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SEQUENCE STRATIGRAPHY AND SOURCE ROCK CHARACTERIZATION
OF ORGANIC-RICH SHALES WITHIN THE JURASSIC SMACKOVER
FORMATION, CONECUH EMBAYMENT, ALABAMA, U.S.A.

A Thesis
presented in partial fulfillment of requirements
for the degree of Master of Science
in the Department of Geology and Geological Engineering
The University of Mississippi

By

PATRICK W. NIEMEYER

August 2011

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ABSTRACT

The Upper Jurassic Smackover Formation is a prolific producer of hydrocarbons known throughout the U.S. Gulf Coast region, and typically consists of carbonate lime mudstones, ooid grainstones, microbial boundstones, and dolostones. Recent exploration efforts in the Conecuh Embayment of southwest Alabama revealed the presence of two black, siliciclastic shale layers containing abundant terrestrially derived organic matter within the Smackover Formation. The shale layers provide interesting insight into the sequence stratigraphy and paleoclimate of the Conecuh Embayment, and the source of the hydrocarbons accumulated there.

The two shale layers reach a maximum thickness of 50 feet along the longitudinal axis of the embayment and pinch out along the rim of the embayment. X-ray diffraction shows the mineralogy of the shales to be dominated by clay minerals, with lesser amounts of quartz and carbonate. The dominant clay mineral found within the shales is illite and mixed layer illite-smectite. The dominant presence of illite is considered to be a result of diagenesis and related to the advanced thermal maturity of the samples. Detrital chlorite is also present within the samples along with minor amounts of potassium feldspar, pyrite, and kaolinite. Palynological analysis of the organic matter within them revealed the presence of several genera of ferns, mosses, and conifers suggesting a warm, humid climate during the late Jurassic. Source rock analysis of the shales shows insufficient total organic carbon (0.32 %) and poor quality Type-III kerogens for consideration as a source rock.

Deposition of the Smackover Formation occurred during a third-order sea level rise during the late Jurassic. Deposition of the shale layers is interpreted to have occurred during

relative falls in sea level allowing a greater influx of siliciclastics into the embayment. The relative sea level falls may be a result of imposing higher order sequences on the third-order sequence. In the model presented here the Smackover Formation is divided into three sequences with the Smackover carbonates forming the transgressive and highstand systems tracts, where the shales represent lowstand systems tracts. The results of this study provide a better understanding of the Jurassic petroleum system contained within the Conecuh Embayment.

DEDICATION

This thesis is dedicated to my friends and family who have supported me not only in my educational endeavors, but throughout my life. I would especially like to dedicate this to my mother and late father for instilling in me the importance of education at an early age, and to my brothers for always being there. For without those closest to me this thesis would not have been possible.

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CHAPTER 1 – INTRODUCTION

The Triassic rifting of Pangea and the subsequent opening of the Gulf of Mexico during the Jurassic resulted in the deposition of a series of sedimentary wedges that thicken basinward into the Gulf of Mexico and into the centers of four marginal salt basins (Wade and Moore, 1993; Mancini et al., 1990). Within the Conecuh Embayment of southwest Alabama the Jurassic stratigraphy consists of evaporites, carbonates, and siliciclastics derived from the Appalachian highlands to the northeast (Mancini et al., 1990). Deposition of Mesozoic strata proved favorable for the formation of oil and gas reservoirs in southwest Alabama, and there are several economic accumulations of hydrocarbons within and around the Conecuh Embayment. The most notable of these reservoirs is the Little Cedar Creek Field, which lies within the study area along the northern edge of the Conecuh Embayment. Cumulative production from the field as of April 2011 has been in excess of 12 million barrels of oil, with monthly production totals greater than 175,000 barrels of oil (Alabama Oil and Gas Board, 2011). Little Cedar Creek Field represents the most significant discovery of hydrocarbons in the onshore Gulf of Mexico region in the last 50 years (Baria, personal communication). Recent exploration efforts revealed two black, organic-rich shales containing terrigenous pollens and plant material within the carbonate Smackover Formation. The shales were first described by Baria et al. (2008) and could have implications for the Jurassic sequence stratigraphy of southwest Alabama.

Seven conventional cores from within the Conecuh Embayment were examined for lithology, color, and sedimentary structures. To verify core descriptions, previous petrographic work and facies descriptions were incorporated into the study. Well log data (Gamma Ray,

Spontaneous Potential, Neutron Porosity) from 25 wells within the study area were calibrated with core descriptions and used to construct cross-sections and a sequence stratigraphic model. While well logs and core descriptions served as the primary dataset, limited seismic data were also incorporated to better understand the stratal geometries of the Jurassic sediments in the Conecuh Embayment.

Eight shale samples and one Smackover carbonate sample from five wells were collected and analyzed for hydrocarbon source potential. X-ray diffraction was used to determine the mineralogy of the Conecuh shales. In addition to describing the lithology, mineralogy, and source potential of the shales, palynology data were also obtained to identify the terrigenous organic matter within the shales.

The goal of this study is to further describe the Conecuh Embayment shales, to investigate their potential as a hydrocarbon source rock, and to add to previous sequence stratigraphic interpretations for the up-dip portions of the Jurassic strata of southwest Alabama. The presence of terrestrial organic matter within the Smackover is a significant discovery and could represent a changing climate and depositional environment for the Alabama portion of the carbonate ramp that rimmed the developing Gulf of Mexico. The sequence stratigraphic model presented here could also have a significant impact on exploration within the Conecuh Embayment as current production is located within highstand systems tracts of Smackover units B and C (Baria et al., 2008).

CHAPTER 2 – CONECUH EMBAYMENT

The study area is located in the northern of arm of the Conecuh Embayment (Fig. 1), a bilobate embayment created by the marine transgression onto the southern extension of the Paleozoic Appalachian fold belt. The embayment is approximately 50 miles wide at its mouth, extends inland for up to 30 miles, and is bounded by the Conecuh Ridge complex to the north and the Pensacola Arch to the south. Within the embayment the Smackover Formation ranges in thickness from 0-320 feet. The present structural configuration of the Conecuh Embayment consists of monoclinial dip to the southwest at approximately 150 ft/mile (Baria et al., 2008).

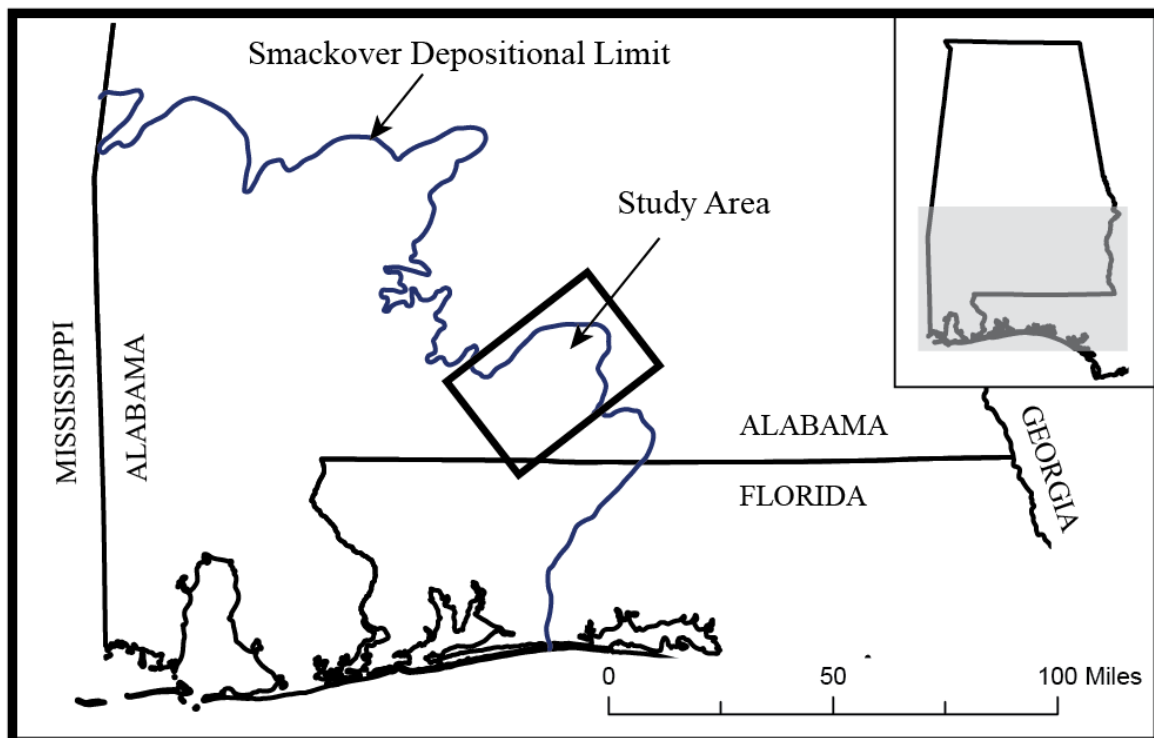


Figure 1 - Conecuh Embayment Study Area with Smackover Depositional Limit (Depositional limit from Baria et al., 2008).

The study area is part of the northern Gulf of Mexico rim that is a passive continental margin associated with the opening of the Atlantic Ocean and the Gulf of Mexico (Mancini et al.

2008). During the Late Triassic and the Jurassic, the structural and stratigraphic framework for the Gulf of Mexico was formed as the North American Plate separated from the South American and African plates. Triassic syn-rift deposition into the tensional grabens was initially dominated by red beds and volcanics. Marine flooding first entered the Gulf of Mexico basin from the west during the Callovian and eventually became connected to the Atlantic Ocean late in the Jurassic (Salvador, 1987). The resulting Mesozoic and Cenozoic stratigraphic section of the U.S. Gulf Coast is a seaward-dipping wedge of sediment deposited into several differentially subsiding subbasins. Interior salt basins in Mississippi, Louisiana, and Texas, as well as the Conecuh and Manila Embayments of Alabama served as the primary depocenters for the Mesozoic strata. Basement-related paleotopographic highs and movement of the Jurassic Louann Salt provided the structural elements that affected deposition in the northern Gulf of Mexico rim (Mancini et al., 2008).

Prominent structural features near the updip limit of the eastern Gulf of Mexico rim include a series of northeast-trending pre-Jurassic ridges associated with the South Georgia rift system. The Choctaw Ridge is the northern most structural feature and, along with the Conecuh Ridge, forms the Manila Embayment. The Conecuh Ridge marks the western extent of the South Georgia rift system and forms the northern side of the Conecuh Embayment (Fig. 2). The Pensacola Arch to the southeast of the embayment is related to folding or drape over the Paleozoic rocks of the Chattahoochee Arch and extends southwest into the Florida panhandle (Prather, 1992). To the southwest of the study area, the Wiggins Arch remained a prominent positive structural feature throughout most of the Jurassic. Evidence for this is the absence of the Jurassic Louann Salt over much of the arch and the rapid thinning of later sediments against the flanks of the arch (Cagle and Khan, 1983). The Conecuh and Manila Embayments are separated

from the eastern side of the Mississippi Interior Salt Basin by the Mobile Graben and by a northwest trending fault system (Prather, 1992). The southern extension of the Appalachian fold belt and the Mesozoic extensional features of southwest Alabama created a complex setting for Smackover deposition into the embayments and subbasins of Alabama (Baria et al., 2008).

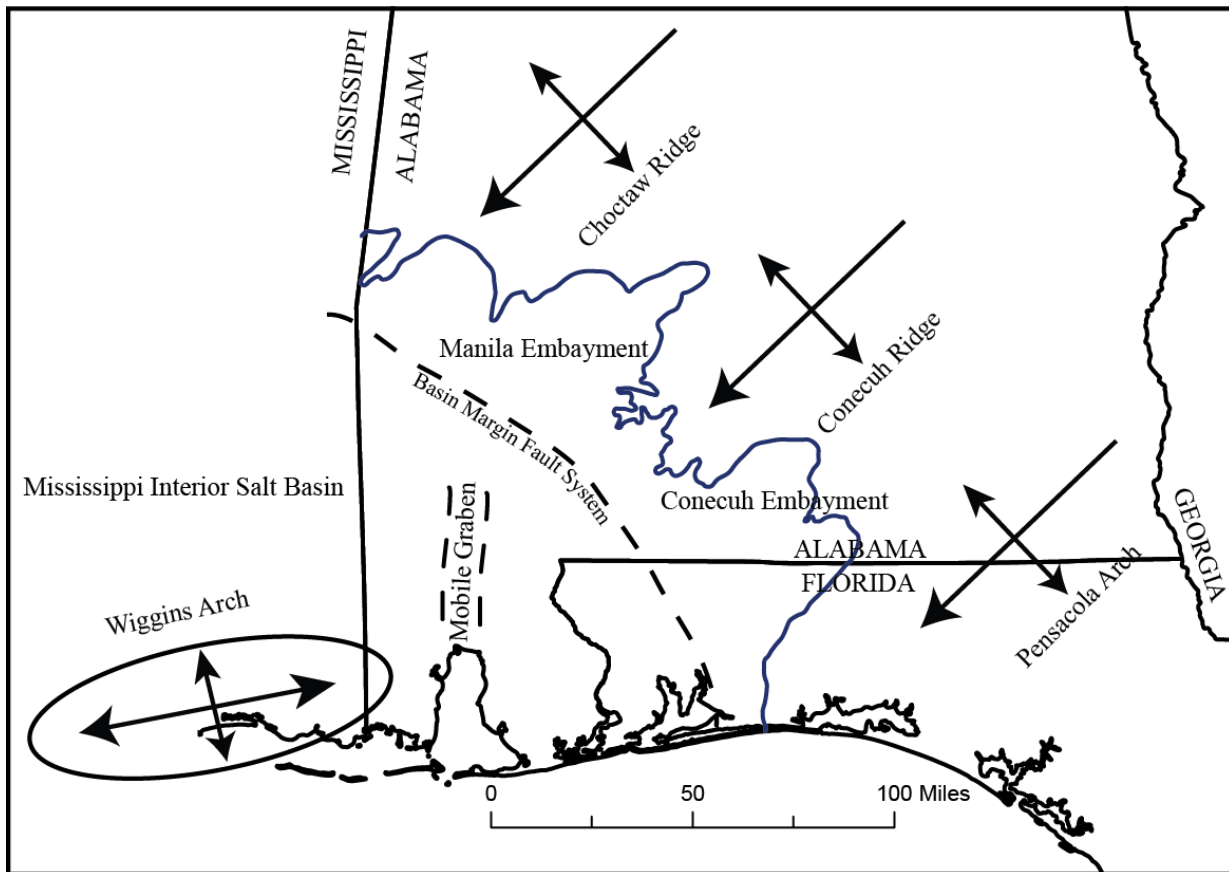


Figure 2 - Structural Features of southwest Alabama (Modified from Mancini et al., 1992; Prather, 1992; Baria et al., 2008).

2.1 – Regional Stratigraphy

Underlying the Mesozoic sedimentary sequence of southwest Alabama are Paleozoic sedimentary rocks similar to those that crop out in the Valley and Ridge province of north Alabama, and metamorphic and igneous rocks. The Late Triassic marked the beginning of sedimentary deposition into the depocenters of the northern Gulf of Mexico rim (Fig. 3, 4).

Regional Stratigraphy

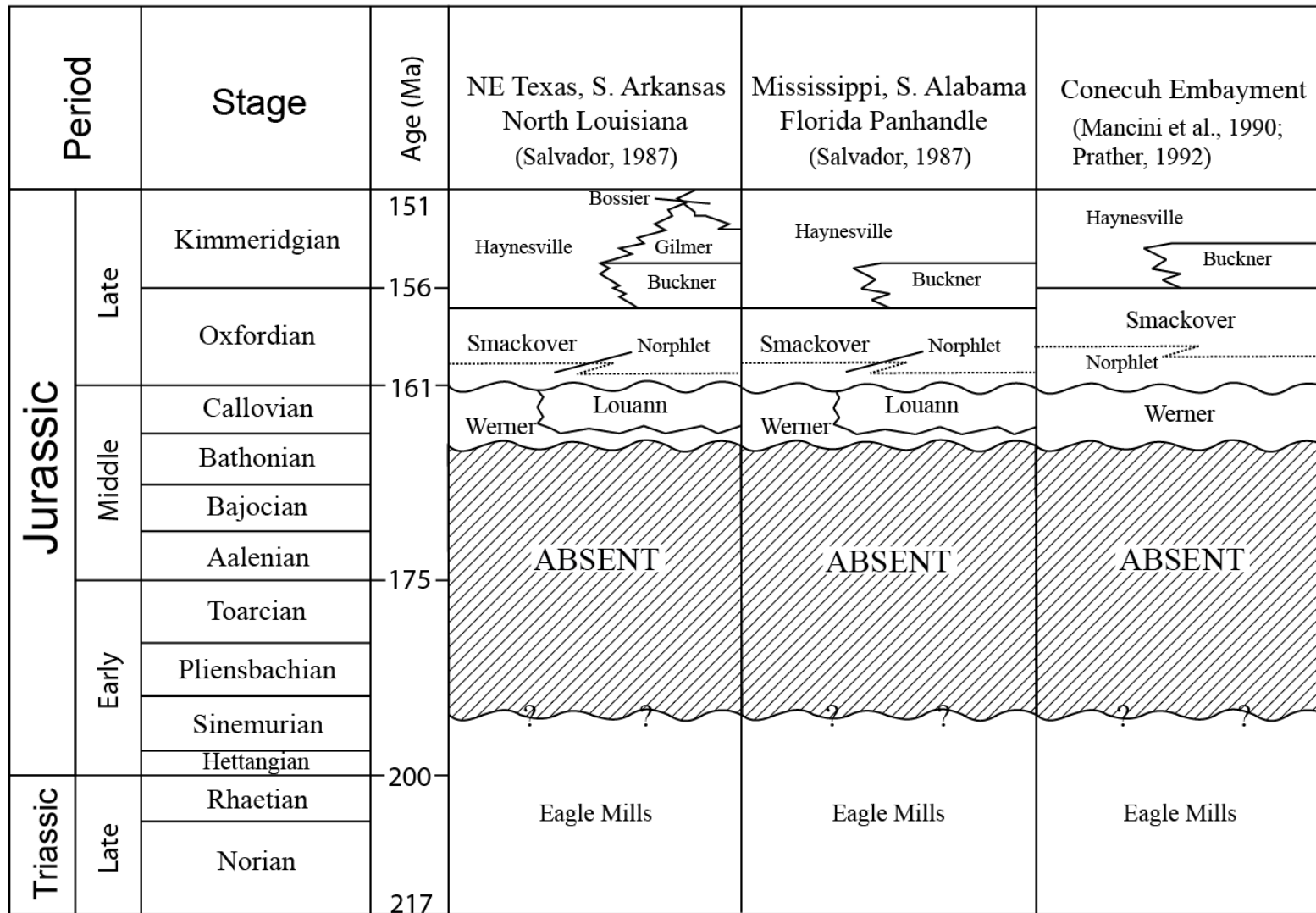


Figure 3 - Northern Gulf of Mexico Regional Stratigraphy (from Salvador, 1987; Mancini et al., 1990; and Prather, 1992).

