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T-R Cycle Characterization and Imaging: Advanced Diagnostic Methodology for Petroleum Reservoir and Trap Detection and Delineation

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ABSTRACT

Characterization of stratigraphic sequences (T-R cycles or sequences) included outcrop studies, well log analysis and seismic reflection interpretation. These studies were performed by researchers at the University of Alabama, Wichita State University and McGill University. The outcrop, well log and seismic characterization studies were used to develop a depositional sequence model, a T-R cycle (sequence) model, and a sequence stratigraphy predictive model.

The sequence stratigraphy predictive model developed in this study is based primarily on the modified T-R cycle (sequence) model. The T-R cycle (sequence) model using transgressive and regressive systems tracts and aggrading, backstepping, and infilling intervals or sections was found to be the most appropriate sequence stratigraphy model for the strata in the onshore interior salt basins of the Gulf of Mexico to improve petroleum stratigraphic trap and specific reservoir facies imaging, detection and delineation.

The known petroleum reservoirs of the Mississippi Interior and North Louisiana Salt Basins were classified using T-R cycle (sequence) terminology. The transgressive backstepping reservoirs have been the most productive of oil, and the transgressive backstepping and regressive infilling reservoirs have been the most productive of gas.

Exploration strategies were formulated using the sequence stratigraphy predictive model and the classification of the known petroleum reservoirs utilizing T-R cycle (sequence) terminology. The well log signatures and seismic reflector patterns were determined to be distinctive for the aggrading, backstepping and infilling sections of the T-R

cycle (sequence) and as such, well log and seismic data are useful for recognizing and defining potential reservoir facies.

The use of the sequence stratigraphy predictive model, in combination with the knowledge of how the distinctive characteristics of the T-R system tracts and their subdivisions are expressed in well log patterns and seismic reflection configurations and terminations, improves the ability to identify and define the limits of potential stratigraphic traps and the stratigraphic component of combination stratigraphic and structural traps and the associated continental, coastal plain and marine potential reservoir facies.

The assessment of the underdeveloped and undiscovered reservoirs and resources in the Mississippi Interior and North Louisiana Salt Basins resulted in the confirmation of the Monroe Uplift as a feature characterized by a major regional unconformity, which serves as a combination stratigraphic and structural trap with a significant stratigraphic component, and the characterization of a developing play in southwest Alabama, which involves a stratigraphic trap, located updip near the pinchout of the potential reservoir facies.

Potential undiscovered and underdeveloped reservoirs in the onshore interior salt basins are identified as Jurassic and Cretaceous aggrading continental and coastal, backstepping nearshore marine and marine shelf, and infilling fluvial, deltaic, coastal plain and marine shelf.

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INTRODUCTION

The University of Alabama, Wichita State University and McGill University have completed a cooperative 3-year research project involving the characterization and modeling of transgressive-regressive (T-R) cycles (sequences) to facilitate exploration for underdeveloped and undiscovered petroleum resources associated with stratigraphic traps and with specific facies in continental and coastal geologic systems that have reservoir potential.

EXECUTIVE SUMMARY

The University of Alabama, Wichita State University and McGill University have completed a cooperative 3-year research project involving the characterization and modeling of transgressive-regressive (T-R) cycles (sequences) to facilitate exploration for underdeveloped and undiscovered petroleum resources associated with stratigraphic traps and with specific facies in continental and coastal geologic systems that have reservoir potential.

The objectives of the project are to develop through T-R cycle (sequence) characterization and modeling a sequence stratigraphic predictive model that can be used for improved petroleum stratigraphic trap and reservoir facies imaging, detection and delineation by using the characteristics and geometries of T-R cycles (sequences) and their associated bounding surfaces to provide a reliable and advanced approach for targeting stratigraphic

traps and specific reservoir facies associated with continental, coastal plain and marine depositional systems and to demonstrate the importance of using the concept of T-R cycles (sequences) in the formulation of advanced exploration strategies in the search for underdeveloped and undiscovered petroleum resources associated with stratigraphic traps and with specific continental, coastal plain and marine reservoir facies.

Characterization of stratigraphic sequences, T-R cycles or sequences included outcrop studies, well log analysis and seismic reflection interpretation. These studies were performed by researchers at the University of Alabama, Wichita State University and McGill University. Researchers at the University of Alabama studied Jurassic, Cretaceous and Tertiary (Paleogene) stratigraphic sequences of the Gulf of Mexico using outcrop, well log and seismic data. Researchers at Wichita State University characterized Mesozoic stratigraphic sequences of the Bighorn Basin of Montana and Wyoming using outcrop and well log data. Researchers at McGill University studied Mesozoic stratigraphic sequences of the Atlantic Shelf, Alberta, New Mexico and the Gulf of Mexico using seismic and well log data.

The outcrop, well log and seismic characterization studies were used to develop a depositional sequence, a T-R cycle (sequence) model, and a sequence stratigraphy model. The published depositional sequence model was evaluated and was found to be a reasonable model for classifying Tertiary (Paleogene) strata of the Gulf Coastal Plain. The published T-R cycle (sequence) model was modified to divide the transgressive systems tract into an aggrading section and a backstepping section and to divide the regressive systems tract into an infilling section and a forestepping section. This developed T-R cycle (sequence) model was found to be the most appropriate model for classifying Jurassic and Cretaceous strata of the Mississippi Interior and North Louisiana Salt Basins.

The sequence stratigraphy predictive model developed in this study is based primarily on the modified T-R cycle (sequence) model. In developing a sequence stratigraphy model, the best approach is to refer to the sequences as stratigraphic sequences that are bounded and subdivided by distinctive surfaces and recognize the subdivisions within the sequences as systems tracts. In the study, the T-R cycle (sequence) model using transgressive and regressive systems tracts and aggrading, backstepping, and infilling intervals or sections was found to be the most appropriate sequence stratigraphy model for the strata in the onshore interior salt basins of the Gulf of Mexico to improve petroleum trap and reservoir imaging, detection and delineation.

The known petroleum reservoirs of the Mississippi Interior and North Louisiana Salt Basins were classified using T-R cycle (sequence) terminology. To date, the transgressive backstepping reservoirs have been the most productive of oil, and the transgressive backstepping and regressive infilling reservoirs have been the most productive of gas. In the Mississippi Interior Salt Basin, the transgressive aggrading, transgressive backstepping, and regressive infilling are about equally productive of oil and gas. The transgressive aggrading facies in the North Louisiana Salt Basin have not been as productive as the transgressive backstepping and regressive infilling facies in this basin.

Exploration strategies for strata in the Mississippi Interior and Louisiana Salt Basins were formulated using the sequence stratigraphy predictive model and the information from classifying the known petroleum reservoirs utilizing T-R cycle (sequence) terminology. The aggrading alluvial, fluvial, eolian and coastal facies are recognized by a smooth cylinder-shaped gamma ray or SP well log pattern and by a thick interval (several seismic cycles) of seismic reflectors exhibiting an aggradational reflection configuration. The backstepping nearshore marine, barrier bar and marine shelf facies are identified by an overall increase in gamma ray or change to a more positive SP log response (bell-shaped or fining upward trend in well log pattern) and by a thin interval (one or two seismic cycles) of seismic reflectors exhibiting a concordant, parallel reflection configuration characterized by onlap stratal terminations. The infilling fluvial, deltaic, coastal plain, tidal, and marine shelf facies are recognized by an overall decrease in gamma ray or change to a more negative SP log response (funnel-shaped or coarsening upward trend in well log pattern) and by a thick interval (several seismic cycles) of seismic reflectors exhibiting an oblique, progradational reflection configuration characterized by offlap (downlap) stratal terminations.

The use of the sequence stratigraphy predictive model, in combination with the knowledge of how the distinctive characteristics of the T-R systems tracts and their subdivisions (aggrading, backstepping and infilling) are expressed in well log patterns and in seismic reflector configurations and terminations, improves the ability to identify and define the limits of potential stratigraphic traps and combination stratigraphic and structural traps, and the associated potential reservoir facies. Stratigraphic traps and the stratigraphic component of combination (stratigraphic-structural) traps can be recognized and delineated through well log and seismic studies, stratal correlation using stratigraphic and structural cross sections, and subsurface mapping. The use of seismic data has proven useful in defining combination traps in the onshore interior salt basins; however, stratigraphic traps are defined essentially by well log correlation, preparation of stratigraphic and structural cross sections, and subsurface mapping. Seismic data are useful in identifying the updip stratigraphic pinchout of potential reservoir facies, but well log correlation and subsurface mapping is required to define the subtleties of the stratigraphic trap.

The assessment of the underdeveloped and undiscovered reservoirs and resources in the Mississippi Interior and North Louisiana Salt Basins using the sequence stratigraphy predictive model and developed exploration strategies resulted in the confirmation of the Monroe Uplift as a feature that is characterized by a major regional unconformity, which produces a combination trap characterized by a significant stratigraphic component. The potential for additional resources to be discovered by drilling to deeper depths on this uplift is high. This assessment also assisted with the characterization of a developing play in southwest Alabama, which involves a stratigraphic trap located updip near the pinchout of the reservoir facies. The potential for additional updip stratigraphic traps to be discovered in this area is high.

By using the sequence stratigraphy predictive model and the T-R cycle (sequence) classification for the known petroleum reservoirs in the onshore interior salt basins of the Gulf of Mexico, potential undiscovered reservoirs in the Mississippi Interior and North Louisiana Salt Basins were identified to be subsalt Triassic continental facies and deeply buried Upper Jurassic continental, coastal and marine facies. Potential underdeveloped reservoirs include Lower Cretaceous continental, coastal plain, deltaic and marine facies, and Upper Cretaceous coastal, nearshore marine, barrier bar, and marine shelf facies.

PROJECT OBJECTIVES

The objectives of the project are to develop through T-R cycle (sequence) characterization and modeling a sequence stratigraphic predictive model that can be used for improved petroleum stratigraphic trap and reservoir facies imaging, detection and delineation by using the characteristics and geometries of T-R cycles (sequences) and their associated bounding surfaces to provide a reliable and advanced approach for targeting stratigraphic traps and specific reservoir facies associated with continental, coastal plain and marine depositional systems and to demonstrate the importance of using the concept of T-R cycles (sequences) in the formulation of advanced exploration strategies in the search for underdeveloped and undiscovered petroleum resources associated with stratigraphic traps and with specific continental, coastal plain and marine reservoir facies.

EXPERIMENTAL

Work Accomplished

Outcrop, well log, and seismic characterization studies-Characterization of stratigraphic cycles (sequences) included outcrop studies, well log analysis and seismic reflection interpretation. These studies were performed by researchers at the University of Alabama, Wichita State University and McGill University.

Researchers at the University of Alabama characterized Jurassic, Cretaceous and Tertiary (Paleogene) stratigraphic sequences of the Gulf of Mexico using outcrop, well log and seismic data. Researchers at Wichita State University studied Mesozoic stratigraphic sequences of the Bighorn Basin of Montana and Wyoming using outcrop and well log data. Researchers at McGill University characterized Mesozoic stratigraphic sequences of the Atlantic Shelf, Alberta, New Mexico and the Gulf of Mexico using seismic and well log data.

University of Alabama Studies-The following is a summary of the studies performed by researchers at the University of Alabama.

1. Tertiary (Paleogene) outcrop studies by Ernest A. Mancini.

Characterization of Tertiary (Paleogene) stratigraphic sequences in the Gulf of Mexico in this study involved field examination of the Paleogene unconformity-bounded units described by Mancini and Tew (1991). Mancini and Tew recognized 21 unconformity-bounded sequences in the Alabama –Mississippi area (Table 1). They utilized the terminology of Baum and Vail

(1988) to categorize these strata (Figures 1 and 2). A typical Paleogene type 1 depositional sequence (Figures 3 and 4) consists of marine shelf, barrier and/or marginal marine cross-bedded sands (lowstand deposits) of variable thickness, but generally less than 50 ft thick; and marine, marginal marine, and/or deltaic sands, silts, clays and/or lignite beds (highstand regressive deposits), generally 100 ft or more in thickness (Mancini and Tew, 1991). A typical type 2 depositional sequence consists of the transgressive and highstand systems tract deposits described above, except that lowstand systems tract deposits are absent and can be replaced by shallow water, marine shelf margin, glauconitic sands or sandy limestones (Mancini and Tew, 1991). In this study, we found that the use of depositional system terminology as published by Posamentier et al. (1988a) was reasonable for categorizing these Paleogene strata (Figures 5 and 6). Sequence boundaries are recognized by unconformities, such as subaerial unconformities (Figure 7A), ravinement surfaces (Figures 7B, D), or transgressive surfaces (Figures 7C, 8A). In the absence of lowstand systems tract deposits, these surfaces merge and the recognizable surface is a transgressive or ravinement surface (Figure 7D). A transgressive or ravinement surface separates transgressive systems tract deposits from lowstand systems tract deposits (Figure 8B). A condensed section generally occurs between transgressive and highstand regressive systems tracts as a series of transition beds (Figure 8C) and a surface or maximum sediment starvation or maximum marine flooding can be present in the condensed section (Figures 8C, 8D). We found that the term shelf margin systems tract was not useful in describing these sequences. Thus, the sequences consisted of two types, sequences including lowstand systems tract deposits and sequences where lowstand deposits were not present or recognizable.

