The Tuscaloosa Marine Shale: Geologic History, Depositional Analysis, and Exploration Potential

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The Tuscaloosa Marine Shale: Geologic History, Depositional Analysis, and Exploration Potential

By
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Presented to the Faculty of the Graduate School of
Stephan F. Austin State University
In Partial Fulfillment of the Requirements

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The Tuscaloosa Marine Shale: Geologic History, Depositional Analysis, and Exploration Potential

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ABSTRACT

The Tuscaloosa Marine Shale (TMS) was deposited across southern Louisiana and Mississippi during the Upper Cretaceous. The study focuses on a core region containing vast deposits of Cretaceous-aged sediments that have economic importance for oil and gas exploration. This region has been conventionally drilled for decades, focusing on the recovery of the Cretaceous hydrocarbons. Explorers within this region had traditionally targeted the massive sand units of the Lower and Upper Tuscaloosa Group while neglecting the middle Tuscaloosa Marine Shale unit. With the onset of unconventional drilling technology, new explorers to the region have begun to delineate the Tuscaloosa Marine Shale’s capability for commercial production requiring a more detailed geologic investigation of how this area formed and what factors lend to the viability of this region. This study evaluated the geologic history and formation of the Tuscaloosa Group sediments within the core of the producing basin. Petrophysical logs were used to evaluate the complexity of the study area and the formations depositional features. The data from these logs were used to analyze the structure of the shale unit to develop structural maps of the Lower Tuscaloosa Formation and the Tuscaloosa Marine Shale.

The analyses of this study found that the Tuscaloosa Marine Shale exhibited a relatively stable deposition across the study area, consisting of sediments high in clay and mica content. The Tuscaloosa Group represents a full transgressive-regressive cycle
directly influencing the deposition of a basal massive sand unit, followed by the deposition of marine shale on a large shelf environment capped with the deposition of sands as the ocean transgressed seaward. The Tuscaloosa Marine Shale was found to have localized depositional variance generated from regional tectonic events coupled with the influx of terrigenous sediments from multiple deltas contributing to the prograding oceanfront.

The study area yields high economic significance for further hydrocarbon exploration given the estimates of a seven billion barrel resource potential within the Tuscaloosa Marine Shale unit. New unconventional technology in the industry will allow for this area to be better delineated given the deeper depths to the shale unit and will allow for greater extraction volumes to occur. Studies similar to this report allow for petroleum explorers and others to gain the geologic insight needed in order to more accurately pinpoint target areas for new drilling to take place in an otherwise expanding region.
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INTRODUCTION

The Tuscaloosa Marine Shale (TMS) was deposited near the coast of southern Louisiana and into western Mississippi (Figure 1.0.1) during the Cenomanian to Turonian stage of the Upper Cretaceous, approximately 95-89 million years ago (Mancini and Puckett, 2002). The Tuscaloosa Group is comprised of three main units, the Lower Tuscaloosa Formation, the Tuscaloosa Marine Shale, and the Upper Tuscaloosa Formation. The Tuscaloosa Marine Shale is the middle unit of the larger Tuscaloosa Group and is known as an unconventional source of crude oil.

The Tuscaloosa Group is bounded above by an unconformable surface before proceeding to the deposition of the Eutaw Formation. The lower boundary of the Tuscaloosa Group is marked by a subaerial unconformity that is thought to have lasted approximately one million years, during which the Lower Cretaceous Washita Group was subaerially exposed prior to the deposition of the Lower Tuscaloosa Formation (Figure 1.0.2) (Mancini and Puckett, 2002).

The deposition of the full Tuscaloosa Group represents a complete succession of a transgressive-regressive cycle. This depositional event is recognized as the fifth transgressive-regressive cycle recorded in the Gulf of Mexico basin, more commonly referred to as the T-R 5 cycle (Mancini and Puckett, 2002). The Lower Tuscaloosa
Massive Sands represent the transgressive phase as the beach front aggraded onto the coastal plain. The middle Tuscaloosa Marine Shale, and a portion of the sandstones beneath, signify the back-stepping phase of the cycle (Mancini and Puckett, 2002). The final regressive phase of the cycle is characterized by the deposition of the Upper Tuscaloosa Formation consisting of massive sandstones interbedded with clays and fossil fragments.

**Figure 1.0.1:** Map showing the regional extent of the Tuscaloosa Marine Shale basin within the eastern Gulf of Mexico margin (adapted from John *et al.*, 2005)
**Figure 1.0.2:** Generalized stratigraphic section of the Upper Cretaceous as defined by Mancini and Puckett (2002), the red box highlights the study formation (figure from Mancini and Puckett, 2002).

Hydrocarbon exploration began in the Lower Tuscaloosa massive sandstones in the early 1950’s in southern Alabama (Mancini *et al.*, 1987). Conventional hydrocarbon exploration has led to significant development and infrastructure in place throughout the
regional extent of the Tuscaloosa Group. Recent breakthroughs in unconventional hydrocarbon exploration have led operators to begin exploration within the Tuscaloosa Marine Shale.

Unconventional exploration activity began in the unit with the first successful well targeting the Tuscaloosa Marine Shale in 1978 in Tangipahoa Parish, Louisiana (John et al., 2005). This activity has been gradually increasing in the last decade with the majority beginning in 2014. Estimates have concluded that the Tuscaloosa Marine Shale could provide a seven billion barrel resource of crude oil, as operators perfect drilling techniques in the highly overpressured reservoir (John, et al., 1997). Increasing operational efficiencies and drilling techniques have led major operators across North America to begin the process of hydrocarbon extraction in the Tuscaloosa Marine Shale with the expectation of unlocking the next major shale oil play.

The study area is located across the southern Louisiana border with Mississippi, spanning an area of approximately eight million acres (Figure 1.0.1). The primary objective of this study was to isolate and analyze the Tuscaloosa Marine Shale across southern Louisiana and Mississippi using corresponding well logs to interpret the unit’s depositional history, lithology, stratigraphy, and geomorphological characteristics influencing the shale’s deposition for associated hydrocarbon exploration. The primary objectives for this study include:
1. Evaluation of petrophysical well logs across a selected geographic region of the Tuscaloosa Marine Shale study area;
2. Analysis of stratigraphy using developed cross sections to determine a depositional history and patterns;
3. Analysis of the sedimentology of the Tuscaloosa Marine Shale from cross-section and stratigraphic evaluation;
4. Evaluation of the deposition of the Tuscaloosa Marine Shale from generated stratigraphic and structural cross sections;
5. Determination of hydrocarbon exploration potential through percentage of shale content from the analyses of sedimentological and structural variations.
Geologic History

The Tuscaloosa Marine Shale (TMS) was deposited along the Gulf Coast region of the continental United States during the Upper Cretaceous within the Cenomanian-Turonian Stage approximately 94-92 million years ago. The Tuscaloosa Marine Shale has recently garnered much attention in unconventional hydrocarbon exploration as operators begin to decipher the shale’s overpressured reservoir. Recent estimates conducted by the Basin Research Institute of Louisiana State University has estimated seven billion barrels of oil present as recoverable resources (John et al., 1997). Further exploratory progress and increased drilling techniques, coupled with a complete subsurface geological understanding of the formation, will allow operators to exploit the full potential of the Tuscaloosa Marine Shale.

The Tuscaloosa Marine Shale is the middle unit of the large Tuscaloosa Group that spans southern Louisiana, Mississippi, and Alabama. The Tuscaloosa Group is split into three main units of descending order, the Upper Tuscaloosa Formation, the Tuscaloosa Marine Shale, and the Lower Tuscaloosa Formation. Exploration in the region first began in the early 1950s when operators targeted the massive sand interval within the Lower Tuscaloosa Formation. As operators drilled to the formation, they encountered a highly over-pressured zone that seemed to contain vast amounts of hydrocarbons but operators were unable to extract the hydrocarbons in an efficient
manner. Alfred C. Moore (from John et al., 1997) stated that the Tuscaloosa Marine Shale was the most likely source of the oil that was being found within the Lower Tuscaloosa Formation. During Moore’s (from John et al., 1997) analyses of approximately 50 wells drilled across the region, he was able to determine that the Tuscaloosa Marine Shale was highly fractured and that the fractures were interconnected leading him to conclude that the shale unit was the source of the hydrocarbons migrating into the Lower Tuscaloosa Formation. Further early analyses of petrographic well logs and associated isopach maps revealed the hydrocarbons pooling around structural highs such as sand bars within the Lower Tuscaloosa Formation (John et al., 1997).