Conecuh Embayment Stratigraphy

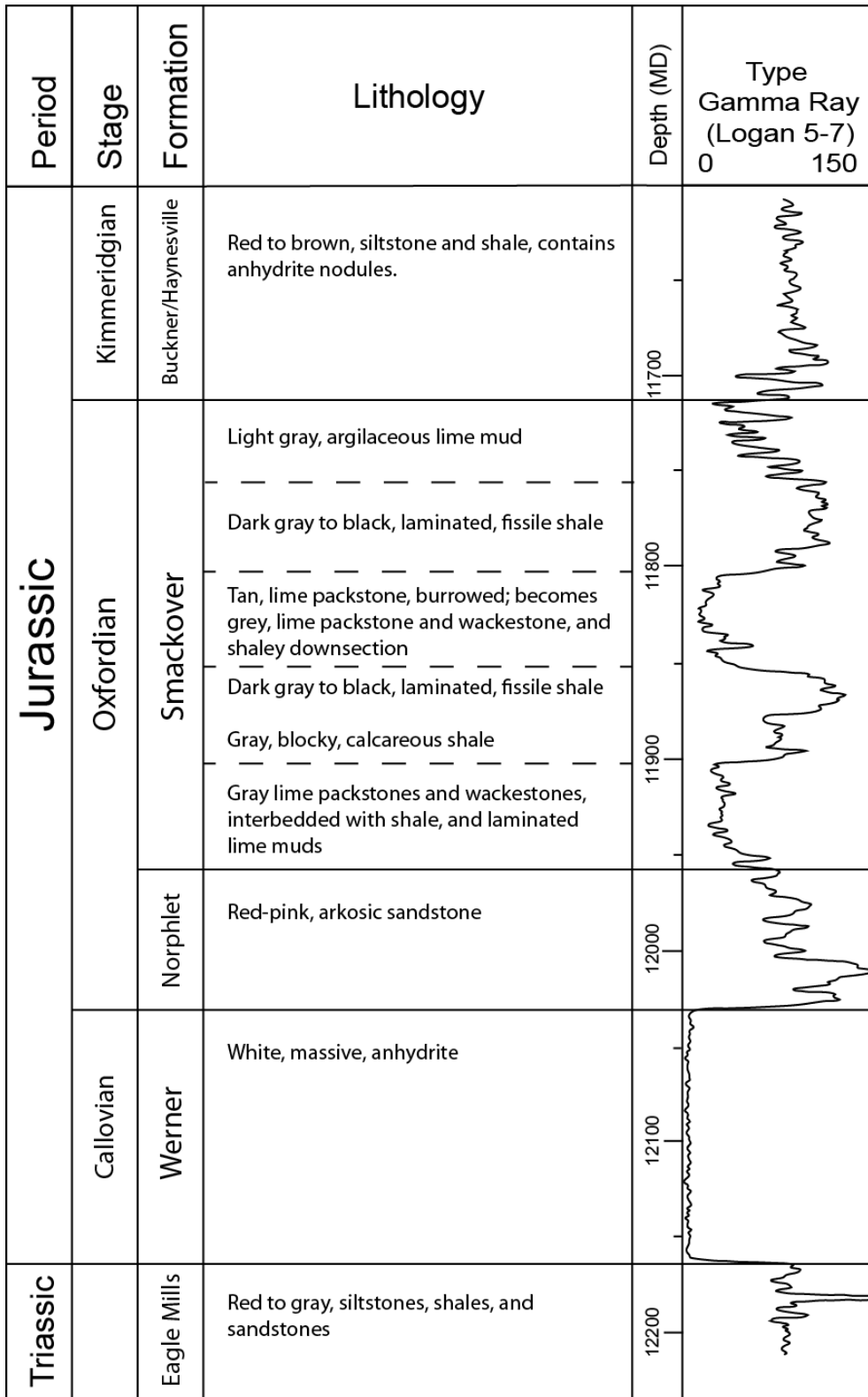


Figure 4 - Detailed Conecuh Embayment Stratigraphy (Lithologic descriptions from: Benson, 1988; Wade and Moore, 1993; Baria, personal communication; and the author).

During the Triassic to early Jurassic the Eagle Mills Formation was deposited unconformably onto Paleozoic basement. Deposition of the Eagle Mills Formation occurred as syn-rift deposition associated with the break-up of Pangea. The Eagle Mills Formation consists of red-to-gray terrigenous shale, siltstone, sandstone, and conglomerate. In the absence of the overlying Louann-Werner evaporites, the Eagle Mills grades upward into the Norphlet sands with no recognizable breaks in well log data or in cuttings (Wade and Moore, 1993).

The deposition of the Werner Anhydrite and Louann Salt represents the first marine incursion into the developing Gulf of Mexico following rifting. Deposition of these units occurred within highly restricted lagoons in flooded rift valleys and basins (Prather, 1992). Within the study area the Werner Anhydrite consists of white, finely crystalline, massive anhydrite. The distribution of the Werner Anhydrite has led to interpretations that it is a marginal facies of the more extensive Louann Salt (Wade and Moore, 1993). The unit reaches a maximum thickness of approximately 500 feet within the adjacent Mississippi Interior Salt Basin where active subsidence was taking place. It is thinner and much less extensive in the Conecuh Embayment. The Werner Anhydrite has been assigned a Callovian age based on regional stratigraphic relationships (Mancini et al., 1990). Within the Conecuh Embayment the Werner Anhydrite is easily identifiable in well log data and appears to have been deposited in topographical lows during the initial transgression of Jurassic seas.

The Louann Salt overlies the Werner Anhydrite (Fig. 3) and is a much more extensive evaporite deposit found in marginal basins around the Gulf rim and beneath the continental shelf and slope of the Gulf of Mexico. Although salt movement and dissolution have led to variations in present thickness of the Louann Salt, estimates place the original thickness of the formation between 5,000-10,000 feet. The updip depositional limits of the Louann Salt were controlled by

peripheral fault systems around the northern Gulf rim (Wade and Moore, 1993). The Louann Salt, like the underlying Werner Anhydrite, has been interpreted to have been deposited during intermittent marine incursion into topographic lows and actively subsiding depocenters. The Louann Salt is absent along the crest of the Wiggins Arch, and on the Choctaw and Conecuh Ridge complexes, including within the Conecuh Embayment. The Louann has been assigned a Callovian to earliest Oxfordian age based on palynomorph data (Mancini et al., 1990).

The Norphlet Formation overlies the Louann-Werner evaporites along the northern Gulf rim from Texas to the Florida panhandle (Fig. 3 and 4). The formation changes character and thickens from west to east. In southwest Alabama the Norphlet consists of alluvial redbeds, eolian dune and interdune subarkoses, and alluvial fan conglomeratic sandstones (Wade and Moore, 1993). In the absence of the Louann Salt, the Norphlet Formation disconformably overlies the Werner Anhydrite. The Norphlet Formation was deposited on a broad desert plain that was bordered by the Appalachian highlands to the northeast and by the opening Gulf of Mexico to the southeast. While there are several distinct lithofacies recognized in the Norphlet, the up-dip portions are dominated by a conglomeratic sandstone, red-beds in a central position, and by eolian sands down-dip (Mancini et al., 1990). Stratigraphically, the uppermost portion was reworked by transgressing Jurassic seas; however, differentiation of this portion may be difficult where the seas moved across well sorted dunes. In the Conecuh Embayment the Norphlet was deposited as an extensive desert dune and alluvial fan deposits (Prather, 1992). The Norphlet is believed to be Oxfordian-aged (Mancini et al., 1990).

Overlying the Norphlet Formation are the carbonates of the Smackover Formation. The contact between the two is sharp and interfingering rarely occurs between carbonate and sandstone beds (Wade and Moore, 1993). Deposition was greatly influenced by

paleotopography, basin subsidence, salt tectonics, and basement configuration (Mancini et al., 1990). Within the interior salt basins, Smackover thickness may exceed 1,000 feet; however, the formation thins substantially in the study area. Within southwest Alabama the formation averages just 300 feet thick. In the Conecuh Embayment, where Smackover deposition was greatly influenced by paleotopography, the formation thins over paleohighs, thickens around the flanks of the embayment, and then thins again within the embayment center (Wade and Moore, 1993). The Smackover is generally interpreted to have been deposited on a carbonate ramp and is late Oxfordian age based on ammonite data recovered from the lower portions of the unit (Mancini et al., 1990). In addition to significant variations in thickness, the Smackover also varies lithologically from basin to basin in southwest Alabama (Benson, 1988). Smackover lithologies of the Conecuh Embayment will be described in further detail below.

Conformably overlying the Smackover Formation is the Buckner Member of the Haynesville Formation (Fig. 3 and 4). The Buckner/Haynesville units have been interpreted to be Kimmeridgian in age (Mancini et al., 1990). The Buckner of southwest Alabama consists of a basal anhydrite, interbedded anhydrite and shale, massive halite, evaporitic red beds, evaporitic carbonate and arkosic sandstones that, except for the latter, were deposited in a restricted lagoon. In the Conecuh Embayment the majority of the Buckner Member is composed of the evaporitic redbed unit consisting of interbedded red and gray shale, red siltstone, and red to tan argillaceous siltstone. Commonly interbedded anhydrite and dense dolomite are found within the Buckner Member (Wade and Moore, 1993). The contact between the Buckner and underlying Smackover is often gradational and deposition of the Buckner is seen as being the result of continued regression that was responsible for the deposition of the uppermost Smackover carbonates (Mancini et al., 1990).

2.2 – Smackover Formation in Alabama

Depositional basins for the Smackover in Alabama include the eastern limits of the Mississippi Interior Salt Basin, and the Conecuh and Manila Embayments (Fig. 2).

Paleotopography in the area controlled deposition of the Smackover and resulted in large lateral variations from paleohighs into basin centers. The lithology and thickness of the Smackover Formation also varies greatly from basin to basin (Benson, 1988).

The Smackover Formation is typically divided into three informal members: lower (C), middle (B), and upper (A). In general, each successive Smackover sequence shows a basinward shift in facies (Heydari and Baria, 2006; Baria, et al., 2008; Baria, 2011, personal communication). The lower Smackover was deposited during an initial transgression of Jurassic seas that reworked the underlying Norphlet Formation and began Smackover deposition into topographic lows. Initial transgression began during the Callovian and continued rapidly into the Oxfordian. Regional studies indicate that the initial Jurassic transgression occurred from the southeast through the Conecuh Embayment and from the southwest through the Mississippi Interior Salt Basin with the Wiggins Arch remaining a large positive feature to the southwest (Benson, 1988).

Smackover C overlapped the Norphlet and deposition reached the furthest inland of the Smackover sequences in Alabama (Baria, 2011, personal communication). The contact between the underlying Norphlet and Smackover C is usually abrupt (Mancini et al., 1992). Lower Smackover carbonates are typically algal laminites that are commonly interbedded with intraclastic packstone and wackestones. Algal laminites and the lack of bioturbation indicate deposition in a distressed environment such as a tidal flat. There is evidence of periodic subaerial exposure in the lower Smackover, and in Escambia County the presence of fenestrae and a tan to

light-gray color indicate periods of deposition in an oxygenated environment (Benson, 1988). Sea level continued to rise and the algal laminites pass upward into peloidal-oncoidal wackestones and packstones showing a transition into a deeper, more open marine environment. Deposition is indicative of a moderate energy environment. The lack of higher energy grainstones could indicate that the sequence is being driven by rapid sea level rise and that carbonate production was unable to keep up. Smackover C carbonates vary greatly in thickness in southwest Alabama; they are the thinnest near the centers of depositional basins and thicken up-dip and around paleo-highs. The thickening of Smackover C carbonates updip can be attributed to the rapid sea level rise that outpaced carbonate production (Benson, 1988).

Carbonates of the Smackover B sequence overlapped the Smackover C carbonates, presumably after a local regression. Smackover B deposition did not transgress as far inland as that of the original Smackover seas (Baria, 2011, personal communication). The middle Smackover member is dominated by laminated mudstone interbedded with peloidal and skeletal wackestones and packstones (Mancini et al., 1992). Lithologies in the Smackover B are typically limestone although some occurrences of dolomite do exist. Portions of the middle Smackover are heavily burrowed while other portions lack any bioturbation (Benson, 1988). The laminated mudstones are typically dark-gray to black, nonfossiliferous, and lack bioturbation (Sassen and Moore, 1988). The skeletal and peloidal wackestones are light brown to gray. Smackover B carbonates produce a distinctive response on neutron and density logs due to the higher organic and argillaceous contents (Benson, 1988).

Thickness of the middle Smackover can also vary significantly. In the extreme up-dip portions of the embayments and around paleohighs, this member is absent. However, the middle

member thickens basinward and can reach thicknesses of over 400 feet in the Mississippi Interior Salt Basin (Benson, 1988).

The Smackover A sequence represents the termination of carbonate deposition in the study area during the Oxfordian. Smackover A carbonates are conformably overlain by the Buckner Member of the Haynesville Formation. The contact between the two is often gradational (Mancini et al., 1992). The upper Smackover member is also the most varied and complex lithologically (Benson, 1988). Smackover A consists of subtidal to intertidal, oolitic, oncolitic, and peloidal grainstones and packstones that are interbedded with intertidal and supratidal laminated or fenestral mudstones and local anhydritic sabkha deposits. Siliciclastics are common in the upper member of the Smackover, particularly in the updip portions of the embayments (Mancini et al., 1992). Thickness of the Smackover A also varies greatly throughout southwest Alabama and is inversely proportional to that of Smackover B. While the Smackover A does not encroach landward as far as Smackover B, it is thickest in the updip portions of the basins and thins basinward (Benson, 1988).

2.3 – Source Potential of the Smackover

Jurassic reservoirs of the Norphlet and Smackover formations have been prolific producers of hydrocarbons throughout the Gulf Coast region (Sassen et al., 1987). In Alabama the Smackover has been the most prolific hydrocarbon producer since the late 1960's (Benson, 1988). Norphlet and Smackover reservoirs are typically bounded below by the Louann Salt or the Werner Anhydrite (locally in the Conecuh Embayment) and above by the Haynesville Shale and Buckner Anhydrite, providing geological evidence for a close association between source and reservoir rock. Geochemical analysis of rock samples and crude oil suggests that the

laminated mudstones of the lower Smackover are the main source of hydrocarbons in Jurassic reservoirs (Sassen et al., 1987).

The lower Smackover consists of laminated mudstones deposited in an anoxic and probably hypersaline environment. Such an environment is favorable for the preservation of organic matter. Sassen et al. (1987) found that samples collected from the lower Smackover throughout the Gulf Coast region contained a mean total organic content (TOC) of 0.51%, and samples collected from Alabama wells contained a mean TOC of 0.60%. While not incredibly rich in organic carbon, carbonate source rocks are generally accepted to have generative potential with 0.3% or greater TOC (Tissot and Welte, 1984). Visual kerogen assessment indicates that the lower Smackover contains an oil-prone algal-derived kerogen and that kerogen from higher land plants is not a significant component in the lower Smackover. An advanced maturity history of lower Smackover rocks also indicates that partial conversion of kerogen has occurred, meaning that the TOC amounts may have been higher than currently present levels (Sassen et al., 1987)

Upper Smackover rocks from the Gulf Coast were found to have a mean TOC of 0.24% and a mean TOC of 0.34% in samples collected from Alabama. This indicates a significantly lower source potential for the upper Smackover member. No other significant source potential was found in other Jurassic rocks of the Gulf Coast region (Sassen et al., 1987).

Several factors may have contributed to the lower Smackover being able to generate commercial quantities of hydrocarbons even at lower TOC values. Because of diagenetic factors, kerogen was concentrated along laminations and stylolites that resulted in very efficient expulsion of generated hydrocarbons. Also, the kerogen found in the lower Smackover is of algal origin and undiluted by terrestrial input from higher land plants giving it greater oil generative potential. Lastly, because of the regional stratigraphy and the presence of multiple seal rocks,

migration did not result in the dispersion of hydrocarbons. Instead, much of the generated hydrocarbons were channeled into Norphlet and Smackover reservoirs (Sassen et al., 1987).

2.4 – Terrestrial Shales in the Conecuh Embayment

Baria et al. (2008) first noted the presence of several organic-rich, siliciclastic shale layers within the nearly pure carbonates of the Smackover Formation in Alabama. The shale layers range in thickness from 0.5-50 feet and are easily correlative across the eastern lobe of the Conecuh Embayment. The shale layers appear to pinch out up-dip and along the rims of the embayment and thicken basinward before grading into the muddy outer-ramp carbonates of the normal Smackover sequence. The shales are black, laminated, and nearly devoid of marine fauna. Terrestrially derived herbaceous organic matter is also found within the shale layers (Baria et al., 2008).