Table 1. Unconformity-bounded sequences in the Alabama –Mississippi area (from Mancini and Tew, 1991).

SEQUENCE DESIGNATION	SEQUENCE TYPE	SEQUENCE COMPONENT	STRATA
TO2.3	1	Highstand	Paynes Hammock clays and sands
		Condensed section and transgressive	Paynes Hammock marls and limestones
TO2.2	2	Highstand	Chickasawhay clays
		Condensed section and transgressive	Chickasawhay marls and limestones
TO2.1	1	Highstand	Chickasawhay clays
		Condensed section and transgressive	Chickasawhay marls and limestones
TO1.2	2	Highstand	Bucatunna carbonaceous clays
		Condensed section and transgressive	Byram marls
TO1.1	2	Highstand	Marianna and Glendon limestones
		Condensed section and transgressive	Mint Spring marls and Marianna limestones
TE3.3	2	Highstand	Red Bluff and Forest Hill carbonaceous clays and sands
		Condensed section	Shubuta marls and clays and Red Bluff/Bumpnose marls, clays, and limestones
		Transgressive	Pachuta marls and limestones
		Shelf Margin	Cocoa glauconitic sands
TE3.2	1	Highstand	North Twistwood Creek clays
		Condensed section and transgressive	Moodys Branch glauconitic sands, marls, and limestones
TE3.1	1	Highstand	Gosport lignitic clays and sands
		Condensed section and transgressive	Gosport glauconitic sands
TE2.4	2	Highstand	Gordon Creek shales and Cockfield cross-bedded sands and carbonaceous shales
		Condensed section and transgressive	Archusa glauconitic sands and marls and Potterchitto glauconitic sands
TE2.3	2	Highstand	Dobys Bluff carbonaceous clays
		Condensed section and transgressive	Dobys Bluff glauconitic sands and marls
TE2.2	2	Highstand	Zilpha shales and Kosciusko cross-bedded sands and carbonaceous shales
		Condensed section and transgressive	Winona glauconitic sands and marls
TE2.1	1	Highstand	Basic City clays and Neshoba sands
		Condensed section	Basic City clays and silts
		Transgressive	Basic City glauconitic sands and marls
		Lowstand shelf	Meridian cross-bedded sands
TE1.1	1	Highstand	Hatchetigbee sands, silts, and carbonaceous clays
		Condensed section and transgressive	Bashi glauconitic sands and marls
TP2.3	2	Highstand	Upper Tuscahoma sands, silts, clays, and lignite beds
		Condensed section and transgressive	Bells Landing glauconitic sands and marls
TP2.2	1	Highstand	Middle Tuscahoma sands, silts, and clays
		Condensed section and transgressive	Greggs Landing glauconitic sands and marls
		Lowstand shelf	Tuscahoma cross-bedded sands
TP2.1	1	Highstand	Grampian Hills and lower Tuscahoma silts, clays, and marls
		Condensed section and transgressive	"*Ostrea thirsae*" glauconitic sands and marls
		Lowstand incised valley	Gravel Creek cross-bedded sands
TP1.5	1	Highstand	Coal Bluff sands, silts, clays, and lignite beds.
		Condensed section and transgressive	Coal Bluff glauconitic sands and marls
		Lowstand shelf	Coal Bluff cross-bedded sands
TP1.4	2	Highstand	Oak Hill sands, silts, clays, and lignite beds
		Condensed section and transgressive	Matthews Landing glauconitic sands and marls
		Shelf Margin	Porters Creek cross-bedded sands
TP1.3	2	Highstand	Porters Creek carbonaceous clays
		Condensed section and transgressive	Porters Creek marls and clays
TP1.2	2	Highstand	McBryde and Porters Creek marls and clays or Porters Creek clays
		Condensed section	McBryde marls and limestones or Porters Creek calcareous clays and limestones
		Transgressive	McBryde marls or Porters Creek sandy marls
		Shelf margin	"*Turritella* rock beds" sandy limestones
TP1.1	1	Highstand	Pine Barren silts and clays or Porters Creek marls and clays
		Condensed section	Pine Barren silts and limestones or Clayton/Porters Creek marls and limestones
		Transgressive	Pine Barren silts and limestones or Clayton silts, marls, and limestones
		Lowstand shelf	Pine Barren glauconitic sands or Clayton glauconitic sands

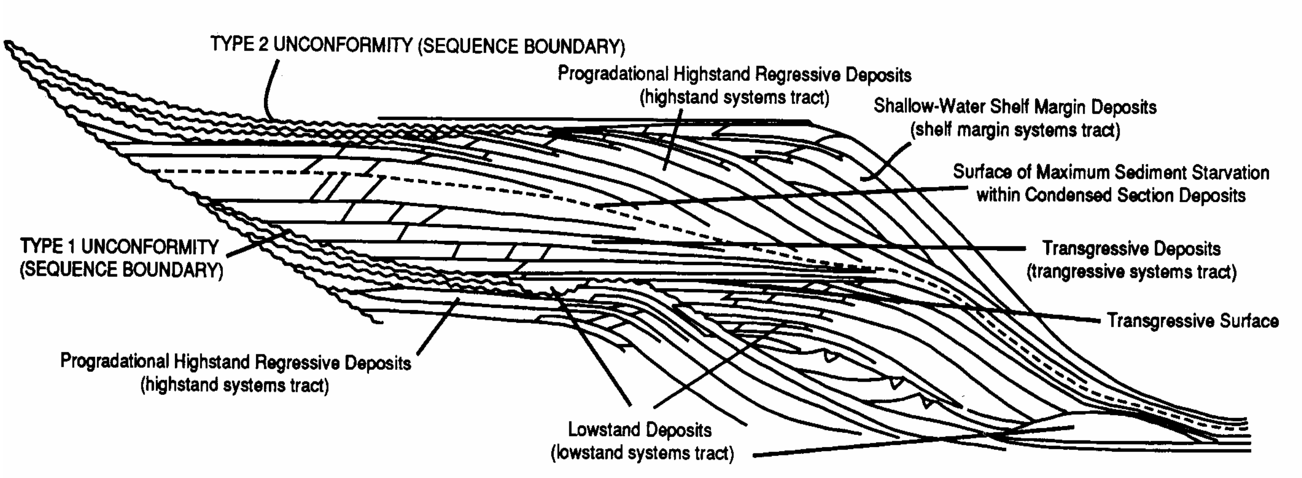


Figure 1. Type 1 and type 2 depositional sequence models illustrating surfaces and depositional sequence components (modified from Baum and Vail, 1988).

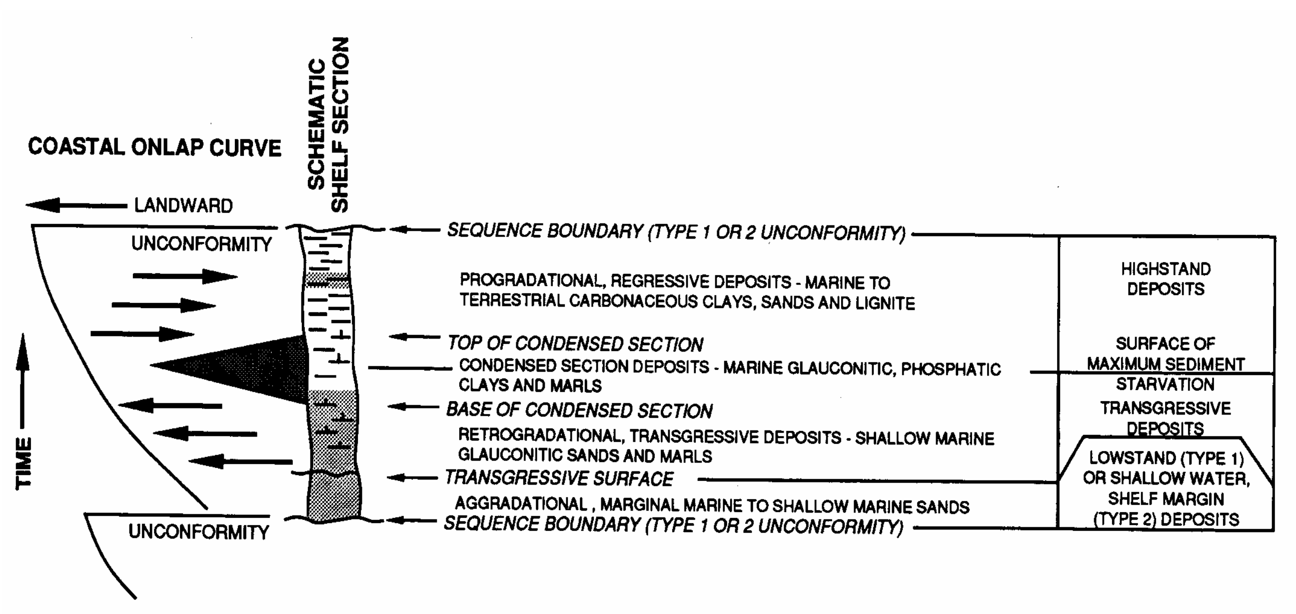


Figure 2. Schematic shelf geologic section in relationship to a coastal onlap cycle (modified from Baum and Vail, 1988).

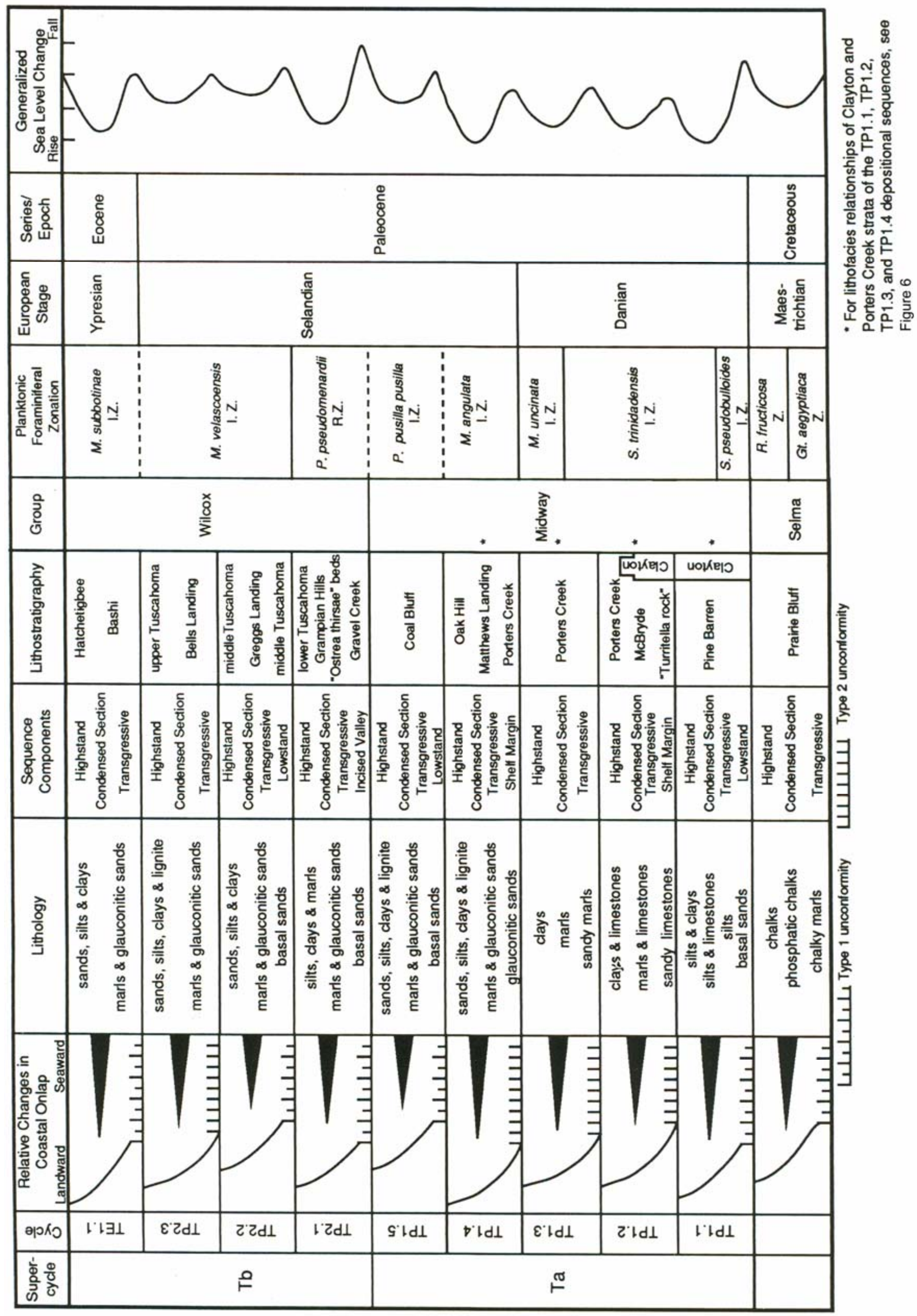


Figure 3. Sequence stratigraphy of Paleocene and lower Eocene strata in the eastern Gulf Coastal Plain (from Mancini and Tew, 1991).