Early geochemical analyses conducted by Koon (1974) concluded that the Tuscaloosa Group contained two primary hydrocarbon types that were later deemed “families.” The Lower Tuscaloosa massive sand interval contained Family 2 oil types that were thought to have migrated through the fractured and faulted Tuscaloosa Marine Shale source rock. The Tuscaloosa Marine Shale was found to contain Family 1 oil type that is postulated to have migrated laterally from stratigraphic trapping of laterally positioned sandstone reservoirs (Koon et al., 1974; Echols et al., 1994). Further research into the migration patterns of Cretaceous hydrocarbons revealed that structural deformation occurred as a result of sediment loading along the northern Gulf Coast Basin (Echols et al., 1994).
2.1 History: Geologic formation of the Gulf Coast Basin

The Tuscaloosa Marine Shale was deposited along the Gulf Coast of the United States. During the Cretaceous Period, the Gulf of Mexico was beginning to form as a passive margin on the southern coast of North America (Scott, 2010), as shown in figure 2.1.1.

Figure 2.1.1: Paleogeography of the proto-Gulf of Mexico during the Lower Cretaceous showing the extent of carbonate platforms and inland deltaic systems (adapted from Scott, 2010)
The Gulf of Mexico began to open as the supercontinent Pangea migrated apart during the early Jurassic Period. The formation of the proto-Gulf of Mexico formed during two major rifting events. The first rifting system began in the early Jurassic and the second rifting event occurred in the middle to late Jurassic (Peel et al., 1995). The first rifting event was characterized as a passive margin that was being created through extensional forces that later formed the proto Gulf of Mexico Basin (Scott, 2010). The second rifting event caused the proto Gulf of Mexico Basin to become flooded with saline waters sourced from the proto Atlantic and the Tethys. As the rifting events began to slow during the Upper Jurassic, a complete waterway connection was created between the Atlantic Ocean and the Gulf of Mexico Basin (Scott, 2010).

At the onset of the complete formation of the Gulf of Mexico, extensive shallow carbonate platforms formed along the basin’s northern edge. These shallow carbonate platforms extended far inland spanning an average length of 4,593 feet along southern Louisiana and Mississippi. The platform had an average thickness of 6,561 feet and a width of 246 – 656 feet, as determined by research of petrographic well logs and core samples (Yurewicz et al., 1993).

During the time of the Tuscaloosa Group’s deposition, local topographic and structural highs altered the depositional patterns throughout the region, as shown in figure 2.1.2 and 2.1.3. Throughout geologic history, regional tectonic events have played a key role in the structural formation of the Gulf of Mexico margin. As a result of these events,
structural features were built that influenced the depositional patterns seen throughout the sedimentology and stratigraphy of the region. The main tectonic features that affected the Tuscaloosa Group’s deposition include the Sabine Uplift, Louisiana and Mississippi Salt Basins, Wiggins Arch, Hancock County High, and Sligo Shelf Margin (Yurewicz et al., 1993) (Dennen and Hackley, 2012). Salt movement from the Jurassic Louann Salt dome has also played an integral role in the hydrocarbon trapping mechanisms with the onset of extensional faults and salt anticlines.

Figure 2.1.2: Figure depicting major tectonic and depositional features affecting the Gulf of Mexico basin in the Early Cretaceous (adapted from Yurewicz, et al., 1993).
Figure 2.1.3: General overview of structural features affecting the entire Gulf Coast Margin during the Cretaceous Period (adapted from Dennen and Hackley, 2012). The red box depicts the general study region.
The Sabine Uplift is thought to have formed in the Jurassic Period and has exhibited multiple movements of its main axis throughout the Cretaceous Period (Granata, Jr., 1962). There are two main units of the Sabine Uplift that occurred at different points in the geologic past. During the Comanchean Age, the region of the Sabine Uplift experienced heavy erosion and uplift that has come to be known as the South Arkansas Uplift event, which began as the continental lithosphere rose north of the Comanche shore front (Granata, Jr., 1962).

Local Comanchean sediment deposits, located on the flanks of the Sabine Uplift, indicate that the area was not affected by the later South Arkansas Uplift (Granata, Jr., 1962). Regional deformation during the South Arkansas Uplift was not found to have extended into the Gulfian Series and is thought to have concluded prior to the deposition of the Tuscaloosa Group, thereby causing no structural effects on its depositional patterns. It is postulated that during the deposition of the Tuscaloosa Group, the Sabine Uplift acted a structural high that only accumulated a light layer of Tuscaloosa sediments and larger deposition occurring on the flanks of the uplifted region. As high levels of sediment loading occurred within the basin, the Sabine Uplift area is estimated to have begun differential warping in conjunction with basin sediment loading, influencing the patterns of deposition (Granata, Jr., 1962).

The Tuscaloosa Group trends to deeper subsurface elevations toward the south and the west as a direct result of the older Sligo Shelf Margin and Edwards Shelf Margin.
The Sligo Shelf Margin and younger Edwards Shelf Margin are key structural features that created the deepening track of deposited Tuscaloosa sediments. The Sligo Shelf margin was deposited during the Lower Cretaceous within the Aptian to Albian series. The Sligo Formation consists of three facies sets including reef, backreef, and lagoonal environments (Kirkland, et al., 1987). The reef facies of the Sligo Formation contain two high topographic buildups, including a coral-caprinid-stromatoporoid barrier reef and a rudist reef, adjacent to the lagoonal facies (Kirkland, et al., 1987). These reef systems have created two elevated mounds which have impacted the depositional patterns of mid-to-late Cretaceous stratigraphy. Immediately prior to Tuscaloosa deposition, the mid-Albian series of the Upper Cretaceous was characterized by a transgressive carbonate platform that was dominated by coastal siliciclastic sediments to the north, shales to the west and muddy carbonate sediments to the south, as shown in figure 2.1.4. The deposited sediments comprise the Paluxy and Fredericksburg sequences (Yurewicz et al., 1993), as shown in figure 2.1.2. The margin of the platform consisted mainly of reefs and carbonate sands.

Following Fredericksburg Group deposition, Upper Albian was dominated by the deposition of Washita Group sediments. The Washita Group consists of platform margin muddy argillaceous carbonates with a high-relief reef complex along the southern margin (Yurewicz et al., 1993). Deposition of the Washita Group ended approximately 94 MYA and is most recognized by a large subaerial unconformity immediately before the Tuscaloosa Group sediments transgressed over the platform.
Figure 2.1.4: Facies map depicting the carbonate platform during the middle Albian series (adapted from Yurewicz et al. 1993).

2.2 History: Deposition of the Tuscaloosa Group

The period of Tuscaloosa deposition is characterized by a full cycle transgressive event occurring during the late Cenomanian to early Turonian, as shown in figure 2.2.1 (Mancini and Puckett, 2002). The transgressive-regressive cycles in the Gulf of Mexico basin were abundant during the Cretaceous with eight recognized horizons spanning the period. Among the known cycles, six unconformities have been mapped along with nine
transgressive episodes (Mancini and Puckett, 2002). The Tuscaloosa Marine Shale represents a complete transgressive-regressive cycle of deposition and is labeled the T-R 5 cycle in the depositional history of the Gulf Coast Basin (Mancini and Puckett, 2002). The margin of the Gulf of Mexico basin was relatively stable during the Jurassic and the Cretaceous, thereby causing sea level changes to be the primary force behind sediment deposition and the underlying stratigraphy (Mancini and Puckett, 2005).