Deposition of the shale layers is interpreted to have occurred as a product of runoff from the paleohighs rimming the Conecuh Embayment during as many as three sea level falls in southwest Alabama. This interpretation is based on the siliciclastic lithology of the shale and the abundance of plant fragments hosted within the shale layers. Locally this interpretation has implications for reservoir development in and around the Little Cedar Creek Field, as the sea level falls disrupted deposition of the reservoir facies found there. Regionally, this interpretation could push earlier sequence stratigraphic interpretations of three Smackover sequences eastward into Alabama (Baria et al., 2008).

CHAPTER 3 – PETROLEUM SOURCE ROCKS

Hunt (1996) defines a petroleum source rock as any rock that has the capability to generate and expel enough hydrocarbons to form an economic accumulation of oil or gas. A petroleum source rock can be further described with respect to thermal maturity. A potential source rock is one that possesses all of the characteristics of a petroleum source rock but is thermally immature and has yet to generate hydrocarbons. An effective source rock is a thermally mature source rock that has generated and expelled hydrocarbons into a reservoir (Hunt, 1996). Inactive source rocks have stopped generating petroleum, possibly due to uplift or erosion, but still have petroleum generating potential. As a petroleum source rock matures even further it may become a spent source rock that lacks any further generative potential (Peters and Cassa, 1994). The ability of a source rock to generate hydrocarbons and the types of hydrocarbons that will be produced is largely dependent on: 1) the type of kerogen or quality of organic matter present, 2) the quantity of organic matter and 3) the level of thermal maturity. Several techniques have been established to help determine a rock's source potential (Hunt, 1996). The techniques used in this study will be discussed in detail in Chapter 5.

3.1 - Kerogen Types and Classification

The most important factor influencing the generation of oil and gas is the hydrogen content found in the organic matter within the source rock. The hydrogen content is directly controlled by the quality of the organic matter and the type of kerogen contained in a source rock (Hunt, 1996). Kerogen is the organic constituent of sedimentary rocks that is neither soluble in aqueous alkaline solvents or the common organic solvents. Organic matter that can be extracted

using the latter solvents is referred to as bitumen (Tissot and Welte, 1984). Small amounts of bitumen originate from lipid components in once-living organisms, however most is generated by the thermal dissociation of kerogen (Peters and Cassa, 1994).

Several methods exist for identifying the type of kerogen present in a source rock, ranging from light microscopy to geochemical methods. Each of the methods has benefits and drawbacks when determining type and quality of organic matter present and should most often be used in combination (Tissot and Welte, 1984).

There are several classification systems for kerogen types. The most popular scheme breaks kerogens into four types: Type I, II, III, and IV (Table 1). The four types can be distinguished using the hydrogen/carbon (H/C) versus oxygen/carbon (O/C) ratios and are commonly plotted on a van Krevelen diagram (Peters and Cassa, 1994). When considering samples taken from various depths within the same formation, the kerogens normally cluster along a curve called an evolution path. Since the original H/O ratios are influenced by the original organic matter and environment of deposition, closely related environments of deposition result in the same path on a van Krevelen diagram (Tissot and Welte, 1984). Modified van Krevelen diagrams (Fig. 5) allow hydrogen index versus oxygen index calculated from Rock Eval data to be used to distinguish between kerogen types (Peters and Cassa, 1994). In general, the higher the hydrogen index the more oil generative potential kerogen has, and kerogens that have a lower hydrogen index are more prone to produce gas (Peters and Cassa, 1994). Strongly reducing environments such as anoxic lakes or silled basins preserve and enhance the amount of hydrogen content in organic matter, whereas oxidizing environments tend to reduce it (Hunt, 1996).

Kerogen Type	Source of Organic Matter (OM)	Depositional Environment	Expected Product
I	Algae, Reworked lipid rich OM	Lacustrine	Oil
II	Phytoplankton, Zooplankton, and other Microorganisms	Marine	Oil Gas
III	Land Plants	Deltas, basin margins	Gas
IV	Highly Degraded OM	Oxygenated Environments	Non-generative

Table 1 - Kerogen types, their depositional environments, and expected hydrocarbon products (from Tissot and Welte, 1984; Hunt, 1996).

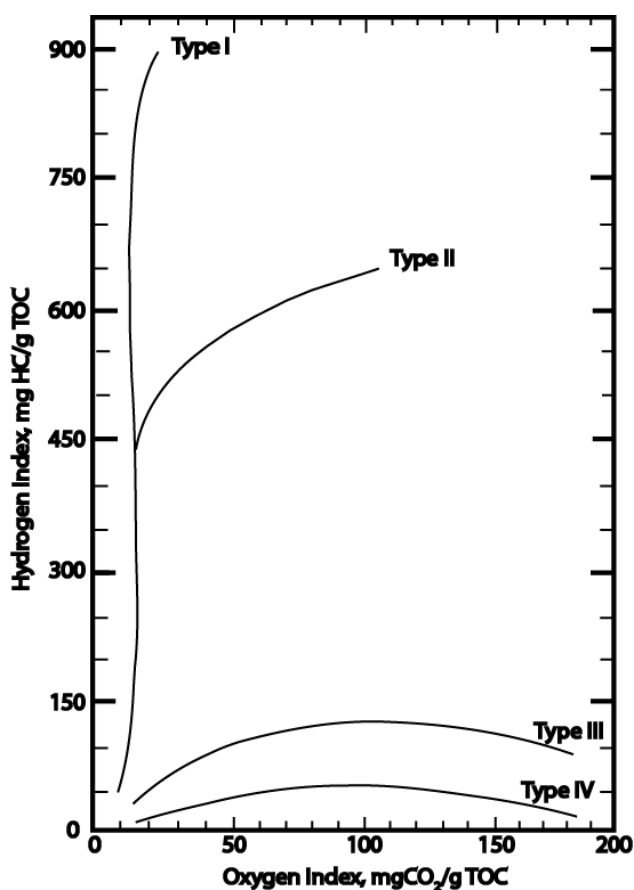


Figure 5 - Modified van Krevelen diagram used for determining kerogen types (modified from Hunt, 1996).

Type I kerogens have a high initial H/C ratio (>1.5) and a low O/C ratio (<0.1) (Tissot and Welte, 1984). The atomic H/C and O/C ratios of Type I kerogens correspond to hydrogen indices greater than 450 and oxygen indices of less than 15 (Fig. 5) (Hunt, 1996). The oil and gas

generative potential for Type I kerogen is the highest of the four types. Type I kerogens are rich in lipid materials and are derived from algal lipids or from organic matter that has been enriched in lipids by microbial activity. Type I has a particularly high proportion of lipid materials that may be the result of selective preservation of algal material or the severe biodegradation of other organic matter. The source of Type I kerogen is predominantly lacustrine algae. Another source of Type I kerogen is from the reworking of organic matter by microorganisms, again resulting in the concentration of lipid-rich material. Type I kerogens are the least common of the four kerogen types and are typically associated with boghead coals and lacustrine depositional environments. Type I kerogens are considered to be oil-prone (Tissot and Welte, 1984).

Type II kerogens have a lower initial H/C ratio than do Type I kerogens but are still very important. The oil generative potential of Type II kerogens is still significant and is found to be the source material in many of the world's oil and gas fields, including those of Jurassic age in the North Sea and Saudi Arabia. Type II kerogens are deposited in a marine environment and are composed of a mixture of phytoplankton, zooplankton, and other microorganisms deposited in a reducing environment (Tissot and Welte, 1984). The atomic H/C and O/C ratios of Type II kerogens correspond to hydrogen indices between 450-600 and oxygen indices of less than 100 (Fig. 5) (Hunt, 1996).

Type III kerogens have a relatively low initial H/C ratio (<1.0) and a high initial O/C ratio (as high as 0.2 or 0.3) (Tissot and Welte, 1984). The atomic H/C and O/C ratios of Type III kerogens correspond to hydrogen indices of less than 125 and a range of oxygen indices from approximately 10-200 (Fig. 5) (Hunt, 1996). Rocks that contain Type III kerogen often lack oil generative potential because they are hydrogen deficient, however at sufficient maturity they may generate significant amounts of gas and oil condensate. Type III is also less productive in

pyrolysis studies. Type III kerogens are derived from terrestrial plant sources and often contains identifiable plant debris. Type III kerogens are frequently found in detrital-rich areas around continental margins (Tissot and Welte, 1984).

Type IV kerogens are very low in initial H/C ratios and high in O/C ratios and lack any hydrocarbon generative potential (Tissot and Welte, 1984).

3.2 - Quantity of Organic Matter

The amount of organic matter in a sedimentary rock is typically expressed as TOC. The overall efficiency of converting organic carbon into economic accumulations of oil and gas is generally less than 15 wt% (Hunt, 1996). The inefficiency of the petroleum system makes establishing the lower boundary of TOC content an important parameter in determining the ability of a rock to generate petroleum (Table 2). For the majority of shale source rocks the TOC content is about 2%. The lower limit for shale-type source rocks has been established to be 0.5% TOC. Some carbonate source rocks have shown generative potential with as little as 0.3% TOC (Tissot and Welte, 1984).

Generation Potential	TOC in Shales (wt. %)	TOC in Carbonates (wt. %)
Poor	0.0-0.5	0.0-0.2
Fair	0.5-1.0	0.2-0.5
Good	1.0-2.0	0.5-1.0
Very Good	2.0-5.0	1.0-2.0
Excellent	>5.0	>2.0

Table 2 - Classic interpretations of TOC content in source rocks based on early oil window maturity (from Jarvie, 1991).

3.3 - Thermal Maturity

The evolution of organic matter during diagenesis, catagenesis and metagenesis changes the properties of the organic matter. These properties can be used to describe the level of maturation for the rock that is being evaluated. Various methods are commonly used in petroleum exploration to determine maturation, ranging from optical to geochemical properties

of the organic matter present. Optical methods include vitrinite reflectance, fluorescence, thermal alteration index, spore color index, and conodont alteration index. Geochemical properties used include pyrolysis, gas chromatography, and biomarkers (Hunt, 1996; Tissot and Welte, 1984). Those used in this study will be discussed in detail in Chapter 5.

As organic matter is subjected to increasingly higher temperatures during burial, the kerogen undergoes thermal degradation. Under reducing conditions the degradation of the kerogen leads to the formation and yield of petroleum-range hydrocarbons (Hunt, 1996). During the initial stages of burial the kerogen undergoes diagenesis. During the diagenesis of kerogen is a marked decrease of oxygen and a correlative increase of carbon content with increasing depth. With respect to petroleum exploration, the kerogen is typically referred to as being immature and little or no hydrocarbon generation has occurred (Tissot and Welte, 1984). Key maturity indicators for the stage of diagenesis include vitrinite reflectance $<0.5\%$ and pyrolysis $T_{\max} < 430^{\circ}\text{C}$ (Hunt, 1996).

The second stage of kerogen degradation is referred to as catagenesis. Catagenesis occurs in deeper samples and is marked by the decrease in hydrogen content and of the H/C ratio. The catagenesis stage corresponds with the main zone of oil generation and the beginning of the cracking zone that produces “wet gas”. Vitrinite reflectance of kerogen during the stage of catagenesis is typically in the range of 0.5-2.0% (Tissot and Welte, 1984).

Metagenesis is the final stage of kerogen degradation and is observed in very deep samples or in areas with a high geothermal gradient. At this stage vitrinite reflectance numbers are $>2.0\%$. The elimination of hydrogen becomes slow and the residual kerogen is composed mostly of carbon. With respect to petroleum exploration the stage of metagenesis lies strictly within the dry gas zone (Tissot and Welte, 1984).

In petroleum exploration the depth interval at which a source rock generates and expels most of its oil is referred to as the “oil window”. Due to variations in the geothermal gradient from basin to basin the oil window cannot be thought of as having a hard depth boundary. Oil windows can also vary slightly depending on the type of kerogen found within a source rock. However, most oil windows occur within the temperature range from 60-160°C and correspond with the earlier stages of catagenesis. Source rock evaluation techniques have different parameters that correspond with respect to the oil window (Figure 6). For pyrolysis data the oil window corresponds with a T_{max} range of about 430-470°C. As the thermal maturity level increases in a source rock it enters the “gas window” and the remaining kerogen begins to produce gas. If maturity continues to increase, hydrocarbon generation will stop and the source rock will have become a spent source rock (Hunt, 1996).

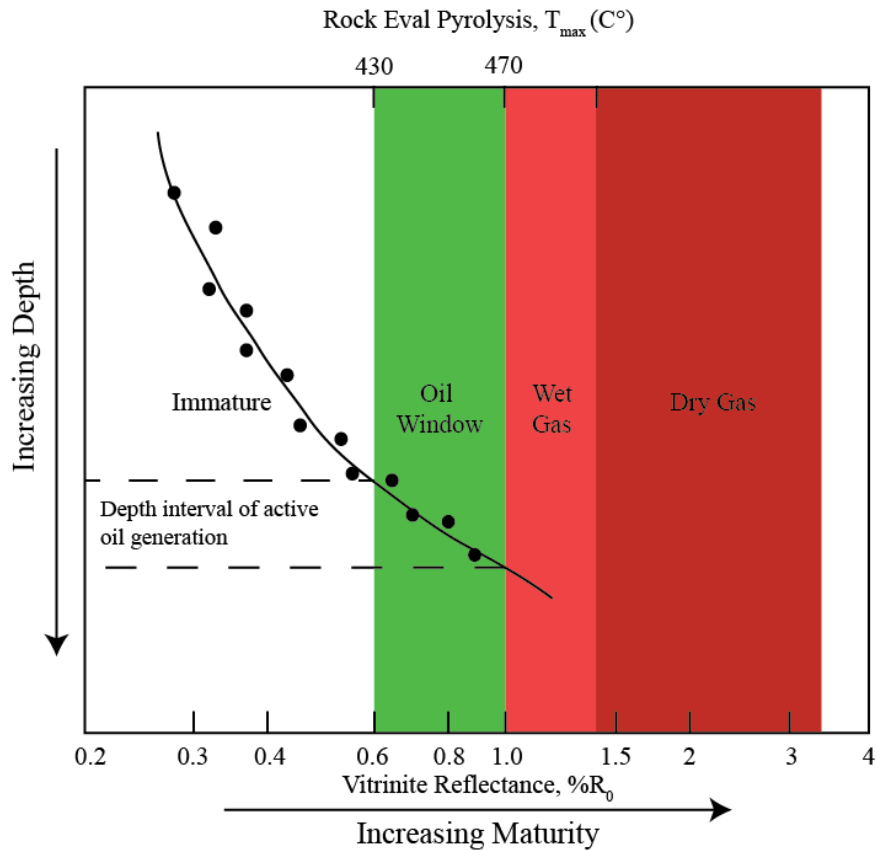


Figure 6 - Zones of hydrocarbon generation with respect to thermal maturity, data is hypothetical (modified from Hunt, 1996).

CHAPTER 4 – SEQUENCE STRATIGRAPHY

Sequence stratigraphy is defined as the study of rock relationships within a time-stratigraphic framework of repetitive, genetically related strata that are bounded by surfaces of erosion and their correlative conformities (Mitchum et al., 1977; Posamentier et al., 1988; Van Wagoner et al., 1988). Sequence stratigraphy is widely regarded to have originated out of the seismic stratigraphy work of Mitchum et al. (1977) that was the culmination of work performed at the Exxon Production Research facility (Fig.7).

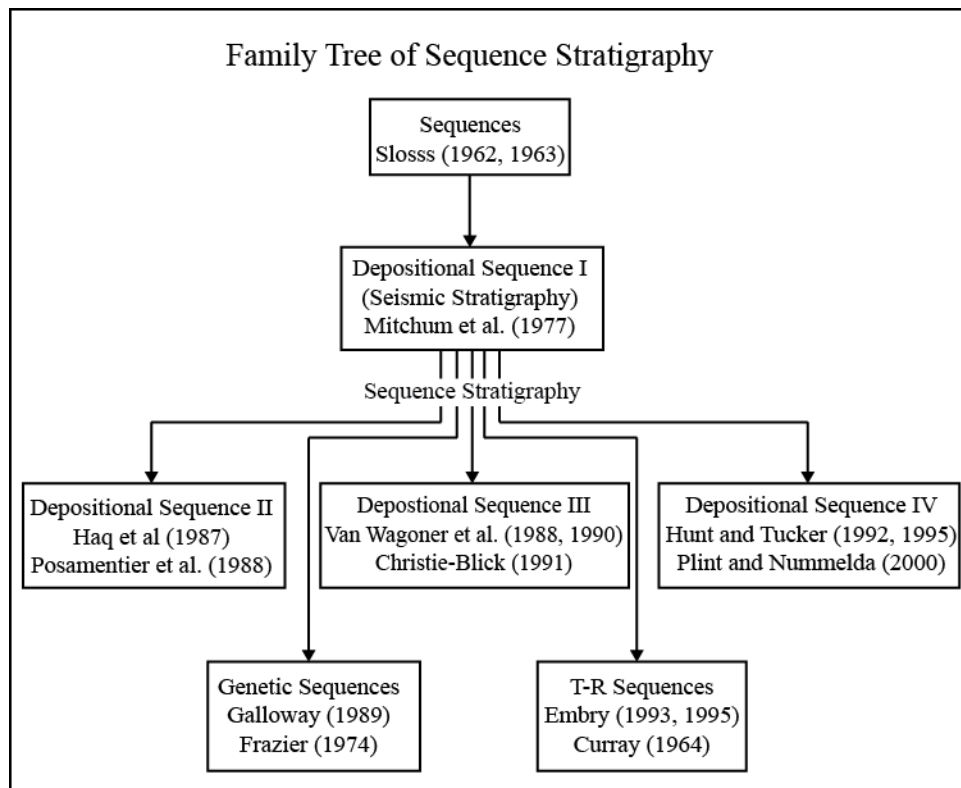


Figure 7 - Family tree of sequence stratigraphy (from Catuneanu, 2006).