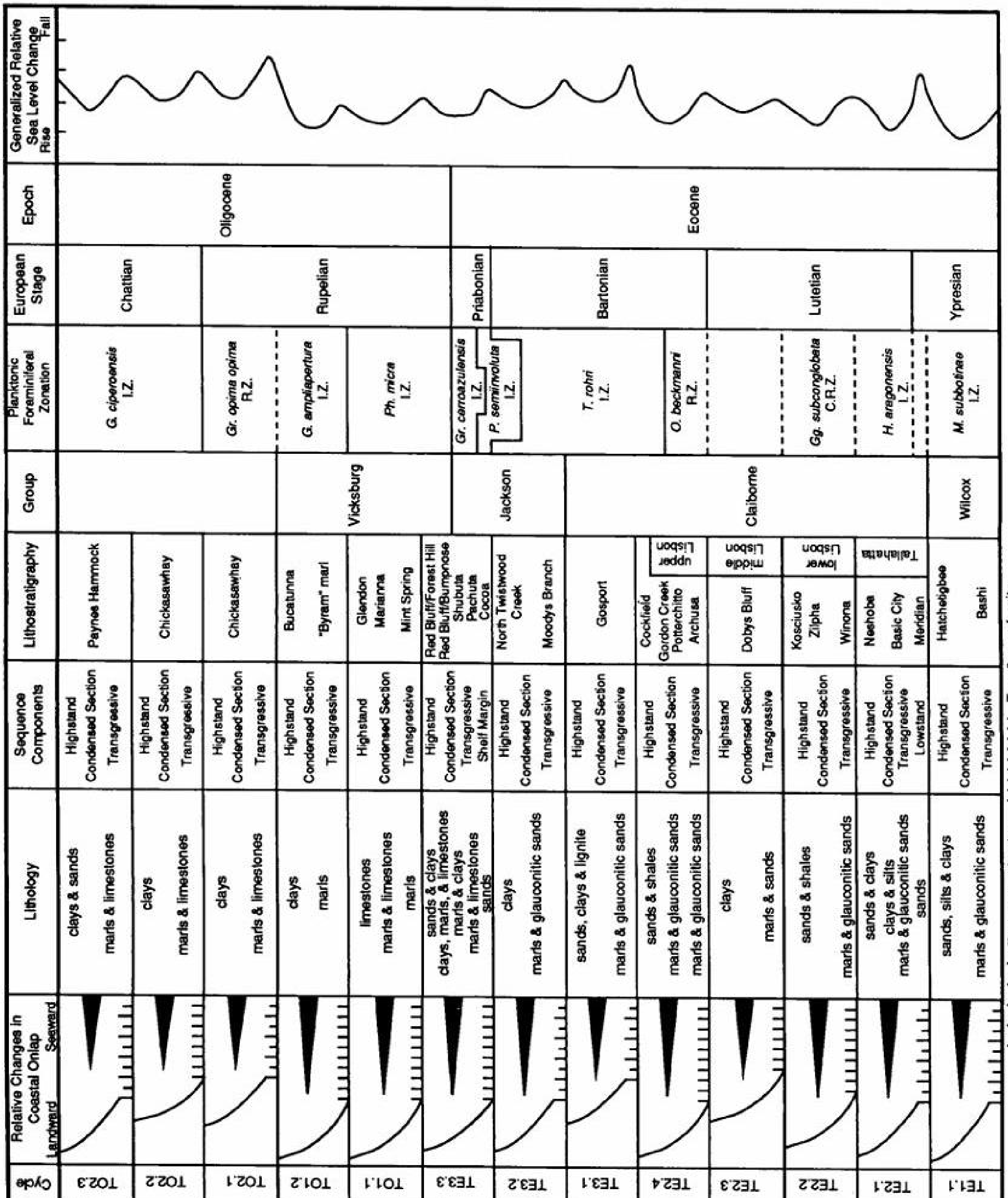


Figure 4. Sequence stratigraphy of Eocene and Oligocene strata in the eastern Gulf Coastal Plain (from Mancini and Tew, 1991).

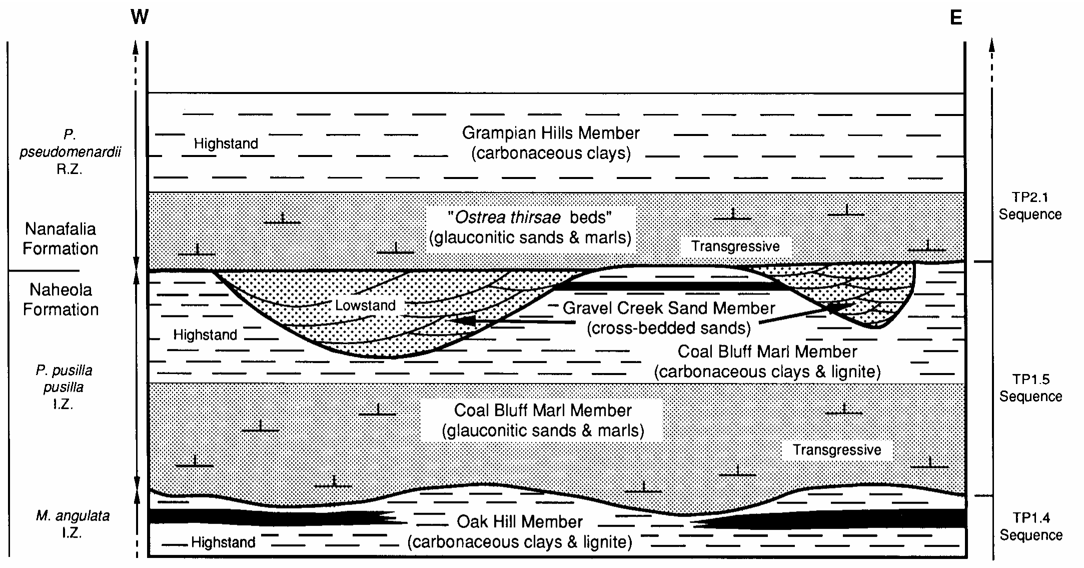


Figure 5. Schematic cross section illustrating lithofacies relationships, planktonic foraminiferal zones, and unconformity-bounded depositional sequences for the Oak Hill and Coal Bluff Marl Members of the Naheola Formation and for the Gravel Creek Sand, "Ostrea thirsae" beds and Grampian Hills Members of the Nanafalia Formation (from Mancini and Tew, 1991).

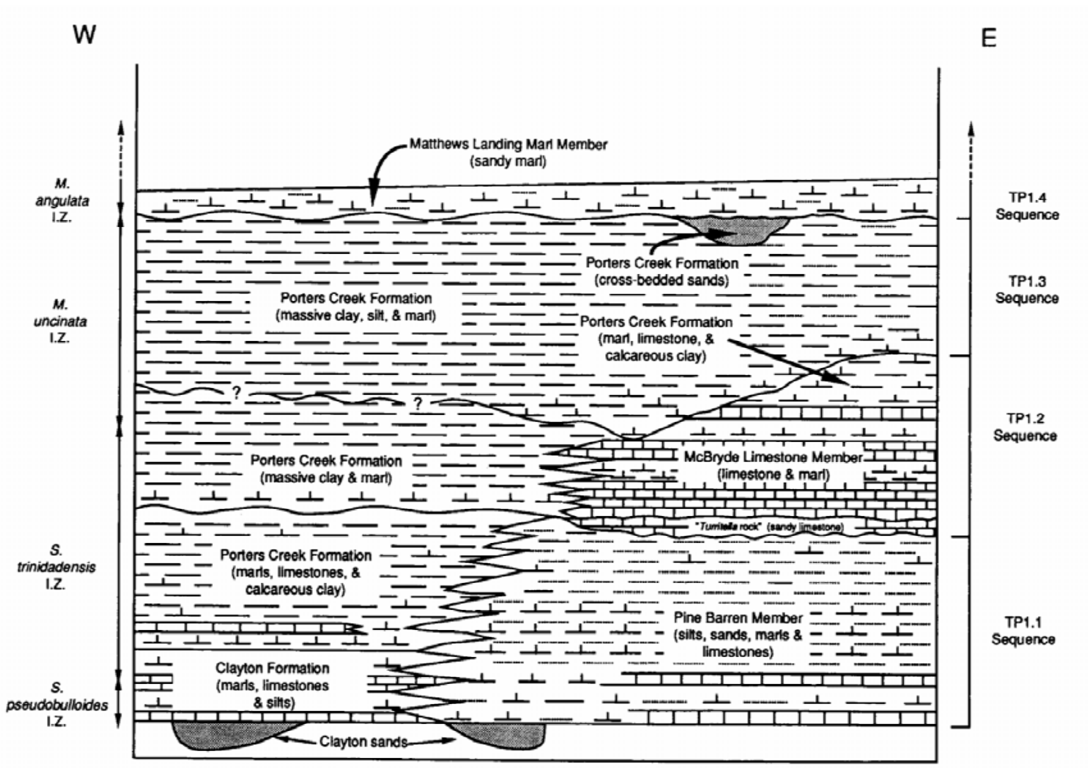


Figure 6. Schematic cross section illustrating lithofacies relationships, planktonic foraminiferal zones, and unconformity-bounded depositional sequences for the Pine Barren and McBryde Members of the Clayton Formation and for the clay beds and Matthews Landing Marl Member of the Porters Creek Formation (from Mancini and Tew, 1991).