The Tuscaloosa Group was deposited immediately following the subaerial unconformity capping the Washita Group (Dennen and Hackley, 2012) (Figure 2.2.2). The subaerial unconformity began with an increase in accommodation space as siliciclastic sediments continued to move into the basin. The loss in accommodation space was marked when sediments built up to the maximum level hindering the continued sediment progradation and subsequent deposition. The system shifted as this maximum level was defined and began to shift back seaward creating an erosional surface (Mancini and Puckett, 2005). Sediments of non-marine origin continued to be deposited as sea levels were lower than the sediment surface. As the sea level began to rise above the sediments, shallow marine deposits prevailed, as exhibited in the deposition of the middle Tuscaloosa Marine Shale unit (Mancini and Puckett, 2005).
Figure 2.2.1: Stratigraphic changes and depositional development during a transgressive-regressive cycle (image from Mancini and Puckett, 2005).
Figure 2.2.2: Stratigraphic column depicting the Eastern Gulf Coast stratigraphy compared to the remaining Gulf Coast margin (Adapted from Dennen, K.O., and Hackley, P.C., 2012).
The Lower Tuscaloosa Formation is a thick sequence of coastal barrier sands that were deposited during the aggrading phase, at the start of the Gulf of Mexico transgressive cycle (Mancini and Puckett, 2002). The formation spans much of the northern Gulf of Mexico basin and was deposited above terrigenous sediments along the subaerial unconformity. The Lower Tuscaloosa Formation has been divided into two groups by Winter (1954) named the Massive Sand unit and the Pilot Sand unit (Mancini et al., 1987). The Massive Sand unit unconformably overlies the Washita Group sediments of the Lower Cretaceous Period. The Massive Sand unit contains basal sandstones that are interbedded with claystone (Mancini et al., 1987). The formation was deposited in a wave-dominated destructive marine delta system as characterized by the sedimentology of its massive sand unit. The Lower Cretaceous strata beneath the massive sands of the Lower Tuscaloosa Formation are of fluvial-deltaic origin with a recent hypothesis that the basal unit of the Lower Tuscaloosa is also of fluvial-deltaic origin before marine waters transgressed fully to dominate deposition (Mancini et al., 1987). Marine dominated deposition is characterized by the interbedding of clays in the sandstone above the basal unit of the Lower Tuscaloosa Formation. At the onset of the interbedded claystone, marine bivalves and small amounts of glauconite are present (Mancini et al., 1987). The Massive Sand unit of the formation has been described by Oomkens (1970) and Mancini et al. (1987) as being sourced from coastal barrier sands that are well-sorted and very quartz rich.
The uppermost unit of the Lower Tuscaloosa Formation is known as the Pilot Sand interval and is approximately 150 feet thick. This particular unit represents the backstepping phase, at the start of the Gulf-wide regressive cycle. The Pilot Sand unit thickens to the south and pinches out to the east (Mancini et al., 1987). The Pilot Sand unit consists mainly of a sand that is highly glauconitic, micaceous, and fossiliferous (Mancini et al., 1987). The upper portion of the Pilot Sand unit is also interbedded with claystone and is described as the onset of marine shelf and lagoonal sediment deposition (Mancini et al., 1987).

The Tuscaloosa Marine Shale is found directly over the Lower Tuscaloosa Formation and is conformable to the Pilot Sandstones. Analyses from multiple core samples indicate that the marine shale is mainly dark grey to black, containing high amounts of micas and fossil fragments (Mancini et al., 1987). The unit is highly calcareous, laminated, and interbedded with a glauconitic siltstone (Mancini et al., 1987). Stratigraphic analyses conducted on core samples taken from southern Alabama (Liu, 2005; Mancini et al., 1980; Mancini and Payton, 1981; Mancini et al., 1987; Claypool and Mancini, 1989) describe the Marine Shale as black, organic-rich shale that is highly laminated. It has been found that an area located in southern Alabama contains a thin oyster packstone at the base of the Tuscaloosa Marine Shale, immediately overlying the Lower Tuscaloosa Formation (Mancini et al., 1987). A diverse assemblage of fossils is also present in the basal unit of the Tuscaloosa Marine Shale which contains large amounts of ammonites, gastropods, and bivalves (Mancini et al., 1987). Further reports
have identified the assemblages to yield high amounts of ammonites, inoceramids, and bivalves (Liu, 2005).

Liu (2005) also identified the marine shale as a silty claystone with high levels of micas and fossil fragments. The fossils found within the formation are indicative of a shallow marine shelf. The basal unit of the Tuscaloosa Marine Shale contains a faunal planktonic assemblage underlying the oyster packstone, immediately above the pilot sand interval of the Lower Tuscaloosa Formation, indicating an abrupt rise in eustatic sea levels (Mancini et al., 1987; Mancini et al., 1980). Further sedimentological analyses showed that the Tuscaloosa Marine Shale belonged to the algal origin kerogen type with organic carbon content of approximately 1.2-2.8% (Liu, 2005; Mancini et al., 1980).

The shallow marine shale beds of the middle Tuscaloosa Marine Shale Formation can be identified on petrographic well logs by identifying the positive SP (Spontaneous Potential) response pertaining to the underlying lithology (Mancini and Puckett, 2002). As shown in figure 2.2.3, the contact surface between the Lower Tuscaloosa Formation and the basal beds of the Tuscaloosa Marine Shale has been identified as a ravinement surface, as noted by a negative SP log response shown by the Lower Tuscaloosa Formation (Mancini and Puckett, 2002). The ravinement surface found between the strata reflects the aforementioned point of separation between the aggrading phase and the backstepping interval (Mancini and Puckett, 2005).
The final regressive infilling phase is represented by the upper beds of the Tuscaloosa Marine Shale and the progradational siliciclastic sediments of the basal Upper Tuscaloosa Formation. The Tuscaloosa Marine Shale conformably underlies the Upper Tuscaloosa Formation. As accommodation space was limited, siliciclastic sediments increased and the fluvial sands of the Upper Tuscaloosa Formation prograded onshore to the updip areas. The Upper Tuscaloosa Formation consists of glauconitic, fossiliferous, sandstone that is interbedded with shale units that spans the northern Gulf of Mexico Basin (Mancini et al., 1987). The formation has an average thickness of approximately 375 feet and exhibits characteristics of an open marine and marginal marine depositional environment (Mancini et al. 1987). Following deposition of the Tuscaloosa Group, a subaerial unconformity existed until deposition of the Eutaw Formation occurred in the middle Coniacian (Mancini and Puckett, 2002; 2005).

The Cretaceous period has been defined as one of the warmest periods in Earth’s history which contained multiple Oceanic Anoxic Events (OAEs) concentrated in areas with specific climate and oceanic conditions (Liu, 2005). OAEs are described as periods where deposition of organic-rich black shales in shallow marine environments was very widespread. It was determined by Jenkyns (1980) that deposition was highest in three main boundaries during the Cretaceous; the Aptian-Albian, Cenomanian-Turonian, and Coniacian-Santonian boundaries (Liu, 2005).
Figure 2.2.3 Well log patterns showing deposition of the Tuscaloosa Group. K2lt refers to the Lower Tuscaloosa Formation while K2mt is referring to the Tuscaloosa Marine Shale and K2ut is the Upper Tuscaloosa Formation (image from Mancini and Puckett, 2002).
2.3 Hydrocarbon Maturation

The Tuscaloosa Group provides predominately oil with associated natural gas and condensates from a highly overpressured reservoir up to 15,000 feet deep. The Tuscaloosa Marine Shale beds are the main source rocks for the conventional hydrocarbon exploration and production that occurred in the Lower and Upper Tuscaloosa sandstones. Petroleum sources within the shale are found amongst multiple traps involving anticlines and various extensional faults throughout the coastal margin of the Gulf of Mexico. The faulting system began in the middle Jurassic and continued throughout the Miocene, affecting the trapping mechanisms and hydrocarbon generation found within the shale (Mancini et al., 1987). Organic geochemistry analyses conducted on oils from the Tuscaloosa Group determined that the oils contain between 91.1-94.9% hydrocarbons, (Mancini et al., 1987). Heavier hydrocarbons containing greater than 15 carbon atoms in one molecule, in the range of C_{15+}, are typically analyzed to determine source quality and the degrees of maturation.

The composition of the crude oils found within the formation likely originated from organic matter found within normal to brackish saline waters on an extensive marine shelf (Mancini et al., 1987). The maturation of the Tuscaloosa oils correlates to the underlying geothermal gradient found within the formation as a result of the underlying structure deepening towards the west to southwest which increases the depth and pressure, thereby yielding a higher geothermal gradient with the increasing depths.
As the geothermal gradient increases, the hydrocarbons found within the formations also mature.

2.4 Post-depositional History

The Tuscaloosa Group ended its deposition in the early to middle Coniacian, marked by a subaerial unconformity followed by the deposition of the Eutaw Formation in the late Cretaceous. During the late Cretaceous, major progradational deltaic systems were formed during the Tuscaloosa and Woodbine depositional episodes. These deltaic systems were formed along the Mississippi Embayment and in the East Texas Basin (Galloway, 2008). The Tuscaloosa Formation was deposited by the larger fluvial deltaic axes; following continued uplift of the interior Sabine Arch (Galloway, 2008). During deposition, the sediments of the Tuscaloosa Group prograded outward onto the shallow shelf and buried the Lower Cretaceous Stuart City Reef trend. These sediments then formed a prograding shelf-margin wedge of Upper Cretaceous sands and marine muds.

