit 3-2 shows a high TOC interval in the Lower Eagle Ford Shale (Benches A and B) at depths of 7,890 ft to below 8,000 ft. In contrast, only minor concentrations of TOC are noted in the shallower Upper Eagle Ford Shale intervals.

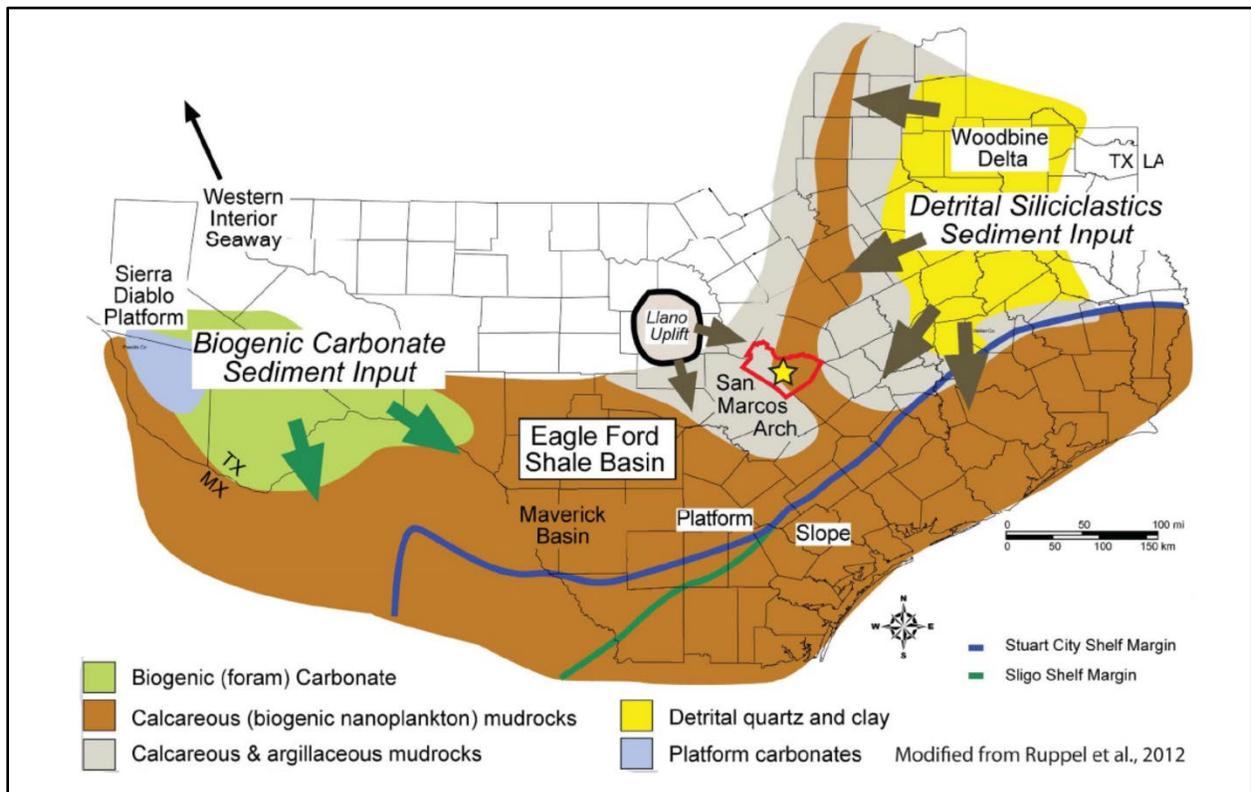
### 3.3 DEPOSITION

The Eagle Ford Shale was deposited in an open marginal marine environment (Pessagno, 1969; Ruppel, 2012). The sediments deposited on the northern shallower shelf represent proximal deltaic facies. The sediments deposited further south and southeast in the central and southern areas of the shale represent distal deltaic facies, Exhibit 3-3 (Donovan and Staerker, 2010).

Core images of the Eagle Ford Shale show black, thinly laminated shales in the Lower Shale Unit. The Upper Shale Unit has abundant light-gray calcareous and mixed siliclastic sediments.

- The Lower Shale Unit has high gamma ray readings of 90 to 135 API units, indicating higher TOC.
- An organically lean carbonate interval called the Kamp Ranch Member separates the Lower and Upper Shale Units.
- The Upper Shale Unit has low gamma ray readings of 45 to 75 API units.
- A variably thick Langley Member separates the Upper Shale Unit from the overlying Austin Chalk (Donovan and Staerker, 2010).

*Exhibit 3-3 Depositional Platform and Slope of South-Central Texas*



Source: Fairbanks, Ruppel, and Rowe, 2016.

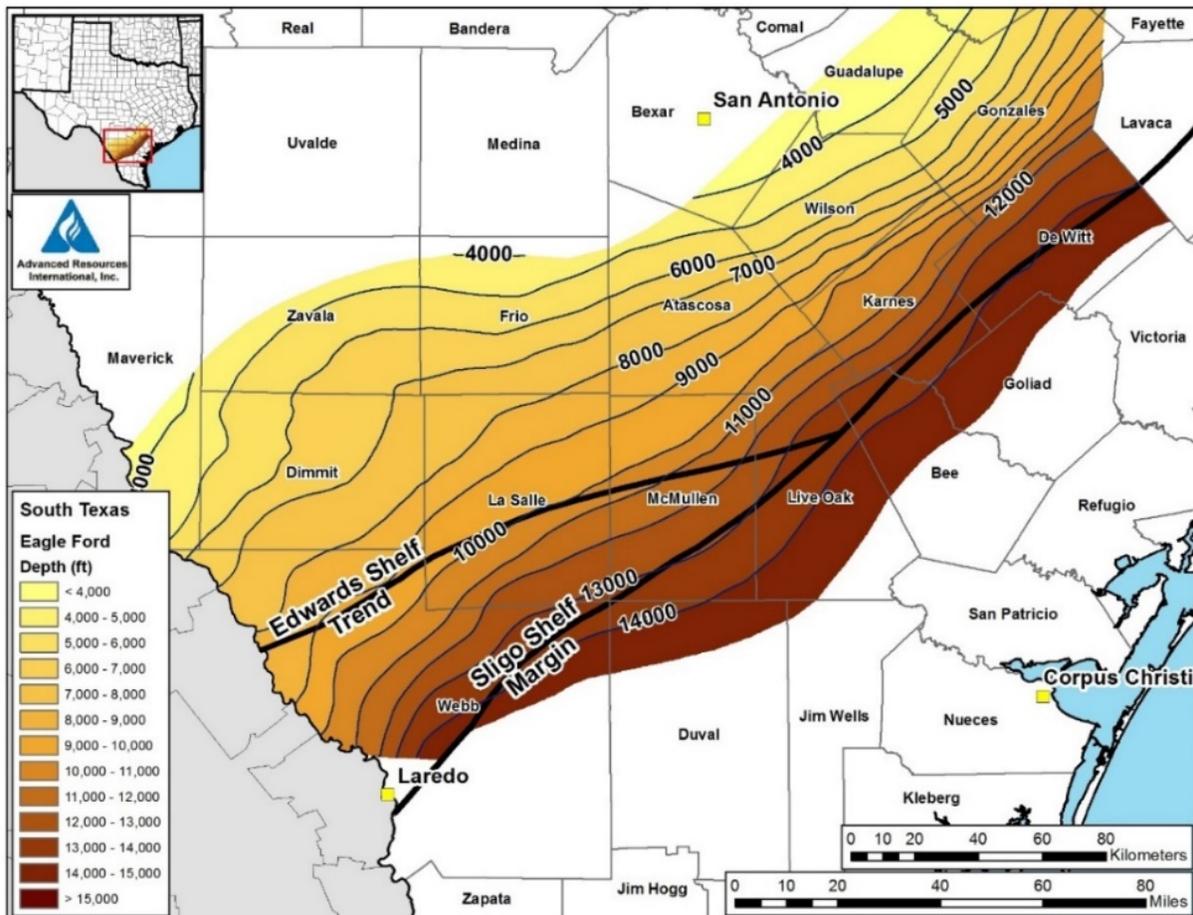
### 3.4 SHALE DEPTH

The Eagle Ford Shale deepens progressively from less than 5,000 ft in the north to below 14,000 ft in the south, following a series of parallel northeast to southwest depth trends, Exhibit 3-4.

A prior set of Austin Chalk exploration and production wells plus subsequent Eagle Ford Shale development wells have provided valuable control points for establishing the depth and other reservoir properties of the shale.

However, very few deep Eagle Ford Shale wells have been drilled in the southern, natural gas dominant area of the shale, limiting the data control points in this area. Similar lack of Eagle Ford Shale wells exists along the northern, shallower oil dominant area of the shale.

*Exhibit 3-4 Eagle Ford Shale Depth*



Source: Advanced Resources International, 2018

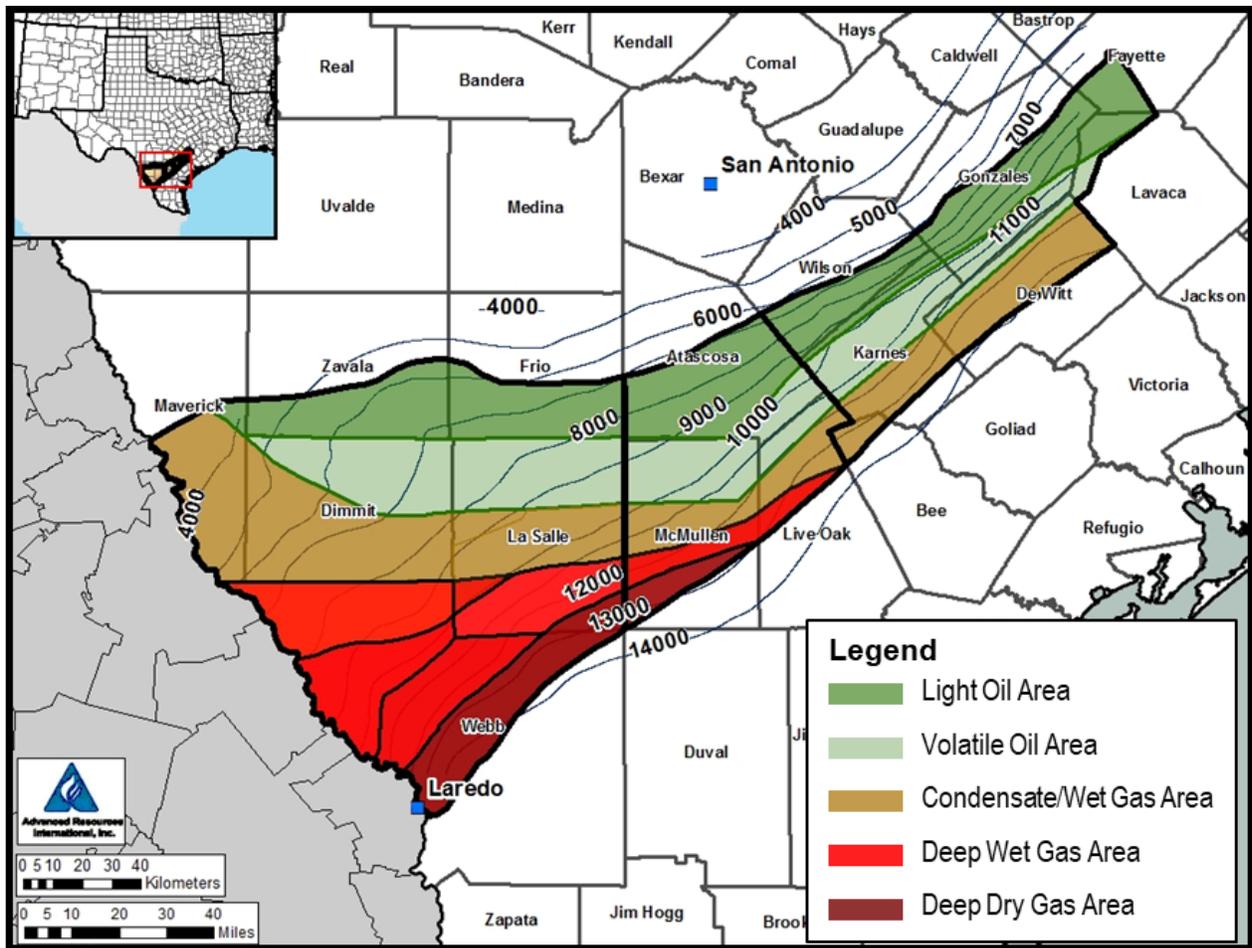
### 3.5 HYDROCARBON WINDOWS

A notable feature of the Eagle Ford Shale is its numerous hydrocarbon “windows,” linked to the thermal maturity and depth of the shale. These hydrocarbon windows include a deep (13,000 to 14,000 ft) dry gas area in the south and a moderately deep 11,000 to 12,000 ft wet gas area in the southwest, Exhibit 3-5.

In the center of the shale deposit is the extensive condensate/wet gas area at depths of 12,000 to 13,000 ft in the east, approximately 10,000 to 11,000 ft in the center, and 7,000 to 9,000 ft in the west.

To the north of the condensate/wet gas area is the volatile oil area at depths of 7,000 to 11,000 ft that has been the primary target area for Eagle Ford Shale development. Further north is the light oil area at depths of 6,000 to 9,000 ft.