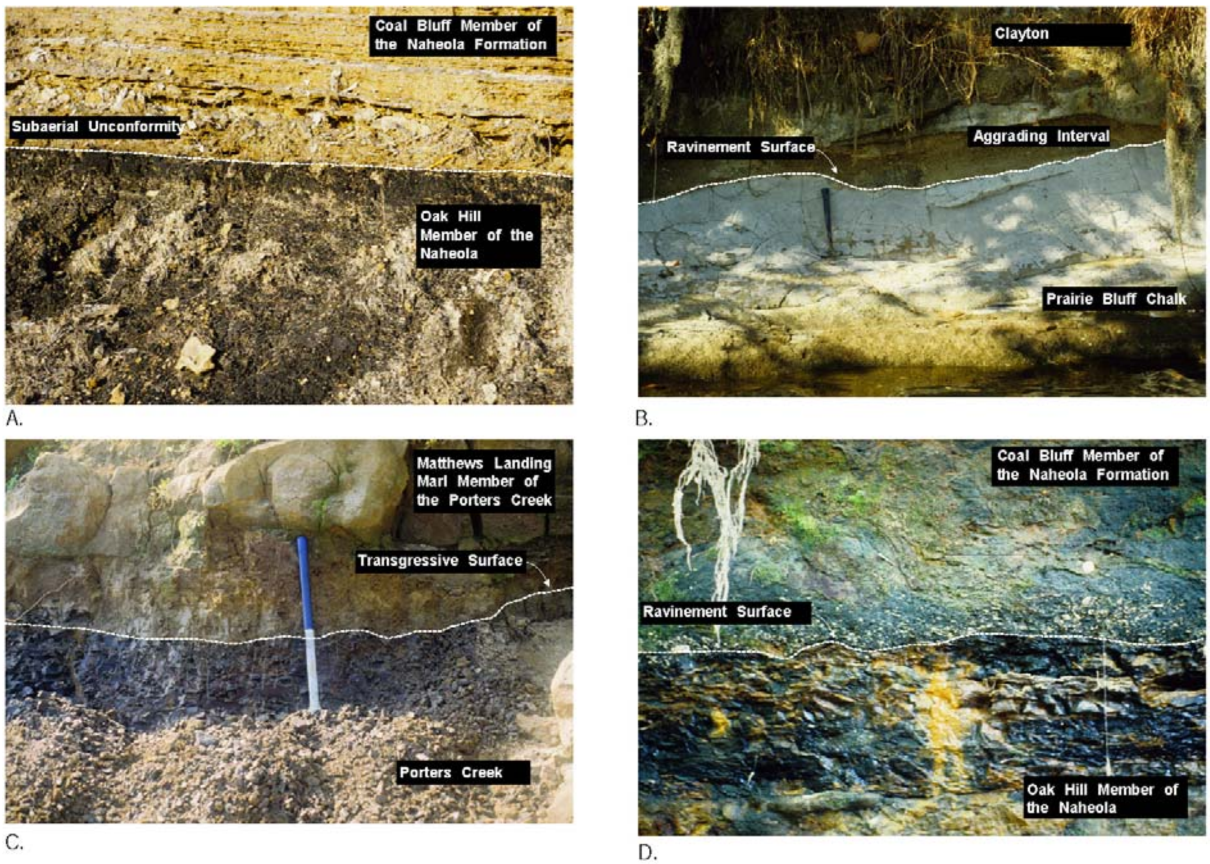


Figure 7. Photographs of outcrops showing physical surfaces: A. Subaerial unconformity at the contact of the Oak Hill Member of the Naheola Formation (swamp deposits) and the Coal Bluff Marl Member of the Naheola Formation (tidal deposits); B. Ravinement surface at the contact of the Prairie Bluff Chalk (marine shelf deposits) and the Clayton Formation (shoreface deposits); C. Transgressive surface at the contact of the Porters Creek Clay (prodelta deposits) and the Matthews Landing Marl Member of the Porters Creek Clay (shoreface deposits); and D. Ravinement surface at the contact of the Oak Hill Member of the Naheola Formation (swamp deposits) and the Coal Bluff Marl Member of the Naheola Formation (shoreface deposits).

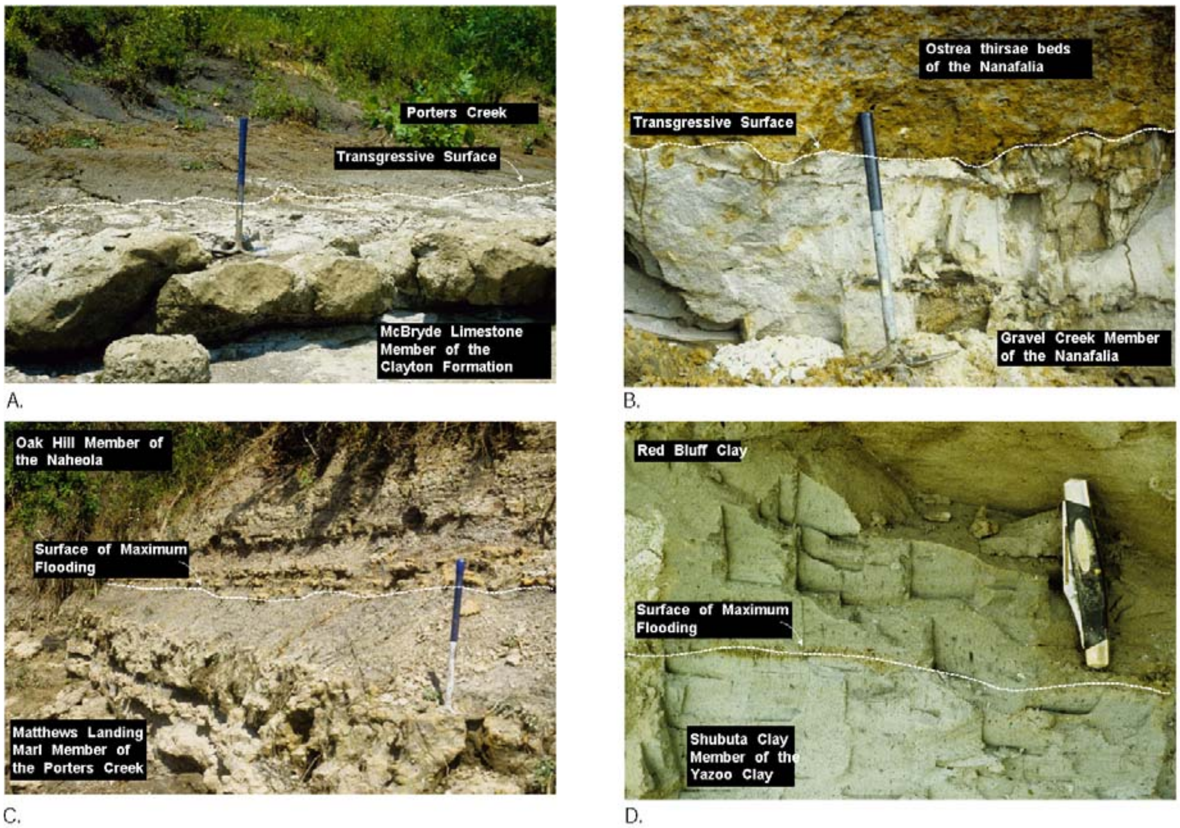


Figure 8. Photographs of outcrops showing physical surfaces: A. Transgressive surface at the contact of the McBryde Limestone Member of the Clayton Formation (marine shelf deposits) and the Porters Creek Clay (prodelta deposits); B. Transgressive surface at the contact of the Gravel Creek Sand Member of the Nanafalia Formation (tidal deposits) and the "Ostrea thirsae" beds of the Nanafalia Formation (marine shelf deposits); C. Condensed section and surface of maximum flooding in the Naheola Formation; and D. Surface of maximum flooding in the Yazoo Clay (Shubuta Clay Member) and Red Bluff Clay.

2. Upper Cretaceous studies involving outcrop studies by Ernest A. Mancini and involving well logs, cores and seismic data by Kaiyu Liu.

Characterization of Upper Cretaceous stratigraphic sequences in the Gulf of Mexico in this study included field examination of the Upper Cretaceous unconformity-bounded units described by Mancini et al. (1996) using a depositional sequence classification and by Mancini and Puckett (2003) using a transgressive-regressive (T-R) classification. In both studies, these authors recognized stratigraphic sequences (Figure 9). However, in the 1996 study, they described the lowermost beds of their lower sequence as lowstand deposits. In the 2003 study, the authors questioned the assignment of these beds to a lowstand systems tract. Mancini et al. (1996) stated that because these beds rested on a subaerial unconformity and were overlain by a disconformity (transgressive surface/ravinement surface); they were by definition lowstand deposits even though these beds were continuous and widespread in their distribution. Mancini and Puckett (2003) elected to describe these beds as the aggrading section of a transgressive systems tract and in turn utilized a T-R cycle (sequence) categorization rather than the original depositional sequence classification for these strata. We concur with this assessment. A T-R sequence consists of an upward deepening event and upward shallowing event separated by a surface of maximum transgression (Mancini and Puckett, 2002). The upward deepening event (transgressive aggrading and backstepping sections) rests unconformably on the preceding cycle (sequence). The unconformity can be a subaerial unconformity (Figures 10A, 11B), a transgressive surface, or a ravinement surface (Figure 11A). The surface between the aggrading and backstepping sections is disconformable (Figure 10B). The surface between the backstepping and infilling sections is marked by a surface of maximum transgression (Figure 10D, 11C). Downdip, the surface between the infilling section and the overlying T-R sequence can be conformable and is described as a surface of maximum regression (Figure 10C). Marine flooding events are evident at vertical facies transitions (Figure 11D).

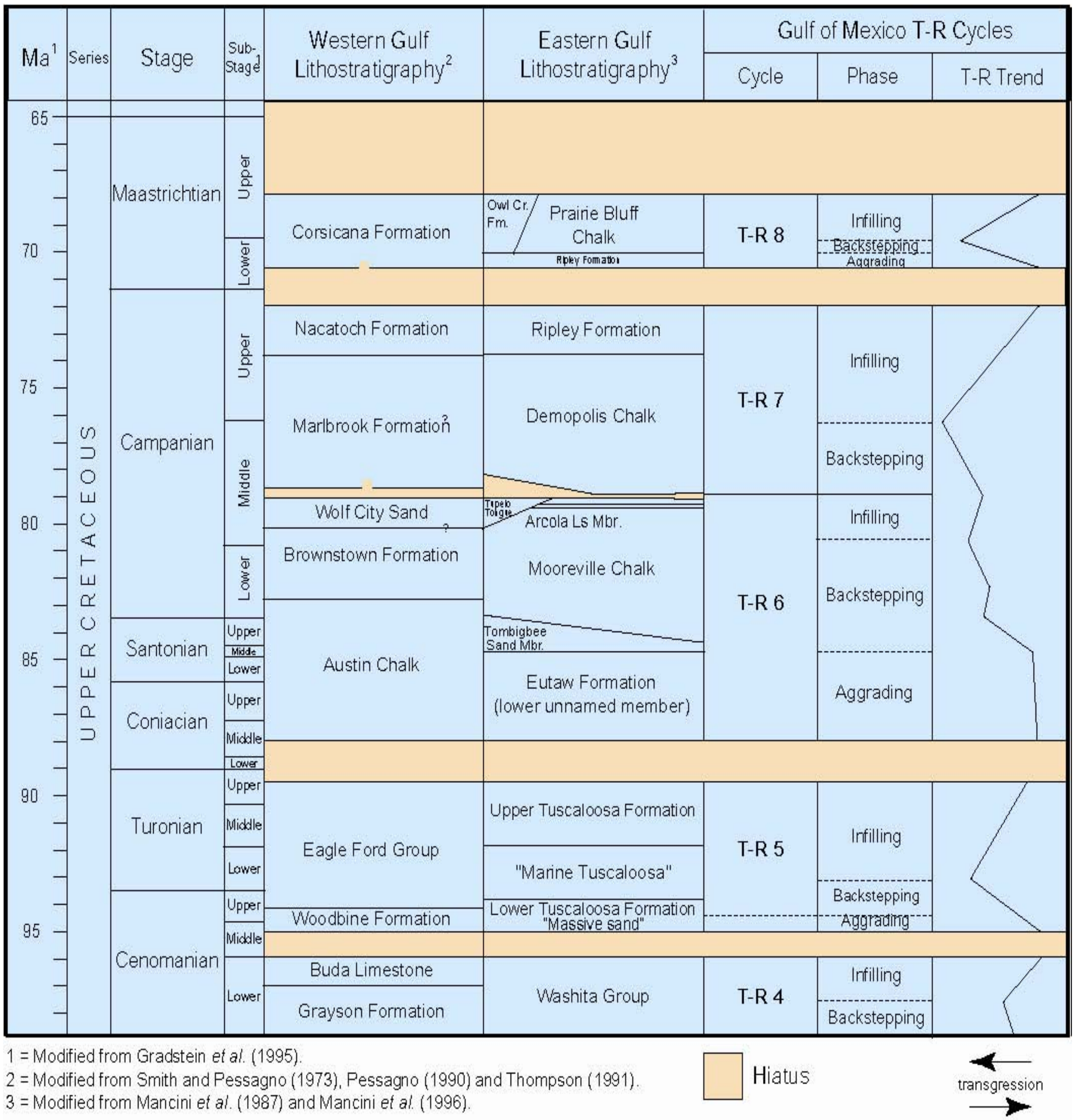


Figure 9. Upper Cretaceous sequence stratigraphy (from Mancini and Puckett, 2003).