In fact, the roots of this method of stratigraphic analysis can be traced as far back as Hutton who recognized the repetition through time of erosion, transport, and deposition. Sloss

(1962, 1963) was the first to recognize the chronostratigraphic significance of rock stratigraphic units that were bounded by unconformities of interregional scope and applied the term sequence to them. Regardless of the historical perspective and origins of sequence stratigraphy, the idea has changed the way stratigraphic analysis of the sedimentary rock record is performed. Since the original seismic stratigraphy concepts were published, several models along with variations in terminology have been developed for the application and practice of sequence stratigraphy. Despite the variations in interpretation, the controls on the stratigraphic signatures in the rock record remain the interaction of tectonics, eustasy, and climate. Tectonics and eustasy control the available space for the accumulation of sediment, while all three have influence on the sediment supply available to fill the accommodation space (Catuneanu, 2006). Key terminology and several of the sequence stratigraphic models that are in use today are discussed in this chapter.

4.1 – Sequence Stratigraphy Terminology

A complex jargon of terminology has been applied to the concept of sequence stratigraphy since the introduction of seismic stratigraphy by Mitchum et al. (1977). Despite sequence stratigraphy being widely accepted into geologic literature, there has been no standardization of terminology as there has been with other types of stratigraphy. The lack of standardization arises from a lack of consensus on some basic principles and the complex terminology that is used is difficult to standardize (Catuneanu, 2006). Due to variations in the terminology a brief review of the key terminology used in this study will be given here.

The fundamental unit of any sequence stratigraphic interpretation is the depositional sequence. Mitchum et al. (1977) defines a sequence as a stratigraphic unit of genetically related strata bounded at its top and base by unconformities or their correlative conformities. For the purposes of sequence stratigraphy an unconformity, the key bounding surface of a sequence, is

defined as an observable discordance in a given stratigraphic section that shows evidence of erosion or nondeposition with obvious strata terminations (Mitchum et al., 1977). Subaerial unconformities are the stratigraphic surfaces that are the bounding surface of a depositional sequence on the continental side of a basin (Catuneanu, 2006). Basinward of the unconformities are areas of continuous deposition, and here the unconformities are replaced by their correlative conformities for the purposes of dividing depositional sequences (Mitchum et al., 1977).

Correlative conformities can be defined as the stratigraphic surface that best approximates the paleo-seafloor at the end of a forced regression (Catuneanu, 2006). Chronostratigraphically a depositional sequence is significant because it was deposited during a given interval of geologic time defined by the sequence boundaries. Chronostratigraphic surfaces that are related to sequences are the unconformities and their correlative conformities that make up the sequence boundaries and strata surfaces within the sequence boundaries. A depositional sequence is an interpretation that is not primarily dependent on rock type, fossils, or depositional processes as they are widely variable within a depositional sequence. Therefore, sequence boundaries and strata surfaces may or may not be parallel to lithostratigraphic surfaces such as formations and lithofacies (Mitchum et al., 1977). Regardless of whether these surfaces are unconformable or conformable, they mark changes in the sedimentation regime across the boundary. Sequences are the result of a full stratigraphic cycle of changing depositional trends, and are often considered to be the result of a full cycle of relative sea level change (Catuneanu, 2006).

Sequences are composed of at least two or more systems tracts depending on the model used for interpretation. Systems tracts include all of the strata that accumulate during a particular stage of shoreline shifts. Systems tracts, like the sequences that they compose, are divided or bounded by key stratigraphic surfaces that have chronostratigraphic significance (Catuneanu,

2006). How each of the individual systems tracts are defined is typically model-dependent and basic definitions will be given here. The sequence models themselves will be discussed in further detail below.

The basal systems tract in a depositional sequence and therefore the stratigraphically oldest is the lowstand systems tract (LST). Deposition of the lowstand systems tract occurs during an interval of relative sea level fall and subsequent slow relative sea level rise. Falling sea level results in a steepening of the fluvial gradient and rivers are therefore forced to incise downward into existing strata. Reworked sediments and fluvial loads from the hinterland are carried further basinward and are deposited onto the previous highstand slope. This condition persists until sea level stabilizes and the lowstand systems tract begins to prograde as sediment supply begins to outpace accommodation space. The lowstand systems tract can be divided into a fan, deposited during sea level fall, and a wedge, deposited during the prograding phase as sea level stabilizes and begins to rise (Emery and Myers, 1996).

The transgressive systems tract (TST) is deposited during a relative rise in sea level when the accommodation space is increasing faster than the rate of sediment supply. Depositional systems during a relative sea level rise include alluvial, paralic, coastal and shelfal systems. Distally a TST may form a condensed section characterized by extremely low rates of deposition. The end of a TST occurs at a point when accommodation space and sediment supply become equal and progradation begins again. The strata surface that marks the end of the TST is known as the maximum flooding surface (Emery and Myers, 1996).

The youngest of the systems tracts is the highstand systems tract (HST) and is deposited after maximum transgression when the rate of sediment supply begins to again outpace the creation of accommodation space. Stratal architecture during a HST is initially aggradational

followed by progradation as sediment supply outpaces accommodation space during initial sea level falls, but before the development of the sequence boundary (Emery and Myers, 1996).

Several key stratigraphic surfaces are used to divide systems tracts within a depositional sequence. The maximum regressive surface is the surface that separates prograding strata below and the retrograding strata above and corresponds with the change from a regressive shoreline to a transgressive shoreline. The maximum regressive surface separates the LST from the TST. The maximum flooding surface is the point at which the shoreline shifts from being transgressive to regressive in nature. The surface separates retrograding strata below to prograding strata above. A maximum flooding surface marks the change from a transgressing shoreline to that of a regressive shoreline and separates the TST from the HST. These surfaces are easiest to identify in a seismic dataset where the geometries of onlapping or offlapping strata can be readily identified (Catuneanu, 2006).

4.2 – Sequence Models

Since the original work of Mitchum et al. (1977) several variations of sequence models have been employed. The main variation in all of the models currently in use is how strata are packaged into a sequence (Fig. 8). They each use a different timing system for systems tracts and the placement of sequence boundaries in relation to each cycle of shoreline shifts. Each model has benefits and pitfalls to interpretation and each may work better in a particular set of circumstances (Catuneanu, 2006). Some of the aspects of the various sequence stratigraphic models are discussed below.

The depositional sequence models use the subaerial unconformity and the correlative conformity as the bounding surface of a sequence. The sequence boundary for depositional models is placed at the base of the lowstand systems tract (Catuneanu, 2006). In depositional

sequence models the sub-aerial unconformity is equated to the stage of base-level fall at the shoreline and correlative conformities are picked as the seafloor at the onset of regression. Depositional sequence IV is similar to the first three except that a falling stage systems tract (FSST) is recognized. Much of the debate within the depositional sequence interpretations centers around the placement of sequence boundaries within the shallow-marine environment. The continental side of a basin is likely to have a well developed sub-aerial unconformity during prolonged periods of base-level fall that becomes progressively younger as it develops basinward yet is easily recognizable. Basinward the correlative conformity also is likely recognizable due to strata geometries. However, in the shallow marine environment it is possible that portions of the correlative conformity could be reworked and make placement of the sequence boundary difficult. Regardless of the depositional sequence model used, the key to a valid interpretation is the recognition of facies shifts and shoreline shifts (Catuneanu, 2006).

When compared with the transgressive-regressive (T-R) model the depositional sequence models possess some distinct positives. In depositional sequence models the sequence boundaries are defined relative to the base-level curve and therefore are independent of sedimentation rates. Sedimentation rates may vary greatly along strike making the development of maximum flooding and maximum regressive surfaces that bound the T-R sequences highly diachronous and lessening the chronostratigraphic significance. Placing sequence boundaries at the subaerial unconformities effectively separates packages of genetically related strata. The key pitfall to these models is the interpretation of sequence boundaries in shallow-marine settings (Catuneanu, 2006).

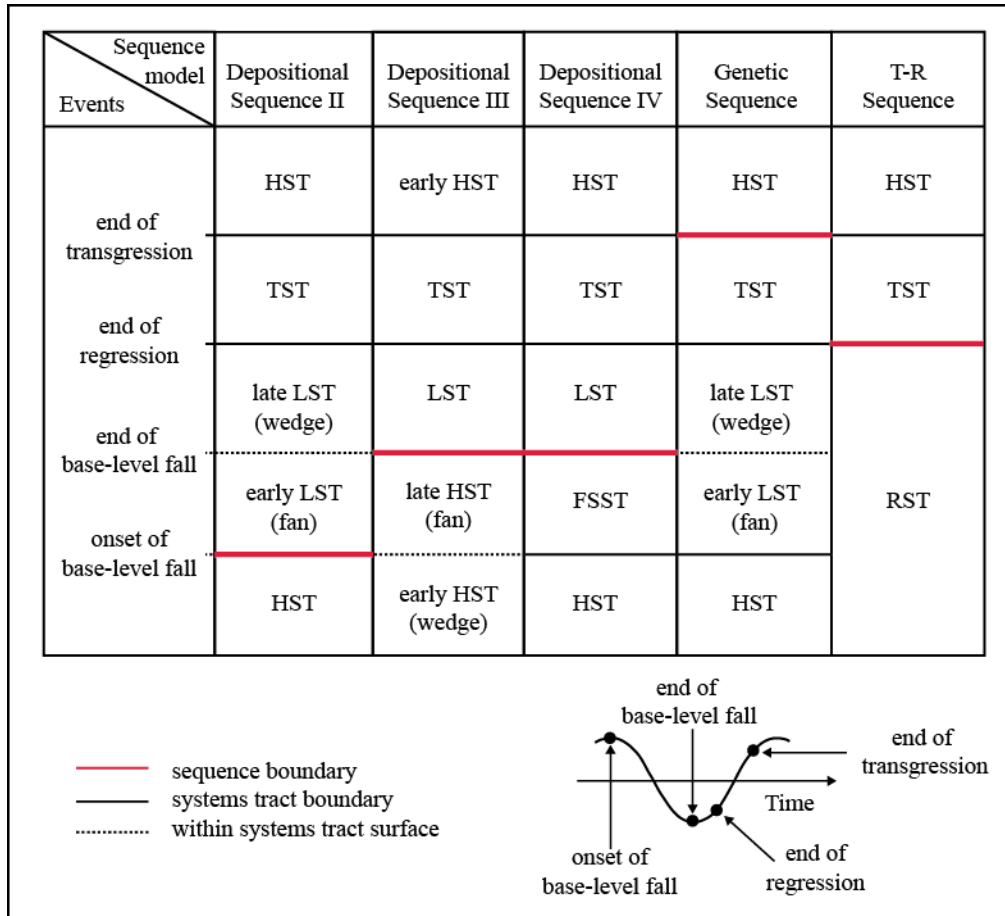


Figure 8 - Sequence models, the placement of sequence boundaries within them, and their resulting systems tracts (from Catuneanu, 2006).

The transgressive-regressive (T-R) sequence (Embry and Johannessen, 1992) offers an alternative way to package sedimentary strata into depositional sequences. The T-R sequence is bounded by surfaces that include subaerial unconformities on the basin margin and the maximum regressive surfaces seaward. The T-R sequence was developed in an attempt to bypass interpretation pitfalls found in earlier models and is useful in shallow-marine successions, especially in the absence of seismic data for corroboration. T-R models recognized the value of the subaerial unconformity as a sequence boundary at the continental margins of basins but eliminated the use of the correlative conformity in favor of the surface of maximum regression due to it being easily recognizable in shallow-marine environments. However, the development of the maximum regressive surface may be harder to recognize in deeper water settings. The

transgressive and regressive systems tracts of the T-R model are divided by the maximum flooding surface. The T-R model is not useful from an exploration perspective since much of the resolution is lost by the amalgamation of systems tracts into two large systems tracts (Catuneanu, 2006).

The genetic stratigraphic sequence model (Fig. 8) uses the maximum flooding surfaces as sequence boundaries. The sequence of the genetic stratigraphic sequence model is divided into three systems tracts, the highstand, lowstand, and transgressive systems tracts. The systems tracts are defined in the same way as they are in the depositional sequence II model. The genetic sequence model overcomes some of the problems associated with other models, especially in shallow marine environments, in that maximum flooding surfaces are relatively easy to map across a basin. Maximum flooding surfaces are also typically easier to distinguish in well logs than subaerial unconformities. This means that the sequences of this model are bounded by a single and easily identifiable stratigraphic surface. This model is linked to the distinct recognition of shoreline regressions and transgressions and therefore evidence for syndepositional shoreline shifts must be found. Therefore, this model does not work for overfilled basins or for fluvial systems that act independent of base level changes. It can be particularly useful though in basins that exhibit a continuous rise in base level and there is an absence of subaerial unconformities for use as sequence boundaries (Catuneanu, 2006).

4.3 – Sequence Stratigraphy and Carbonate Ramps

Carbonate ramps are gentle seaward dipping surfaces with low gradients, generally on the order of a few meters per kilometer (Fig.9). Deposition on a ramp typically consists of updip shallow-water carbonates transitioning to deeper water and then into basinal sediments farther offshore (Tucker and Wright, 1990). Ramps can be divided into two main categories: homoclinal

ramps, that exhibit a gentle gradient into the basin, and distally steepened ramps reflected by gradient increases in the outer-ramp region (Tucker and Wright, 1990; Tucker et al., 1993).

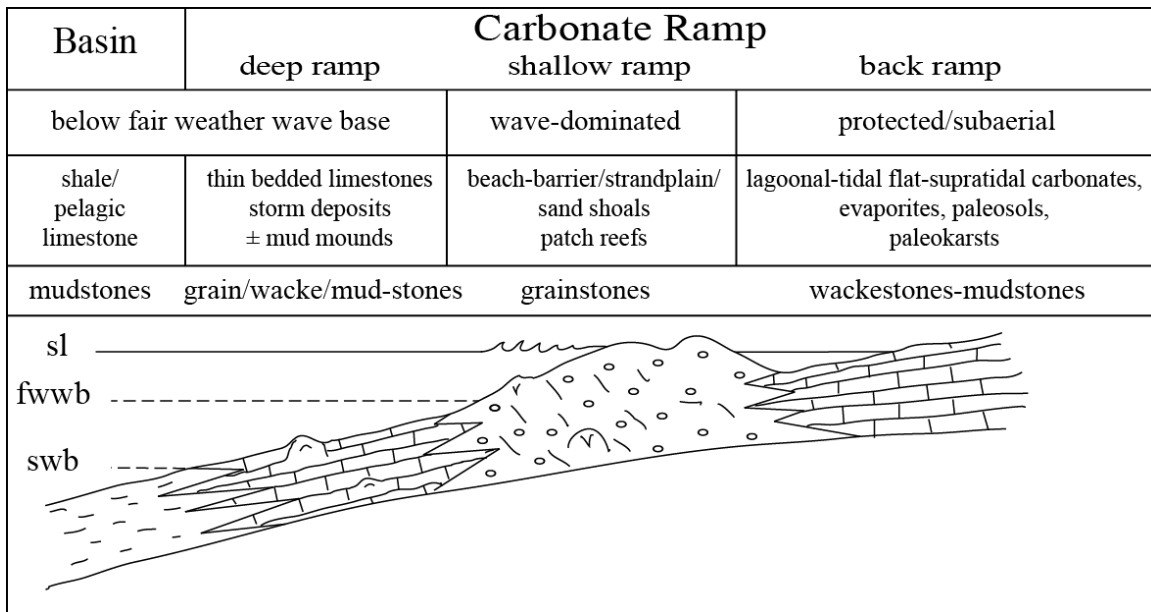


Figure 9 - Carbonate ramp depositional environments and associated facies. Abbreviations: sl – sea level, fwwb - fair-weather wave base, swb - storm-weather wave base (from Tucker et al., 1993).

Whether carbonate ramps are homoclinal or distally steepened, deposition on carbonate ramps typically takes place in one of two environments, either shallow ramp and back ramp (shallow-water) or deep ramp and basin (deep-water) regions (Fig. 9). For this paper the shallow and back ramp regions will be referred to as the inner ramp, and the deep ramp and basin regions will be referred to as the outer ramp. Ramps can exhibit variations in facies patterns, particularly on the shallow and back ramp areas. Commonly the inner ramp will be dominated by a strandplain complex or a barrier-lagoon shoreline. Both strandplain complex and barrier-lagoon shoreline settings exhibit moderate- to high-energy environments. The third type of inner ramp setting is a low-energy ramp that is dominated by tidal flats, lagoons, and some sand shoals. Reefs are generally poorly developed on ramps, however patch reefs and pinnacle reefs do occur in the inner ramp setting and mud mounds develop on the outer ramp (Tucker et al., 1993). The

Jurassic Smackover Formation of the U.S. Gulf Coast was one of the first formations to be interpreted using the carbonate ramp model of deposition (Tucker and Wright, 1990).

Sequence stratigraphy concepts can be applied to carbonate ramps relatively easily, especially when compared with the steeper-sided carbonate shelf environment (Tucker and Wright, 1990). The primary difference between siliciclastic shelves and carbonate ramps and shelves is the source of sediment. Siliciclastic shelves rely on the input of terrigenous sediment eroded from exposed highlands. In a carbonate environment the sediment is essentially created *in situ* given the right depositional conditions. The up-dip portions of ramps present a complex interplay of siliciclastic influx and carbonate production that may complicate interpretation. However, tectonics, climate, and global sea level influence the amount of sediment and the volume of space available for sediment deposition (Catuneanu, 2006).