Along the eastern Gulf of Mexico margin, the early Cretaceous Stuart City Reef system was the dominant feature until burial from the carbonate deposits and marine muds of the Tuscaloosa Group and Woodbine (Galloway, 2008). The reef system was the main feature that dictated the bathymetry of the Cenozoic Gulf of Mexico strata (Galloway et al., 2000). Immediately basinward of the Lower Cretaceous reef system, water depth increased dramatically, yielding a steep slope where later sediments would eventually migrate to be deposited along the basin floor. The Cretaceous Tuscaloosa
sediments acted as the defining break between the shallow shelf platform and the deep water abyssal plain of the Gulf of Mexico basin (Galloway *et al.*, 2000).

In the western Gulf of the Mexico basin, compression from the Laramide Orogeny occurred throughout the Paleocene, creating a Paleocene shelf that was eventually displaced from the reef system. During compression, the Tuxpan Platform from the Mesozoic subsided to create a plateau along the Laramide compressional foreland basin later creating the present-day western margin of the Gulf of Mexico (Galloway *et al.*, 2000). At this time, the eastern Gulf of Mexico was dominated by a broad marine platform that was rimmed with a shallow depositional shelf and a carbonate ramp along the Florida escarpment (Galloway *et al.*, 2000).

Sediments moving into the basin were largely sourced from inland deposits of the Laramide tectonic uplifts. The Laramide uplifts extended around much of the Gulf of Mexico margin, where eroded sediments were transported into the Gulf of Mexico basin by two delta systems, the Houston Delta and the Holly Springs Delta. Throughout the Cenozoic, the basin experienced up to eight episodes of sediment dispersal that were largely sourced by major delta systems in the area, such as the Houston Delta and the Holly Springs Delta (Figure 2.4.1). The Houston Delta is by far the largest system, transporting sandy sediments. Upon sediment deposition into the Gulf waters, strong wave-dominated shores carried much of the deposited sediments into the Burgos Basin of Mexico and along the southern coast. During the early Cenozoic, the central margin of
the Gulf of Mexico basin moved further basinward indicating that the sediments from the Houston and Holly Springs deltas created a sediment apron which has now been buried under younger sediments (Galloway et al., 2000).

**Figure 2.4.1:** Paleogeography of the Lower Wilcox depositional event (image from Galloway et al., 2000).

During the Early Eocene, the margin along the Texas coast was dominated by sandy fluvial systems and further deposition from rivers fed by eroded sediments of the East Texas Basin, as shown in figure 2.4.2. Together, this fluvial system created the Carrizo sandstones (Galloway et al., 2000). During the deposition of the Carrizo sands,
sediment influx was unusually high; however, the continental margin was only marginally extended outward. The coastal margin was inundated by high amounts of growth faults due to the expansion of the Late Paleocene shale margin. Along the Mississippi Embayment, sediment influx created a platform delta extending outward on the Gulf of Mexico shelf which was later reworked to create a sandy shelf that extended further into the central portion of the basin (Galloway et al., 2000).

**Figure 2.4.2:** Paleogeography of the Gulf of Mexico in the Early Eocene (image from Galloway et al., 2000).
During the Middle Eocene, clastic sediments once again inundated the Gulf of Mexico basin as a direct result of the uplifting Mexican Cordillera. Depositional sediments of this period reflect crustal heating and regional uplift due to the Mexican Cordillera, showing volcanic ash in the sediment layer. During the Oligocene, continued crustal heating and continental-scale uplifts, resulted in a massive sediment influx into the western Gulf of Mexico basin (Galloway et al., 2000). Regional uplifting along the western margin of the basin and vast volcanism resulted in the creation of multiple depocenters along the western margin containing sandy Frio and Vicksburg sediments (Galloway et al., 2000). Moving into the Miocene, the Gulf of Mexico basin remained relatively stable in terms of structural deformation. The Miocene is marked by the redistribution of drainage patterns across the coastal margin as a result of the onset of Basin and Range extension upwarping the interior plains (Galloway, 1989).

During the reworking of the network of rivers and estuaries, Cretaceous and early Cenozoic sediments were brought into Miocene deposits through the uplift and subsequent erosion of the Edwards Plateau. At this point, the Houston Delta was abandoned as the migration patterns favored the Red River axes and through progradation along the central Red River axis, the Mississippi River Delta system was created (Galloway et al., 2000) (Figure 2.4.3). The late Miocene and early Pliocene were marked by a single, fluvial-dominated deltaic system by combining the East and Central Mississippi axis. The combined deltas prograded across the central Gulf shelf, creating
multiple sandy turbidites and lobe complexes that extend to the basin plain (Galloway et al., 2000).

Figure 2.4.3: Paleogeography of the late Miocene to early Pliocene. The figure depicts the combined Mississippi delta system to the east (image from Galloway et al., 2000).

Moving into the late Pliocene, the Red River delta axis continued to dominate the overall supply of inland sediments. The three main Gulf Coast deltas merged into a single fluvial delta system dominated by the Red River drainage axis (Galloway et al., 2000).

Further into the late Pliocene, evidence of freshwater ice melts draining into the basin was recorded through oxygen isotope data and an influx of glacial debris (Joyce et
The northern ice sheets once again reworked the drainage systems across the southern coastal margin. The Mississippi delta system showed the largest expansion of increased sediment loads and freshwater drainage. Glacial outwash continued into the Pleistocene creating further drainage changes and increased onshore sediments being deposited in the northern Gulf of Mexico basin, as shown in figure 2.4.4. Throughout the Cenozoic, multiple depositional and tectonic events altered the Gulf of Mexico basin and created its unique characteristics. Figure 2.4.5 summarizes the main events that have occurred throughout the Cenozoic.

Figure 2.4.4: Paleogeography of the mid to late Pleistocene (image from Galloway et al., 2000).
Figure 2.4.5: Distribution systems of sediment supply and tectonic events affecting the paleogeography of the Gulf of Mexico basin through the Cenozoic (image from Galloway et al., 2000).
METHODOLOGY

The research behind this study was conducted in multiple stages in order to perform analyses on the sedimentology and stratigraphy of the Tuscaloosa Group. The study area is located across southern Louisiana and into Mississippi spanning multiple parishes and counties. The Tuscaloosa Group has been drilled extensively for conventional resources by many large and small operators, with this study mainly focused on the middle unit of the Tuscaloosa Marine Shale between 9,500 feet to 14,500 feet with minor emphasis being placed on the bounding Upper and Lower Tuscaloosa formations. Early conventional wells targeted the Lower Tuscaloosa unit beneath the study interval, overlying lower Cretaceous Washita Group strata. This study utilized various methodologies, including,

1. Synthesis of multiple petrographic well logs that run through the Tuscaloosa Marine Shale target within the study area boundary;
2. Analyses of aforementioned petrographic logs that permeate the Tuscaloosa Marine Shale unit;
3. Construction and development of stratigraphic and structural cross sections of the Tuscaloosa Marine Shale;
4. Development of structure maps for the Tuscaloosa Marine Shale study area.
3.1 Synthesis of Petrographic Well Logs

The recent onset of unconventional shale drilling has brought attention to the middle Tuscaloosa Marine Shale unit and has attracted many large drilling operators who have begun to exploit the shale’s crude oil. There are many available petrographic well logs that penetrate the middle shale unit and target the Lower Tuscaloosa sandstones. This study utilized electric logs including Spontaneous Potential (SP), Gamma Ray (GR), Neutron (N), Density (D), and Resistivity (R) logs. Figure 3.0.1 illustrates the well locations identified within the study area.

Figure 3.0.1: Well locations in green with raster log's present showing selected formation top of the Tuscaloosa Marine Shale.

Spontaneous Potential (SP) logs measure the electrical potential of the geologic strata. This is done by measuring the difference in voltage between the rock strata and an
electrode that is in contact with the ground’s surface. The SP log is used for correlation purposes and determination of the lithology, porosity and permeability, and formation water salinity (HLS, 2007).

Gamma Ray (GR) logs are used to determine rock lithology and the correlation of rock units. The GR log works by measuring the natural radioactivity within the formation, downhole. Radioactive elements are most commonly recorded in shales, where high GR readings are often found. As the shale content inside of the unit increases, the GR signature will also increase recording the high level of radioactive content. Minerals such as potassium feldspars, micas, and waters containing uranium can also invoke a high GR response within the unit regardless of shale content (Asquith, et. al., 2004). GR signatures are also used to calculate the shale volume within a porous rock unit (Asquith, et. al., 2004).