*Exhibit 3-5 Eagle Ford Shale Hydrocarbon “Windows”*



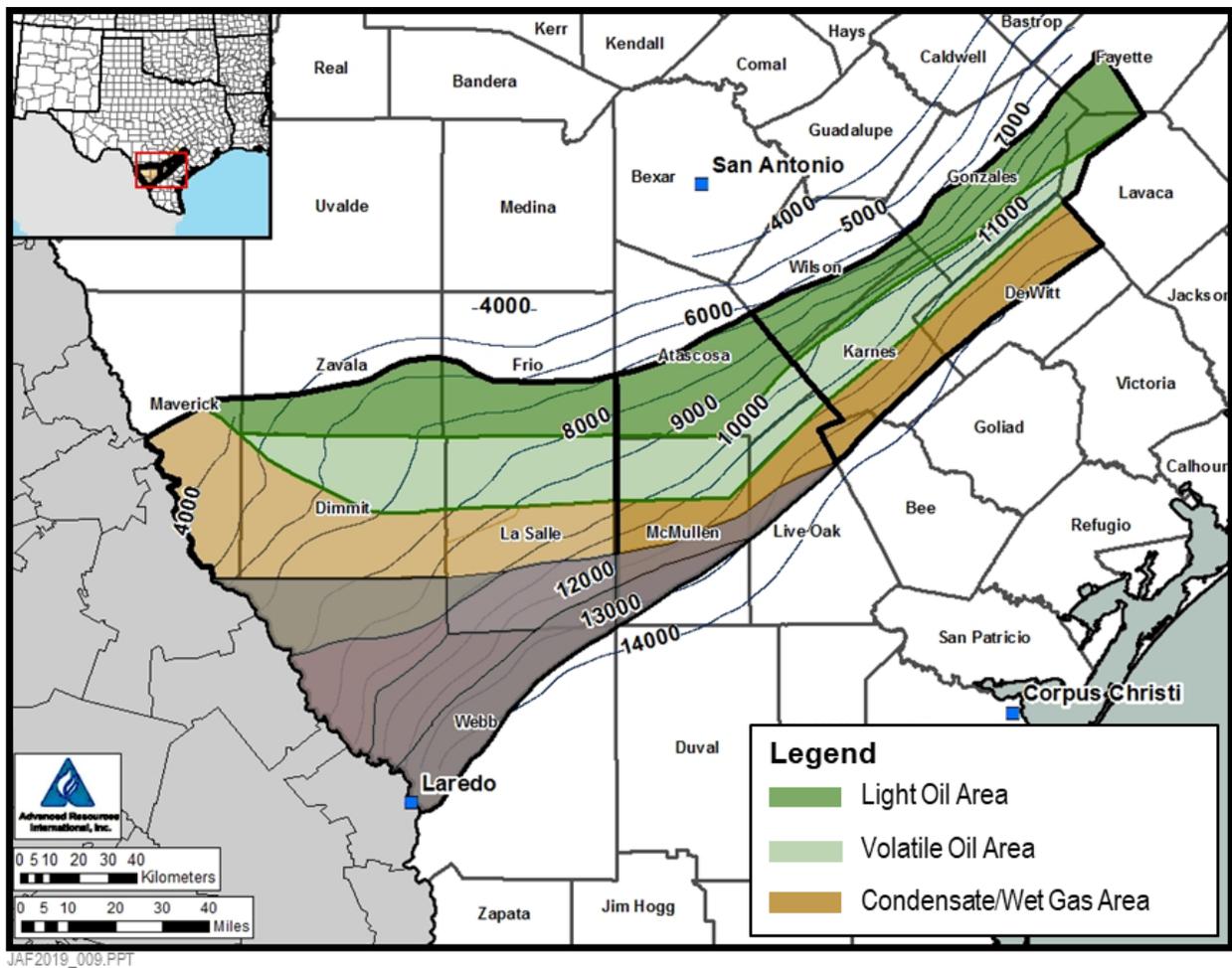
Source: Advanced Resources International, 2019

### 3.6 OIL DOMINANT AREA

Exhibit 3-6 shows the location of the oil dominant portion of the Eagle Ford Shale, including the condensate/wet gas, volatile oil and light oil areas in the northern and eastern portions of the shale. These three oil dominant shale hydrocarbon windows extend from Maverick County on the west to Fayette County on the east. Along with production of oil and condensate, the oil dominant areas of the Eagle Ford Shale produce significant volumes of wet associated gas.

The natural gas dominant portion of the Eagle Ford Shale, consisting of wet and dry gas areas, exists in the southwestern portion of the shale, primarily in southern LaSalle and McMullen counties and in Webb county. The natural gas dominant portions of the Eagle Ford Shale also provide modest by-product volumes of condensate production.

*Exhibit 3-6 Eagle Ford Shale Oil Dominant Area*

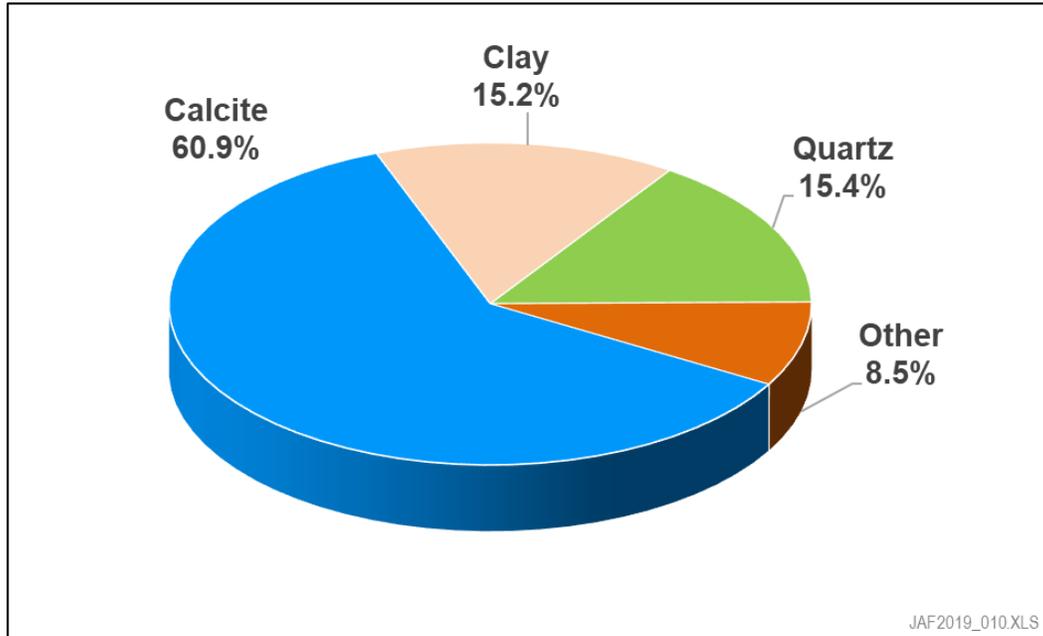


Source: Advanced Resources International, 2018

### 3.7 SHALE MINERALOGY

While commonly labeled a “shale,” the Eagle Ford Formation is composed of organic-rich calcareous mudstones and chinks (calcite), with moderate quartz and low clay content, Exhibit 3-7.

*Exhibit 3-7 Eagle Ford Shale Mineralogy*



*Source: Modified from Stoneburner, 2013.*

The Upper Shale Unit has a higher quartz content, lower clay content, and lower organic content than the average mineral concentration values shown on Exhibit 3-7. The Lower Shale Unit has lower quartz content, higher clay content, and notably higher organic content than the average mineral concentration values shown in Exhibit 3-7.

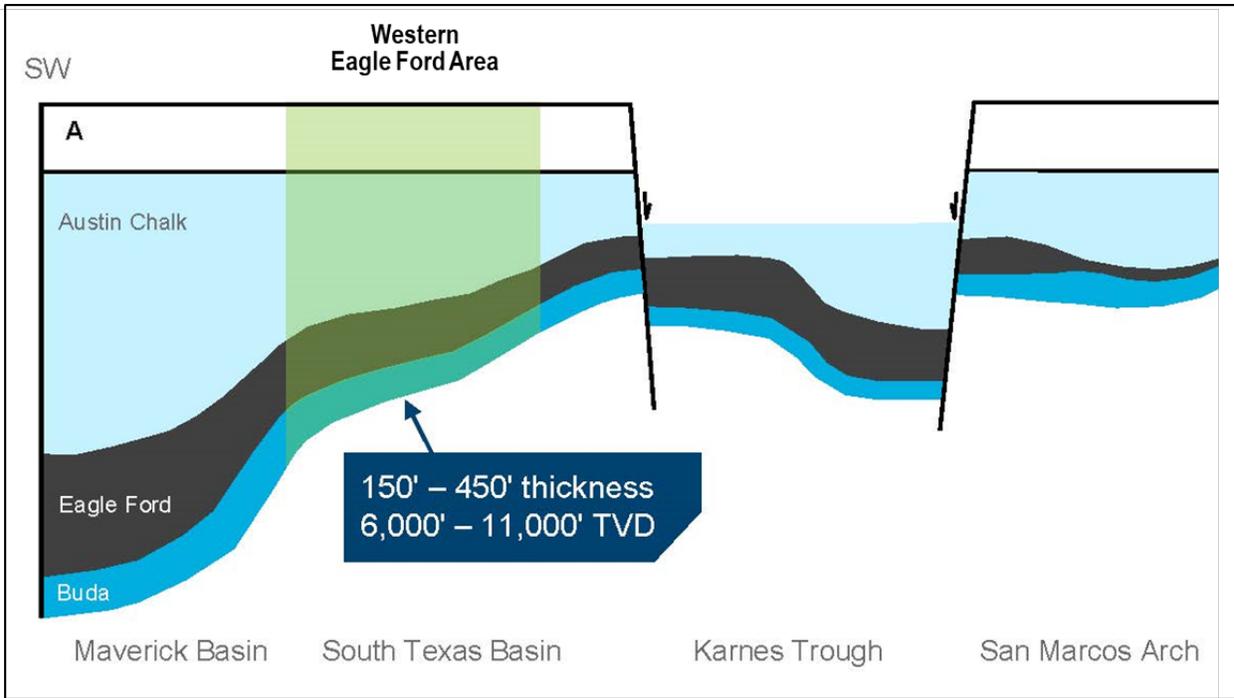
The organically-rich Lower Shale Unit’s lower quartz content, makes this shale interval somewhat less brittle and more prone to proppant imbeddment (Cipolla, 2009).

### 3.8 STRUCTURAL SETTING

The Edwards Reef Margin and Sligo Reef Margin are two major structural features along the southern portion of the Eagle Ford Shale area. These two features, illustrated previously on Exhibit 3-4, controlled the sediment deposition in the Hawkville Trough in LaSalle and McMullen counties, providing a thick interval of Lower Eagle Ford Shale.

In addition, a variety of fault systems exist across the Eagle Ford Shale area. The normal fault system in the Karnes Trough area of Karnes County (in the northeastern portion of the shale area) provides and helps maintain a higher permeability shale setting, contributing to the highly productive wells developed in this area, Exhibit 3-8.

*Exhibit 3-8 Karnes Trough Area of the Eagle Ford Shale*



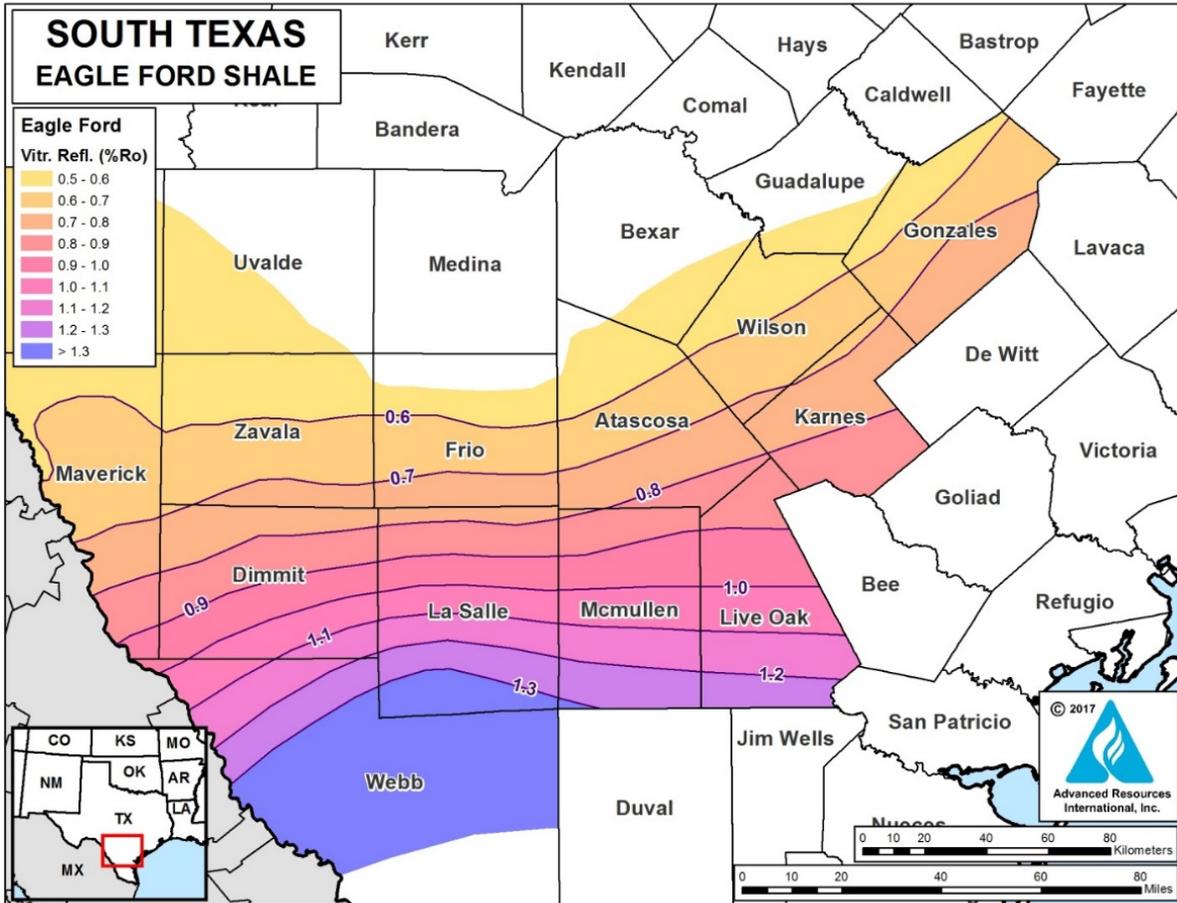
Source: Modified from Chesapeake Energy, 2019

### 3.9 THERMAL MATURITY

The thermal maturity of the Eagle Ford Shale, that governs its hydrocarbon windows, ranges from a Ro (vitrinite reflectance) of 0.6 to 0.7 in the north (in the light oil window) to a Ro of over 1.3 in the south (in the dry gas window).