With respect to sequence stratigraphy, the most important depositional periods for carbonate ramps are the transgressive and highstand systems tracts (TST and HST). Lateral migration and ramp facies thickness is dependent on sea level changes and subsidence rates. Small sea level changes can have major impacts on the inner-ramp where the water is shallow. In deeper ramp settings sea level changes typically affect the location of the wave base and are important controls on the amount of reworking of bottom sediments. Homoclinal ramps exhibit a simple geometry that results in facies belts moving either up or down the ramp in response to relative sea level changes. During the TST the facies geometries that are created are dependent on the relative rates of sea level rise and carbonate sedimentation. When sea level rise outpaces carbonate sedimentation, a backstepping of the shoreline occurs and a drowning of earlier inner ramp facies occurs. If carbonate sedimentation is greater than the rate of sea level rise then

aggrading or prograding of the inner ramp can occur. During the HST aggrading and prograding of inner ramp facies may occur (Tucker et al., 1993).

Lowstand systems tracts (LST) may display a variety of facies and depositional environments related to the relative fall of sea level (Catuneanu, 2006). Typically on a low-gradient homoclinal ramp there will simply be a basinward shift in facies. During the lowstand a new area of inner-ramp deposition may occur at the shore face. Prolonged sea level standstill during the lowstand will result in the progradation of carbonate sands that compose a systems tract analogous to the shelf margin wedge (SMW) on siliciclastic margins. This is common during the formation of type-2 sequence boundaries, where sea level does not break below the shelf margin. If there is an active uplift of the hinterlands during the relative fall in sea level, an influx of siliciclastic material can be expected, resulting in the development of lowstand deposits. During the LST the inner ramp may be exposed and result in the formation of a sequence boundary (Tucker et al., 1993). The Smackover of the north-central Gulf of Mexico rim exhibits the formation of an LST during the formation of a type-2 sequence boundary on a carbonate shelf in an arid climate (Sarg, 2001). In this area the Smackover is a generally shallowing upward sequence that is capped by the development of anhydrites and red beds of the Buckner Member of the Haynesville Formation (Sarg, 2001; Heydari and Baria, 2006).

In general, thick successions ramp limestones are comprised of 1-10 m-scale cycles that are generally shallowing upward cycles comprised of the TST and HST. The cycles are generally made up of lime-mudstones with storm beds that pass upwards into shallow-water grainstones deposited near the shoreface. The LST at the top of the sequence results in the development of paleokarsts, paleosols, or dolomite and/or evaporite beds dependant of climate (Tucker and Wright, 1993).

4.4 – Smackover Sequence Stratigraphy

Several interpretations of the Jurassic sequence stratigraphy of the U.S. Gulf Coast currently exist. Most of these studies have focused on the north-central Gulf Coast (Sarg, 2001; Heydari and Baria, 2006), southwest Alabama (Wade and Moore, 1993), the Mississippi Interior Salt Basin (Mancini et al., 1990), and the Manila Embayment (King and Hargrove, 1991). Prather (1992) interpreted the evolution of the Conech Embayment using a sequence stratigraphic model; however, the terrestrial shales recently discovered in the Conech Embayment were not incorporated into the interpretation.

Heydari and Baria (2006) proposed a sequence stratigraphic framework for the Smackover Formation of the north-central Gulf Coast (Fig. 10). The study combined the use of core, log, and seismic data from northern Louisiana and southern Arkansas resulting in the division of the Smackover into three sequences. The sequences named in ascending order are the Smackover “C”, the Smackover “B”, and the Smackover “A”. The lowstand systems tract (LST) for the “C” sequence is the Norphlet Formation. Following the LST, a shoaling-upward lithofacies succession was recognized ranging from a laminated lime mudstone, thin-bedded lime mudstone, bioturbated lime mudstone, wackestones – packstone, to an ooid grainstone. The absence of a deepening upward facies is interpreted to be due to the rapid sea level rise that deposited the Smackover Formation and that a recognizable transgressive systems tract (TST) was not deposited. The “C” sequence is a beach to basin prograding high stand systems tract (HST) (Heydari and Baria, 2006).

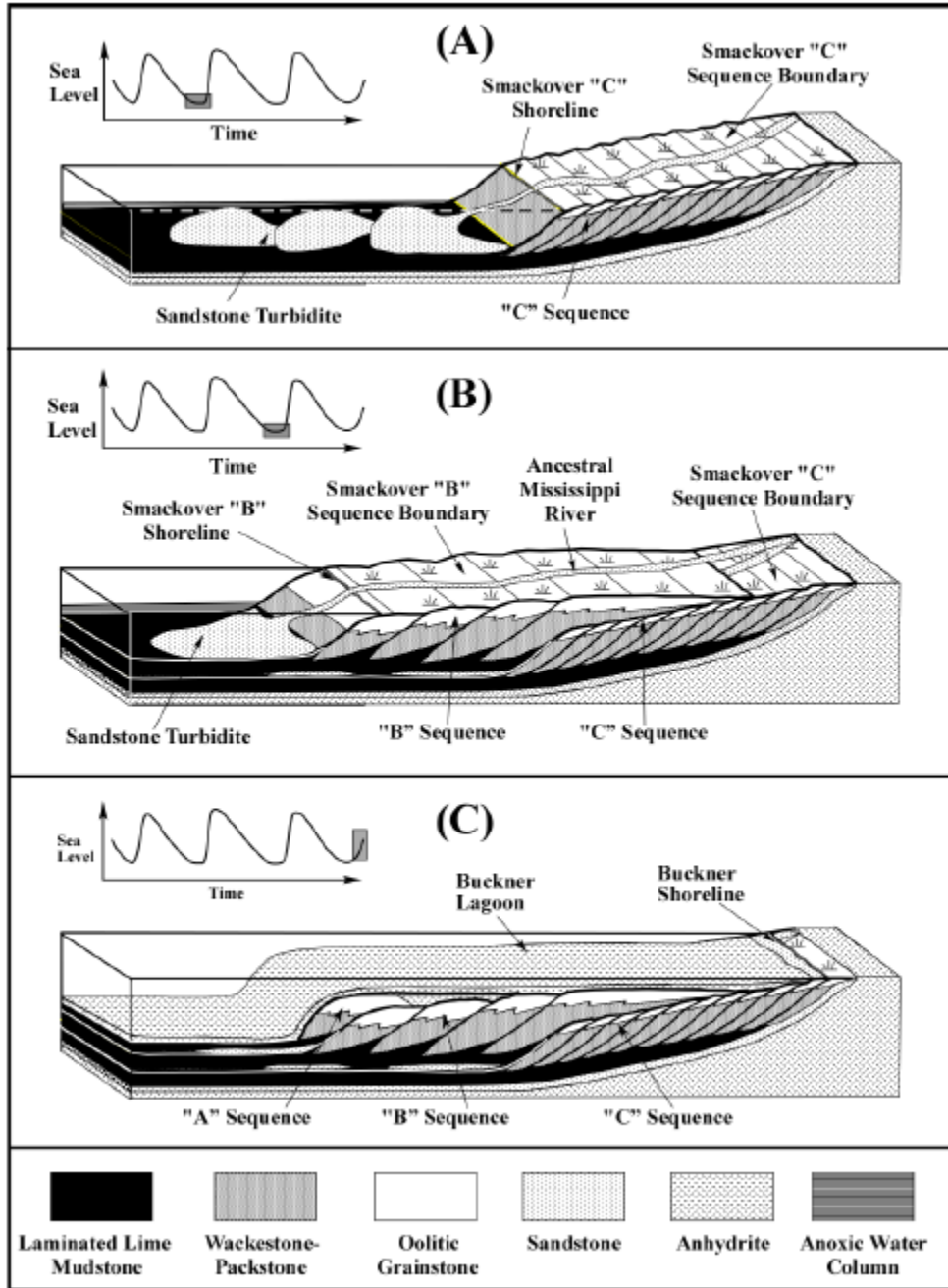


Figure 10 - Sequence stratigraphic model for the Smackover Formation in the north-central U.S. Gulf Coast. Note the development of 2 LSTs represented here by the basinal sandstone turbidites (from Heydari and Baria, 2006).

Capping the top of the C sequence are caliche deposits that formed during exposure to meteoric waters during a relative sea level fall. Also, near the bottom of the B sequence the presence of turbidites is used as evidence for a sea level fall. The base of the B sequence is

interpreted as the LST in the model. Another rise in sea level resulted in the deposition of a shoaling upward carbonate sequence that passes from wackestones to packstones to ooid grainstones. The absence of TST sedimentation resulted in the interpretation that sea level rise was again rapid. The grainstones at the top of the B sequence were subsequently exposed to subaerial processes during another sea-level fall. The base of the A sequence contains turbidites and sand was delivered to the shelf margin. The A sequence carbonates show a shoaling upward progression of lithofacies and were exposed to meteoric processes during a third sea level fall. Buckner Member evaporites overlie the Smackover A sequence and are interpreted to have been deposited during a relative sea level rise (Heydari and Baria, 2006).

Prather (1992) divided Oxfordian deposition in the Conech Embayment into three main systems tracts by constructing time-slice lithofacies maps. In this interpretation the Smackover and Haynesville were placed together into one genetic sequence. The basal sequence boundary was placed within the Norphlet Formation before Jurassic seas encroached into the embayment. The re-worked portion of the Norphlet and deposition of the laminated lime-mud portion of the Smackover represents the TST, which during this time showed the typical onlapping and retrograding geometry. Subsequent shallowing upward and prograding sequences are interpreted as the HST and shelf margin wedges (SMW). The Buckner/Haynesville anhydrites and shales cap the sequence and are interpreted to have been deposited during a slow rise in relative sea level (Prather, 1992).

The recent shale discoveries in the Conech Embayment provide the opportunity to further understand the stratigraphic relationships of Oxfordian deposition in the area. In light of the additional data provided by recent drilling, the genetic sequence of Prather (1992) will be further subdivided using the model set forth by Heydari and Baria (2006).

CHAPTER 5 – METHODOLOGY

Conventional cores taken from six wells and well logs from an additional 20 wells within the Conecuh Embayment were used as the primary dataset for this study (Fig. 11). Limited seismic data were also used to understand the geometries of the Jurassic strata within the study area. The Smackover shales were sampled from five of the wells and analyzed for their geochemical properties and mineralogy. Palynological data were acquired to identify the terrestrial pollens and materials first recognized by Baria et al. (2008). Core descriptions, seismic data and well log signatures, along with detailed petrographic analyses made available from previous studies, were used to place the deposition of the shales into a sequence stratigraphic framework.

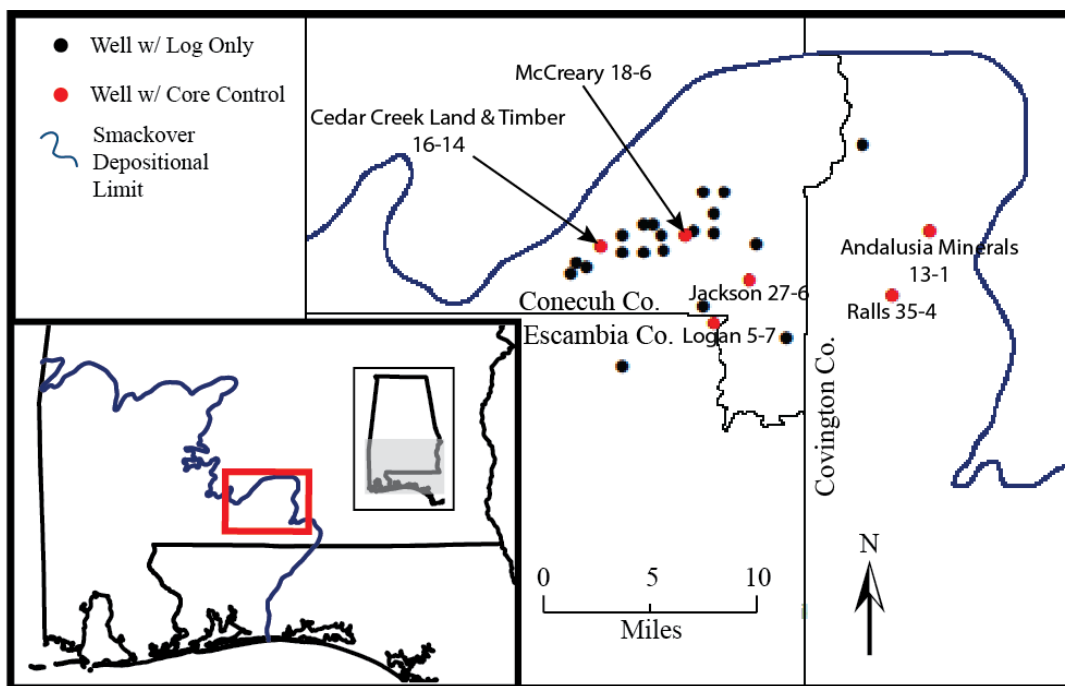


Figure 11 - Well locations within the study area. Wells with core control were chosen based on the presence of shale and to achieve a representative sample across the longitudinal axis of the northern arm of the Conecuh Embayment.

5.1 – Applied Source Rock Geochemistry

The field of organic geochemistry has made significant contributions to the petroleum exploration industry, particularly the ability to identify and map source rocks for a petroleum system. Source rocks are mapped for richness, type, and thermal maturity to determine the geographic and stratigraphic extent of the petroleum source. Identification of an active source rock in a basin reduces exploration risk (Peters and Cassa, 1994). The most commonly used analytical methods for the purpose of identifying source rocks are total organic carbon content analysis, Rock Eval pyrolysis, and vitrinite reflectance analysis (Dembicki, 2009). To determine the richness, type, and thermal maturity of the Conecuh Embayment Smackover shales, samples were obtained from whole cores and sent to Geomark Research, Ltd. for analysis using the following methods.

5.1.1 – Total Organic Carbon Analysis

Total organic carbon (TOC) is used to determine the organic richness of sedimentary rocks. TOC analysis is typically the first screening process to evaluate the potential of a formation to generate hydrocarbons. If a formation has enough organic richness, further evaluations must then be made to determine the quality of the source rock. The most common methods for determining TOC are the Leco combustion method and the combined pyrolysis-oxidation method of Rock Eval (Jarvie, 1991). For this study the Leco combustion method was used to determine TOC and percent carbonate for the Smackover shales in the Conecuh Embayment.

The Leco combustion method of analysis requires approximately 1 g of crushed rock. The sample is first treated to remove any inorganic carbon that may be in the sample in the form of carbonates. To accomplish the removal of inorganic carbon the sample is soaked in

hydrochloric acid (HCl) and stirred intermittently for 12-16 hours. After the complete dissolution of carbonates is observed, the sample is rinsed free of HCl solution using water, filter paper, and a filtering flask. The sample is then allowed to dry (Jarvie, 1991).

The Leco Carbon Analyzer is calibrated with a steel standard of known carbon content. The sample is then placed in the analyzer and the carbon in the sample is then oxidized to carbon dioxide. The carbon dioxide is detected by either an infrared (IR) detector or a thermal conductivity detector (TCD). The IR detector is specific to carbon dioxide, however a TCD will respond to other compounds such as sulfur dioxide and water. If the latter are not properly removed while using a TCD the TOC values may be inflated (Jarvie, 1991).

Carbonate carbon is also calculated using this method by completing two analyses. The total carbon content minus the total organic carbon in a sample gives the total carbonate carbon (Jarvie, 1991).

5.1.2 – Rock Eval Pyrolysis

The best method for correctly evaluating the quality and maturation of kerogen is by determining the atomic H/C and O/C ratios and plotting them on van Krevelen diagrams. However, this method is very time consuming and expensive, creating the need for a faster evaluation method. The Rock Eval pyrolysis method was developed and first published by Espitalie et al. in 1977 as an alternative method for accurately determining these atomic ratios (Hunt, 1996).

Rock Eval pyrolysis involves passing a stream of helium through 100 mg of pulverized rock that has been initially heated to 300°C. The temperature of the oven is then increased about 25°C min⁻¹ until the temperature reaches 550°C. The vapors that are expelled from the sample are analyzed with a flame ionization detector (FID). The results of the test are recorded by the S₁,

S₂, and S₃ peaks as shown in Fig. 12. The first peak (S₁) represents any free hydrocarbons that are present in the sample either from the time of deposition or that have been generated from kerogen since deposition. The free hydrocarbons are distilled from the rock by the initial heating to 300°C. Between 300 and 390°C the carboxyl groups in the kerogen break off, yielding CO₂ that is trapped and analyzed later during the cooling phase. As the temperature rises above 350°C until it reaches the maximum of about 550°C, hydrocarbons are generated from any kerogen in the rock and are recorded by the second peak (S₂). The temperature of the oven that corresponds with the S₂ peak is recorded as T_{max} and is later used during interpretation as an indicator of thermal maturity. At this point only residual non-generating carbon remains in the sample. During the cooling cycle the previously trapped CO₂ is analyzed by a thermal conductivity detector and is recorded by the third peak (S₃). All results are recorded in mg HC per gram of rock and mg CO₂ per gram of rock, respectively (Hunt, 1996).