Neutron (N) logs measure the hydrogen ion concentration of the rock unit. Neutron log signatures reflect low responses when the rock unit contains fluid-filled pores or gas as a result of lower hydrogen concentrations in the fluids. Likewise, oil containing units will respond with a higher neutron signature due to the higher concentration of hydrogen ions in the oil (Asquith et., al, 1982). Neutron-Density (ND) logs measure porosity simultaneously and can also be used to determine formation lithology (Asquith et., al, 1982). Porosity measured by ND logs is often used in limestone units but can also measure the porosity of sandstone units, much like the Upper
and Lower Tuscaloosa Massive sandstones, and is commonly utilized to identify gas-bearing zones.

Resistivity (R) logs measure the rock unit’s resistance to the flow of electrical current. Hydrocarbons are highly resistive to electrical flow within the formation; however, saltwater acts as a good conductor and will allow for the flow of electrical current within the formation. R is most commonly used to determine the formation porosity, fluid type, and rock type (Meyer and Nederlof, 1984). Each of these factors allow for the determination of the formations hydrocarbon content and relative porosity.

### 3.2 Cross Section Analyses

Reference logs were created and classified based on relative abundance of stratigraphic tops showing clear and precise log track signatures to be used during correlation. A total of 21 well logs were used for correlation of the stratigraphic beds to generate cross sections using Petra software (Figure 3.2.1). Multiple correlations were generated between marker beds of the Upper Tuscaloosa Formation, the Tuscaloosa Marine Shale, and the Lower Tuscaloosa Formation.

Stratigraphic cross sections were generated using the top of each unit to illustrate the variation in deposition between each bed of the Tuscaloosa Group. Two sets of cross sections were generated relative to modern sea-level, trending from north to south and east to west. The east to west cross section was generated by hanging the correlated strata on the relative modern day surface elevation as recorded on each petrographic log. The
Figure 3.2.1: Location of the reference log identified from the Cockrell Corporation.
method of using modern day surface elevation was conducted so the depth and
depositional variation of each marker bed could be identified.

A reference log was created by using a petrographic log run by the Cockrell
Corporation in East Feliciana County of Louisiana (Amelia Resources) (John, et. al,
1997). The reference log displays each unit of the Tuscaloosa Group with detailed
precision (Table 3.2.1; Figure 3.2.2). The Upper Tuscaloosa Formation was identified
from the base of the Eutaw Formation as marked by a positive spike in resistivity.

**Table 3.2.1:** Identified formations within the reference log from the Cockrell Corporation
with associated depth characteristics.

<table>
<thead>
<tr>
<th>Formation</th>
<th>Abbreviation Given</th>
<th>Top Boundary Subsea Depth</th>
<th>Lower Boundary Subsea Depth</th>
<th>Isopach (Thickness)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cretaceous Lithology</td>
<td>K</td>
<td>11,500</td>
<td>13,000</td>
<td>1,500</td>
</tr>
<tr>
<td>Eutaw Formation</td>
<td>EUT</td>
<td>13,000</td>
<td>13,155</td>
<td>155</td>
</tr>
<tr>
<td>Upper Tuscaloosa Formation</td>
<td>UTFM</td>
<td>13,155</td>
<td>13,640</td>
<td>485</td>
</tr>
<tr>
<td>Tuscaloosa Marine Shale</td>
<td>TMS</td>
<td>13,640</td>
<td>13,850</td>
<td>210</td>
</tr>
<tr>
<td>Lower Tuscaloosa Formation</td>
<td>LTFM</td>
<td>13,850</td>
<td>14,170</td>
<td>320</td>
</tr>
</tbody>
</table>

The Tuscaloosa Marine Shale unit was determined by identifying a slight negative
shift in resistivity coupled with a steady SP response indicating a shale baseline. The
Lower Tuscaloosa Formation was determined from the identification of a negative
resistivity response and two distinct positive gamma ray responses representing the
massive sand intervals within the formation. A subaerial unconformity occurs beneath the
Figure 3.2.2: Reference log identified as the Tuscaloosa Group units. EU: Eutaw Formation, UTFM: Upper Tuscaloosa Formation, TMS: Tuscaloosa Marine Shale, LTFM: Lower Tuscaloosa Formation, LFTMB: Base of the Lower Tuscaloosa Formation (Amelia Resources) (John et al., 1997)
Lower Tuscaloosa Formation before Washita Group deposition and marks the lower bounding surface of the Tuscaloosa Group. The base of the Upper Tuscaloosa Formation was used as the upper marker bed identifying the slight negative response in resistivity and the top marker bed of the Lower Tuscaloosa Formation was used as the lower bounding sequence.

3.3 Structural Analyses

Evaluation of the structural influences on hydrocarbon generation and extraction potential was analyzed by creating structural maps on the surface of each unit within the Tuscaloosa Group. Structural maps were created relative to modern surface elevations as done with cross section analyses. The structural surface of each unit was plotted using Petra software and contours were constructed through each data point of the study area. The contours were then shaded to better delineate structural differences between each petrographic log to determine subsurface effects. Structural maps are crucial in determining hydrocarbon potential in order to evaluate optimum drilling locations to enable maximum extraction with minimal structural features influencing hydrocarbon migration within the unit. A structural map was created for each unit within the Tuscaloosa Group.
RESULTS

The Tuscaloosa Marine Shale has long been identified as a prospective, economically-viable, oil shale resource. Numerous studies have been conducted to estimate the reserve potential of the marine shale and several large exploration and production companies have begun to exploit the shale’s resources. The reservoir conditions that the formation presents prove challenging to these operators with many overspending proposed budget’s to properly delineate the core areas of the play. The formation itself is inundated with multiple structural faults resulting from salt movement and other tectonic evolution along the Gulf Coast margin. Through the advancement of drilling technology and further exploration from the operators on the area, the Tuscaloosa Marine Shale has the ability to become a viable resource for commercial level production.

4.1 Synthesis of Petrographic Well Logs

Upon initial investigation of selected wells throughout the study area, a total of 51 wells were identified for potential analyses (Appendix 1: Initial list of well logs reviewed). Upon viewing the log signatures captured on each of these well logs, a total of 21 wells were ultimately selected for further analyses due to their proximity to the core area of the prospective Tuscaloosa Marine Shale (Appendix 2: Final list of well logs used within the study). The core area of the formation was identified by collating the counties receiving the majority of drilling activity by exploration and production operators since
the onset of unconventional exploration within the play. The 21 wells used within the study were identified as oil producing wells with completion dates spanning a time frame of 1950 to 2012. Each of these wells was run through the study formation of the Tuscaloosa Marine Shale and contained a maximum subsea depth of 25,416 feet.

To synthesize the study group of well logs, the younger Cretaceous stratigraphy immediately above the identified Eutaw Formation, at subsea depths greater than 10,400 feet, were grouped together to be labeled ‘Cretaceous Lithology’ and used as a marker for further log signature identification. The overlying Eutaw Formation was identified as a marker bed to aid in the identification of the top of the Upper Tuscaloosa Formation.

A reference log was identified to give clear and concise contact signatures between the relevant formations to use as a proxy for correlation between each log (Figure 3.2.1). Each formation identified was assigned a specific abbreviation and the upper and lower boundaries were identified via correlation to the selected reference log from the Cockrell Corporation (Table 3.2.1). This reference well was completed in March 1970, located within East Feliciana Parish in Louisiana, and was drilled to a total depth of 15,020 feet, as shown in figure 3.2.2.

The general isopach of the Tuscaloosa Marine Shale and the Upper Tuscaloosa Formation was calculated by subtracting the subsea depth of the upper and lower bounds of each unit within the reference log. Utilizing this methodology, the Upper Tuscaloosa
Formation was found to be approximately 485 feet thick as previous studies have also shown. The Tuscaloosa Marine Shale has been previously identified as having a thickness ranging from 200 feet thick and increasing to over 500 feet thick. Within the reference log identified, the Tuscaloosa Marine Shale exhibited an approximately thickness of 210 feet. The overall thickness of the shale unit varied within each cross section with the thickest portions of the unit being found within Louisiana and thinning into Mississippi.