The oil dominant areas of the Eagle Ford Shale, the focus of this study, have thermal maturity values that generally range from 0.6 Ro in the north to 1.0 Ro in the south, Exhibit 3-9.

*Exhibit 3-9 Eagle Ford Shale Thermal Maturity*



Source: Advanced Resources International, 2018.

## 4 RESERVOIR PROPERTIES

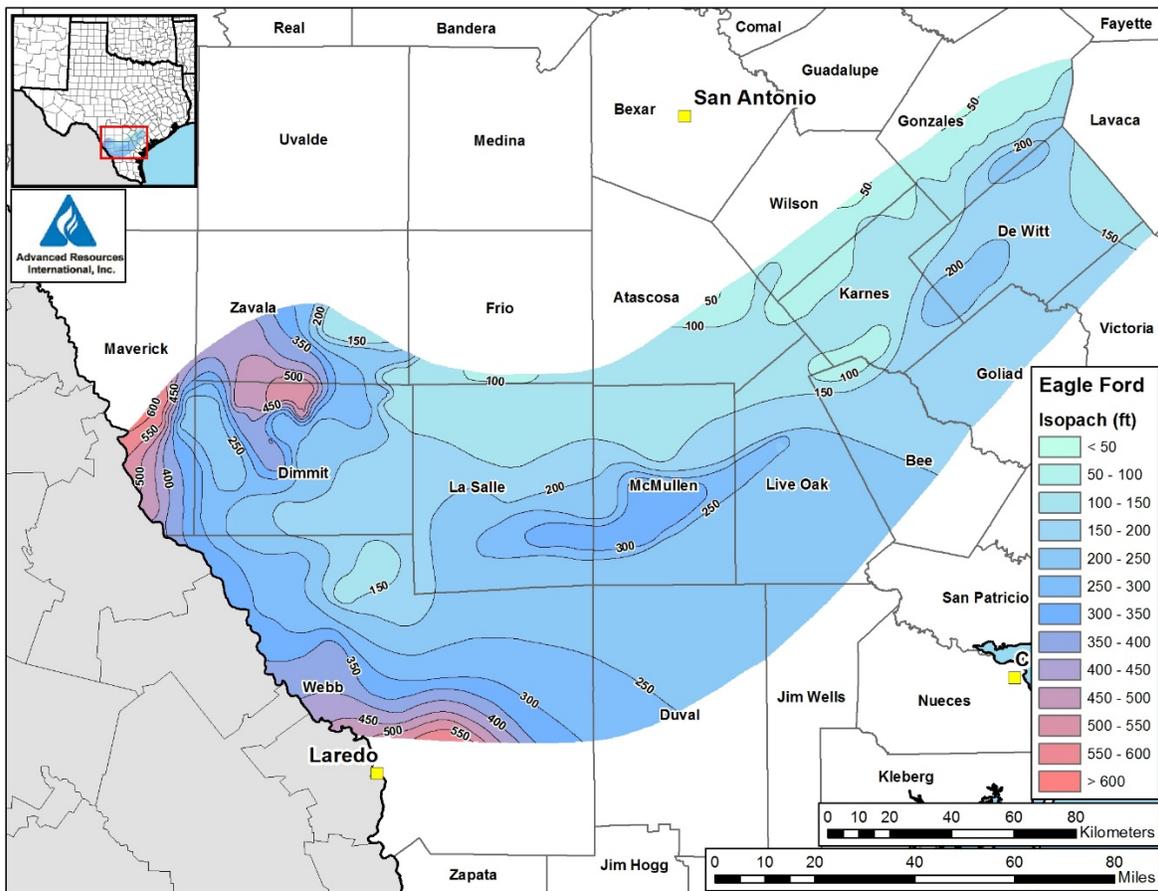
The reservoir properties of the Eagle Ford Shale vary greatly, both vertically within the Eagle Ford Shale interval and horizontally across the large shale deposition area. To capture the key reservoir property values and their distribution, we have assembled published data on the Eagle Ford Shale from a variety of sources as well as performed some of the data assembly, interpretation and mapping ourselves.

The information on reservoir properties will concentrate on the Lower Shale Unit, the primary development target of the Eagle Ford Shale.

### 4.1 SHALE ISOPACH

The thickness of the Eagle Ford Shale (Lower Unit) interval ranges from 50 ft on the north to over 500 ft in selected areas on the west and south. In the actively developed areas of the Eagle Ford Shale, the shale interval generally ranges from 100 ft on the north to 300 ft on the west and south, Exhibit 4-1.

*Exhibit 4-1 Eagle Ford Shale Lower Unit Isopach*

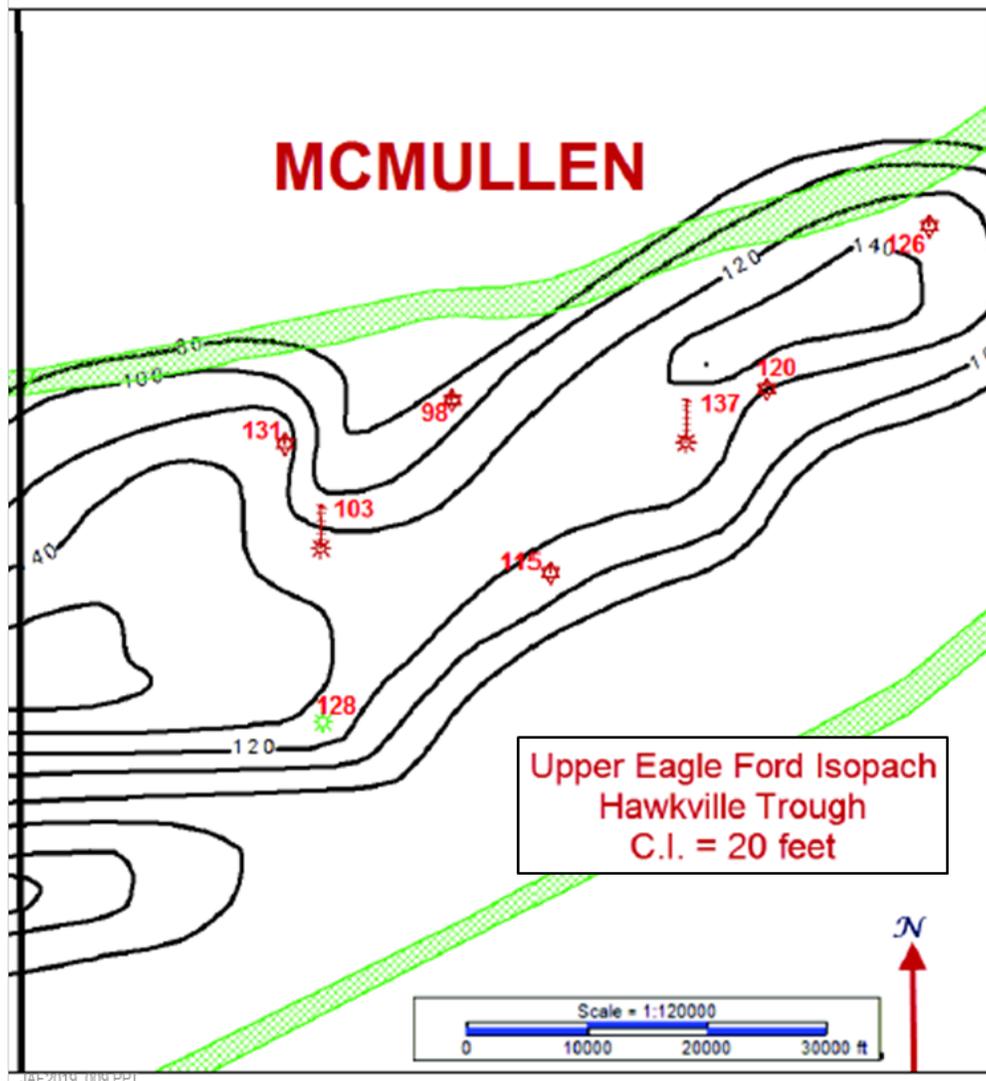


Source: Advanced Resources International, 2018.

The central and eastern portions of the Eagle Ford Shale have high net-to-gross pay ratios, approaching 100 percent. In the western portion of the Eagle Ford Shale, with its high gross thickness, the net-to-gross ratio ranges down to 50 percent.

A more detailed look at the Lower Eagle Ford Shale interval in the central portion of the Eagle Ford Shale area is shown in Exhibit 4-2 for the Hawkville Trough, in central LaSalle and McMullen counties. The isopach map of the Lower Eagle Ford Shale in this area indicates a thickness of 100 to 150 ft, based on well data from 21 wells.

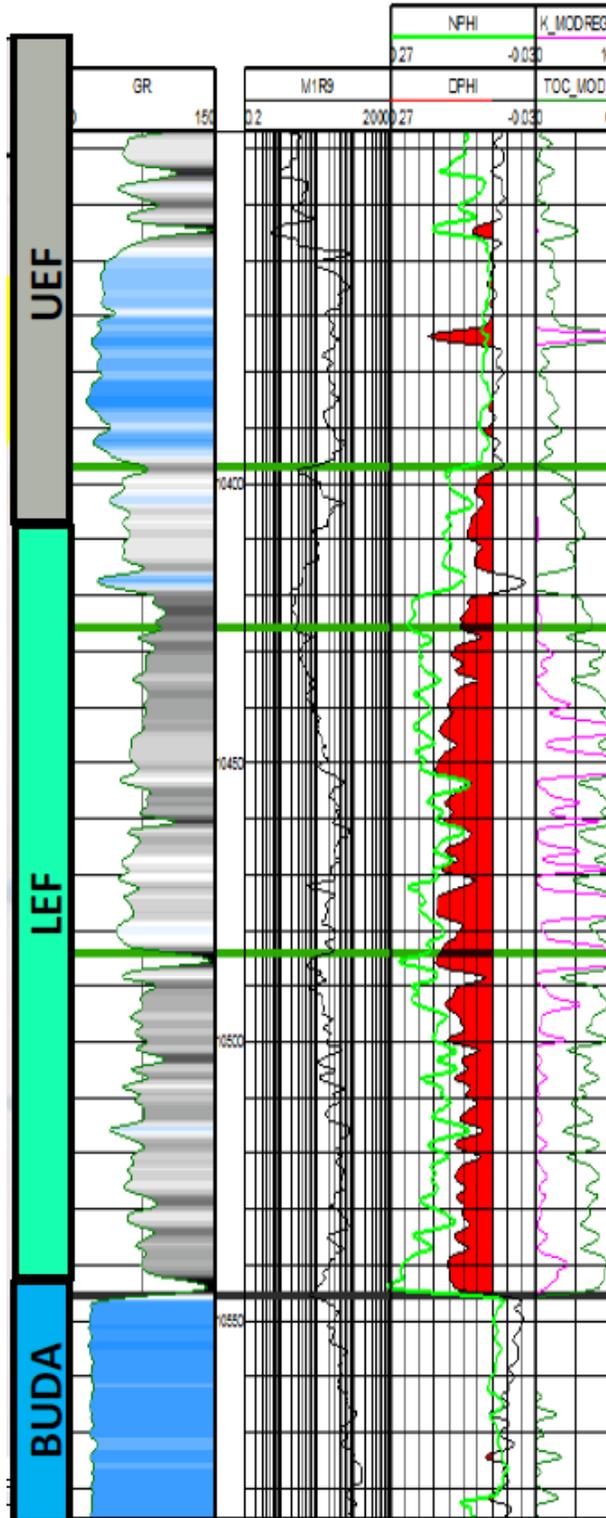
**Exhibit 4-2 Lower Eagle Ford Shale Isopach, Hawkville Trough**



Source: Hendershott, Z. P., 2012.

A published log of the Sanchez Energy Wycross Unit well in the northern McMullen County shows a 150 ft gross interval for the Lower Eagle Ford Shale, with a net-to-gross ratio of about 90 percent, Exhibit 4-3.

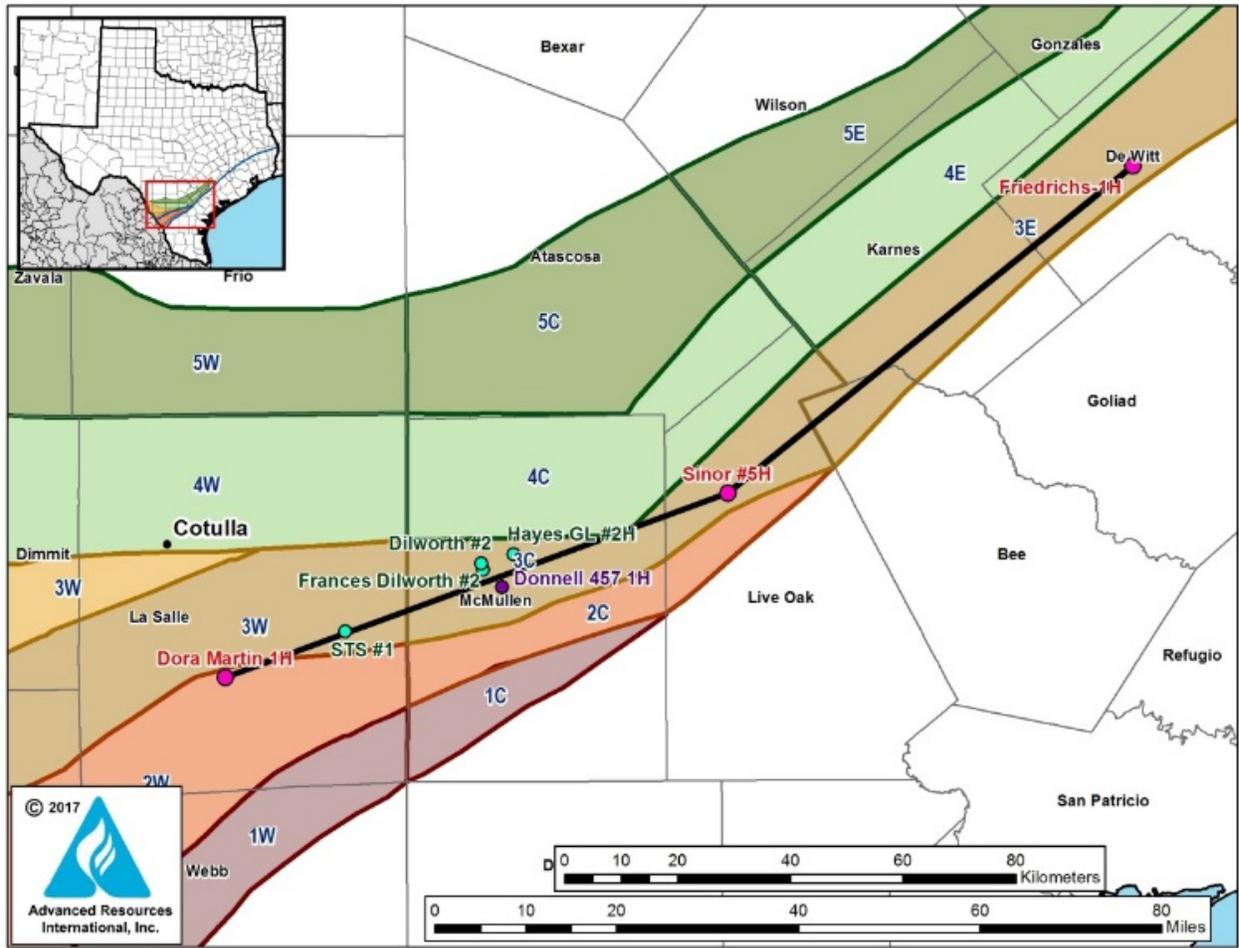
**Exhibit 4-3 Wycross Unit Well Log**



Source: Sanchez Energy, 2014..