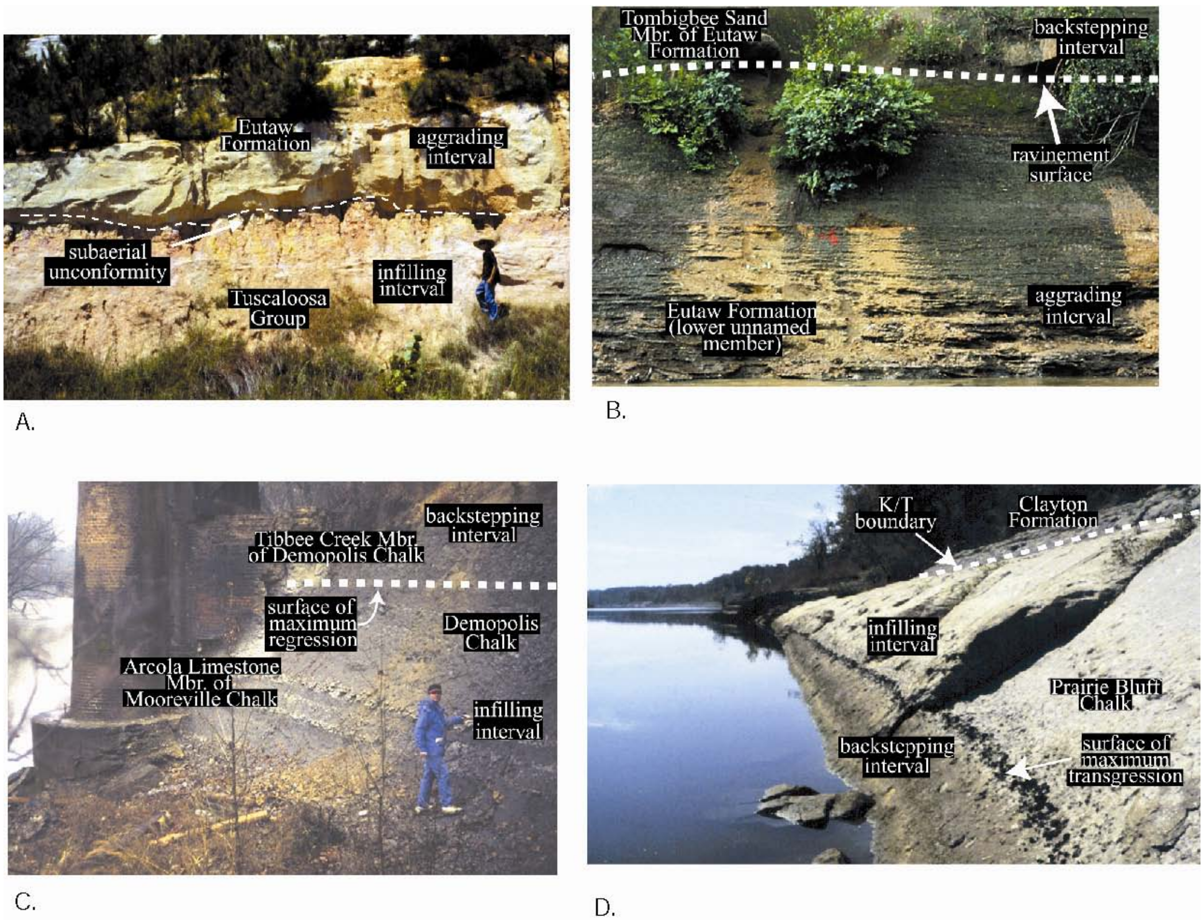


Figure 10. Photographs of outcrops showing physical surfaces: A. Subaerial unconformity at the contact of the Tuscaloosa Group (fluvial deposits) and the Eutaw Formation (estuarine deposits); B. Ravinement surface at the contact of the unnamed member of the Eutaw Formation (tidal deposits) and the Tombigbee Sand Member of the Eutaw Formation (nearshore deposits); C. Surface of maximum regression at the contact of the Arcola Limestone Member of the Mooreville Chalk (marine shelf deposits) and the Tibbee Creek Member of the Demopolis Chalk (marine shelf deposits); D. Surface of maximum transgression in the Prairie Bluff Chalk (marine shelf deposits).

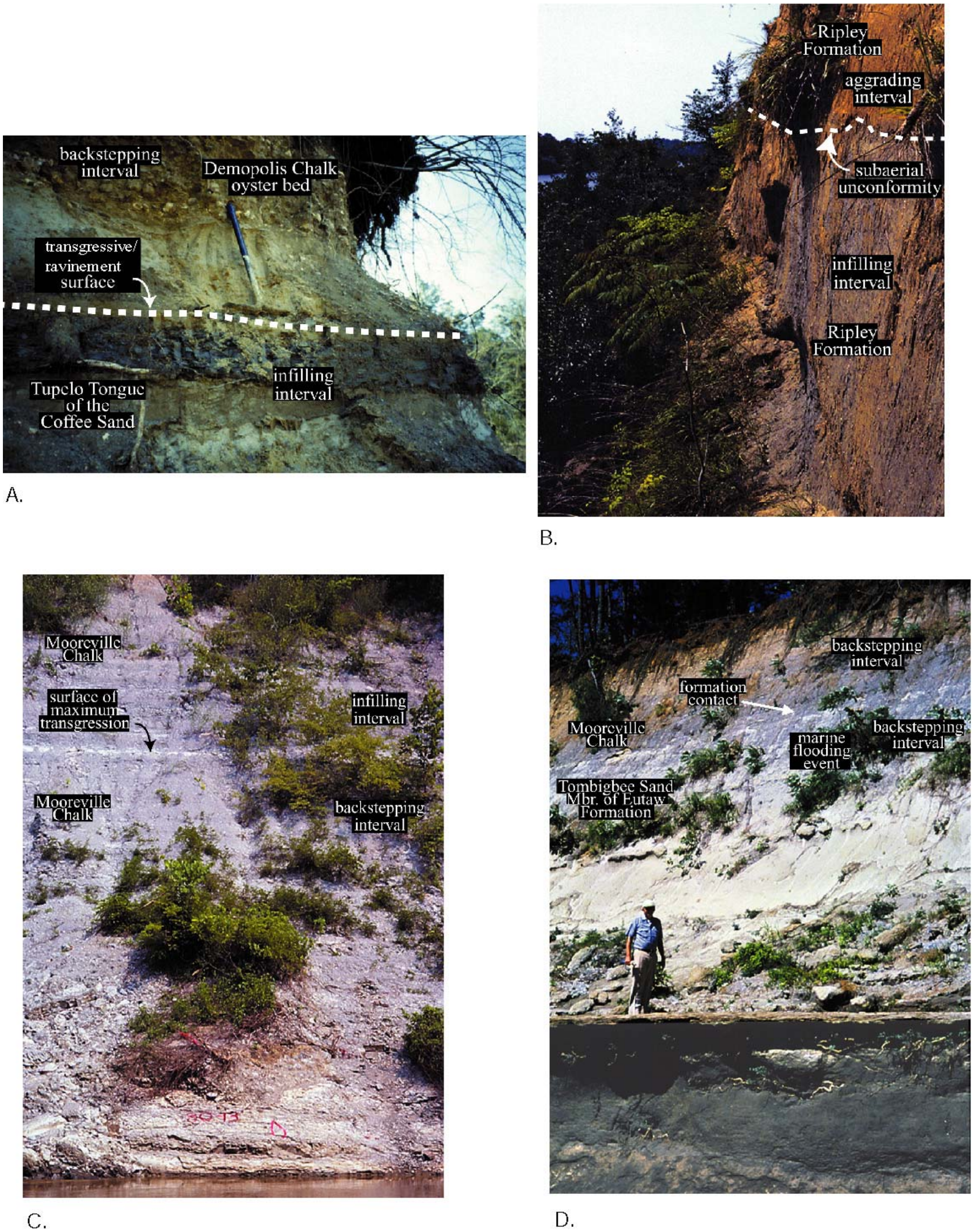


Figure 11. Photographs of outcrops showing physical surfaces: A. Transgressive/ravinement surface at the contact of the Tupelo Tongue of the Coffee Sand (marginal marine deposits) and the sands of the Demopolis Chalk (nearshore deposits); B. Subaerial unconformity at the intraformational unconformity in the Ripley Formation; C. Surface of maximum transgression in the Mooreville Chalk (marine shelf deposits); and D. Marine flooding event at the contact of the Tombigbee Sand Member of the Eutaw Formation (nearshore deposits) and the Mooreville Chalk (marine shelf deposits).

Characterization of Upper Cretaceous stratigraphic sequences in the Gulf of Mexico, using well logs, cores and seismic data in their studies consisted essentially of the dissertation research of Liu (2006), which built on the work of Mancini et al. (1996) and Mancini and Puckett (2003).

The following is from the dissertation research of Liu (2005).

Introduction

The sequence stratigraphy of the Upper Cretaceous strata in the northeastern Gulf of Mexico has been studied in outcrop in central and western Alabama and eastern and northeastern Mississippi (Hancock, 1993; Mancini et al., 1996; Puckett and Mancini, 2000; Mancini and Puckett, 2003) and in the subsurface in the offshore Alabama and Mississippi area (Liu, 2004).

Sequence stratigraphic studies that are based entirely on either outcrop or subsurface data have advantages and limitations. In outcrop, sedimentary characteristics such as grain size, texture, and sedimentary structure can be observed directly. Furthermore, detailed biostratigraphic work can establish a time frame for the purpose of age estimation of the strata. Changes in sea level and depositional history can be interpreted from depositional facies and facies relationships combined with an established biostratigraphic /chronostratigraphic framework.

However, outcrop work has its limitations. First, sediment stacking patterns on a regional scale can not be seen directly and have to be interpreted from facies relationships among rocks exposed at various locations. In addition, the sections from outcrops represent only the inner and middle portions of the Late Cretaceous continental shelf. Facies changes on the continental shelf cannot be understood without knowledge of the unexposed sediment in the middle and outer portions of the continental shelf. Finally, the magnitude of the shoreline migration (coastal onlap changes), which is closely related to the magnitude of sea-level fluctuations cannot be fully understood without knowledge of the changes in sedimentary facies and depositional environments in the outer shelf area.

In subsurface studies, sediment stacking patterns on a regional scale, such as prograding (downlap) and retrogradational or backstepping (onlap), can be observed and determined directly from seismic data. Facies changes on a regional scale can be interpreted from well logs, which are available in southwestern Alabama and in areas of offshore Alabama. In addition, the outer portion and part of the middle portion of the Late Cretaceous continental shelf in the northeastern Gulf of Mexico are not exposed, and therefore, have to be studied in subsurface strata.

One of the shortcomings of subsurface studies is the limited access to rock samples of the strata; therefore, subsurface interpretations have to be made mainly based on geophysical data, such as seismic and well log information. Difficulty in dating surfaces identified from seismic sections is a limitation.

Integrated studies that incorporate surface and subsurface data can provide for an improved interpretation. The Upper Cretaceous strata in the northeastern Gulf of Mexico offer an excellent opportunity for such integrated studies. The Upper Cretaceous strata in the eastern Gulf Coastal Plain are relatively undeformed. These strata are exposed in a wide crescent-shaped belt extending from northeastern Mississippi into central Georgia (Figure 12); and these strata dip gently toward the basin center and are encountered in the subsurface.

The objectives of this study are: 1) to review previous surface and subsurface sequence stratigraphic interpretations of the Upper Cretaceous strata in the northeastern Gulf of Mexico area, 2) to correlate important surfaces that have chronostratigraphic significance, such as sequence boundaries and maximum flooding surfaces, across the Late Cretaceous continental shelf through the study of well log data, and 3) to determine dip directional facies changes of the Upper Cretaceous strata in the established sequence stratigraphic framework.

Geological Setting

The study area is located in the northeastern Gulf of Mexico (Figure 12). Late Cretaceous sediment deposition in the northeastern Gulf of Mexico began in the late Middle Cenomanian as sea level rose and marine transgression occurred on the continental shelf following the mid-Cenomanian sea-level fall, which formed a prominent unconformity known as the mid-Cretaceous Unconformity and has been recognized throughout most of the periphery of the Gulf of Mexico basin. This unconformity represents a profound change in the depositional regime from widespread carbonate deposition of Early Cretaceous times to mostly siliciclastic and mixed siliciclastic and carbonate deposition in the Late Cretaceous. Because of its significance, this mid-Cenomanian stratigraphic break has been used to mark the boundary between the "Upper Cretaceous" and "Lower Cretaceous", although the internationally established boundary between these two series is located at the base of the Cenomanian (Salvador, 1991).