When identifying the reference log formations, key signatures on the resistivity logs at the contact between the Eutaw Formation and the Upper Tuscaloosa Group were identified for correlation. The resistivity, R, log displayed a positive spike at a depth of 12,810 feet and was assigned the marker corresponding to the Upper Tuscaloosa Formation. The Upper Tuscaloosa Formation is sandstone that produces commercial quantities of predominately oil hydrocarbons with little associated gas as demonstrated by a higher resistivity measurement on the reference log. The contact between the Upper Tuscaloosa Formation and the Tuscaloosa Marine Shale was identified by a small spike in the R log before the resistivity decreased marginally for approximately 200 feet. As the log signatures moves toward the lower portion of the shale unit, the resistivity increases, identifying the most prospective areas of the unit for hydrocarbon exploration. Within the reference log, this section of the unit can be found approximately 70 to 100 feet above the contact with the Lower Tuscaloosa Formation. The Lower Tuscaloosa Formation exhibits multiple spontaneous potential signatures indicating the presence of larger sandstone
units interbedded within the formation. The Lower Tuscaloosa Formation has historically been targeted for commercial quantities of oil generation. Sandstone pockets are present at depths of approximately 13,880 to 13,920 feet, 13,930 to 14,000 feet, and 14,040 to 14,140 feet.

4.2 Cross Section Analyses

Cross sections were created at key locations throughout the study area in order to identify the subsurface elevation and isopach changes within the study formations. These cross sections were created from the evaluation and identification of key marker beds within petrophysical logs which transected the study formation of the Tuscaloosa Marine Shale. An initial cross section was constructed trending west to east through the study area, consisting of six logs. This cross section was constructed as an initial identification of the Tuscaloosa Marine Shale unit given the specific log signatures as described by Mancini and Puckett (2002) and as identified in the reference log chosen from the Cockrell Corporation (Figure 3.2.1, 4.2.1, 4.2.2).
Figure 4.2.1: Map of cross section #1 and #2 below, depicting the well locations used for the study. Generated using Petra.
Figure 4.2.2: Cross section #1 trending east to west identifying the Tuscaloosa Marine Shale as highlights in green. Generated using Petra.
A second cross section was constructed, trending west to east, containing a larger subset of wells for the identification of the overlying Cretaceous lithology to use as a marker bed for identification of the units above the Tuscaloosa Marine Shale (Figure 4.2.3, 4.2.4).

The Cretaceous strata were given an identification abbreviation of K to be used throughout the remaining cross sections (Table 3.2.1). Upon the identification of the overlying Cretaceous stratigraphy, a third cross section was constructed identifying the remaining units within the study zones (Figure 4.2.3, 4.2.5).

Along the selected cross section in figure 4.2.5, wells transecting East Feliciana Parish of Louisiana illustrate an increased subsea depth of all units. Within this county, the units drop approximately 1,500 feet from neighboring Wilkinson County, Mississippi. A north to south cross section was constructed beginning in Wilkinson County, Mississippi and extending south to East Feliciana Parish of Louisiana (Figure 4.2.6, 4.2.7).

The cross section depicted further demonstrates the increasing depth of the Tuscaloosa Group toward the south along the Gulf Coast margin. Each of the constructed cross sections show several distinct trends present within the underlying strata. When flattening the cross section along the cretaceous strata, the underlying deepening of the Tuscaloosa sediments are more visible (Figure 4.2.8). In figure 4.2.9 below, the cross
Figure 4.2.3: Map of cross section #2 and 3 moving west to east across Louisiana and Mississippi, identifying further formations within the stratigraphy. Generated using Petra.
Figure 4.2.4: Cross section #2 trending west to east with the identified Cretaceous Lithology depicted in pink. The Tuscaloosa Marine Shale is shown in the green highlighted section. Moving from the first well at the western-most edge of the cross section, the formations experience an increased depth illustrating a depocenter in East Feliciana Parish of Louisiana. Generated using Petra.
Figure 4.2.5: Cross section #3 depicting all identified stratigraphy within the study area parameters. When moving from the west to the east, all lithology experiences an increase in subsea depth. K = Cretaceous Lithology shown in red, EUT = Eutaw Formation shown in tan, UTFM = Upper Tuscaloosa Formation shown in purple, TMS = Tuscaloosa Marine Shale shown in green, LTFM = Lower Tuscaloosa Formation shown in blue, LTFB = Base of the Lower Tuscaloosa Formation shown as a dark blue line. Generated using Petra.
Figure 4.2.6: Map of cross section #4, trending north to south beginning in Mississippi. Generated using Petra.
Figure 4.2.7: Cross section #4 trending north to south beginning in Mississippi. Moving south, all stratigraphy increases depth at a fast rate moving closer to the reef margin. K = Cretaceous Lithology shown in red, EUT = Eutaw Formation shown in tan, UTFM = Upper Tuscaloosa Formation shown in purple, TMS = Tuscaloosa Marine Shale shown in green, LTFM = Lower Tuscaloosa Formation shown in blue, LTFB = Base of the Lower Tuscaloosa Formation shown as a dark blue line. Generated using Petra.
Figure 4.2.8: Cross section from west to east flattened along the upper cretaceous stratigraphy (K). K = Cretaceous Lithology shown in red, EUT = Eutaw Formation shown in tan, UTFM = Upper Tuscaloosa Formation shown in purple, TMS = Tuscaloosa Marine Shale shown in green, LTFM = Lower Tuscaloosa Formation shown at the blue line. Generated using Petra.
Figure 4.2.9: Cross section along the Tuscaloosa Marine Shale formation. K = Cretaceous Lithology shown in red, EUT = Eutaw Formation shown in tan, UTFM = Upper Tuscaloosa Formation shown in purple, TMS = Tuscaloosa Marine Shale shown in green, LTFM = Lower Tuscaloosa Formation shown at the blue line. Generated using Petra.
section has been flattened along the Tuscaloosa Marine Shale sediments and illustrates a uniform deposition pattern across the study area.

4.3 Structural Analyses

Structure maps were created for the identified interval bounding the upper surface of the Tuscaloosa Marine Shale. The structure maps created show several varying structural highs present within southern Mississippi and Louisiana which were potentially induced by the depositional environments that span the study area, differing compaction rates, and post-depositional structural influences along the Gulf Coast margin during the Cenozoic. Throughout most of the southern portion of the study area, the homogeneous nature of the depositional environment is shown within the structure maps as much of the deformation seems to occur toward the northeast, out of the study area.

Figure 4.3.1 depicts the top of the Tuscaloosa Marine Shale using 200 foot contour intervals to illustrate the dramatic increase in the depth of the formation as it trends to the south along the early Cretaceous reef system. The structure map also displays the relative homogeneity of the formation through the study area with the main geologic influence pertaining to the increase in depth towards the south. The largest structural high is present within Washington Parish, Louisiana with the highest relief
Figure 4.3.1: Structure map showing the top of the Tuscaloosa Marine Shale formation using 200 foot intervals. Unit's structure depicts multiple depositional centers occurring at the time of the TMS's deposition. Blue circles show the study wells.
at 11,100 feet. To the west of this structural high, St. Helena and Tangipahoa Parish’s
also contain a structural high with an elevation range of 11,700 to 12,300 feet.
Immediately to the south of this relief, the formation itself deepens at a fast pace,
exceeding 17,100 feet along the southern edge of the study area. The majority of well
activity thus far has focused within the base of these structural highs at an area where the
formation itself is relatively homogenous, thicker due to the increased deposition, and is
still within an adequate depth range for current drilling techniques. The average depth of
the formation in Louisiana where the majority of drilling activity has occurred thus far
ranges between 12,500 to 15,000 feet. Mississippi drilling targeting the Tuscaloosa
Marine Shale has occurred between 11,000 and 12,000 feet and has been concentrated
within Amite and Wilkinson counties. These areas of interest are also located
immediately adjacent to a structural high, as shown in Amite County, and within an area
of homogeneous structural relief, as in Wilkinson County.
4.4 Isopach Analyses

Isopach maps were plotted across the study area for the Upper Tuscaloosa Formation and the Tuscaloosa Marine Shale, as shown in figure’s 4.4.1 and 4.2.2. Each isopach was calculated as a thickness of the unit determined from log correlations using Petra software. Isopach analyses allows for variations in deposition to be identified in regards to the depositional environment and rate of deposition. Isopach analyses are able to delineate the areas where increased rates of deposition occurred, creating thicker sections of each unit enabling the evaluation of possible delta deposition into the prograding seafront. Isopach analyses also enable the evaluation of unit heterogeneity across the study area with implications on vertical deposition.