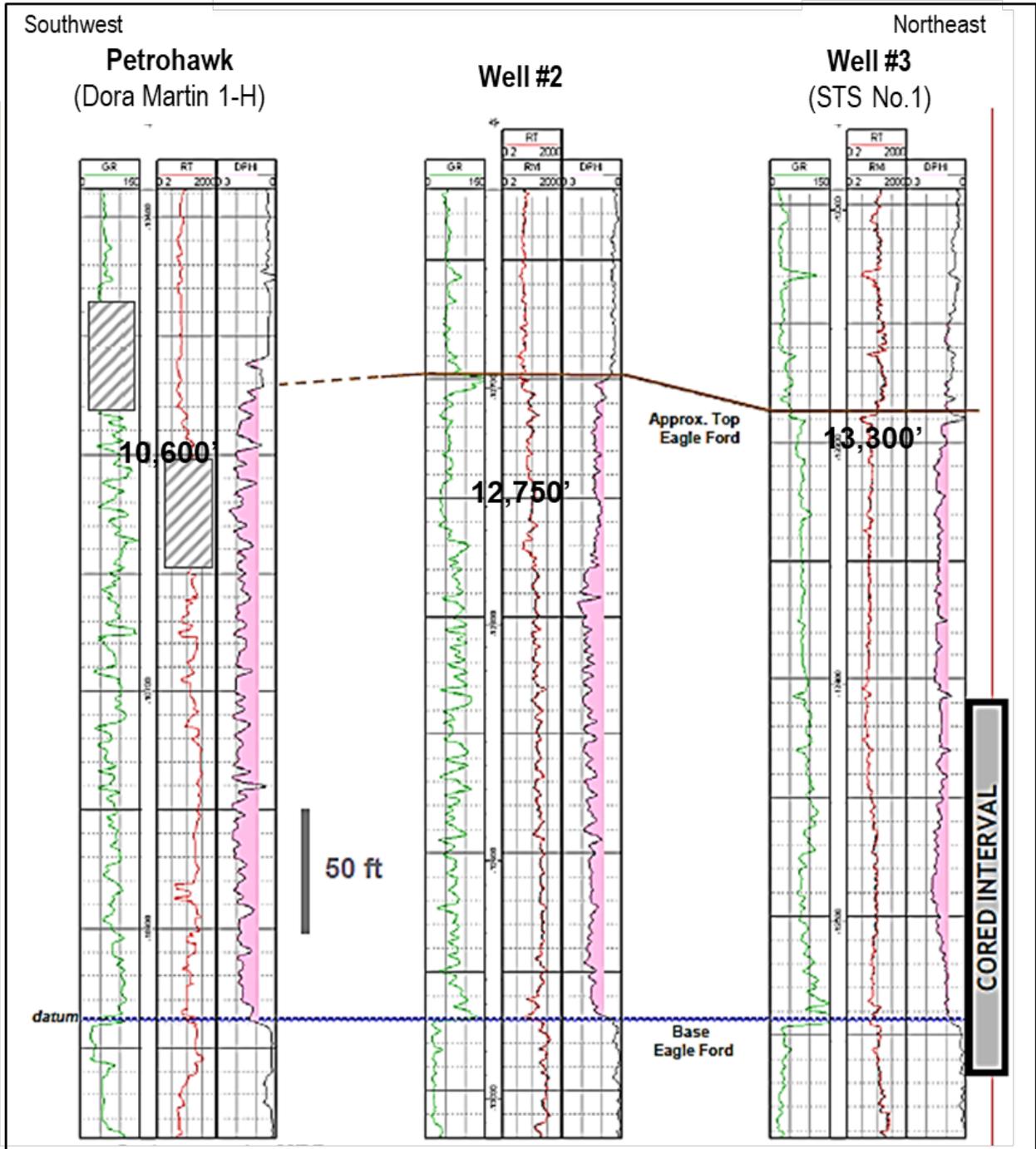
A three well cross-section, traversing across much of the central and eastern portion of the Eagle Ford Shale area, shows gross thickness of about 250 ft with high net-to-gross thickness values, Exhibit 4-4 and Exhibit 4-5.

*Exhibit 4-4 Location of Eagle Ford Shale SW to NE Cross-Section*



Source: Advanced Resources International, 2018.

Exhibit 4-5 Three Well Eagle Ford Shale SW to NE Cross-Section



JAF2019\_009.PPT

Source: Pioneer Natural Resources 2009.

## 4.2 RESERVOIR POROSITY

Information on the porosity of the Eagle Ford Shale is scarce in the technical literature for specific areas of the shale. Particularly challenging is establishing the significant porosity values in the organic portions of the shale. Based on industry published information, the porosity of the Eagle Ford Shale matrix ranges from 8 to 11 percent in the Lower Shale Unit and from 4 to 6 percent in the Upper Shale Unit. The natural fracture system adds about 0.1 percent to the matrix porosity values.

## 4.3 OIL AND WATER SATURATION

Laboratory derived information for the Eagle Ford Shale indicates that the shale, in the oil dominant area, has an initial oil saturation of about 80 percent and an immobile water saturation of about 20 percent. The initial oil saturation in the natural fracture system is estimated to be slightly higher, at about 90 percent. (Gala, D., and Sharma, M. , 2018)

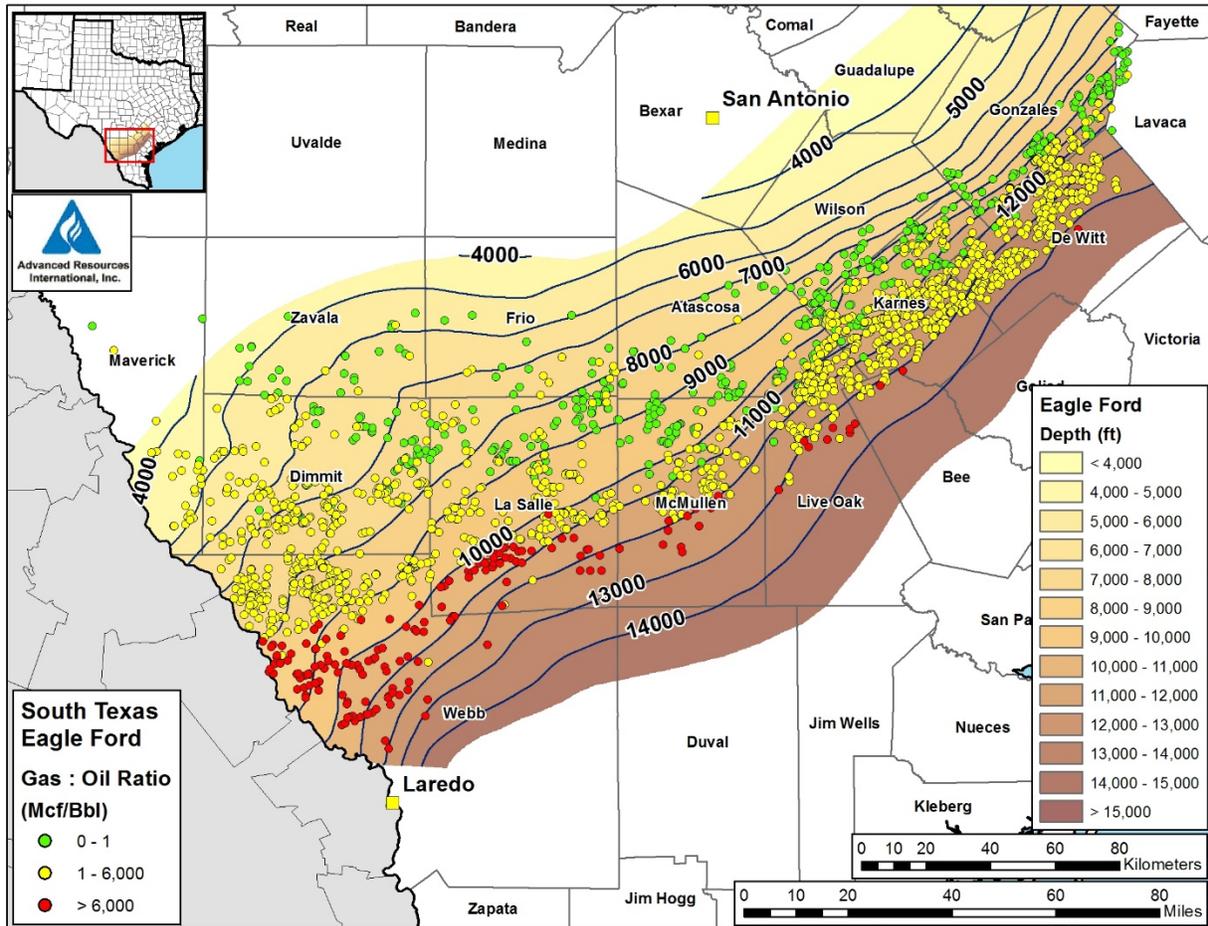
## 4.4 PRODUCING GAS-OIL RATIO

The producing gas-oil ratio of the Eagle Ford Shale changes rapidly in line with its distinct hydrocarbon windows, shown previously on Exhibit 3-5. From a gas-oil ratio of over 6 Mcf/Bbl in the southern wet gas area, the gas-oil ratio declines rapidly from 6 Mcf/Bbl to 1 Mcf/Bbl in the central condensate and volatile oil areas, and to below 1 Mcf/Bbl in the northern light oil area of the Eagle Ford Shale, Exhibit 4-6.

## 4.5 OIL GRAVITY

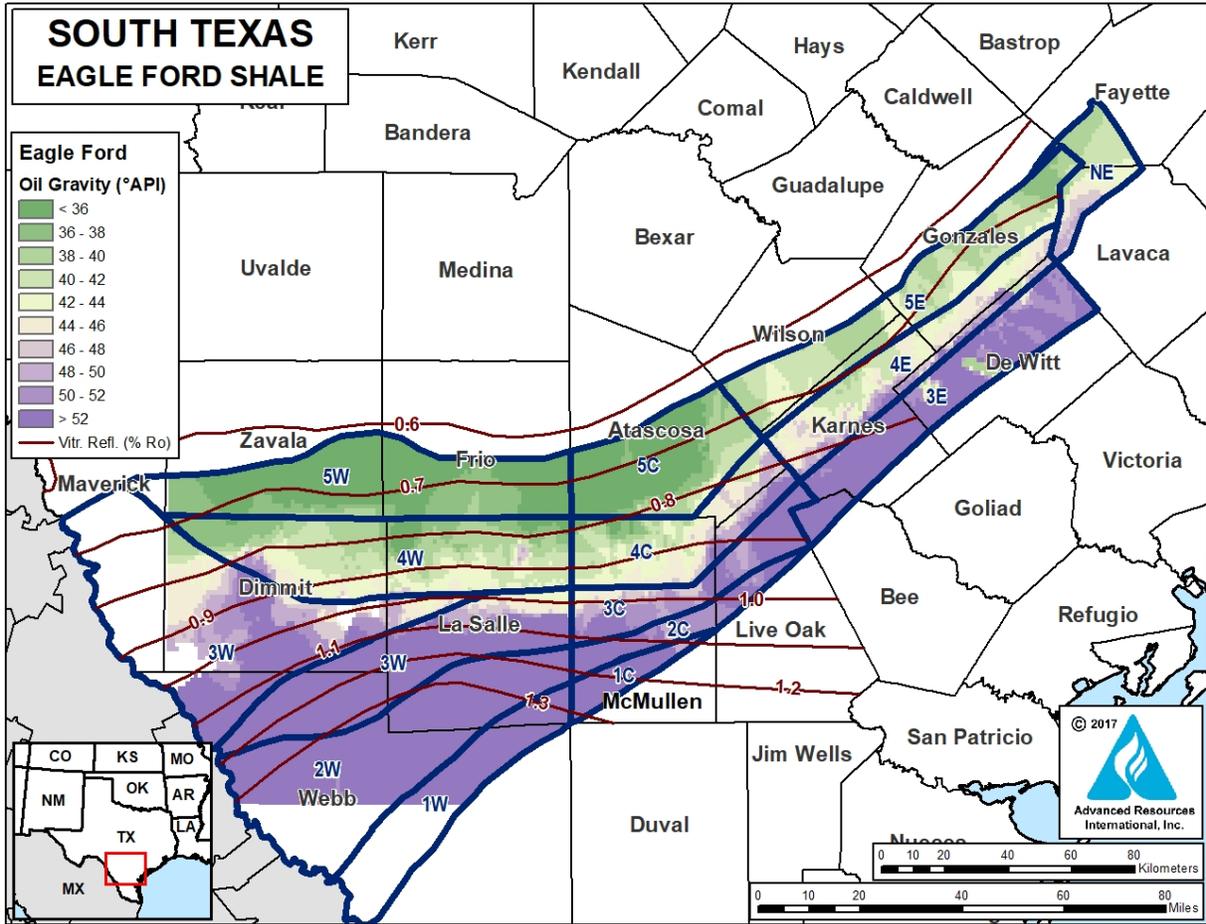
The API gravity of Eagle Ford Shale liquids ranges from light oil of 36 to 42 degrees on the north (volatile and light oil windows) to higher API gravity values, in excess of 50 degrees, in the condensate/wet gas windows on the south, Exhibit 4-7. These values are consistent with the thermal maturity map of the Eagle Ford Shale shown previously on Exhibit 3-9.