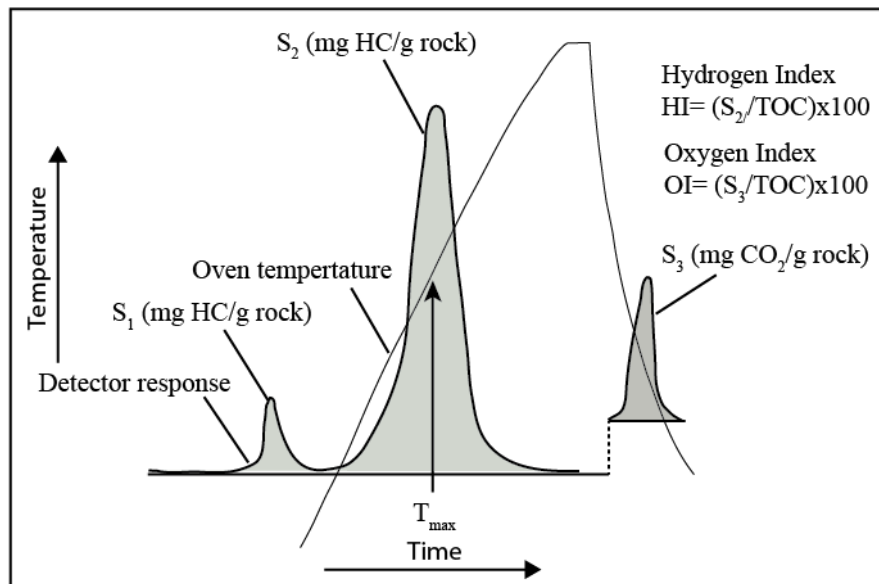


Figure 12 - Typical detector response from the Rock Eval analysis (from Hunt, 1996).

Data collected during pyrolysis is then used to calculate the hydrogen index (HI) (S_2/TOC) and oxygen index (OI) (S_3/TOC) for a sample. It has been shown that the indices are independent of the amount of organic matter and are closely related to the elemental composition

of the kerogen. Therefore the indices can be used in place of the atomic H/C and O/C ratios to determine kerogen type. The indices can be plotted on a van Krevelen diagram and interpreted the same way as the elemental analysis of a kerogen (Tissot and Welte, 1984).

5.1.3 – Interpretation of TOC and Rock Eval Pyrolysis Data

It is commonly thought that just because a sediment has a high TOC content it will be a good petroleum source rock. Sufficient organic content does not qualify a rock as having source potential, although the lack of sufficient organic matter can be used to immediately dismiss source potential. In order for organic matter to generate hydrocarbons the carbon must be associated with hydrogen. The more hydrogen associated with the carbon in the kerogen, the more hydrocarbons that can be generated. As a source rock matures and more of the kerogen is cracked to hydrocarbons, TOC values found in the rock will decrease over time. Essentially a source rock will look less and less like a source rock as it matures. Therefore, it is essential to take into account the regional maturity trends when analyzing TOC data (Dembicki, 2009).

Rock Eval pyrolysis can be used to rapidly identify the generative potential of petroleum source rocks. However, there are several factors that must be considered when interpreting Rock Eval data. Proper interpretation techniques require information on lithologies, the relative abundances of organic matter and mineral matrix, well conditions (i.e. – type of drilling fluids used), the presence or lack of generated hydrocarbons, pyrograms, and geochemical logs. For example, the source potential of organic-poor, clay-rich rocks may be downgraded when compared to tests on isolated kerogen due to the adsorption of pyrolyzate on the clays. This is shown in Rock Eval data by lower HI values and higher T_{max} temperatures. Illite is particularly prone to downgrading pyrolysis results, followed by montmorillonite, calcite, and kaolinite (Peters, 1986). It has been shown that up to 85% of pyrolyzate may be retained by an illite

matrix. Type III kerogens are most the most prone to this problem due to the generation of less pyrolyzate per gram of organic matter (Peters, 1986).

It is also important to consider regional maturity trends when interpreting Rock Eval data, as the method is less reliable in immature sediments. Estimation of maturity using T_{max} values from Rock Eval may also be unreliable in some samples. T_{max} for small S_2 peaks with values $<0.2 \text{ mg HC g}^{-1} \text{ TOC}$ are generally unreliable. T_{max} may also be influenced by organic matter type, contamination from well fluids, and the mineral matrix in addition to the level of thermal maturity (Peters, 1986).

Organic lean sediments, where TOC is $<0.5\%$, have been shown to be strongly affected by the previously mentioned mineral matrices. Peters (1986) notes that Rock Eval data becomes less reliable at lower TOC values and lower levels of thermal maturity.

The most reliable way to overcome common interpretation problems is by collecting large amounts of data. Peters (1986) makes the recommendation of using at least one sample every 30-60 feet down the borehole. Despite the interpretation problems previously mentioned, Rock Eval is a reliable and cost effective way to screen potential petroleum source rocks. When performing detailed studies of source rocks, other more detailed methods such as kerogen isolation and light microscopy may be employed (Peters, 1986).

5.2 – Sequence Stratigraphy

Like any geological interpretation, the accuracy of a sequence stratigraphic analysis is limited by the amount and quality of data available. An ideal situation would involve the integration of outcrops, cores, well logs, and seismic datasets into the interpretation (Catuneanu, 2006). To place the deposition of the Smackover shales into a sequence stratigraphic framework, conventional cores and well logs were the primary datasets used in this study as the Smackover

Formation does not crop out in the Gulf Coast region. Limited seismic data were available to establish a basis for interpretation and to understand strata geometries in the Conecuh Embayment.

Catuneanu (2006) provides a basic workflow for performing a sequence stratigraphic analysis (Fig. 13). The first step in the workflow is to establish the tectonic setting for the study area. Since the key to sequence stratigraphic interpretation is to understand the interplay between sea level, accommodation space, and sediment supply, it is imperative to understand the type of basin, and therefore the subsidence patterns. Tectonic settings are typically reconstructed using regional datasets that include seismic interpretation, well log and core correlations, and biostratigraphic information (Catuneanu, 2006). Due to the limited data available for this project the tectonic setting was established during an extensive literature review of the study area along with analysis of selected cores and well logs.

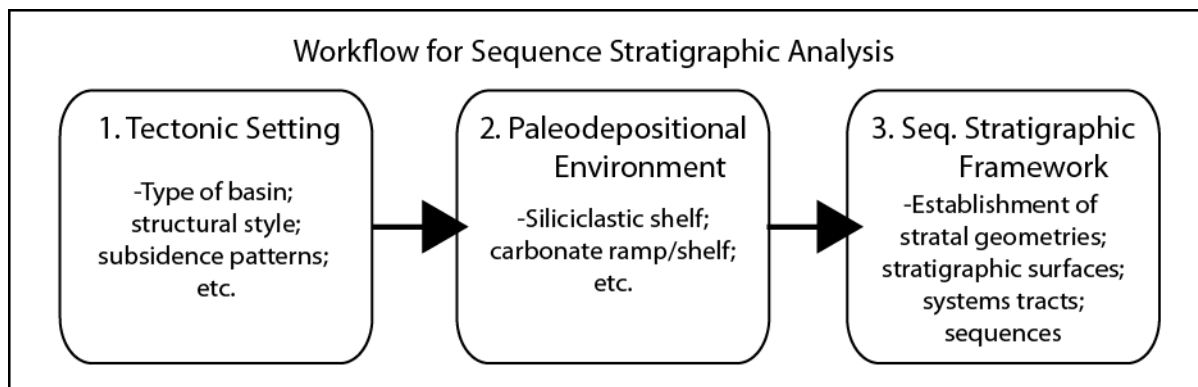


Figure 13 - Workflow used for sequence stratigraphic interpretation (from Catuneanu, 2006).

The second step in a sequence stratigraphic analysis (Fig. 13) is the determination of paleodepositional environments. From a sequence stratigraphic perspective, understanding the temporal and spatial distribution of depositional systems and their shift through time is imperative for the validation of the sequence stratigraphic surfaces assigned to an area (Catuneanu, 2006). Core analysis, as shown in Appendix C, was combined with literature review

was used to understand the paleodepositional environments within the Conecuh Embayment study area.

Finally, the strata that are being studied are placed into a sequence stratigraphic framework (Fig. 13). A sequence stratigraphic framework accounts for the genetic context in which the chronostratigraphic surfaces, and the strata they separate are placed into a model that accounts for the temporal and spatial relationships of the facies that fill a sedimentary basin. The ultimate goal is for the model to be used in an efficient exploration approach for natural resources as the development of facies patterns should be predictable within the genetic framework (Catuneanu, 2006).

The first step in establishing the sequence stratigraphic framework is the recognition of stratal terminations. This involves the recognition of the geometric relationships of strata and the stratigraphic surfaces against which they terminate. This may be done using continuous subsurface datasets such as 2D seismic. Stratal terminations may also be inferred by correlating well logs based on knowledge of the depositional settings and the trends that are expected in that environment. Whether strata are onlapping, offlapping, downlapping, etc. may provide clues as to the direction of shoreline shift (Catuneanu, 2006).

Once the framework has been established and the geometric relationships are understood, the next step is to assign the stratigraphic surfaces. These can be identified using several criteria, including 1) the nature of the contact, 2) the depositional systems that are adjacent to that surface, 3) the associated stratal terminations, and 4) the depositional changes above and below that surface. Once the aforementioned steps have been completed and the position and types of stratigraphic surfaces have been identified, the identification of systems tracts on cross-sections becomes a straightforward procedure. The completed model allows the interpreter to reconstruct

the depositional history of an area and to predict the location of facies as an exploration tool (Catuneanu, 2006).

CHAPTER 6 – RESULTS AND DISCUSSION

Two dark gray-black siliciclastic shale layers were recognized in core and on well logs within the Conecuh Embayment of southwest Alabama. In keeping with the naming convention established by Baria et al. (2008) the shales will be referred to as Shales B and C. Shale C overlies the lower Smackover C unit and Shale B overlies the middle Smackover B unit. Shale A (Baria et al., 2008) was not observed in this study. Shale layers B and C are known to contain millimeter-scale turbidites and significant amounts of herbaceous organic matter, though this is not apparent in all cores (Baria et al., 2008).

Shale C reaches a maximum thickness of approximately 50 feet within the study area and has two distinct intervals that are recognizable both in the core and in well logs on the Gamma Ray curve (Fig. 14). Shale C thickens basinward and pinches out to the northeast against the rims of the northern arm of the embayment. Shale C was described and sampled from two wells: Sklar Logan 5-7 and Midroc Jackson 27-6 (Fig. 11). The lower interval of shale C consists of a light gray, blocky calcareous shale approximately 25-30 feet thick in the study area. The lower part of Shale C contains some algal features and evidence of minor burrowing. The upper portion of shale C is a dark gray-black, fissile shale that is 20-25 feet thick. The upper Shale C is laminated, and lacks evidence of bioturbation and marine fossils. The fissile portion of the shale is distinguished by a sharp break on the Gamma Ray curve.

X-ray diffraction was performed on both shale intervals, as described in Appendix A. X-ray diffraction data of Shale C also shows a distinctive trend from the lower to the upper intervals. The lower Shale C is mostly carbonate of which calcite is the main constituent.

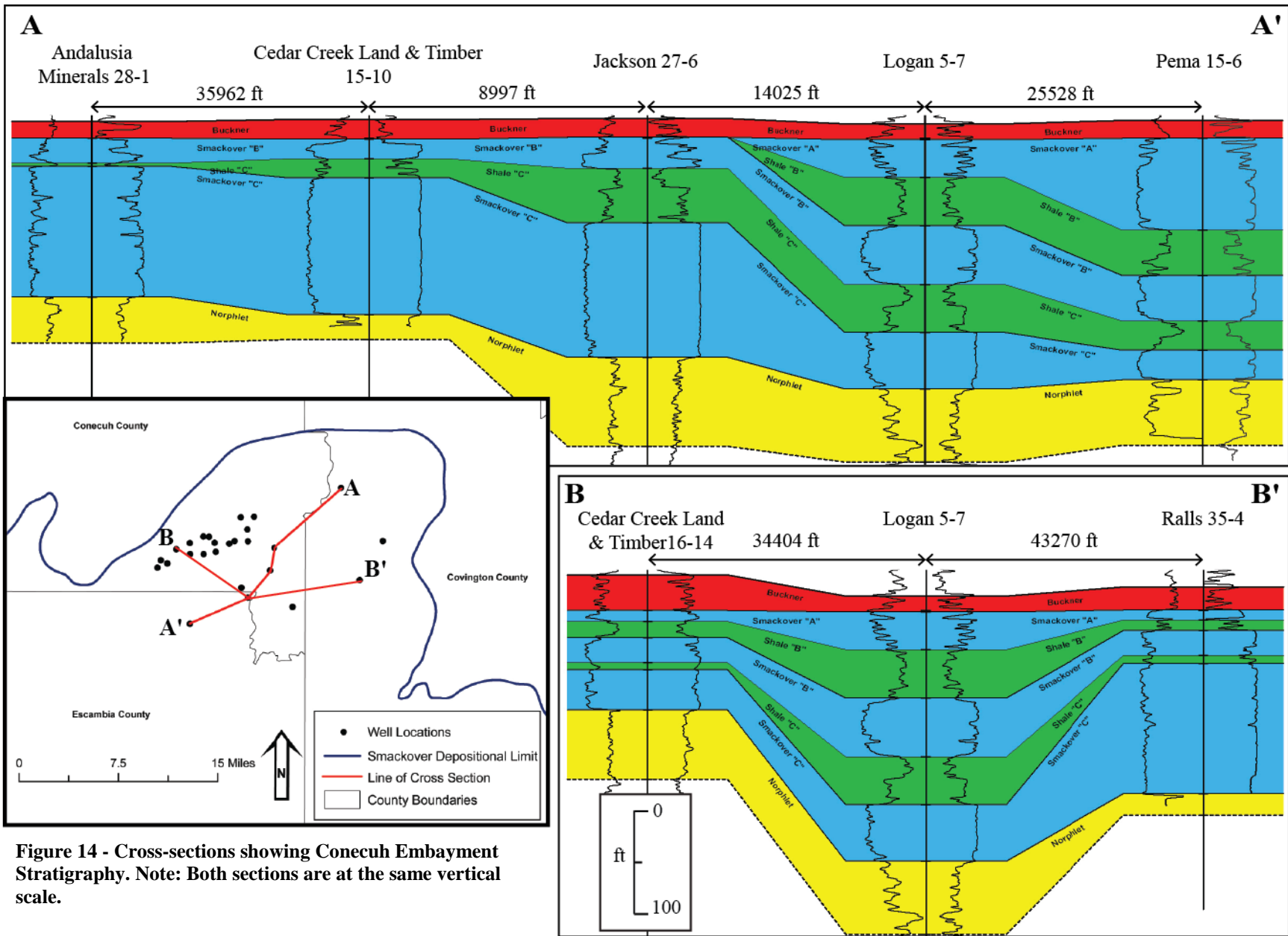


Figure 14 - Cross-sections showing Conecuh Embayment Stratigraphy. Note: Both sections are at the same vertical scale.

The lower portion of Shale C also contains abundant quartz, and illite with minor amounts of kaolinite, pyrite, and chlorite. The upper Shale C is predominantly quartz followed by lesser amounts of calcite. The upper Shale C also contains about the same amounts of illite, chlorite, pyrite, and feldspar as the lower C. The shift in the dominant mineralogy from calcite to quartz upsection along with the shale being darker due to higher amounts of organics and more fissile, is believed to be the result of a greater influx of siliciclastics from the exposed rim of the embayment.

Shale B reaches a maximum thickness of about 30 feet within the study area. Much like Shale C, Shale B thickens basinward and pinches out updip and along the rims of the northern arm of the embayment. Shale B was only sampled from the Logan 5-7 well as it thins rapidly to the northeast and is absent in the Jackson 27-6 well. This shale unit was recognized in log signatures in other wells down dip that did not have core available. Shale B is a dark gray, laminated, fissile shale that becomes more blocky and calcareous in nature downsection. X-ray diffraction analysis of shale B shows quartz to be the dominant mineralogy followed closely by illite. Minor amounts of calcite and chlorite were also detected with smaller amounts of kaolinite and pyrite.

Both shale layers exhibit a blocky, calcareous nature near the bottom of their respective sections. X-ray diffraction confirms an abundance of carbonate phases in the samples collected at the base of these shales, which could represent a late high stand deposit nearing the end of carbonate production. A greater influx of siliciclastics into the embayment is shown by a shift in the mineralogy to being dominantly quartz and illite. The influx of siliciclastics is believed to be the result of a relative drop in sea level that terminated carbonate production and deposited the upper portions of shale C and B as lowstand deposits in a prograding deltaic environment. The

chlorite is believed to be detrital from the surrounding highlands as nearby wells that penetrated the underlying basement have included low to moderate grade phyllite and schist metamorphics (Baria, 2011, personal communication). While the ratio of illite-kaolinite is a useful determination of depositional environment and climate in more recent rocks, clay mineralogy can be greatly affected through diagenesis. Rocks that have been buried and reached a level of thermal maturity with respect to oil generation often show an abundance of illite regardless of original mineralogy (Eslinger and Pevear, 1988). The presence of illite may also downgrade the petroleum generative potential determined from Rock Eval analysis, as it has been shown that the pyrolyzate may be retained by the mineral matrix (Peters, 1986).

6.1 – Palynology

The fossil plants and organic matter found within the Conecuh Embayment shales represent the first known occurrence of land plant material found within the Smackover Formation (Baria, 2011, personal communication). Palynological analysis of the shales was performed to identify the plant matter within the shales. The assemblage found in the Smackover shales is typical to the late Jurassic of North America, however it lacks the latest Jurassic *schizaeaceous* spores. Palynology is typically a crude tool for dividing the Jurassic but there is nothing in the assemblage inconsistent with an Oxfordian age for the Smackover Formation (Hotton, 2010, personal communication). Therefore, the pollens do little to better constrain the timing of the depositional events within the study area.

Palynology and paleobotany have been used in determining paleoclimate (Taylor, 1981), and is used in the following sequence stratigraphy interpretation to infer differences in paleodepositional environments and paleoclimate around the northern Gulf rim. Identification of pollen and spores was performed to the genus level and at least 12 different genera were

positively identified (Appendix B) including ferns, mosses, and conifers. In addition to the pollens and spores identified, the samples included abundant degraded plant tissue, corroded spores, one foraminiferal test, and assorted algal cysts (Baghai-Riding, 2010, personal communication).