The average thickness of the Tuscaloosa Marine Shale within the study area was approximately 210 feet (Figure 4.4.1), while the average thickness of the Upper Tuscaloosa Formation carried at approximately 485 feet (Figure 4.4.2). The Tuscaloosa Marine Shale exhibits a seemingly heterogeneous deposition across the study area.
Figure 4.4.1: Isopach of the Tuscaloosa Marine Shale using 50 foot contours.
Figure 4.4.2: Isopach of the Upper Tuscaloosa Formation using 100 foot contours.
The Tuscaloosa Marine Shale has been identified as an emerging shale play within the United States but has not had much exploration and development activity thus far. At the onset of the shale boom, several major operators began to enter the play by purchasing cheaper land which contained producing vertical wells that had targeted the Upper or Lower Tuscaloosa formations. Throughout the exploration and production of the plentiful oil resources found within the sandstones of the Upper and Lower Tuscaloosa, operators had encountered a unit of lithology which provided higher pressures in the drilling process. As horizontal drilling evolved and operators were able to increase resource production, early movers into the area began identifying zones of potential shale production capabilities. Larger operators then moved into the area and began developing the fields and deploying innovative drilling techniques to target the overpressured shale system. Operators within the area are also faced with higher operating costs as a direct result of the increased depth of the formation itself. Structural analyses of the formation through petrographic logs illustrate structural trends throughout the play yielding a distinct depth variance. Combined analyses of 21 petrographic logs enabled these structural trends to be identified on a spatial and vertical method to allow for the characterization of the Tuscaloosa Marine Shale unit across Louisiana and Mississippi.
5.1 Discussion of Analyses

The Tuscaloosa Marine Shale located in southern Louisiana and Mississippi was found to have a relatively consistent depositional profile through the synthesis of 21 well logs trending from northern Louisiana to southern Louisiana and from the east to the west ending is Mississippi. The shale unit exhibited a uniform pattern of structure and thickness within each of the well logs identified; however, there are several instances of thickening and increased deposition occurring within the southern portion of Mississippi in Wilkinson County, as shown in figure 4.2.5 and 4.2.9.

When comparing the well log within this county to the structural map in figure 4.3.1, the shale unit exhibits a localized structural depocenter with a subsea depth ranging between 11,500 to 12,300 feet allowing for increased deposition of the shale unit within this localized zone of depression. The area surrounding this region of deposition has a consistent subsea elevation of approximately 11,500 feet. During the deposition of the Lower Tuscaloosa Group in the Lower Cretaceous, multiple inland deltaic systems inundated the study area as fresh water was deposited within the early Gulf of Mexico prior to sea level rise depositing the Tuscaloosa Marine Shale unit (Mancini et al., 1987). Through the movement of fresh water emptying into the Gulf of Mexico, increased erosion and localized depressions occurred; however, due to the creation of lowstand areas, greater amounts of overlying sediments were deposited as sea levels transgressed onshore depositing the remaining units of the Tuscaloosa Group. During the deposition of
the Tuscaloosa Group, the margin was relatively stable, allowing for uniform deposition 
of both sands and deep marine sediments with the Tuscaloosa Marine Shale as can be 
seen throughout figures 4.2.7, 4.2.8, and 4.2.9, which show the Tuscaloosa Marine Shale 
having a uniform thickness throughout the study area (Mancini and Puckett, 2005).

In cross section 4.2.5, when moving from the west in Wilkinson County, 
Mississippi and into East Feliciana Parish of Louisiana, the Tuscaloosa Group’s subsea 
depth decreases from almost 12,000 feet in Mississippi to a depth of 12,500 feet in 
Louisiana further depicting the shift into deeper elevations from the underlying Sligo and 
Edwards Shelf Margin of the early Cretaceous (Yurewicz, et al., 1993). When coupling 
the cross section in figure 4.2.5 and the structural map in figure 4.3.1, it is seen that East 
Feliciana Parish of Louisiana also contains a regional lowstand depocenter which is 
located in the relative region of inland deltaic systems emptying along the Gulf of 
Mexico margin during Tuscaloosa deposition (Scott, 2010). The northeastern counties of 
St. Helena, Tangipahoa, and Amite in Mississippi also exhibited similar structural trends. 
Structural influence was also directly affected by inland tectonic events that altered the 
sediments such as the Sabine Uplift and the Louann Salt movement (Yurewicz, et al., 
1993).
CONCLUSION

The Tuscaloosa Marine Shale is a tight dark grey to black marine shale unit which was deposited during the Cenomanian to Turonian stages of the Upper Cretaceous period, approximately 95-89 million years ago (Mancini and Puckett, 2002). The Tuscaloosa Marine Shale is the middle unit of the larger Tuscaloosa Group which also consists of multiple sand beds of the Lower and Upper Tuscaloosa formations. Deposition of the Tuscaloosa Group within the study area represents a complete transgressive-regressive cycle, known as the T-R 5 cycle (Mancini and Puckett, 2002).

Throughout the Gulf Coast margin’s geologic history, multiple regional tectonic events played key roles in the resulting topographic and structural features of the study area. These structural deformities played a direct role in the resulting depositional patterns of the Tuscaloosa Group. During deposition of the Tuscaloosa Group, the Jurassic Sabine Uplift acted as a structural high which only contained a thin layer of Tuscaloosa sediments on the highest elevated areas with the majority of deposition occurring around the flanks. The patterns of Tuscaloosa deposition were altered and influenced by differential warping in the Sabine Uplift area combined with localized sediment loading throughout the basin (Granata, Jr., 1962).

During the deposition of the Tuscaloosa Group, the Gulf Coast margin was relatively stable, allowing for uniform deposition of both coastal sands and deep marine sediments of the Tuscaloosa Marine Shale, as illustrated in the isopach map in figure
4.4.1. Just prior to the Tuscaloosa Group’s deposition, the proto-Gulf of Mexico had formed through the breakup of Pangea in the Jurassic. Once the Gulf of Mexico had fully formed through further rifting and separation, a large carbonate platform extended across the Gulf of Mexico passive margin for much of the Upper Cretaceous.

Throughout the Upper Cretaceous, multiple inland deltas formed across the Gulf Coast margin in close proximity to the study area. Through the movement of fresh water emptying into the Gulf of Mexico from these inland deltas, increased erosion and localized depressions occurred adjacent to these delta lobes. The delta lobes proximal to the study area carried large amounts of siliciclastics sourced from inland sediments being transported downstream. Evidence of increased sediment loading is visible within figure 4.2.9 which has isolated the Tuscaloosa Marine Shale unit showing thicker sediments within Wilkinson County, Mississippi and within St. Helena and Washington Parish of Louisiana. These two regions are located within the same region as the delta lobes present during the Upper Cretaceous which likely increased the amount of sands being intermixed within the shale unit allowing for a thicker profile to be seen. The region in between Wilkinson County, Mississippi and St. Helena and Washington Parish, Louisiana shows a thinner profile of Tuscaloosa Marine Shale sediments which likely contains more clay content and has undergone heavier differential compaction rates.

The deposition of the Tuscaloosa Group is indicative of a calm open water environment reflected within the resulting analyses of the study area which has yielded a
homogenous depositional profile throughout the various cross sections and isopach analysis. Deformation of the Tuscaloosa Group likely occurred after deposition through tectonic influences, delta reworking during the Cenozoic, and salt migration patterns across the Gulf Coast Margin. Migration from the interior Mississippi Salt Basin and the Jurassic LouAnn Salts were likely the main contributors to post-depositional salt deformation occurring within the study area. The structure map of the top of the Tuscaloosa Marine Shale unit shows multiple regions of highstand areas within Washington and Tangipahoa County’s in Louisiana which exhibit a dome structure that was likely influenced by buried salt migration (Figure 4.3.1). Coupling this pattern with the isopach map (Figure 4.4.1) shows a similar thickness within the shale unit, indicative of a homogenous pattern of deposition with any resulting structural abnormalities occurring post-depositionally, through salt migration and structural deformation.

The Tuscaloosa Group also exhibits a uniform southwestern gradient of deepening subsea depths along the buried shelf edge. Following subsurface elevations, maturation profiles correlate to the deeper subsea elevations found to the south as the unit deepens to the shelf edge and increases its geothermal gradient. The main study area sits within an average subsea depth of approximately 10,000-14,000 feet and yields predominately crude oil. As the formation deepens and increases its geothermal gradient, the hydrocarbon present also increase maturity to end with dry natural gas to the southernmost extent of the basin. Current exploration has been focused in the study region at approximately 11,000 to 13,000 feet, targeting the crude oil hydrocarbons.
Exploration of the Tuscaloosa Group began in the early 1950’s using conventional drilling techniques targeting the massive sand intervals of the Tuscaloosa Group. Early development yielded large amounts of oil and associated natural gas that continued for decades. Throughout the rise of unconventional drilling, explorers returned to the fields of the study area to tap into the overpressured shale unit.