**Exhibit 4-6 Eagle Ford Shale Producing Gas-Oil Ratios**



Source: Advanced Resources International, 2018.

Exhibit 4-7 Eagle Ford Shale API Gravity



Source: Advanced Resources International using data from DrillingInfo, 2017.

## 4.6 OIL COMPOSITION

PVT data and oil composition for the Eagle Ford Shale was based on SPE paper 191488 - “Compositional and Geomechanical Effects in Huff-n-Puff Gas Injection IOR in Tight Oil Reservoirs” (Gala and Sharma, 2018). The oil composition is characterized by 14 components for solution gas-oil ratios (GORs) of 500, 1000, 1200 and 2000 scf/Bbl, Exhibit 4-8.

*Exhibit 4-8 Eagle Ford Shale PVT and Oil Composition Data*

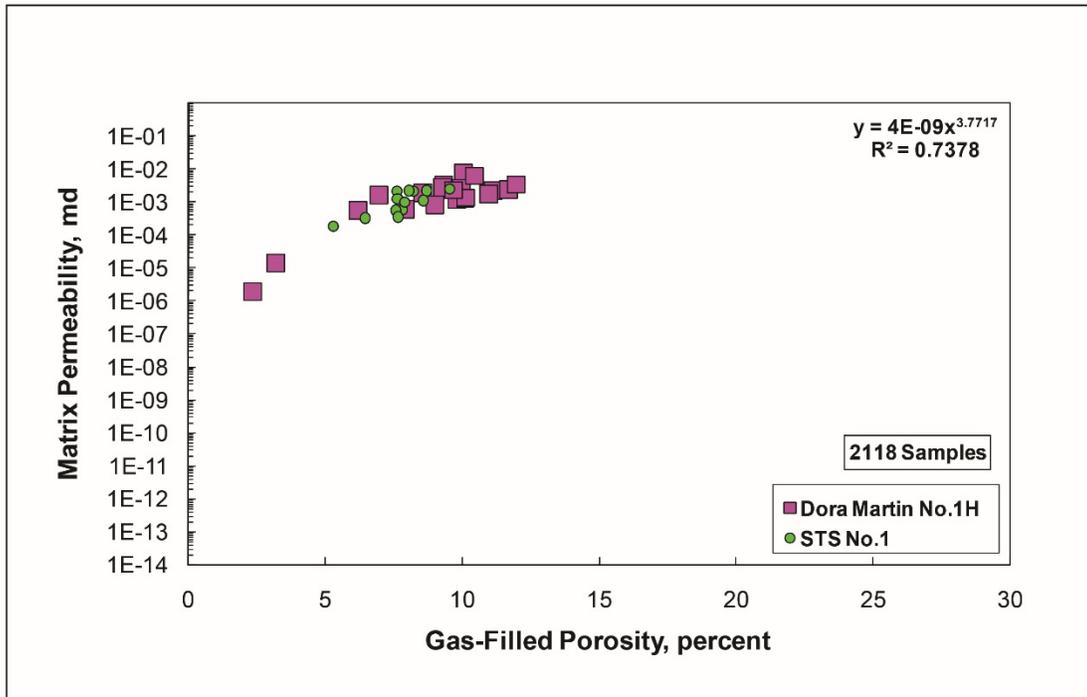
	Solution GOR (scf/Bbl)			
	500	1000	1200	2000
<b>C1</b>	31.231	44.522	47.929	56.447
<b>N2</b>	0.073	0.104	0.112	0.132
<b>C2</b>	4.314	5.882	6.284	7.288
<b>C3</b>	4.148	4.506	4.598	4.827
<b>CO2</b>	1.282	1.821	1.960	2.306
<b>iC4</b>	1.35	1.298	1.285	1.251
<b>nC4</b>	3.382	2.978	2.874	2.615
<b>iC5</b>	1.805	1.507	1.431	1.24
<b>nC5</b>	2.141	1.711	1.601	1.325
<b>nC6</b>	4.623	3.28	2.936	2.076
<b>C7+</b>	16.297	11.563	10.350	7.316
<b>C11+</b>	12.004	8.94	8.078	5.924
<b>C15+</b>	10.044	7.127	6.379	4.509
<b>C20+</b>	7.306	4.762	4.186	2.745

*Source: Modified by Advanced Resources Int'l from Gala, D., and Sharma, M., 2018.*

## 4.7 MATRIX PERMEABILITY

Core analysis of the Dora Martin No. 1H and STS No. 1 wells provides a relationship between gas filled porosity and matrix permeability for the Eagle Ford Shale. At low, 3 to 4 percent, values for gas filled porosity, the shale matrix has low permeability of  $1 \times 10^{-5}$  to  $1 \times 10^{-6}$  md (presumably at ambient conditions). At higher, 8 to 11 percent, values for gas filled porosity, the shale matrix has a permeability of about  $1 \times 10^{-3}$  md.

*Exhibit 4-9 Relationship of Matrix Permeability to Gas Filled Porosity*



Source: Petrohawk, 2009.

## 4.8 RESERVOIR TEMPERATURE

The bottom-hole reservoir temperature of the Eagle Ford Shale correlates with the depth of the shale and can be approximated using the equation:

$$T (\text{°F}) = 70\text{°} + 1.8\text{°}/100 \text{ ft}$$

Based on this equation, a 10,000 ft shale reservoir would have a temperature of about 250°F, consistent with information in the technical literature.

## 4.9 RESERVOIR PRESSURE

The reported pressure gradients for the Eagle Ford Shale range from somewhat overpressured (0.55 psi/ft) along the northern, shallower portions of the shale area to highly overpressured (0.75 psi/ft) in the deeper portions of the shale area. A mid-point pressure gradient of 0.65 psi/ft gives a 10,000 ft shale reservoir a pressure of 6,500 psi.

## 5 ESTIMATES OF ORIGINAL OIL IN-PLACE (OOIP)

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### 5.1 CHALLENGES IN ESTIMATING ORIGINAL OIL IN-PLACE

Given its highly heterogeneous and complex geology, establishing a rigorous estimate for the OOIP in the Eagle Ford Shale is a most challenging task, influenced by numerous uncertainties, including:

- Determining how much of the vertical Lower Eagle Ford Shale interval should be included as net productive pay, given uncertainties about minimum porosity cut-off values typically used for defining net pay.
- Developing reliable estimates for porosity for a resource where a significant portion of the porosity is within the organic content of the shale.
- Arriving at a reasonable value for the areal extent of the oil dominant shale area, given uncertainties as to the dividing line between the oil dominant and the natural gas dominant areas of the shale. Similar uncertainties exist for the northern, shallower limit of the light oil area of the Eagle Ford Shale.
- Establishing appropriate formation volume factors for converting reservoir barrels to stock tank barrels for the highly variable data on solution gas-oil ratios and the compositions of the oil and condensate in the oil dominate areas of the Eagle Ford Shale.

Even with these challenges and uncertainties, developing an estimate for OOIP (admittedly with a considerable error bound) is a useful exercise. It puts into print the assumptions and data used for the OOIP resource estimate. It also provides a placeholder for additional information sharing by industry and researchers on newly collected geologic and reservoir properties for the Eagle Ford Shale.

Our discussions with industry confirm that companies have invested significantly in building in-depth geologic models for their acreage positions in the Eagle Ford and other shale basins. However, so far, only limited portions of this information have been placed into the public domain.

### 5.2 SOURCES OF INFORMATION FOR OOIP RESOURCE ESTIMATE

Our OOIP resource estimate for the Eagle Ford Shale is based on the following set of information sources assembled for this Basin Study:<sup>i</sup>

- Assembly of information from prior well completion and other reports to establish data on formation tops and the gross interval for the Eagle Ford Shale.
- Review of information, in various prior studies and technical reports, on geologic and reservoir properties published for the Eagle Ford Shale.

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<sup>i</sup> A great bulk of the information on Eagle Ford Shale reservoir properties has been assembled from prior work performed by Advanced Resources International for various clients. Advanced Resources is contributing a portion of this earlier work to this Basin Study. However, the underlying data used to construct the maps in this report is proprietary data work and is not available for public release.

- Compilation of publicly shared industry information on Eagle Ford Shale reservoir properties for selected lease areas provided by industry.

### **5.3 ASSESSMENT METHODOLOGY**

To provide some granularity to the estimates of OOIP, the Basin Study has partitioned the oil dominant portion of the Eagle Ford Shale into Eastern, Central and Western areas. It then further subdivided each of these three geographically established areas into: (1) a condensate/wet gas area; (2) a volatile oil area; and (3) a light oil area, as discussed previously in Section 3.5 of the report, Hydrocarbon Windows. For each area, the study assembled representative volumetric and other reservoir properties essential for estimating OOIP.

First, the study established the areal extent for each of these nine resource assessment units of the Eagle Ford Shale. Then, the study risked these areas assuming that about 80 percent of each assessment unit would be accessible and geologically viable. In the future, a somewhat higher accessibility and viability value may prove to be appropriate for the Eastern shale area and a somewhat lower access and viability value may prove to be appropriate for the Western shale area.

The primary focus is establishing OOIP values for the organically-rich Lower Unit of the Eagle Ford Shale that is the target of current primary recovery efforts and also the likely first target for applying enhanced oil recovery. Future expansions of this Basin Study may add the Upper Unit of the Eagle Ford Shale to the resource assessment.

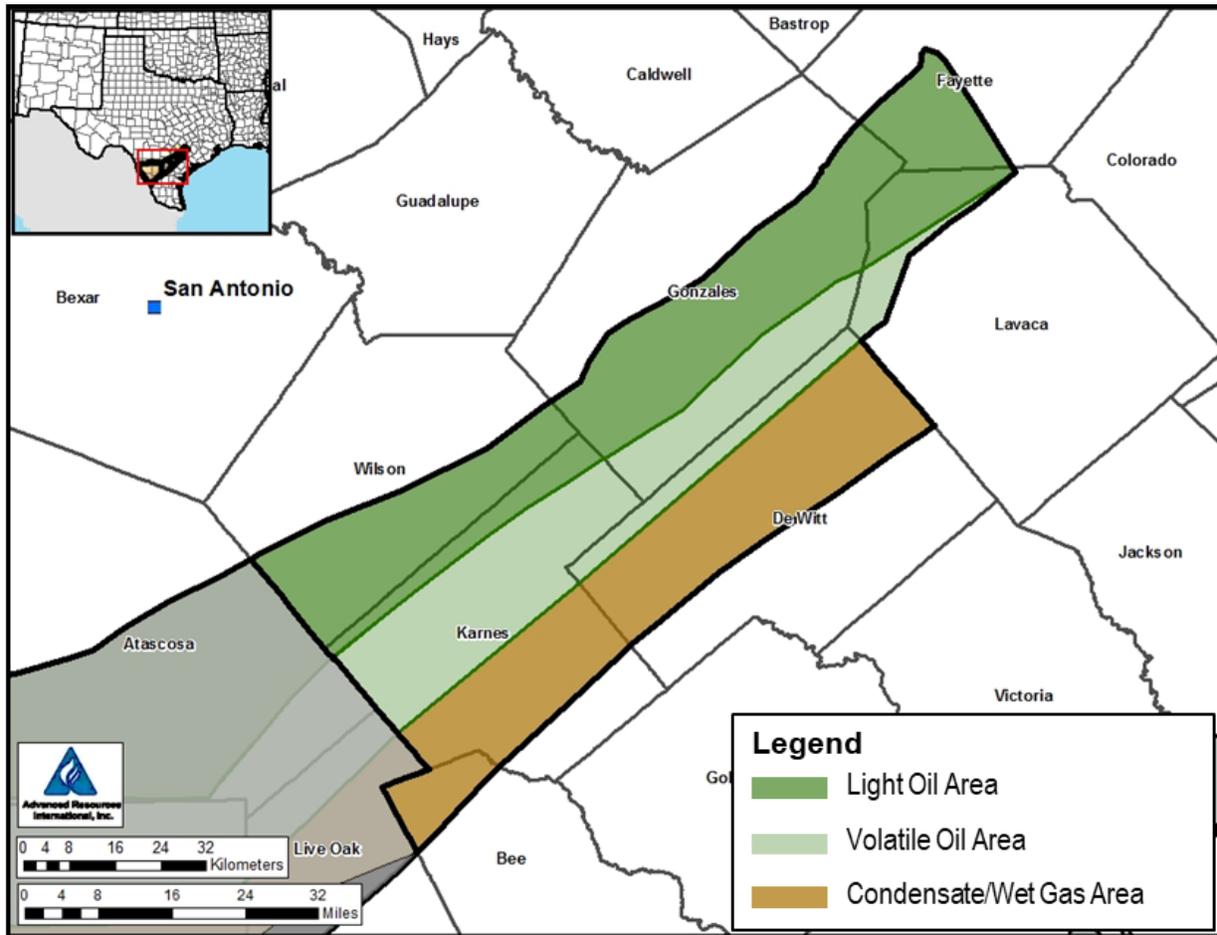
The OOIP resource estimates draw heavily on the series of maps and exhibits provided in the earlier sections of this report. The resource estimates also benefitted from insights and data gained from the reservoir simulation of primary oil recovery for the Central Area of the Eagle Ford Shale discussed previously in Section 5 of this report. Additional geologic and reservoir property information specific to each of the nine resource assessment units in the three geographic areas of the shale – Eastern, Central and Western areas – was assembled from the technical literature.