Bryophytes refer to a phylum of non-vascular plants that contain mosses. Living bryophytes are terrestrial and live in relatively humid environments. Several genera of ferns belonging to the order Filicales were also identified. Filicales or true ferns are most widely developed in the tropics though many species are also present in more temperate regions. The extant members of the families of ferns identified are confined to tropical and sub-tropical regions. Of the genera of conifers identified, the most dominant within the samples is the now extinct *Classipollis*. Like the extant conifers of today, those of the Mesozoic represent large, woody, perennials that live in temperate to tropical climates (Taylor, 1981). From the pollen assemblage identified in the Smackover shales it is inferred that the climate of the study area was tropical to sub-tropical during the Oxfordian.

6.2 – Source Rock Characterization

Wade et al. (1987) discussed a terrestrial signature to some of the hydrocarbons produced from the eastern Smackover trend, particularly in the embayments of southwest Alabama. To determine if the dark, organic-rich shales in the Conecuh Embayment during recent exploration efforts and first described by Baria et al. (2008) were contributing hydrocarbons and providing the terrestrial signatures found in the area, a preliminary source rock analysis was performed. A total of nine samples from five wells (Fig. 11) were collected from whole cores stored at the Alabama Oil and Gas Board. Eight of the samples were collected from the Smackover shales in four different wells located along the longitudinal axis of the Conecuh Embayment. Curiale

(2008) noted that the amount organic matter found in a rock can vary greatly both stratigraphically and geographically even on a laminae and meter scale respectively. Though we were limited by the number of samples obtained for analysis care was taken to achieve representative a representative sample of the shales. One sample of a Smackover laminated lime mud was collected from a well within Little Cedar Creek Field along the northwestern margin of the embayment and located stratigraphically between the upper and lower reservoir. All of the samples were sent to Geomark Research Ltd. and analyzed for TOC and hydrocarbon generative potential (Rock Eval).

The shale samples displayed a wide range of carbonate content, from 14% to nearly 58%. The average carbonate content was 30%. The variance in carbonate abundance within the samples was also confirmed by XRD. The amount of organic matter found in the shales was low with respect to shale source rocks (Table 2). TOC for the samples analyzed ranged from 0.16% to 0.55% with an average TOC for the shales of 0.32% (Table 3).

Sample ID	Description	Depth (MD, ft)	Leco TOC (wt. % HC)	Percent Carbonate (wt. %)
S-01	Fissile shale	11779	0.26	20.30
S-02	Fissile shale	11852-856	0.33	22.66
S-03	Fissile shale	11868-870	0.36	31.69
S-04	Laminated lime mud	11584	0.42	32.35
S-05	Fissile shale	11415-420	0.23	17.85
S-06	Fissile shale	11446-448	0.29	47.92
S-07	Fissile shale	10631-635	0.34	25.05
S-08	Fissile shale	10671-677	0.55	13.99
S-09	Blocky shale	11238-243	0.16	57.66

Table 3 - Results of the LECO TOC analyses for nine samples from the Smackover Formation in the Conecuh Embayment.

The laminated lime mud sample from the Midroc 16-14 well (Sample S-04 in Table 3) is comparative with previous Smackover source rock research conducted by Sassen et al. (1987).

The Smackover lime mud was found to have a carbonate content of 32.35% and a TOC of

0.42%. While this is only one sample, it does fall above the minimum TOC cutoff for fair generation potential in carbonate source rocks (Table 2).

Determining the type of hydrocarbons that a source rock will produce is also an important factor in source rock evaluation. The type of hydrocarbons produced by a petroleum source rock can be directly related to the type of kerogens it contains (Tissot and Welte, 1984; Hunt, 1996).

The shale samples in this study were found to have very low hydrogen indices (HI) and high oxygen indices (OI). The average HI and OI for the samples is 55 and 65 respectively (Table 4). These numbers are indicative of a Type III kerogen derived from a terrestrial source and are gas prone (Fig. 15).

The Smackover lime mud sample had an HI of 221 and an OI of 38 (Table 4). When plotted on a van Krevelen diagram this sample plots as a mixed Type II/III kerogen that has some oil generative potential (Fig. 15). However, the plot of TOC vs. remaining generative potential shows that the kerogen quality in this sample is poor.

Sample ID	Description	Depth (MD, ft)	Hydrogen Index	Oxygen Index	T _{max}
S-01	Fissile shale	11779	42	85	435
S-02	Fissile shale	11852-856	58	67	431
S-03	Fissile shale	11868-870	75	75	430
S-04	Laminated lime mud	11584	221	38	436
S-05	Fissile shale	11415-420	39	13	432
S-06	Fissile shale	11446-448	72	62	428
S-07	Fissile shale	10631-635	44	62	427
S-08	Fissile shale	10671-677	62	35	428
S-09	Blocky shale	11238-243	44	119	422

Table 4 - Data for the Rock Eval results shown in Figure 15.

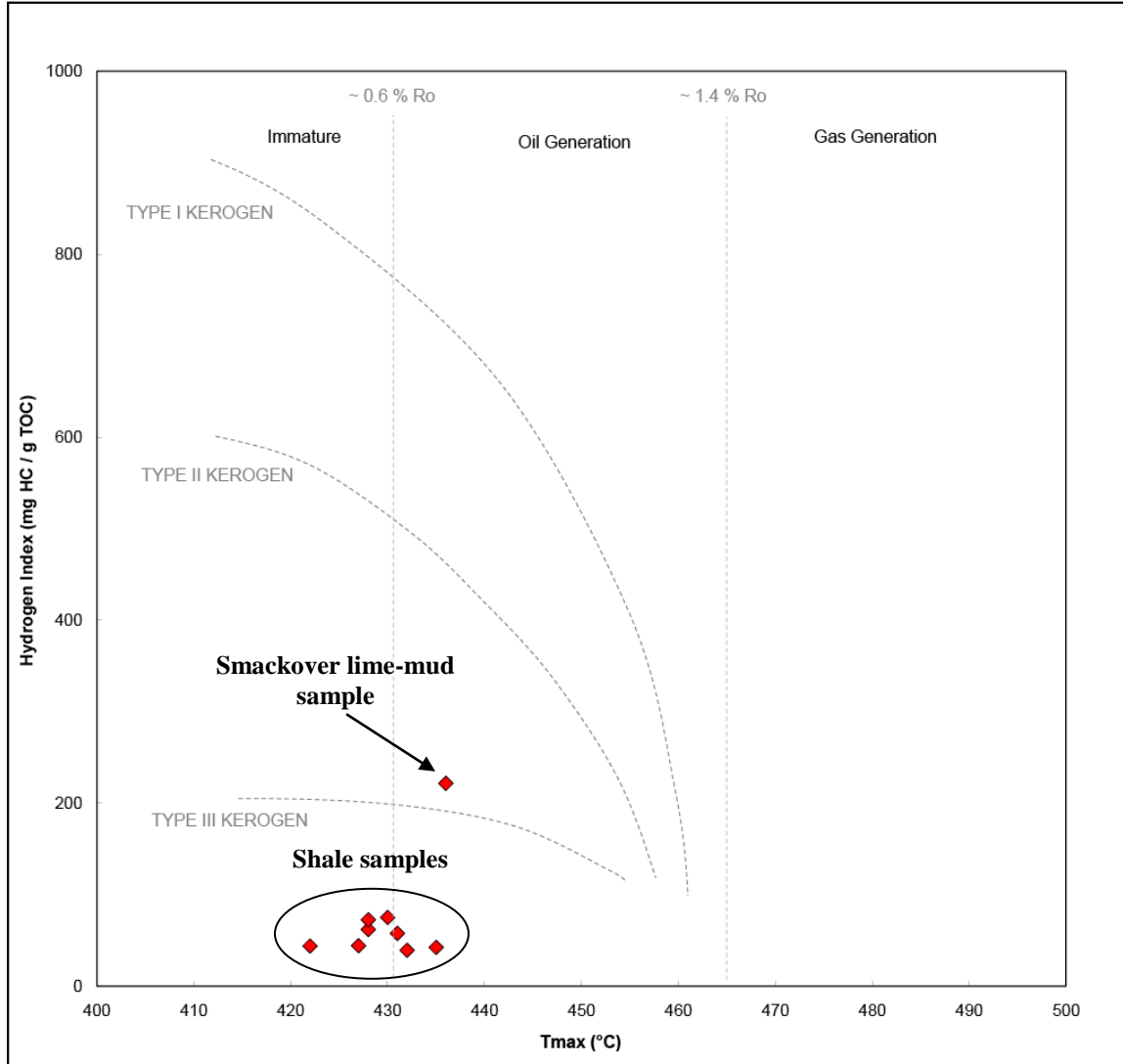


Figure 15 - Rock Eval pyrolysis results plotted on van Krevelen diagram for the nine samples listed in Table 4.

Thermal maturity for all samples was determined through the T_{max} numbers obtained during Rock Eval pyrolysis. T_{max} was found to be between 422-435°C which places all of the samples near the lower boundary of the oil window (Fig. 15). Thermal maturity data from this study is regionally consistent with work presented by Sassen and Moore (1988).

6.3 – Sequence Stratigraphy

The Jurassic Smackover Formation is interpreted to have been deposited during the late Oxfordian following a rapid third-order rise in global sea level. Within the study area the

Smackover unconformably overlies the continental dune fields of the Norphlet Formation. The contact between the Norphlet and overlying Smackover is abrupt. Overlying the Smackover is the anhydrite of the Buckner Member of the Haynesville Formation. Within the study area the Buckner/ Haynesville consists of red shale with anhydrite nodules. The contact between the two is often gradational (Benson, 1988). Prather (1992) considered the deposition of the Smackover/Haynesville within the Conecuh Embayment to be a genetically related package deposited during one cycle of relative sea level. Heydari and Baria (2006) further subdivided Smackover deposition of the north-central Gulf Coast into three sequences deposited during fluctuations in relative sea level. Using the Heydari and Baria (2006) model and the discovery of the Conecuh Embayment shales, the author has subdivided the Smackover within the study area into three sequences. It is possible that these sequences represent higher-order (fourth or fifth) fluctuations in sea level overprinted onto the third-order sea level rise that deposited the Smackover/Haynesville package.

When developing the sequence stratigraphic model used in this study, several factors were considered since the key to a valid interpretation is understanding all of the factors involved in the deposition of strata and the shift in facies through time (Catuneanu, 2006). Factors included tectonic setting, provenance of sediment, paleoclimate, paleogeography, and relative sea level. In establishing the tectonic setting for the study area, differences were found between the eastern and the central-western Gulf of Mexico. The formation of the entire Gulf rim was associated with the rifting of Pangea during the late Triassic and into the Jurassic (Salvador, 1987; Benson, 1988; Prather, 1992). However, the eastern Gulf of Mexico region was subjected to lower subsidence rates and higher clastic influx than the depocenters located farther to the west (Wade and Moore, 1993). In addition to the regional variations, locally the Conecuh

Embayment was not influenced by salt tectonics due to the absence of the Louann Salt. Since the Jurassic strata of the Conecuh Embayment lay on top of Paleozoic basement and to the northeast of major fault systems (Fig. 2), the area is assumed to be rather stable tectonically. Deposition was also considered to be strongly influenced by paleotopography initially with a lessening affect in the later stages during Smackover deposition.

The development of the LST facies differs from the Heydari and Baria (2006) model where they are composed of turbidite sands delivered to the basin by the ancestral Mississippi River. In this study the LST facies are characterized primarily by organic-rich fissile shales deposited during relative sea level falls. The different facies for the same relative-falls in base-level are attributed to the difference in climate and provenance. The north-central Gulf rim is characterized by the presence of both evaporites and dolomitized carbonates, also to date there are no instances of preserved terrestrial organic matter within the Smackover suggesting a more arid climate. The pollen assemblage found within the Conecuh Embayment shales suggests a sub-tropical to tropical environment. Plate reconstructions of North America during the Jurassic rotate the continent slightly counter-clockwise during this time (Scotese, 1991). Therefore, it is possible that the northern and western Gulf rim reached higher latitudes and a more arid climate before the eastern trend that remained at least sub-tropical until very late in the Oxfordian. Provenance of the sediment is also considered to be different as nearby wells drilled into Paleozoic basement reveal low- to moderate-grade metamorphic rocks of the Appalachian orogen, which could supply more siliciclastic detritus than sediment sources from the mid-continent region.

Following consideration of the tectonic setting and paleodepositional environments, several 2D seismic transects were studied for an establishment of stratal geometries (Fig. 16). It was determined that the Smackover C onlaps the Norphlet on the ramp and around paleotopographic highs and encroaches the farthest inland of the Smackover sequences. Smackover Units B and A also onlap the underlying strata. Smackover B pinches out against the Smackover C and they are separated down dip by a low-amplitude shale package designated as Shale C. Smackover A is confined to the down-dip portions of the study area and again pinches out against the underlying Smackover B unit and is also separated down dip from the previous Smackover by another shale package designated as Shale B. The entire sequence of Smackover deposition is capped by the Buckner/Haynesville shale.

The first sequence boundary (SB-1) (Fig. 17) is placed at the top of the Norphlet Formation which was deposited during a sea level lowstand as an aeolian/alluvial facies. Smackover seas transgressed rapidly over the underlying Norphlet resulting in the uppermost portion of the Norphlet being reworked. The Smackover C composes the TST and HST of the first sequence. Though the TST is difficult to correlate due to the rapid transgression, the TST is represented by the laminated lime-mudstones, wackestones, and interbedded shales of the lower Smackover C. The HST is composed of the generally shoaling upward facies consisting of packstones and grainstones. Near the top of the HST the rocks change color to tan representing a more oxygenated environment. Observed dissolution features near the top the Smackover C are used as evidence for subaerial exposure and the formation of a sequence boundary (SB-2).

Deposition of the fissile portion of Shale C represents the LST that was deposited during a relative sea level fall and is the basal unit of the next sequence. Due to the mineralogical characteristics of the lower portion Shale C, which contains abundant carbonate phases, it has

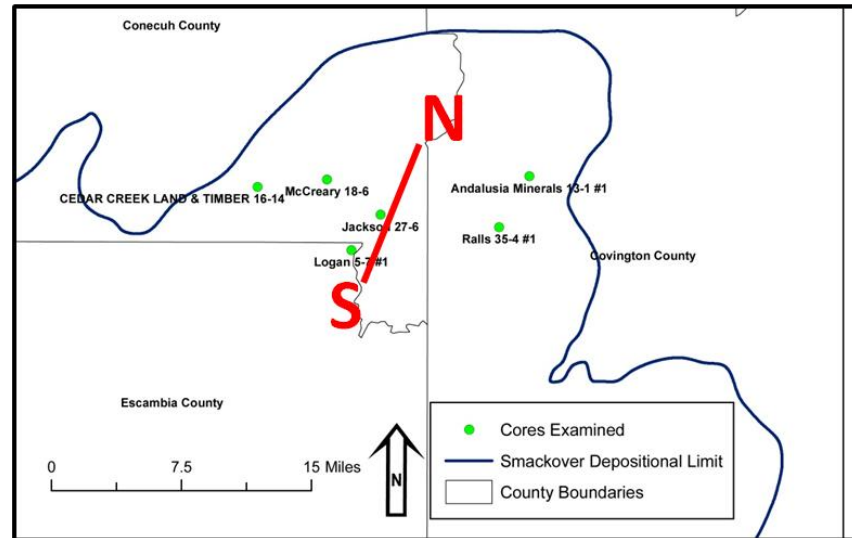
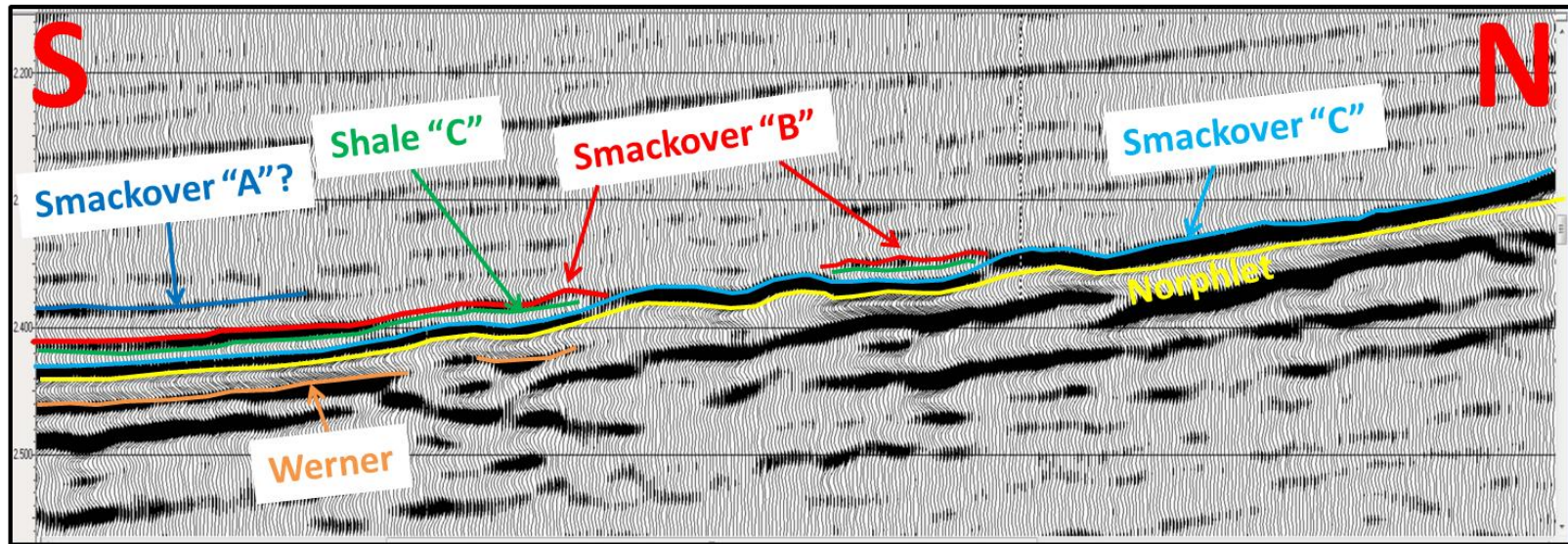


Figure 16 - North-South seismic transect illustrating stratal geometries for the Werner, Norphlet, and Smackover Formations in the Conecuh Embayment. Seismic line courtesy of Jura-Search, Inc. and published with the permission of SEI, Inc.

been placed in the previous HST systems tract representing the late HST. Deposition of a second shoaling upward set of facies (Smackover B) begins with laminated lime-muds and passes upward into wackestones and packstones representing the TST-2. HST-2 is represented by the tan packstones and grainstones near the top of the sequence. Caliches and dissolution porosity that are found up-dip (Baria, 2011, personal communication) are used as evidence for the development of the third sequence boundary (SB-3) as shown in Fig. 17.