Within the study area, exploration has focused within St. Helena, Tangipahoa, and Washington parishes of Louisiana and Wilkinson and Amite counties of Mississippi. The average depth to the shale unit within each of these areas is approximately between 11,500 and 12,500 feet. These regions directly correspond to the areas with increased sediment deposition intermixed with inland sands form the emptying of past delta lobes which will increase the average porosity of the shale unit in these areas. The natural fracture networks within the Tuscaloosa Group also help to enhance reservoir connectivity and allow for further migration of the hydrocarbons present. Through hydraulic fracturing in unconventional drilling of the shale unit, this reservoir connectivity is artificially enhanced for better extraction of the molecules found in the tight unit.

The Tuscaloosa Marine Shale has the potential to become the next large oil resource in later years following the proper delineation and targeting of new drilling locations. Despite petroleum exploration and development activity slowing down recently, after the drop in global oil price in mid-2014, the Tuscaloosa Marine Shale is
expected to contain over seven billion barrels of oil in place. Future operators to the region can benefit by targeting the Tuscaloosa Marine Shale within the study area, specifically within the St. Helena, Washington, and Tangipahoa parishes in Louisiana and Amite and Wilkinson counties of Mississippi to capture the thicker shale unit within increased sand content.

Future studies within this region should focus on identifying proper target areas for new wells or identifying older vertical wellbores to rejuvenate for new horizontal technology targeting the shale unit. This will follow closely with this study where regions of thicker and more uniform depositional patterns have been identified for potential drilling location. Further technological research should also be carried out to identify new or more refined drilling practices to combat the reservoir properties and allow for more thorough exploitation of the Tuscaloosa Marine Shale unit. The Tuscaloosa Marine Shale unit, identified within the study, has the potential to be the next big producing resource and target for the energy industry. While this shale unit has declined in popularity over the past two years due to elevated costs coupled with the recent industry downturn, the Tuscaloosa Marine Shale has the ability to become rejuvenated into a key exploration target for the industry as a leading oil field.
REFERENCES


Dennen, K.O. and Hackley, P.C. 2012. Definition of Greater Gulf Coast Basin Lower Cretaceous Shale Gas Assessment Unit, United States Gulf of Mexico Basin Onshore and State Waters. Search and Discovery. Article # 10429


Oomkens, E. 1970. Depositional Sequences and Sand Distribution in the Postglacial Rhone Delta Complex. SEPM Special Publication n. 15, pp. 198-212


APPENDIX 1

Appendix 1: Full list of well logs initially reviewed for analysis.

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<td>49</td>
<td>WAGNER BROWN</td>
<td>VENTRESS L T</td>
<td>157</td>
<td>408</td>
<td>KB</td>
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<td>13,664</td>
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</tr>
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<td>PINNACLE OPERATING COMPANY INCORPORATED</td>
<td>WEVERHAUSER</td>
<td>1ST02</td>
<td>316</td>
<td>KB</td>
<td>12,610</td>
<td>15,395</td>
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</tr>
</tbody>
</table>
# APPENDIX 2

Appendix 2: Final list of well logs used within the study.

<table>
<thead>
<tr>
<th>Well</th>
<th>Operator</th>
<th>Well Name</th>
<th>Well #</th>
<th>Elevation</th>
<th>Log Type</th>
<th>Min Depth</th>
<th>Max Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ARKLA EXPLORATION COMPANY</td>
<td>ARKLA ARK LONGMIRE</td>
<td>1 27</td>
<td>379</td>
<td>KB Composite Resistivity Sonic</td>
<td>2,810</td>
<td>12,292</td>
</tr>
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<td>2</td>
<td>ARKLA EXPLORATION</td>
<td>ARKLA HARVEY</td>
<td>1 80</td>
<td>214</td>
<td>GL Composite Resistivity Sonic</td>
<td>3,990</td>
<td>15,105</td>
</tr>
<tr>
<td>3</td>
<td>CABOT OIL GAS</td>
<td>CAVERN HAM FOREST IND</td>
<td>5 33</td>
<td>32</td>
<td>KB Composite Resistivity Neutron Density</td>
<td>3,950</td>
<td>14,850</td>
</tr>
<tr>
<td>4</td>
<td>COCKRELL CORP.</td>
<td>COCKRELL RANDOLPH PIPES ETAL</td>
<td>1 81</td>
<td>282</td>
<td>KB Resistivity</td>
<td>4,218</td>
<td>15,041</td>
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<tr>
<td>5</td>
<td>EXXON CORP.</td>
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<td>235</td>
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</tr>
<tr>
<td>6</td>
<td>HUGHES HUGHES</td>
<td>HUGHES J.H. PERCY HEIRS</td>
<td>1 160</td>
<td>189</td>
<td>KB Composite Resistivity Sonic</td>
<td>4,000</td>
<td>15,920</td>
</tr>
<tr>
<td>7</td>
<td>HUGHES EASTERN PETROLEUM</td>
<td>HUGHES PHILIP G. HOLLAND</td>
<td>1 53</td>
<td>253</td>
<td>GL Composite Resistivity Sonic</td>
<td>3,756</td>
<td>13,227</td>
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<tr>
<td>8</td>
<td>KECK PARTNERS</td>
<td>KECK DENKMAN</td>
<td>1 5</td>
<td>184</td>
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<tr>
<td>9</td>
<td>CHINN EXPLORATION CO.</td>
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<td>227</td>
<td>KB Composite Resistivity Neutron Density</td>
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<td>12,362</td>
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<tr>
<td>10</td>
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<td>13,070</td>
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<tr>
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<td>Company</td>
<td>Well</td>
<td>Depth</td>
<td>Type</td>
<td>Composited Resistivity Soncic</td>
<td>Neutron Density</td>
<td>Value 1</td>
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<td>11</td>
<td>MONCRIEF W.A.</td>
<td>MONCRIEF ROSEDW N PLANTATION</td>
<td>1</td>
<td>100</td>
<td>KB</td>
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<td>12</td>
<td>PATTERSON PET LP</td>
<td>PP</td>
<td>F98</td>
<td>50</td>
<td>GL</td>
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<td>AMERICAN QUASAR PETR.</td>
<td>QUASAR DON CLEMONS</td>
<td>1</td>
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<td>KB</td>
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<td>12,323</td>
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<tr>
<td>14</td>
<td>RADZEWICZ EXPLORATION DRILLIN</td>
<td>RADZEWICZ M.I. HAVEY ET AL</td>
<td>1</td>
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<td>KB</td>
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<tr>
<td>15</td>
<td>SABINE</td>
<td>SABINE CROWN ZELLERBACH</td>
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<td>KB</td>
<td>3,870</td>
<td>13,200</td>
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<tr>
<td>16</td>
<td>SABINE CORPORATION</td>
<td>SABINE J. J. LEAKE</td>
<td>1</td>
<td>17</td>
<td>KB</td>
<td>2,670</td>
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<tr>
<td>17</td>
<td>SHELL ASHLAND</td>
<td>SHELL EDWIN BARBIN</td>
<td>2155</td>
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<td>18</td>
<td>DEVON ENERGY PRODUCTION CO. L.P.</td>
<td>SOTERRA 6 H</td>
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<td>19</td>
<td>SUN OIL COMPANY</td>
<td>SUN ROBERT D. BRIDGES</td>
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<td>20</td>
<td>TEXACO</td>
<td>TEXACO DART FRANKLIN</td>
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<td>GL</td>
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<tr>
<td>21</td>
<td>TEXAS PACIFIC OIL</td>
<td>TEXAS WINFRED BLADES</td>
<td>1</td>
<td>42</td>
<td>KB</td>
<td>2,985</td>
<td>11,950</td>
</tr>
</tbody>
</table>
VITA

Jessica Pair is a graduate of Sam Houston State University with a Bachelor’s of Science in Geology and Biology, with a minor in Business Administration in 2012. Jessica has worked in the consulting side of the energy industry for over 3 years on North American Shale projects and a few International Shale projects. She will graduate from Stephen F. Austin State University with a Master of Science in Geology in May of 2017.

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Style: Geological Society of America

This thesis was typed by Jessica D. Pair