## 5.4 EASTERN SHALE AREA

The Eastern Area of the oil dominant Eagle Ford Shale extends across 2,250 square miles in Karnes, DeWitt, Gonzales and Wilson counties. Portions of this area, particularly in Karnes and DeWitt counties, have seen extensive well drilling, including a series of highly productive shale wells in the Karnes Trough portion of Karnes County. A total of 6,800 Hz Eagle Ford Shale oil wells have been drilled and completed in the Eastern Area of the Eagle Ford Shale.

The Eastern Shale Area has three parallel trending hydrocarbon windows that range from a condensate (with wet gas) region on the south, a volatile oil region in the center, and a light oil region on the north, Exhibit 5-1.

*Exhibit 5-1 Hydrocarbon Windows of the Eastern Eagle Ford Shale Area*

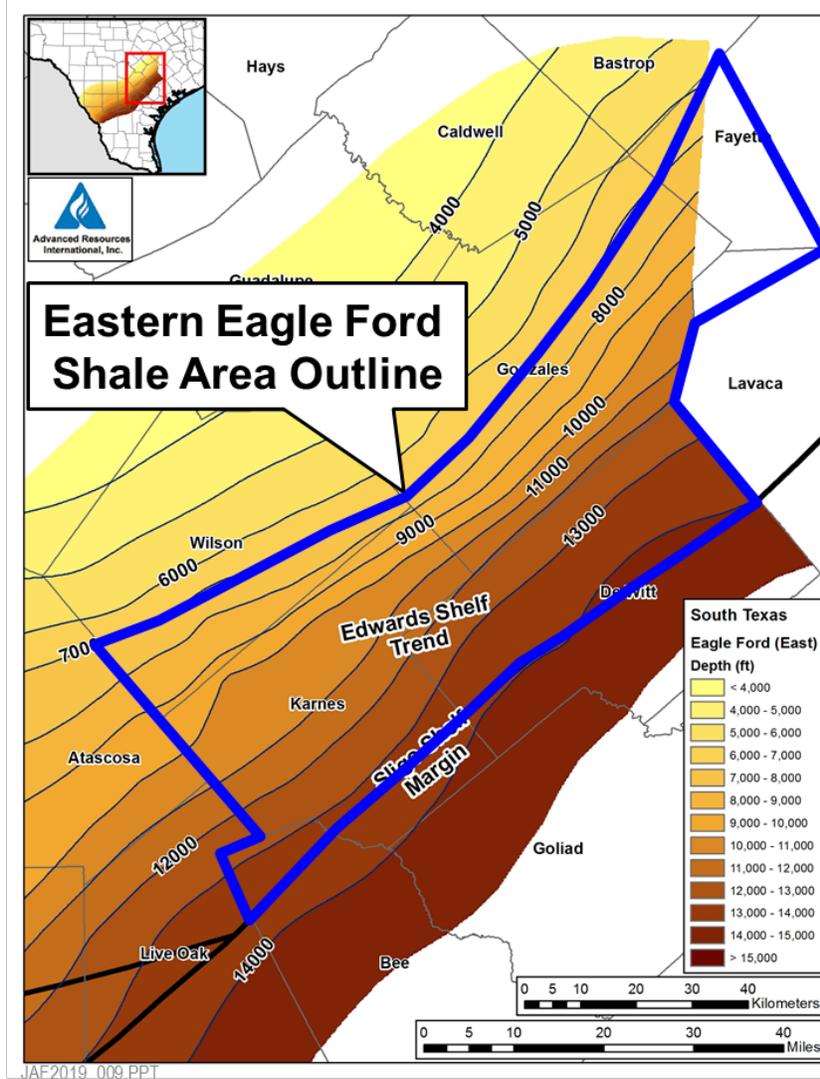


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Source: Advanced Resources International, 2018

The depth of the Eagle Ford Shale in the Eastern Area ranges from about 6,000 ft ~~on~~<sup>in</sup> the north to below 13,000 ft in the south, Exhibit 5-2. Based on lack of well drilling, the study has limited the northern productive limit of the light oil area to the 7,000 ft depth contour and limited the southern productive limit for the condensate/wet gas area to the 14,000 ft depth contour. (Additional potentially productive resource may exist in the shallower areas of the Eagle Ford Shale in Gonzales and Wilson counties and the deeper areas of the Eagle Ford Shale in Karnes and DeWitt counties.)

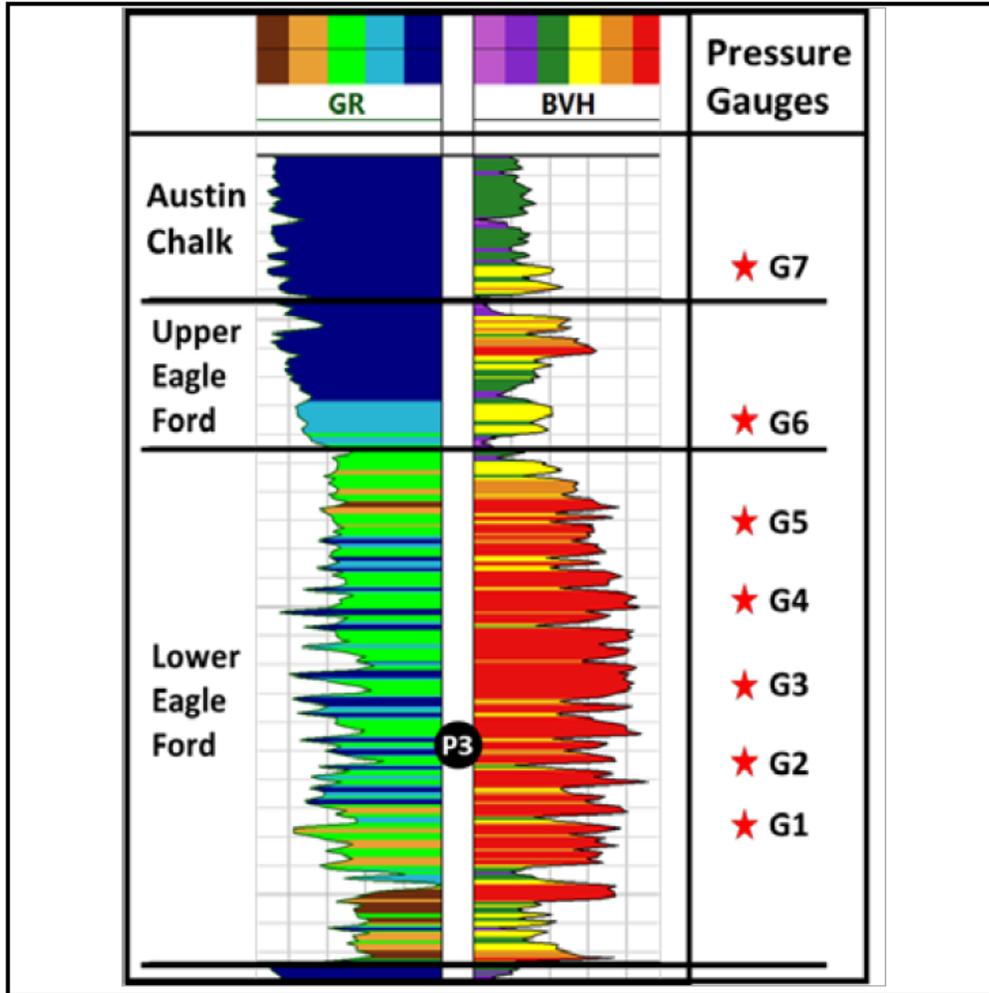
*Exhibit 5-2 Depth Map for the Eastern Eagle Ford Shale Area*



Source: Advanced Resources International, 2018

The type log for the Eastern Eagle Ford Shale Area, located at the border of the condensate/wet gas and volatile oil areas, is provided as Exhibit 5-3. It illustrates the thick and organically rich Lower Unit of the Eagle Ford Shale. Exhibit 5-3 also illustrates a thinner, lower organic Upper Shale Unit not included in the resource assessment.

*Exhibit 5-3 Type Log for the Eastern Area Eagle Ford Shale*



Eagle Ford type log showing gamma ray (GR) colored by volume carbonate and calculated bulk volume hydrocarbon (BVH).

*Source: Raterman, K. T. et al., 2017*

The net pay for the Lower Shale Unit in the Eastern Shale area ranges from 100 to 150 ft. Reservoir porosity is estimated at 10 percent, with a matrix oil saturation of 80 percent. Given the highly variable solution gas-oil ratios, ranging from 0.7 Mcf/B to 5 Mcf/B, and the considerable differences in reservoir pressure and temperature, the formation volume factors range from 1.38 to 2.5 RB/STB.

Exhibit 5-4 provides the volumetric and other reservoir properties representative of the three hydrocarbon windows and resource assessment units of the Eastern Eagle Ford Shale Area.

**Exhibit 5-4 Eastern Area Reservoir Properties Used for Estimating OOIP for the Lower Unit of the Eagle Ford Shale**

Reservoir Property	Condensate/ Wet Gas Area	Volatile Oil Area	Light Oil Area
Risked Area	560 mi <sup>2</sup>	530 mi <sup>2</sup>	710 mi <sup>2</sup>
Average Depth	13,000 ft	10,500 ft	9,000 ft
Net Pay (Lower Shale Unit)	150 ft	120 ft	100 ft
Porosity (Lower Shale Unit)			
▪ Matrix	10%	10%	10%
▪ Fracture	0.1%	0.1%	0.1%
Oil Saturation			
▪ Matrix	80%	80%	80%
▪ Fracture	90%	90%	90%
Formation Volume Factor (RB/STB)	2.5	1.69	1.38
Solution GOR (Mcf/B)	5.0	1.3	0.7

Source: Advanced Resources International, 2018

Using the volumetric reservoir properties on Exhibit 5-4, the OOIP for the Lower Shale Unit of the Eastern Eagle Ford Shale Area is estimated at 48,600 million barrels, Exhibit 5-5.

**Exhibit 5-5 OOIP of Lower Shale Unit, Eastern Eagle Ford Shale Area**

Shale Areas	Risked Area (mi <sup>2</sup> )	Resource Concentration (MMB/mi <sup>2</sup> )	Oil/Condensate OOIP (Million Barrels)
▪ Condensate/Wet Gas	560	23.8	13,300
▪ Volatile Oil	530	28.2	14,900
▪ Light Oil	710	28.8	20,400
<b>Total</b>			<b>48,600</b>

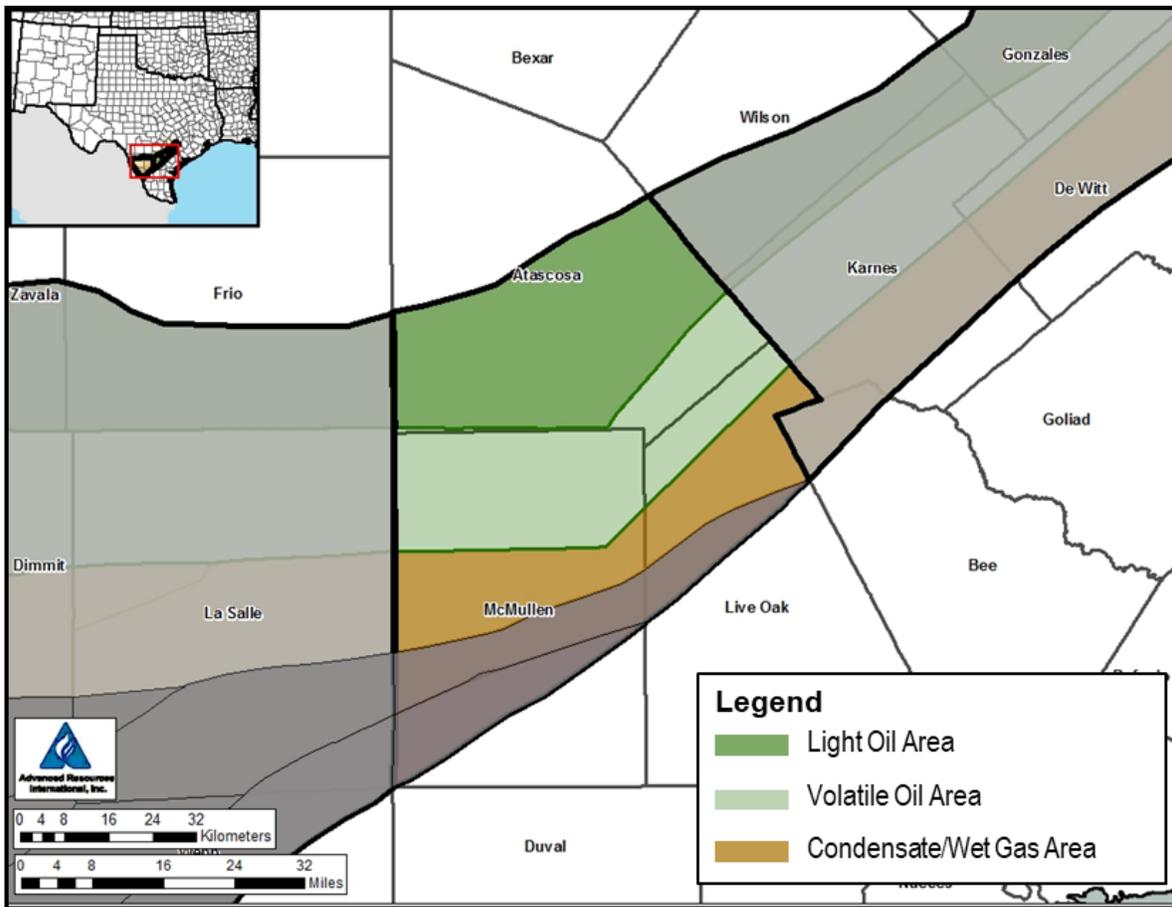
Source: Advanced Resources International, 2018

## 5.5 CENTRAL SHALE AREA

The Central Area of the oil dominant Eagle Ford Shale extends across 1,590 square miles, in Atascosa, Live Oak and McMullen counties. A total of 3,400 Hz Eagle Ford Shale oil wells, many of them recently placed on-line, have been drilled and completed in this three-county area.

The Central Shale Area, like the Eastern Shale Area, has three parallel trending hydrocarbon windows that range from condensate (with wet gas) on the south, volatile oil in the center, and light oil on the north, Exhibit 5-6.