Sea level continued to fluctuate during the Late Cretaceous and sedimentary facies migrated updip and downdip along with sea-level fluctuations. The Upper Cretaceous strata in the northeastern Gulf of Mexico are strongly overprinted by cyclic sea-level fluctuations. Salvador (1991) stated that major unconformities and associated hiatuses were caused by sea-level falls; and some of the lesser and more local unconformities are indicative of minor sea-level oscillations or are related to local tectonic and igneous episodes. Mancini and Puckett (2003) further pointed out that cycles are controlled by changes in accommodation space resulting from stratigraphic base level changes (eustatic and tectonic effects) and sediment supply and accumulation. Salvador (1991) recognized three periods marked by prominent sea-level regressions as represented by three major unconformities: Mid-Cenomanian, Late Turonian-Early Coniacian, Late Maastrichtian-Early Danian. Along the northern margin of the Gulf of Mexico, deposition was generally continuous from Santonian to Campanian time and then again from Campanian to Maastrichtian time, with minor transgressive-regressive cycles being recognized during the Campanian and Maastrichtian (Salvador, 1991).

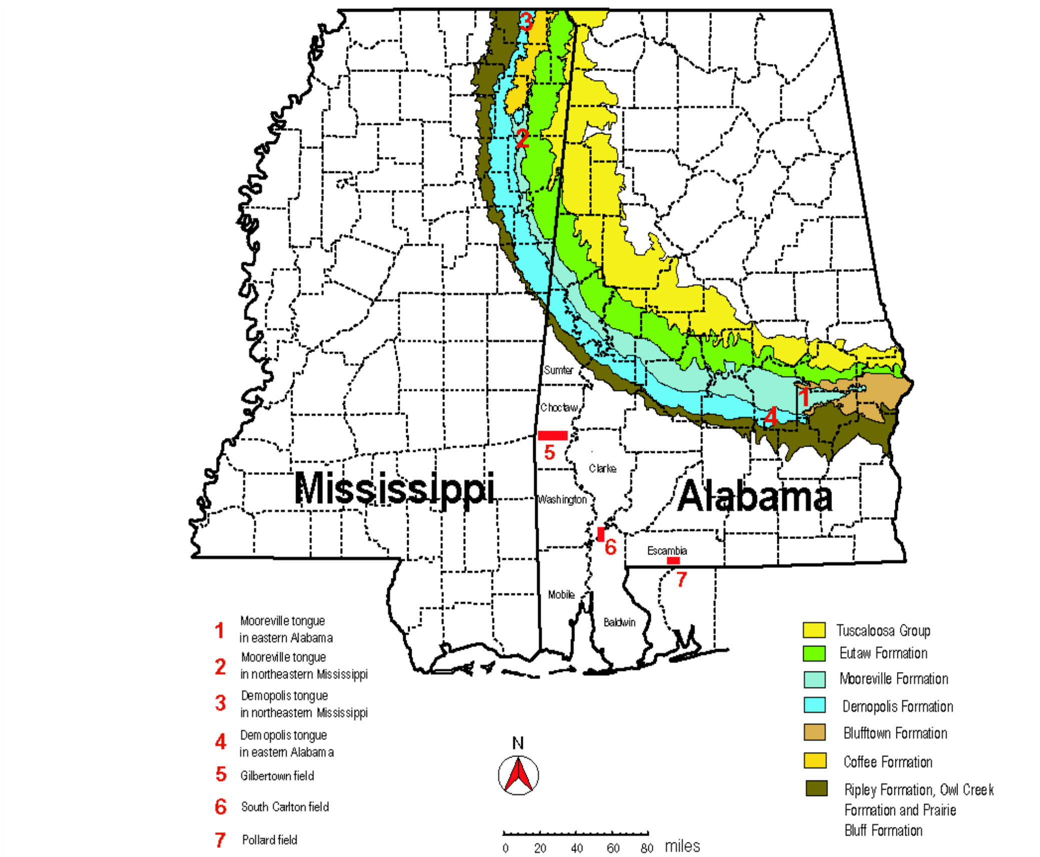


Figure 12. Upper Cretaceous strata outcrop belt, northeastern Mississippi and western and southern Alabama.

Regional Stratigraphy in Outcrop

Lithologically, the Upper Cretaceous strata in the outcrop area are divided into several groups and formations. Figure 13 summarizes the regional stratigraphy of the study area and adjacent areas.

Tuscaloosa Group

The Tuscaloosa Group represents the basal unit of the Upper Cretaceous section in the study area. In areas where Lower Cretaceous strata are not exposed, the Tuscaloosa Group rests directly on the Paleozoic basement rocks (Conant, 1967). In outcrop, the Tuscaloosa Group is divided into two formations: the Coker Formation and the Gordo Formation (Conant, 1967; Copeland, 1968; Russell and Keady, 1983).

The lowest part of the Coker, formerly named as the Cottondale Formation, is present only in the immediate vicinity of Tuscaloosa, Alabama and the Black Warrior River, and consists of a nonmarine sand with small amounts of quartz and chert gravels at the base. The rest of the Coker Formation is mostly of marine to marginal marine origin and consists of two members: the Eoline Member and an unnamed upper member. Most of the Eoline Member consists of stratified and cross-stratified, fine-grained glauconitic sand interbedded with dark-gray carbonaceous and lignitic clay. The upper unnamed member of the Coker Formation consists of light-colored micaceous sand with red mottled clay in the upper part (Monroe, 1964; Conant, 1967, Cook 1993; Raymond et al., 1988). The Coker Formation has been suggested to be deposited during a period of marine transgression and subsequent highstand (Cook, 1993; Pashin et al., 2000; Mancini and Puckett, 2002).

The Gordo Formation is predominantly terrestrial in origin: its lower part consists of gravelly, medium- to very coarse-grained sand, and also contains some purple-mottled gray clay and light-gray clay. The upper part of the Gordo Formation is composed of lenticular beds of red- or purple-mottled clay and crossbedded sand (Monroe, 1964; Conant, 1967;

Raymond et al., 1988; Cook, 1993). Deposition of the Gordo Formation occurred during a major marine regression (Cook, 1993; Pashin et al., 2000; Mancini and Puckett, 2002).

The contact between the Gordo Formation and the Coker Formation can be readily recognized and is easily mappable. This contact was interpreted to be an unconformity by Conant (1967).

Eutaw Formation

The Eutaw Formation overlies the Tuscaloosa Group; the contact between the Eutaw Formation and the Tuscaloosa Group has been interpreted to be an unconformity (Stephenson and Monroe, 1940; Monroe, 1946; Conant, 1967; Copeland, 1968). Although in outcrop in western Alabama, the lower part of the Eutaw Formation is separated and named the McShan Formation; in this paper, the Eutaw Formation refers to the Eutaw Formation, including the McShan Formation. The Eutaw Formation consists of marine and marginal marine sediments characterized by massive glauconitic, fossiliferous sand interbedded with gray laminated clay (Cook, 1993). The Eutaw Formation was further divided into an unnamed lower member and the Tombigbee Sand Member.

The lower Eutaw Formation has been described to be very similar to the Coker Formation of the Tuscaloosa Group (Conant, 1967). That might imply these two stratigraphic units accumulated in similar environments. The Eutaw Formation has been interpreted to be deposited in a nearshore, marginal marine environment of isolated, widely dispersed barrier bars and shoals with associated back-barrier and tidal inlets and tidal flat facies (Cook, 1993) during a marine transgression (Conant, 1967; Pashin et al., 2000; Mancini and Puckett, 2002; Mancini and Puckett, 2003).

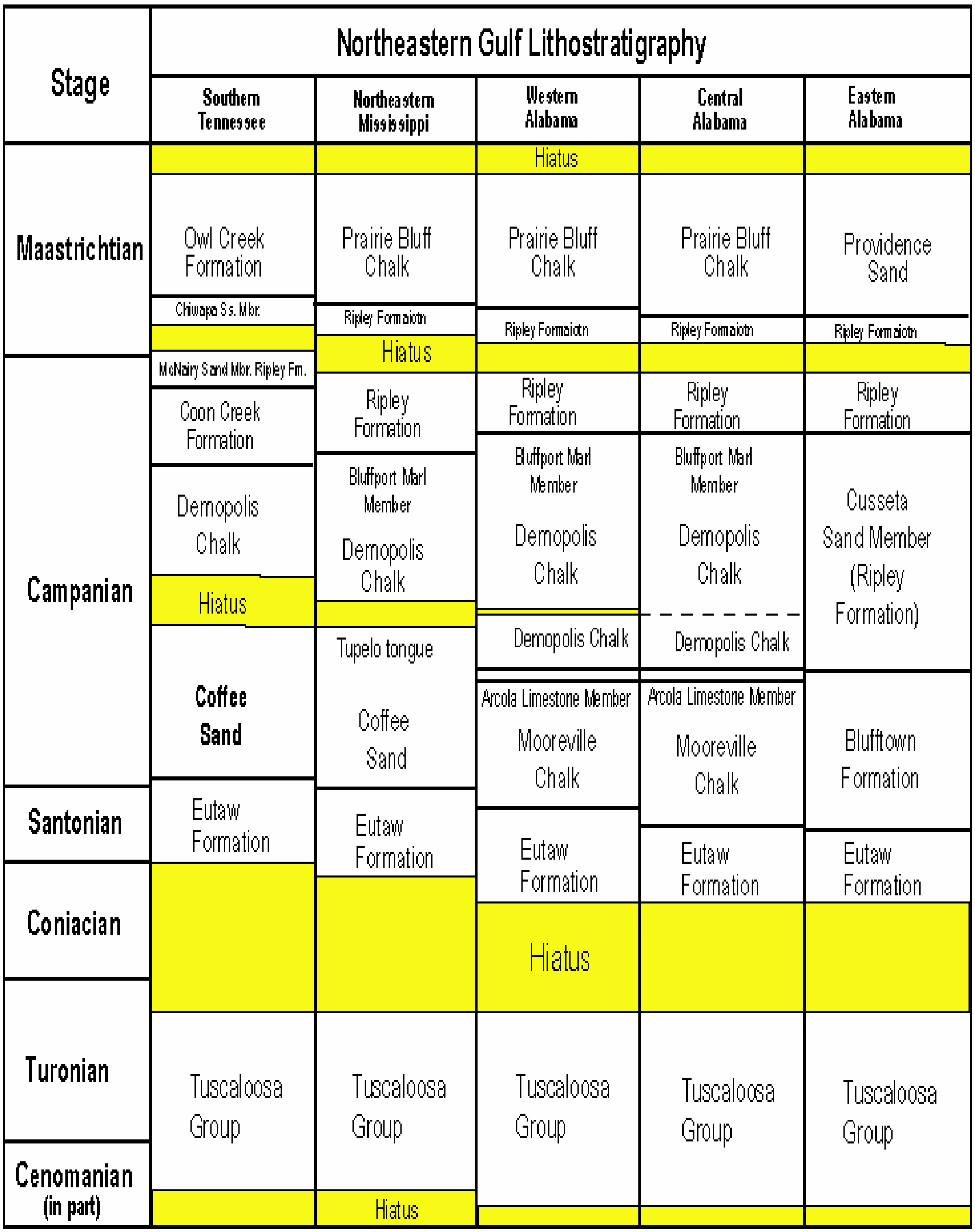

Stage
Northeastern Gulf Lithostratigraphy
Southern Tennessee
Northeastern Mississippi
Western Alabama
Central Alabama
Eastern Alabama
Hiatus
Maastrichtian
Owl Creek Formation
Prairie Bluff Chalk
Prairie Bluff Chalk
Prairie Bluff Chalk
Providence Sand
Chiwapa Ss. Mbr.
Ripley Formaiotn
Ripley Formaiotn
Ripley Formaiotn
Ripley Formaiotn
Hiatus
McNairy Sand Mbr. Ripley Fm.
Campanian
Coon Creek Formation
Ripley Formation
Ripley Formation
Ripley Formation
Ripley Formation
Bluffport Marl Member
Bluffport Marl Member
Bluffport Marl Member
Demopolis Chalk
Demopolis Chalk
Demopolis Chalk
Demopolis Chalk
Cusseta Sand Member (Ripley Formation)
Hiatus
Demopolis Chalk
Demopolis Chalk
Tupelo tongue
Coffee Sand
Coffee Sand
Arcola Limestone Member
Arcola Limestone Member
Mooreville Chalk
Mooreville Chalk
Blufftown Formation
Santonian
Eutaw Formation
Eutaw Formation
Eutaw Formation
Eutaw Formation
Eutaw Formation
Coniacian
Hiatus
Turonian
Tuscaloosa Group
Tuscaloosa Group
Tuscaloosa Group
Tuscaloosa Group
Tuscaloosa Group
Cenomanian (in part)
Hiatus

Figure 13. Upper Cretaceous lithostratigraphy for the eastern Gulf Coastal Plain, after Jones (1967), Puckett (1992), and Mancini et al. (1996).