The subsequent LST is represented by the deposition of Shale B during the relative fall in sea level. Again the lithologic characteristics are primarily used to establish SB-3. A subsequent rise in relative sea level resulted in the deposition of Smackover A. Smackover A is confined to the downdip portions of the study area and was not observed in core. The TST and HST of this sequence were picked from well log character. The fourth sequence boundary (SB-4) was placed at the top of the third order sequence as interpreted in previous studies (Fig. 17).

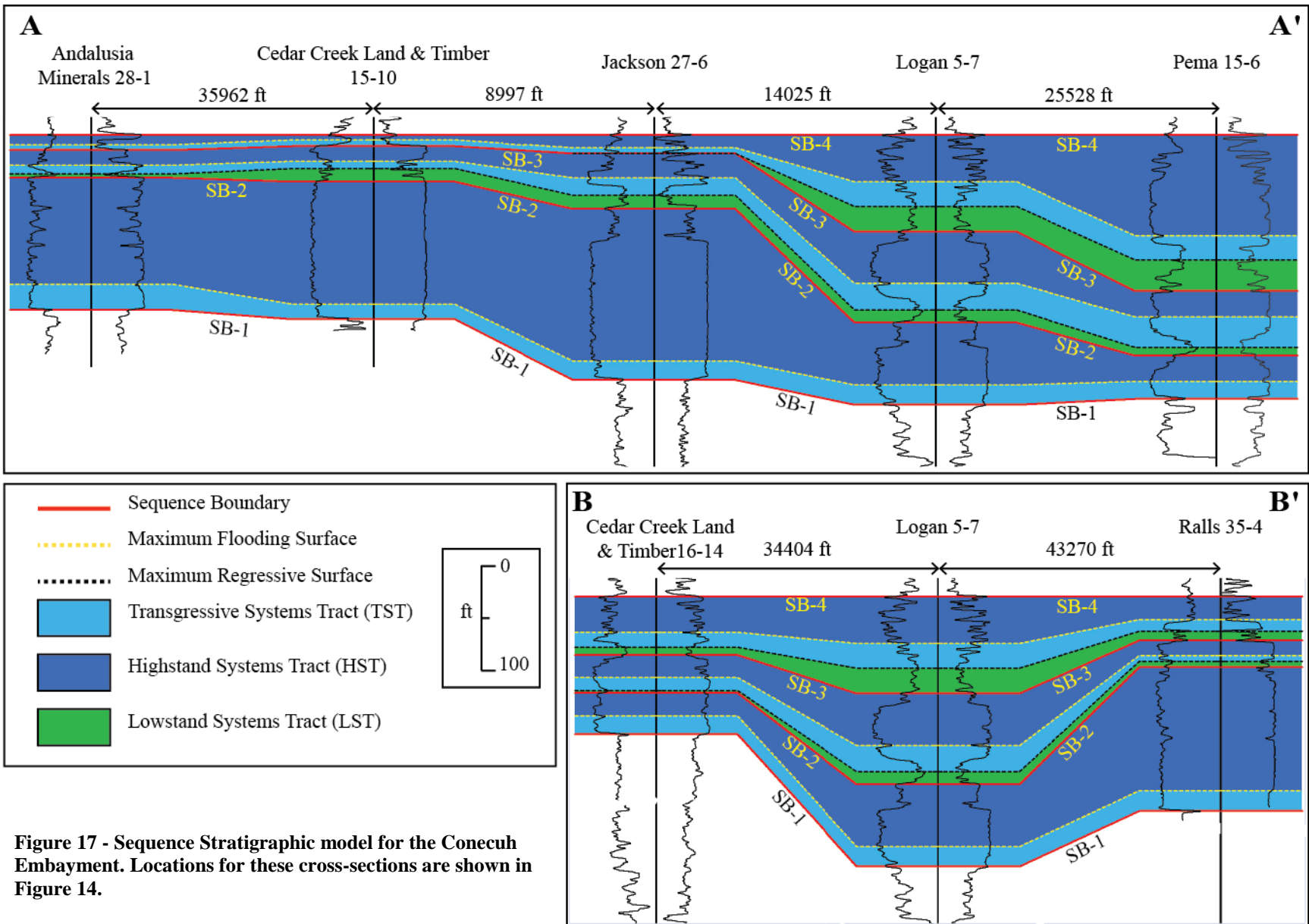


Figure 17 - Sequence Stratigraphic model for the Conecuh Embayment. Locations for these cross-sections are shown in Figure 14.

CHAPTER 7 – SUMMARY AND CONCLUSIONS

The results of the preliminary source rock analysis for the Smackover Formation shales of the Conecuh Embayment make it unlikely that these shales are a potential source rock. The shales lack sufficient organic matter (<0.5%) and have poor quality Type III kerogens. Any hydrocarbons generated by the Conecuh Embayment shales would most likely be gas. However, this is not meant to be a comprehensive source rock study and is severely limited by the number of samples obtained. One of the shale samples analyzed had a TOC of 0.55% placing it just above the lower limit of TOC needed for a shale source rock. It is possible that there are “sweet spots” in the Conecuh Embayment shales that have some limited gas generative potential. Regardless, the Smackover source intervals identified by previous studies should still be considered the primary source rock for the Norphlet and Smackover reservoirs of southwest Alabama.

Deposition of the Smackover Formation in southwest Alabama occurred during a third-order sea level rise and terminated with the deposition of the Buckner Member of the Haynesville Formation. Recent drilling within the Conecuh Embayment revealed two intervals of siliciclastic shales within the Smackover. These shale intervals are interpreted to have been deposited during relative sea level falls during the Oxfordian, and these are the expression of higher-level sequences overprinted onto the general third-order sequence of deposition. While the model used is similar to that of Heydari and Baria (2006), the facies representing each of the systems tracts is different and the sequences chosen here may be difficult to correlate on a

regional scale. Higher subsidence rates, salt tectonics, differences in climate, and differences in siliciclastic input makes correlating the sequences between the depocenters of the Gulf of Mexico region difficult. Lack of sufficient biostratigraphic control is also a limiting component to any regional correlation.

Palynological data from the shales does little to better constrain timing of events, however, it is a significant indicator of a changing climate from west to east during the Jurassic in the Gulf Coast region. The pollens support an interpretation that the climate in the Conecuh Embayment was sub-tropical to tropical. Less dolomitization of the Smackover Formation and the less extensive development of the Buckner Anhydrite Member in this area also supports the interpretation of a more humid climate than in the north-central Gulf Coast region. The pollens identified support a terrestrial source for the organic matter deposited in the Conecuh Embayment during sea level falls.

The mineralogical profile of the Smackover shales also supports the interpretation that siliciclastic sediment was delivered into the Conecuh Embayment during sea level falls. The Smackover shales have a mineralogy that matches what would be expected from the provenance area located updip of Conecuh Embayment.

The ultimate goal of a sequence stratigraphic interpretation is to drive exploration. While this study showed that the Conecuh Embayment shales lack significant hydrocarbon generative potential, it is still possible that their deposition and the processes that controlled deposition had a significant effect on the petroleum system of the Conecuh Embayment. The reservoirs of Little Cedar Creek field are best developed in the HSTs. Exposure of the HSTs during relative falls in sea level may have enhanced the porosity and permeability characteristics of the reservoirs along the updip portions of the Conecuh Embayment. More significant evidence for exposure of the

Smackover carbonates should be found updip and along the rims of the Conecuh Embayment. Deposition of the shales into the center of the embayment may have ultimately focused hydrocarbon migration into the reservoirs and served as a lateral seal for the stratigraphic trap found at the Little Cedar Creek field.

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List of Appendices

Appendix A

Report of X-ray Diffraction Analysis

Eight samples were collected from 5 cores as representing shale facies of the Smackover Formation (Jurassic – Oxfordian) in the Conecuh Embayment of Alabama. An additional sample from the lime mud facies of the Smackover Formation was also collected. Samples were collected by hand grab from cores stored at the Alabama Oil and Gas Board Core Laboratory in Tuscaloosa, Alabama. Samples were crushed to <1cm size and sample splits were sent to Mr. Frank T. Dulong at the USGS in Reston, Virginia. Once in the care of Mr. Dulong, samples were further ground to be <200 mesh (75 μm) in a Retsch mill and prepared as back-loaded powder mounts for X-ray diffraction. A PANalytical PW3040 X-ray diffractometer with an X'Celerator detector was used to scan the sample from 3 to 65° two-theta at the equivalent of counting for 25 seconds every 0.017° two-theta with copper radiation (45 kV and 40 mA). A computer program was used to process the X-ray spectrum and estimate the proportions of major mineral phases (Hosterman and Dulong, 1989). The 002 kaolinite and 004 chlorite peaks at high 24 and low 25 degrees two-theta respectively were examined graphically in order to determine their amounts (Biscaye, 1964).

SUMMARY:

Eight of nine samples contain a moderate amount of carbonate phases, ranging from 10 to 40 percent with calcite being the dominant phase. The combined clay mineral content ranges from 15 to 70 percent with illite, including mixed-layer phases, as the most abundant followed by chlorite and kaolinite. Small amounts of pyrite and K-feldspar are present in all samples. Quartz is present in all samples and ranges from 15 to 33 percent.

Sample ID	Well Name	Depth (MD, ft)	QTZ	FLD	CARB	ILLITE	KAOL	CHLR	PY	OTHR
S-01	Logan 5-7	11,779	31	6	15	23	5	14	5	2
S-02	Logan 5-7	11,852-856	31	6	22	24	3	8	6	1
S-03	Logan 5-7	11,868-870	24	5	33	21	4	7	6	2
*S-04	CCLT 16-14	11,584	33	6	40	11	2	4	4	1
S-05	Jackson 27-6	11,415-420	32	4	10	29	6	16	3	0
S-06	Jackson 27-6	11,440-448	18	3	26	31	4	10	7	1
S-07	Andalusia 13-1	10,631-635	21	1	18	33	7	13	6	1
S-08	Andalusia 13-1	10,671-677	22	2	4	39	5	23	3	0
S-09	Ensign 35-4	11,238-243	15	1	30	28	4	14	6	0
	Average mineral abundances for shale samples		24	4	20	29	5	13	5	1

Table B-1 – X-Ray Diffraction Results for the Conech Embayment shales. Results are reported in percentages and have not been normalized to 100%. *S-04 is a lime mud sample from the Smackover Formation. Explanation of abbreviations: QTZ – quartz, FLD – feldspar, CARB – calcite, ankerite, dolomite, and siderite, ILLITE – illite, illite-smectite, and muscovite, KAOL – kaolinite, CHLR – chlorite, PY – pyrite, marcasite, and sphalerite, OTHR – other.

Sample ID	Well Name	Depth (MD, ft)	Quartz and Feldspar	Illite, Kaolinite, and Chlorite	Carbonate
S-01	Logan 5-7	11,779	37	42	15
S-02	Logan 5-7	11,852-856	37	35	22
S-03	Logan 5-7	11,868-870	29	32	33
*S-04	CCLT 16-14	11,584	39	17	40
S-05	Jackson 27-6	11,415-420	36	51	10
S-06	Jackson 27-6	11,440-448	21	45	26
S-07	Andalusia 13-1	10,631-635	22	53	18
S-08	Andalusia 13-1	10,671-677	24	67	4
S-09	Ensign 35-4	11,238-243	16	46	30
	Avg. mineral abundances in shales		24	46	20

Table B-2 – X-Ray Diffraction Results for the Conecuh Embayment shales. Results are the sums of the major mineral groups from Table B-1 and are reported as percentages and have not been normalized to 100%. *S-04 is a lime mud sample from the Smackover Formation.

Appendix B

Palynology of Smackover Shales

Taxonomic List of Smackover Samples

BRYOPHYTES

Sphagnaceae

cf. *Stereisporites*

LYCOPODIOPHYTA

Lycopodiaceae

Retitriletes semimuris

Neoraistrickia sp.

FILICALES

Cyatheaceae/Dicksoniaceae

Cyathidites sp.

Dipteridaceae

Dictyophyllidites sp.

Schizaeaceae

Concavissimisporites sp.

Ischyosporites

Matoniaceae

Matonisporites sp.

Osmundaceae

Todisporites

FILICALES INCERTAE SEDIS

Leptolepidites rotundus

Verrucosisporites sp.

?*Obtusisporites* sp.

Convolutisporites sp.

?*Cadargasporites* sp.

?*Rotverrusporites major*

SEED PLANTS

Araucariaceae

Araucariacites sp.

Callialasporites sp.

Cheirolepidiaceae

Classopollis (either *C. simplex* or *C. meyeriana*) – very dominant

Taxodiaceae

Exesipollenites cf. *tumulus*

Inaperturopollenites dubius

Inaperturopollenites scabratus

Podocarpaceae

Podocarpidites sp.

Bisaccates incertae sedis

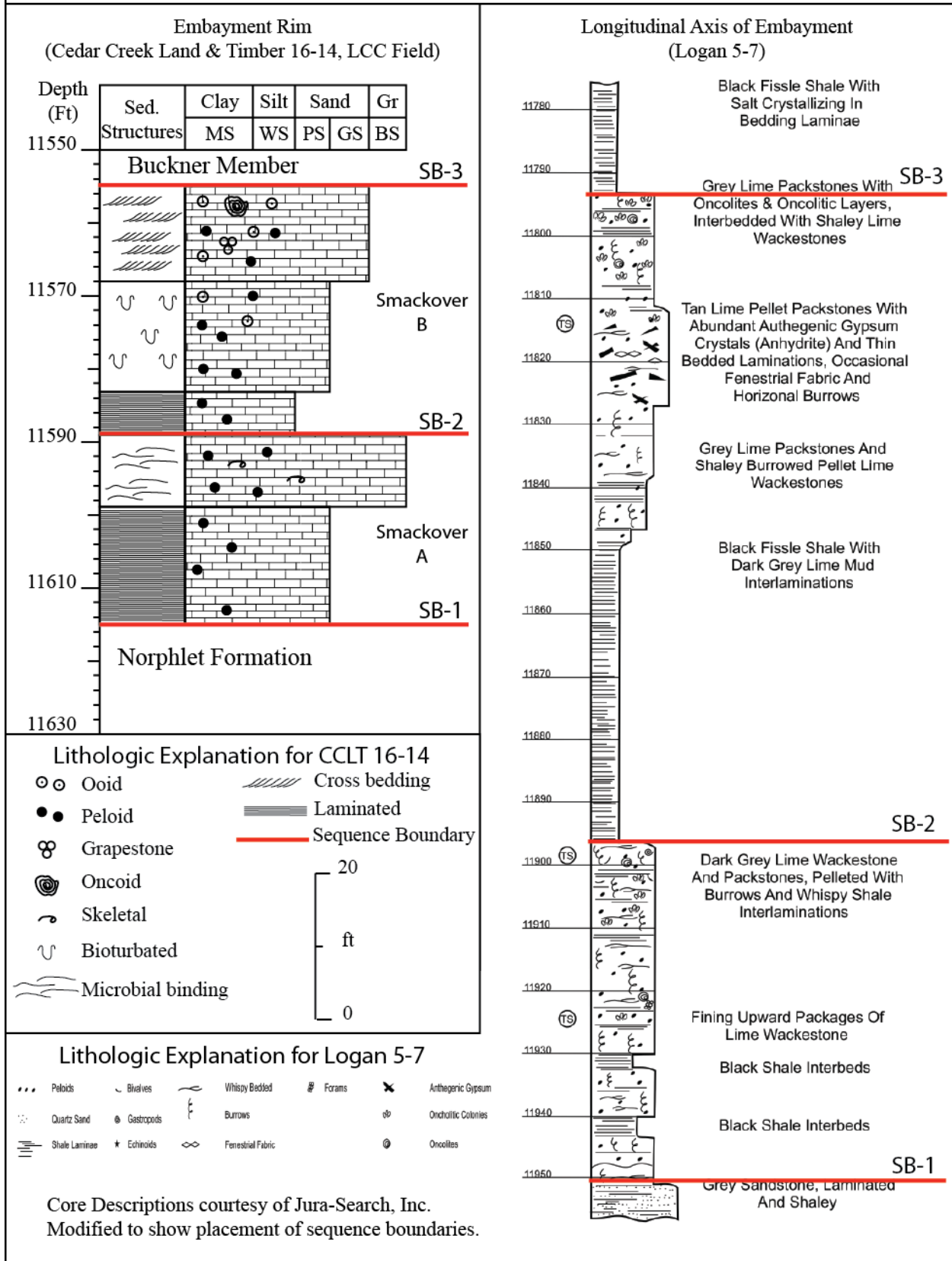
Alisporites sp.

Seed Plant incertae sedis (?Gnetales)

? *Eucommidites* sp.

Appendix C
Core Descriptions

Conecuh Embayment Composite Core Descriptions



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