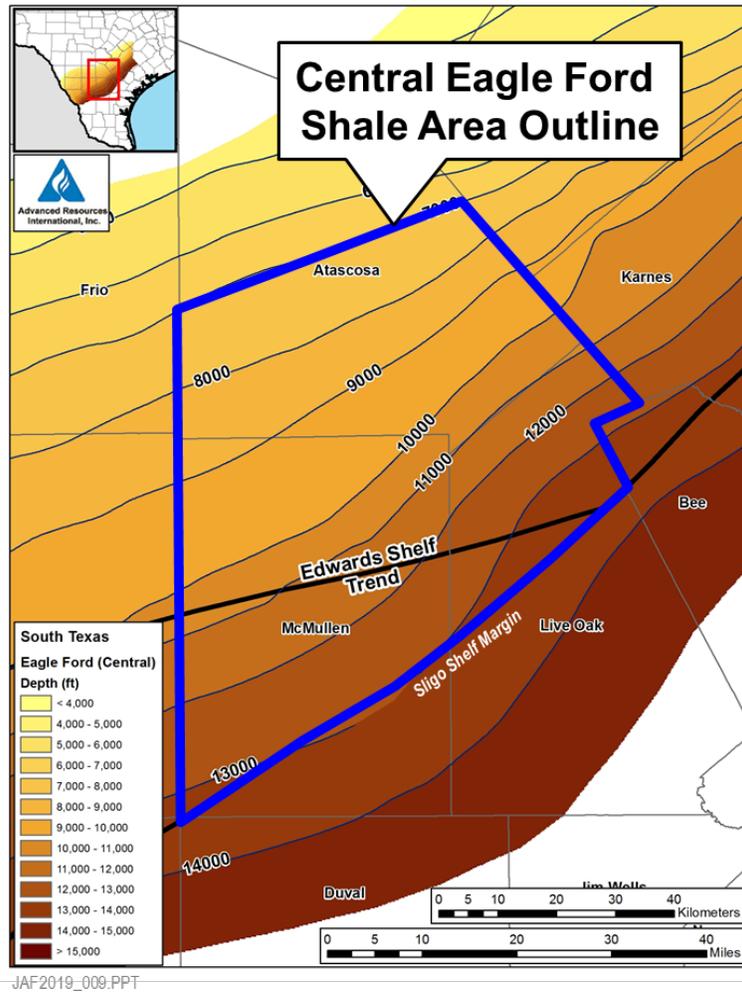
*Exhibit 5-6 Hydrocarbon Windows of the Central Eagle Ford Shale Area*



*Source: Advanced Resources International, 2018*

The depth of the Eagle Ford Shale in the Central Area ranges from about 6,000 ft on the north to 13,000 ft on the south, Exhibit 5-7. Based on lack of well drilling, the study has limited the northern productive limit of the light oil area to the 7,000 ft depth contour. (Additional potentially productive resources may exist in the shallower areas of the Eagle Ford Shale in Atascosa County.)

**Exhibit 5-7 Depth Map for Central Eagle Ford Shale Area**

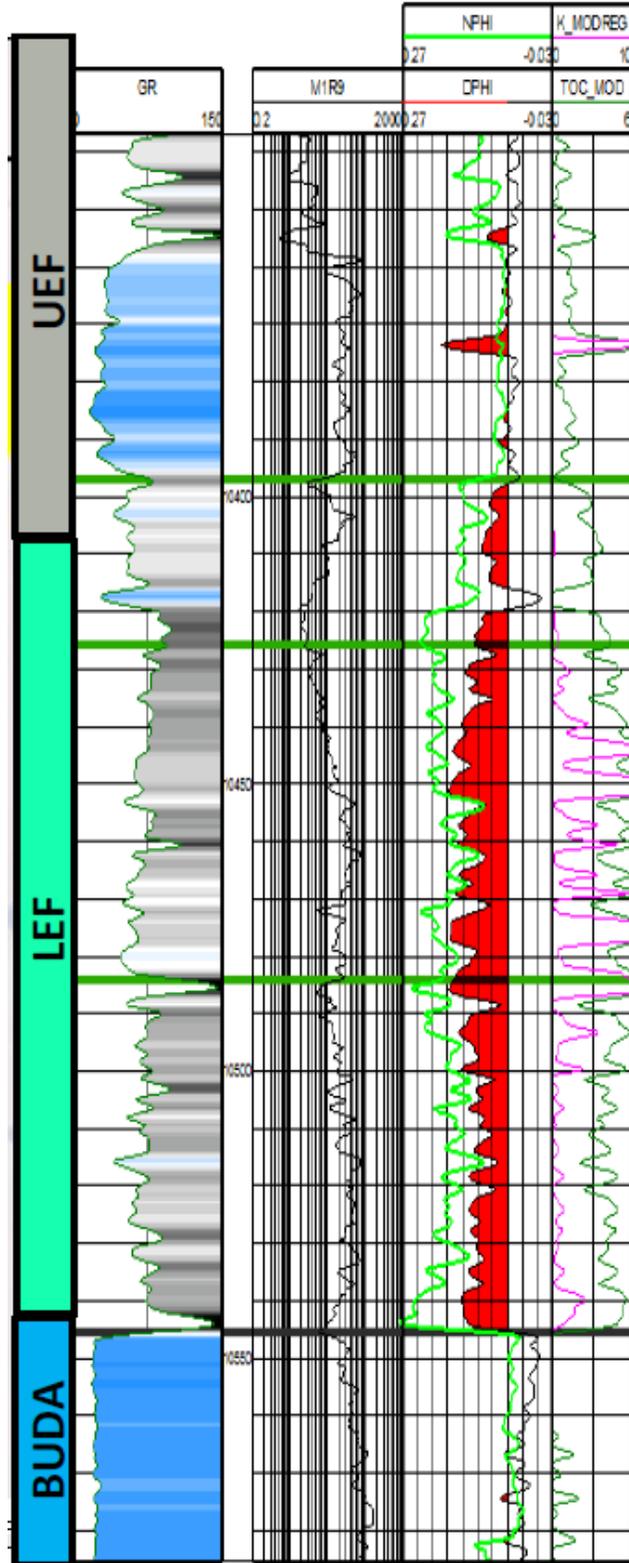


Source: Advanced Resources International, 2018

The type log for the Central Eagle Ford Shale Area, located in northern McMullen County, has a Lower Eagle Ford net pay of about 120 ft, along with a thinner and lower TOC Upper Eagle Ford Unit, Exhibit 5-8.

The gross interval of the Eagle Ford Shale in the Central Area ranges from about 200 ft in central McMullen County to about 100 ft in central Atascosa County. The bulk of the net pay is in the Lower Eagle Ford Shale Unit. Reservoir porosity is estimated at 10 percent, with a matrix oil saturation of 80 percent. Given the solution gas-oil ratio of 0.6 Mcf/B to 4 Mcf/B, and the considerable differences in reservoir pressure and temperature, the formation volume factors range from 1.33 to 2.1 RB/STB.

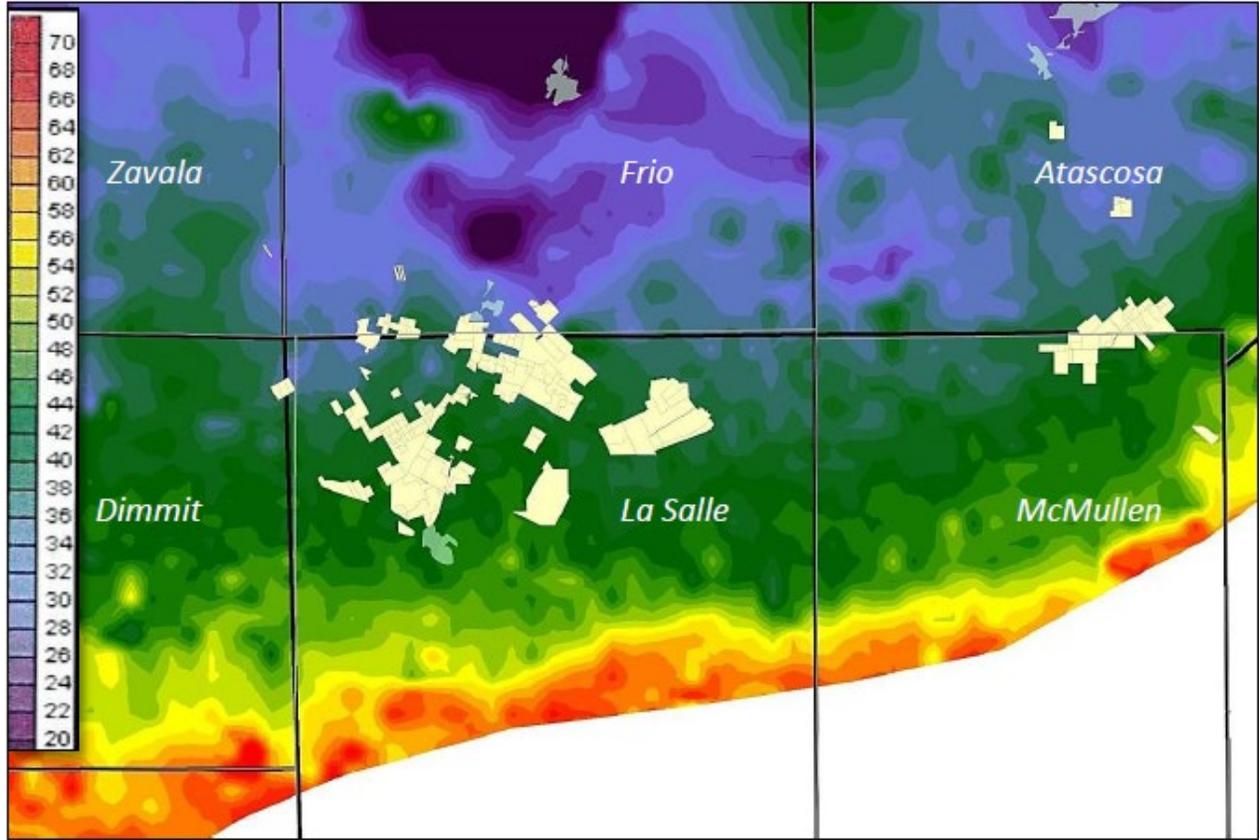
*Exhibit 5-8 Sanchez Energy Wycross Well, Northern McMullen County*



Source: Sanchez Energy, 2014.

Exhibit 5-9 shows the rapid change in the oil gravity from condensate with a gravity of over 60° API in central McMullen County to a light oil with a gravity of 30° to 40° API in central Atascosa County.

*Exhibit 5-9 API Gravity for Central and Western Eagle Ford Shale*



*Source: Carrizo Oil & Gas using Drilling Info initial completion reports (2017)*

Exhibit 5-10 provides the volumetric and other reservoir properties representative of the three hydrocarbon windows and resource assessment units of the Central Eagle Ford Shale Area.

***Exhibit 5-10 Central Area Reservoir Properties Used for Estimating OOIP for the Lower Unit of the Eagle Ford Shale***

Reservoir Property	Condensate/ Wet Gas Area	Volatile Oil Area	Light Oil Area
Risked Area	320 mi <sup>2</sup>	460 mi <sup>2</sup>	490 mi <sup>2</sup>
Average Depth	12,000 ft	10,000 ft	8,500 ft
Net Pay (Lower Shale Unit)	150 ft	120 ft	80 ft
Porosity (Lower Shale Unit)			
▪ Matrix	10%	10%	10%
▪ Fracture	0.1%	0.1%	0.1%
Oil Saturation			
▪ Matrix	80%	80%	80%
▪ Fracture	90%	90%	90%
Formation Volume Factor (RB/STB)	2.4	1.64	1.36
Solution GOR (Mcf/B)	4.5	1.2	0.65

Source: Advanced Resources International, 2019

Using the volumetric reservoir properties on Exhibit 5-10, the OOIP for the Lower Shale Unit of the Central Eagle Ford Shale Area is estimated at 32,700 million barrels, Exhibit 5-11.

***Exhibit 5-11 OOIP of Lower Shale Units, Central Eagle Ford Shale Area***

Risked Shale Area	Risked Area (mi <sup>2</sup> )	Resource Concentration (MMB/mi <sup>2</sup> )	Oil/Condensate OOIP (Million Barrels)
▪ Condensate/Wet Gas	320	24.8	7,900
▪ Volatile Oil	460	29.1	13,400
▪ Light Oil	490	23.4	11,400
<b>Total</b>			<b>32,700</b>