The upper part of the Eutaw Formation is a massive glauconitic sand member named the Tombigbee Sand Member. The contact between the Tombigbee Sand Member and the lower Eutaw Formation is unconformable and is marked by a one to two inch sandstone bed containing phosphatic pebbles, shark teeth, and reworked fossils (Mancini and Soens, 1994). The Tombigbee Sand Member, especially in west Alabama, is a highly bored, unstratified glauconitic sand containing abundant shells of *Exogyra ponderosa*, *Gryphaea wratheri*, *Ostrea battensis*, and other fossils (Conant, 1967). It is about 174 feet in thickness in its type area near Plymouth Bluff, northwest of Columbus, Mississippi (Russell and Keady, 1983; Copeland, 1988). Smith and Mancini (1983) assigned the exposed 42-49 feet (13-15m) of the upper Tombigbee Sand Member to the Cretaceous calcareous nannofossil *Calculites obscurus* Zone (CC17) of Sissingh (1977) and Perch-Nielsen (1979). This nannofossil zone has been related to strata of latest Santonian to earliest Campanian age (Sissingh, 1977; Perch-Nielsen, 1979; Hardenbol et al., 1995; Shipboard Scientific Party, 1998).

The contact between the Tombigbee Sand Member of the Eutaw Formation and the overlying Mooreville Chalk of the Selma Group was described as an unconformity or disconformity by Conant (1967) and Copeland (1968), because chalk nodules are present along this contact. However, Russell and Keady (1983), Mancini and Soens (1994) and Mancini et al. (1996) described this contact as gradational and conformable, because they observed no physical evidence in support of placing an unconformity at the base of the Mooreville. Detailed biostratigraphic work by Mancini et al. (1996) showed that the Mooreville-Tombigbee contact is, in fact, time-transgressive. The contact is about 23 feet below the first occurrence of the planktic foraminifer *G. elevata* near Selma in central

Alabama. In west central Alabama, near Demopolis, the Mooreville-Tombigbee contact occurs above the first occurrence of the planktic foraminifer *Globotruncanita elevata*, but below the last occurrence of the planktic foraminifer *Dicarinella asymetrica*. In east-central Mississippi, the Mooreville-Tombigbee Formation contact lies immediately below the last occurrence of the planktic foraminifer *D. asymetrica* (Figure 14).

The diachronous nature of the Mooreville-Tombigbee Formation contact has been explained by a gradual inundation of the shoreline toward the updip area and the establishment of a deeper water environment characterized by a muddy carbonate shelf across the southwest Alabama (Puckett, 1992; Mancini et al., 1996).

Selma Group

In the outcrop area in western Alabama, the Selma Group consists of about 900 feet of mixed siliciclastic and carbonate chalk/marl sediments. In west Alabama, the Selma Group is divided into several formations, from bottom to top: the Mooreville Chalk (including the Arcola Limestone Member), the Demopolis Chalk (including the Bluffport Marl Member), the Ripley Formation, and the Prairie Bluff Chalk.

The Mooreville Chalk is a fairly uniform chalky marl that consists of interbedded gray marl (calcareous clay) beds with chalk beds. In the outcrop, this formation is about 350-400 feet thick in central Alabama, but thins to about 260-265 feet in eastern Mississippi (Stephenson and Monroe, 1940; Jones, 1967). The uppermost part of the Mooreville Chalk is a gray, indurated calcisphere limestone named the Arcola Limestone Member. It is a distinctive unit that contains very little terrigenous clastic detritus contrasted with the glauconitic, phosphatic, silty chalky marl beds in the Mooreville Chalk. The Arcola Limestone Member is about 14 feet in thickness at Hatchers Bluff, near Selma in central

Alabama, and is composed of four beds with three chalky marl interbeds. These beds gradually thin toward the southeast and northwest in the outcrop belt and merge together (Smith, 1995; Tew, 2000). The Arcola Limestone Member is also found in the subsurface in southwestern Alabama. It can be identified on well logs as a unique high peak on resistivity logs in subsurface areas near the outcrop belt in Dallas, Sumter, Marengo and Choctaw counties, Alabama. The limestone bed extends southward at least to Mobile and Baldwin counties, Alabama, because chips of calcisphere limestone characteristic of the Arcola Limestone Member were found in well cuttings from these counties (Charles C. Smith, 2003, personal communication). Biostratigraphic work has shown that the Arcola Limestone Member is essentially a synchronous unit across a wide geographic area (Smith, 1995). It has been assigned to the upper part of the nannofossil CC19a zone (the lower subzone of the *Calculites ovalis* zone) and the lower part of the foraminiferal zone *Globotruncana ventricosa* of Middle Campanian age (Smith, 1995; Mancini et al., 1996). The Arcola Limestone Member can be used as an important time marker in stratigraphic correlations.

The Demopolis Chalk has a similar lithology as the Mooreville Chalk, but in the outcrop, the Demopolis Chalk is more chalky and indurated. The Demopolis Chalk becomes purer in chalk in the upper part of the formation (Copeland, 1968). The Demopolis Chalk has a thickness of about 450 feet in west Alabama. The upper part of the Demopolis Chalk is a fossiliferous clayey chalky marl member named the Bluffport Marl Member.

Above the Bluffport Marl Member is the Ripley Formation. The Ripley Formation consists of about 100 feet of micaceous sandy silt. The contact between the Demopolis Chalk and the Ripley Formation is gradational. The chalk beds of the Demopolis gradually become more sandy and grade into the micaceous calcareous gray and green sand and chalk beds of the Ripley Formation (Copeland, 1968).

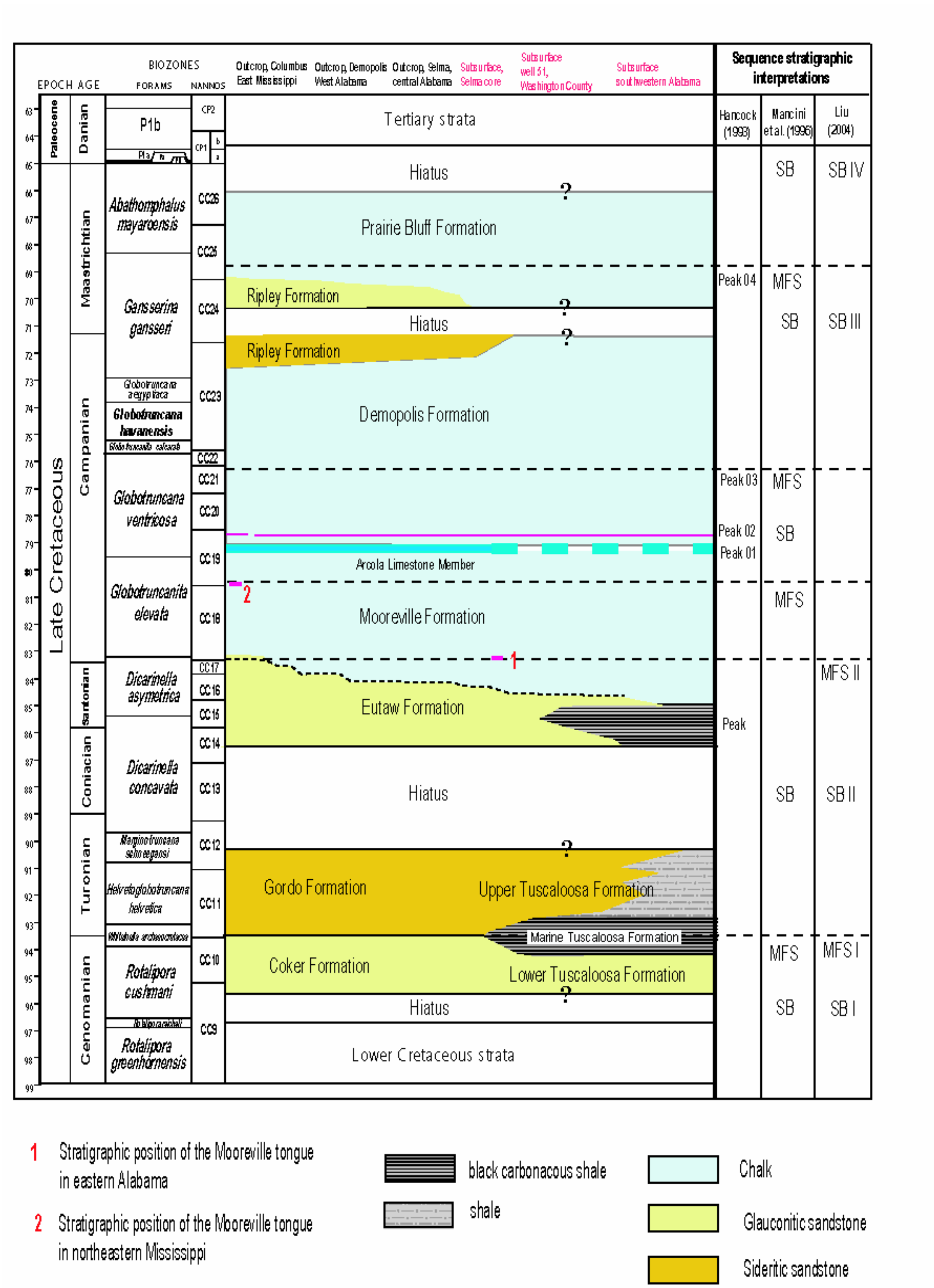


Figure 14. Biostratigraphic framework for the Upper Cretaceous strata in outcrop and subsurface in the northeastern Gulf of Mexico area. Nannofossil zones and foraminiferal zones after Shipboard Scientific Party (1998).

Above the Ripley Formation is the youngest unit of the Upper Cretaceous strata in the northeastern Gulf of Mexico, the Prairie Bluff Chalk in west Alabama and Owl Creek Formation in Mississippi. An important, regional mappable unconformity is recognized as an intraformational unconformity in the Ripley Formation in west Alabama (Mancini et al., 1996, 2002), as an unconformity between the Owl Creek Formation and the McNairy Sandstone Member of the Ripley Formation or as an intraformational unconformity of the Ripley Formation between the Chiwapa Sandstone Member and the McNairy Sandstone Member of the Ripley Formation in northern Mississippi (Russell, 1967; Swann, 1999; Swann, 2003).

The Upper Cretaceous of the northeastern Gulf of Mexico is capped by a regional unconformity that separates the Prairie Bluff Chalk or Owl Creek Formation of the Selma Group from the overlying Tertiary Clayton Formation of the Midway Group (Copeland, 1968; Donovan et al., 1987; Mancini et al., 1989; Salvador, 1991; Smith, 1997). Where the Prairie Bluff Chalk is locally absent in northern Marengo County toward the west and in southern Dallas County toward the east, the Paleogene Clayton Formation rests directly on marly sands and sandstones of the underlying Ripley Formation (Smith, 1997). The duration of the hiatus represented by this unconformity is, however, still in debate. Mancini et al. (1989) assigned the topmost beds of the Prairie Bluff Chalk at Moscow Landing, Sumter County in west central Alabama to the late Middle Maastrichtian *Racemiguembelina fructicosa* Zonule of Smith and Pessagno (1973) and the foraminifera characteristic of the *Abathomphalus mayaroensis* Zone were not observed. Therefore, Late Maastrichtian strata were described as missing at Moscow Landing. Smith (1997) also stressed that Late Maastrichtian strata were absent in the K-T boundary section at Moscow Landing, although he assigned the top beds of the Prairie Bluff Chalk at Moscow Landing to the nannofossil

Nephrolithus frequens Zone (CC26 Zone). Many nannofossil workers relate the nannofossil zone CC26 to the planktic foraminiferal *Abathomphalus mayaroensis* Zone. Smith (1997) further cited evidence from Smith (1975) that the range of *Nephrolithus frequens* actually extends down into the upper portion of the foraminiferal *Gansserina gansseri* Zone; therefore, the presence of the nannofossil *Nephrolithus frequens* does not indicate a latest Maastrichtian age. On the contrary, Habib et al. (1992) assigned the topmost 32 cm of the Prairie Formation at Braggs, Lowndes County, Alabama to the nannoplankton *Micula prinsii* zone, which is considered the upper part of the *Nephrolithus frequens* Zone (CC26 Zone). They concluded that these beds were latest Maastrichtian in age.