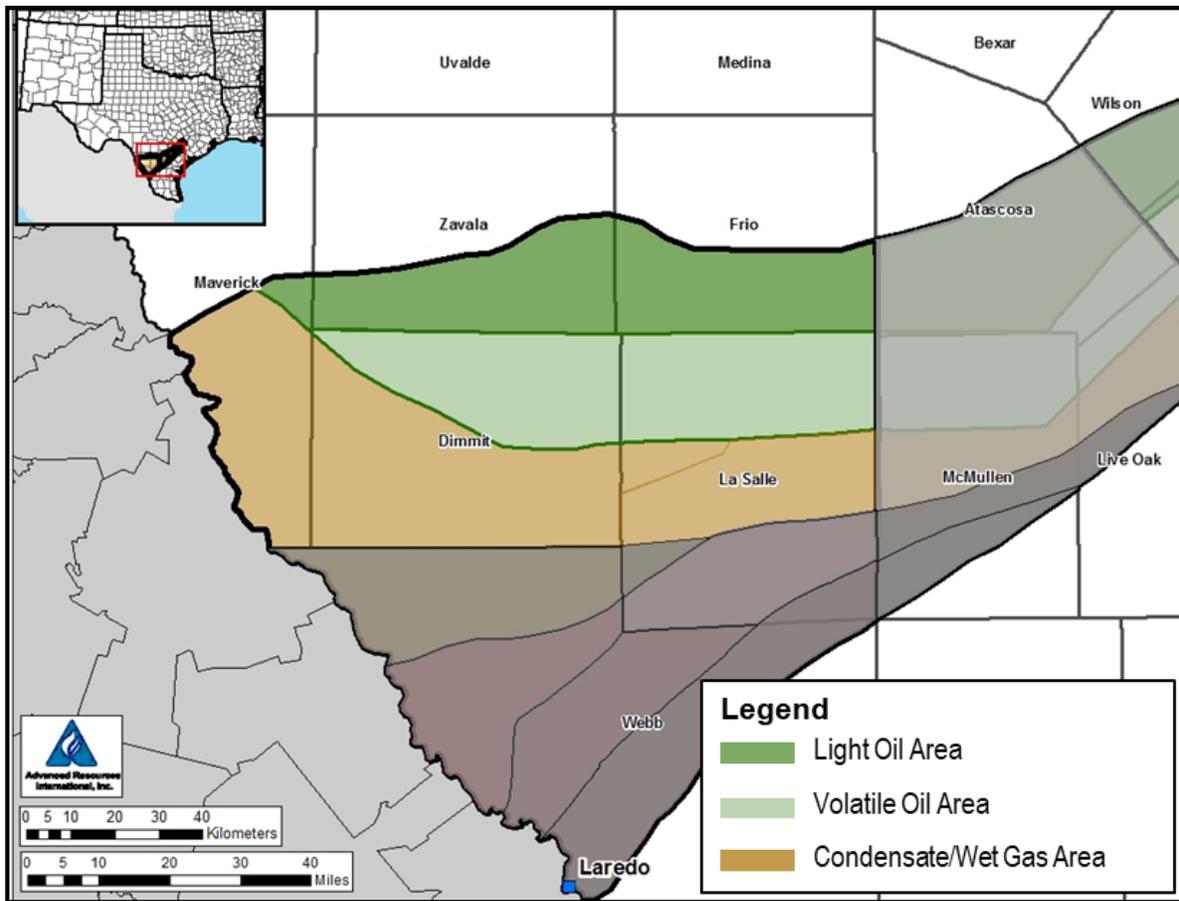
Source: Advanced Resources International, 2018

## 5.6 WESTERN SHALE AREA

The Western Area of the oil dominant Eagle Ford Shale extends across 3,420 square miles, in Dimmit, LaSalle, Frio, Zavala and Maverick counties. A total of 6,000 Hz Eagle Ford Shale oil wells have been drilled and completed in this large, five-county area.

The Western Shale Area, like the Eastern and Central Shale Areas, has three parallel trending hydrocarbon windows that range from condensate (with wet gas) on the south, volatile oil in the center, and light oil on the north, Exhibit 5-12.

*Exhibit 5-12 Hydrocarbon Windows of Western Eagle Ford Shale Area*

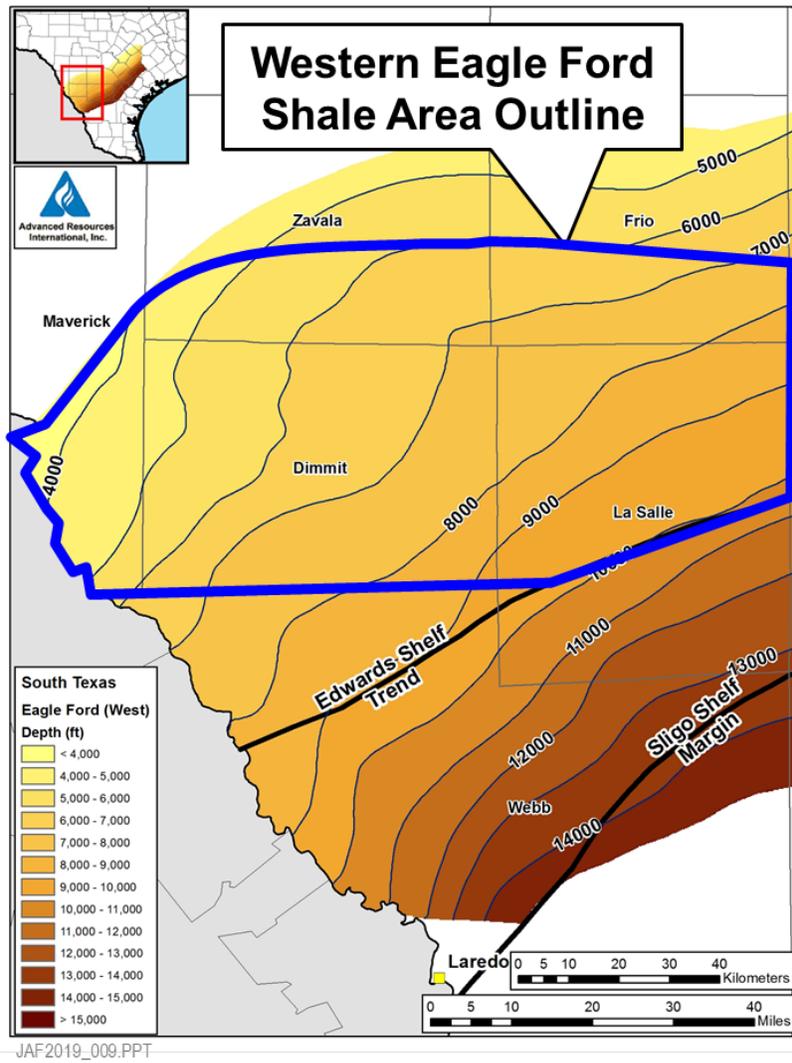


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*Source: Advanced Resources International, 2019*

The depth of the oil dominant Eagle Ford Shale in the Western Area ranges from about 6,000 ft on the north to about 10,000 ft on the south, Exhibit 5-13. Based on lack of well drilling data, the study has limited the productive limit of the light oil area to southern portions of Frio, Zavala and Maverick counties.

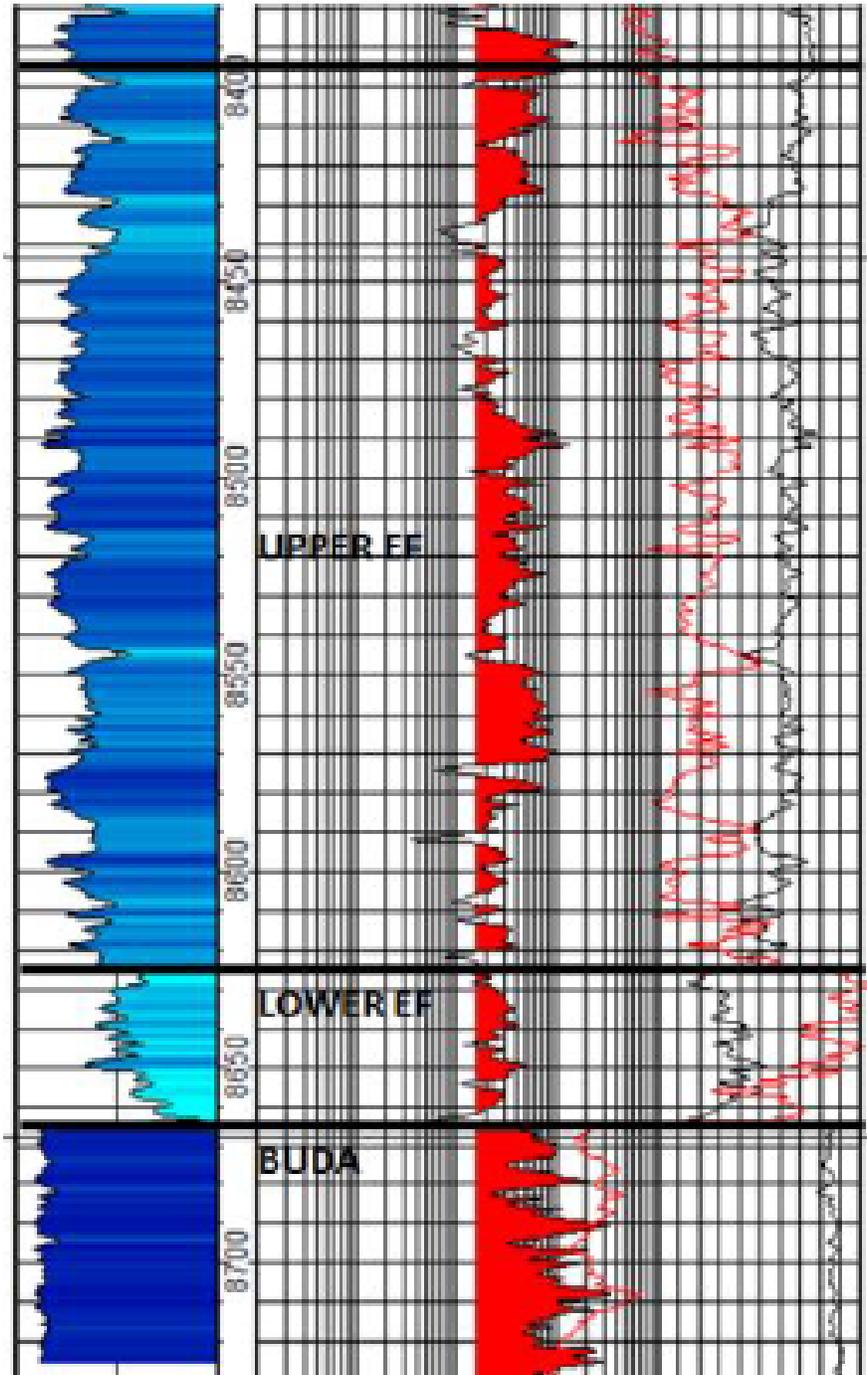
*Exhibit 5-13 Depth Map for Western Eagle Ford Shale Area*



*Source: Advanced Resources International, 2018*

The gross interval of the Eagle Ford Shale thickens dramatically in the Western Shale Area. However, much of this thicker interval is the lower TOC Upper Eagle Ford Shale. While the Upper Eagle Ford Shale in the Western Dimmit County portion of the Eagle Ford Shale may have development potential, this Shale Unit has not been included in the resource estimates provided in this Basin Report, Exhibit 5-14. The study estimates a net pay for the Lower Eagle Ford Shale in the Western Shale Area of 80 to 120 ft. Reservoir porosity is estimated at 8 percent, with a matrix oil saturation of 80 percent. The solution gas-oil ratios range from 0.6 to 4 Mcf/B, linked to formation volume factors that range from 1.33 to 2.1 RB/STB.

*Exhibit 5-14 Western Catarina Well Log, Western Dimmit County*



Source: Sanchez Energy, 2014.

Exhibit 5-15 provides the volumetric and other reservoir properties representative of three hydrocarbon windows and resource assessment units of the Western Eagle Ford Shale Area.

**Exhibit 5-15 Western Area Reservoir Properties Used for Estimating OOIP for the Lower Unit of the Eagle Ford Shale**

Reservoir Property	Condensate/ Wet Gas Area	Volatile Oil Area	Light Oil Area
Risked Area	1,420 mi <sup>2</sup>	849 mi <sup>2</sup>	800 mi <sup>2</sup>
Average Depth	8,500 ft	7,500 ft	6,500 ft
Net Pay (Lower Shale Unit)	120 ft	100 ft	80 ft
Porosity (Lower Shale Unit)			
▪ Matrix	8%	8%	8%
▪ Fracture	0.1%	0.1%	0.1%
Oil Saturation			
▪ Matrix	80%	80%	80%
▪ Fracture	90%	90%	90%
Formation Volume Factor (RB/STB)	2.1	1.58	1.33
Solution GOR (Mcf/B)	4.0	1.1	0.6

Source: Advanced Resources International, 2019

Using the volumetric reservoir properties on Exhibit 5-15, the OOIP for the Lower Shale Unit of the Western Eagle Ford Shale area is estimated at 58,000 million barrels, Exhibit 5-16.

**Exhibit 5-16 OOIP of Lower Shale Unit, Western Eagle Ford Shale Area**

Shale Area	Risked Area (mi <sup>2</sup> )	Resource Concentration (MMB/mi <sup>2</sup> )	Oil/Condensate OOIP (Million Barrels)
▪ Condensate/Wet Gas	1,420	18.2	25,800
▪ Volatile Oil	840	20.1	16,900
▪ Light Oil	800	19.1	15,300
<b>Total</b>			<b>58,000</b>

Source: Advanced Resources International, 2018

## 5.7 TOTAL EAGLE FORD SHALE AREA

Combining OOIP estimates for the nine resource assessment units within the three geographic Eagle Ford Shale Areas – the Eastern Shale Area, the Central Shale Area and the Western Shale

Area – the study estimates an overall risked OOIP value for the Lower Unit of the Eagle Ford Shale of 139,300 million barrels, Exhibit 5-17. With continued use of primary recovery, less than 10 percent of this large oil resource will be technically recoverable.

**Exhibit 5-17 Summary OOIP of the Eagle Ford Shale Area**

Shale Areas	Risked Area (mi <sup>2</sup> )	Resource Concentration (MMB/mi <sup>2</sup> )	Oil/Condensate OOIP (Million Barrels)
<b>Lower Shale Unit, Eastern Eagle Ford Shale Area</b>			
▪ Condensate/Wet Gas	560	23.8	13,300
▪ Volatile Oil	530	28.2	14,900
▪ Light Oil	710	28.8	20,400
<b>Sub-Total</b>			<b>48,600</b>
<b>Lower Shale Units, Central Eagle Ford Shale Area</b>			
▪ Condensate/Wet Gas	320	24.8	7,900
▪ Volatile Oil	460	29.1	13,400
▪ Light Oil	490	23.4	11,400
<b>Sub-Total</b>			<b>32,700</b>
<b>Lower Shale Unit, Western Eagle Ford Shale Area</b>			
▪ Condensate/Wet Gas	1,420	18.2	25,800
▪ Volatile Oil	840	20.1	16,900
▪ Light Oil	800	19.1	15,300
<b>Sub-Total</b>			<b>58,000</b>
<b>Total OOIP</b>			<b>139,300</b>

*Source: Advanced Resources International, 2018*

Reservoir simulation, involving the use of volumetric data for OOIP developed in this report and history matching of Eagle Ford Shale oil production, provided a primary recovery efficiency of 8 percent for the Lower Shale in the Central Shale Area. This work, performed by Advanced Resources International with sponsorship by U.S. DOE/NETL is provided in a separate report entitled “Reservoir Simulation of Enhanced Tight Oil Recovery: Eagle Ford Shale.”

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