Regional Stratigraphy in the Subsurface

In the subsurface in southwest Alabama, the Upper Cretaceous strata are divided into similar lithological units as those in outcrop: the Selma Group, Eutaw Formation and Tuscaloosa Group. The Selma Group and Eutaw Formation have been studied in detail in the Gilbertown Field in Choctaw County (Figure 12) by Pashin et al. (2000). The Tuscaloosa Group has been studied in the South Carlton and Pollard Fields in Clarke, Baldwin and Escambia counties (Figure 12) by Mancini and Payton (1981) and Mancini et al. (1987).

Selma Group

Although the Selma Group is not divided into formal formations in the subsurface, stratigraphic units can be recognized through detailed well log and well cutting studies. Eight intervals labeled S1 through S8 were identified in the Selma Group in the Gilbertown Field in Choctaw County (Figure 15) by Pashin et al. (2000). These units were correlated in the Gilbertown Field and adjacent areas and with the strata in the outcrop.

The S1 interval lies sharply on the underlying Eutaw Formation. The contact is marked by a sharp positive excursion of the SP log and the resistivity log (Figure 15), although this contact appears to be more gradational in nature in cores. The lower three intervals, S1 through S3, have higher resistivity and higher quartz and clay content than the other intervals part of the Selma Group (S4 - S8) in this area. Pashin et al. (2000) postulated that this probably reflects the reworking of sediments from the Eutaw Formation, which was still being deposited in the updip area. Interval S4 is a relatively pure chalk unit and has been interpreted as open-shelf deposition during a relative highstand of sea level. At the top of this interval, a calcisphere packstone was described, which corresponds to the Arcola Limestone Member in outcrop. Therefore, S4 corresponds to the Mooreville Chalk observed in outcrop in west Alabama. Interval S5 is the purest chalk section, and interval S6 is a slightly argillaceous chalk; they correspond to the Demopolis Chalk and its Bluffport Marl Member in outcrop. Interval S7 is another relatively pure chalk section in the Demopolis Chalk. The S8 interval is the Ripley Formation and the Prairie Bluff undifferentiated. The top of the Selma Group is marked by a prominent shift of the SP log to a more positive value. The Tertiary units that overlie the Selma Group are the Danian Clayton Formation and Porters Creek Formation of the Midway Group. The Clayton Formation is a sandy limestone thinner than 20 feet thick; the Porters Creek Formation is a shale unit. Both of these units have a positive SP response tracking near the shale base line.

Eutaw Formation

The Eutaw Formation contains about 290 feet of glauconitic sandstone interbedded with mudstone and shale in the Gilbertown Field. As in the surface, the Eutaw Formation unconformably overlies the Tuscaloosa Group. The contact between the Eutaw Formation and the Tuscaloosa Group is more difficult to define by well log signature, because both units are sandstones. In order to clearly define this contact on the log, well cores and well cuttings need to be studied. The Eutaw Formation is a fining-up and thinning upward succession and has been divided into seven laterally correlative units designated as E1 to E7 in the Gilbertown Field (Figure 15) by Pashin et al. (2000). The glauconitic sandstone beds of the Eutaw Formation grade into chalk and marl beds assignable to the Selma Group in the basinward direction, with the thickness of the Selma Group increasing at the expense of the Eutaw Formation (Liu, 2005).

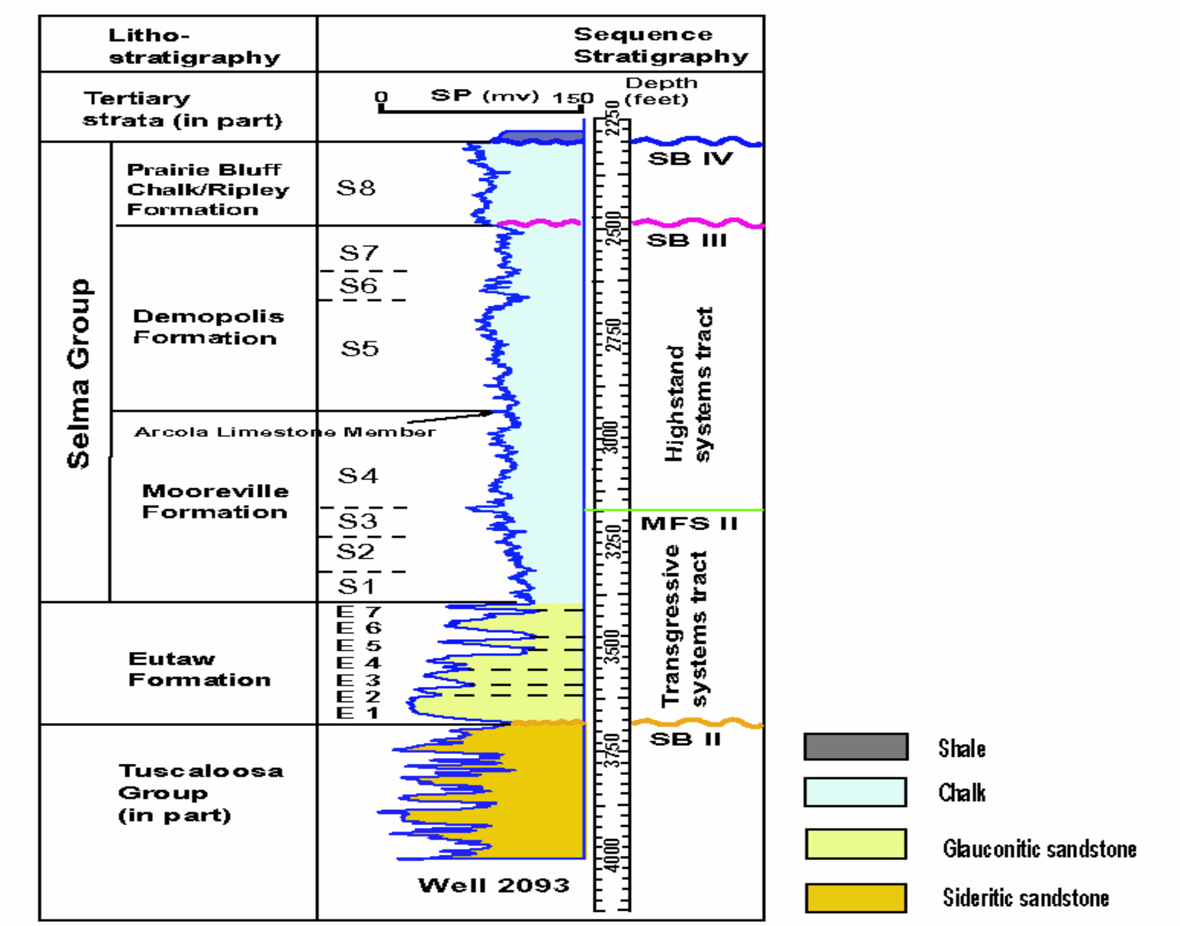


Figure 15. Well log (SP) patterns from well 2093 in the Gilbertown Field, Choctaw County, Alabama, modified from Pashin et al. (2000). Sequence stratigraphic interpretation follows Liu (2004). E1 to E7 and S1 to S8 are laterally correlative units in the Eutaw Formation and the Selma Group recognized by Pashin et al. (2000). SB = sequence boundary; MFS = maximum flooding surface.

Tuscaloosa Group

In the subsurface, the Tuscaloosa Group is divided into three parts according to well log data: the Lower Tuscaloosa Formation, Marine Tuscaloosa Formation, and Upper Tuscaloosa Formation (Winter 1954; Mancini et al., 1987). Figure 16 shows the tripartite division of the Tuscaloosa Group on the well log.

The Lower Tuscaloosa Formation consists of interbedded shale, siltstone and sandstone. The Lower Tuscaloosa Formation in southwestern Mississippi and east central Louisiana has been interpreted to be deposited as part of a fluvial-deltaic system (Berg and Cook, 1968; Corcoran et al., 1993). In southwestern Alabama, the Lower Tuscaloosa Formation was divided into two informally defined units: a lower Massive sand interval and the Pilot sand interval separated by a silty claystone bed of about 20-60 feet in thickness (Winter, 1954; Mancini and Payton, 1981; Mancini et al., 1987). Mancini et al. (1987) described sandstone in the Massive sand interval as well sorted, micaceous, locally fossiliferous, calcareous, glauconitic, fine grained, and quartz rich, containing angular to subangular quartz grains. The Pilot sand interval was described as a well sorted, greenish gray to green-brown, micaceous, fossiliferous, glauconitic, calcareous, very fine to medium-grained quartzose sandstone and was interpreted to have accumulated as part of a marine-bar complex (Mancini and Payton, 1981; Mancini et al. 1987). The Massive sand interval in South Carlton and Pollard fields, southwestern Alabama was interpreted as sands that were deposited in a wave-dominated, highly descriptive delta system, and the Pilot sand interval was concluded to represent shelf sands and clays that accumulated during a marine transgression (Mancini et al., 1987).

The Marine Tuscaloosa Formation overlies conformably the sand of the Lower Tuscaloosa Formation. A gray, silty oyster bed was observed at the base of the Marine Tuscaloosa Formation in parts of the South Carlton field (Mancini et al., 1987). The Marine Tuscaloosa Formation consists primarily of dark gray, silty, micaceous, fossiliferous, calcareous, laminated claystone interbedded with dark gray, silty, micaceous fossiliferous, glauconitic, calcareous siltstone and very fine-grained sandstone in South Carlton and Pollard fields. It has been reported to have been deposited in middle and outer neritic, open marine environments (Mancini and Smith, 1980; Mancini and Payton, 1981; Mancini et al., 1987). Biostratigraphic work by Mancini and Smith (1980) shows that the lower 10 to 20 feet of the 100 feet thick Marine Tuscaloosa can be assigned to the Upper Cretaceous calcareous nannoplankton CC 10 zone (*Microrhabdulus decoratus* Zone) and planktic foraminiferal *R. cushmani* total range zone. Therefore, the lowest part of the Marine Tuscaloosa Formation is Late Cenomanian in age (Figure 14).

The Upper Tuscaloosa Formation, which lies conformably on the Marine Tuscaloosa Formation, consists of primarily greenish gray, glauconitic fossiliferous, fine to medium grained sandstone interbedded with gray and green shale in South Carlton and Pollard fields (Mancini et al., 1987). Mancini et al. (1987) interpreted the Upper Tuscaloosa Formation in South Carlton and Pollard fields as having been deposited in marginal marine and marine shelf environments. The sandstone beds of the Upper Tuscaloosa Formation grade into shale in a basinward direction.

Essentially, the Lower Tuscaloosa Formation and Marine Tuscaloosa Formation correspond to the Coker Formation updip in the outcrop area, and the Upper Tuscaloosa Formation in the subsurface corresponds to the Gordo Formation (Mancini and Payton, 1981; Mancini et al., 1987).

Previous Sequence Stratigraphic Interpretations

The sequence stratigraphy of the Tuscaloosa Group, Eutaw Formation and Selma Group has been studied by several past workers using different methods.

Tuscaloosa Group

The relationship between the deposition of the Coker Formation and the Gordo Formation and sea-level fluctuations were described by Conant (1967) and Russell and Keady (1983). The Tuscaloosa Group, as observed in outcrop, was interpreted as having been deposited in a marine transgressive-regressive cycle. The Coker Formation was deposited during an advance of the sea; while the Gordo Formation was deposited during a subsequent withdrawal of the sea (Conant, 1967; Russell and Keady, 1983).

In the subsurface, the Tuscaloosa Group has also been interpreted as having been deposited in a transgressive-regressive cycle or sequence (Corcoran et al., 1993; Mancini et al., 1996; Mancini and Puckett, 2002; Mancini and Puckett, 2003). A major transgression in the Late Cenomanian to Early Turonian resulted in middle shelf, open marine sediments of the Marine Tuscaloosa Formation overlying the fluvial-deltaic, marginal marine and marine sediments of the Lower Tuscaloosa Formation. A major regression occurred during the Late Turonian, which resulted in the deposition of marginal marine and marine shelf sediments of the Upper Tuscaloosa Formation. These deposits overlie the deeper water, open marine shale of the Marine Tuscaloosa Formation in South Carlton and Pollard fields, southwestern Alabama.

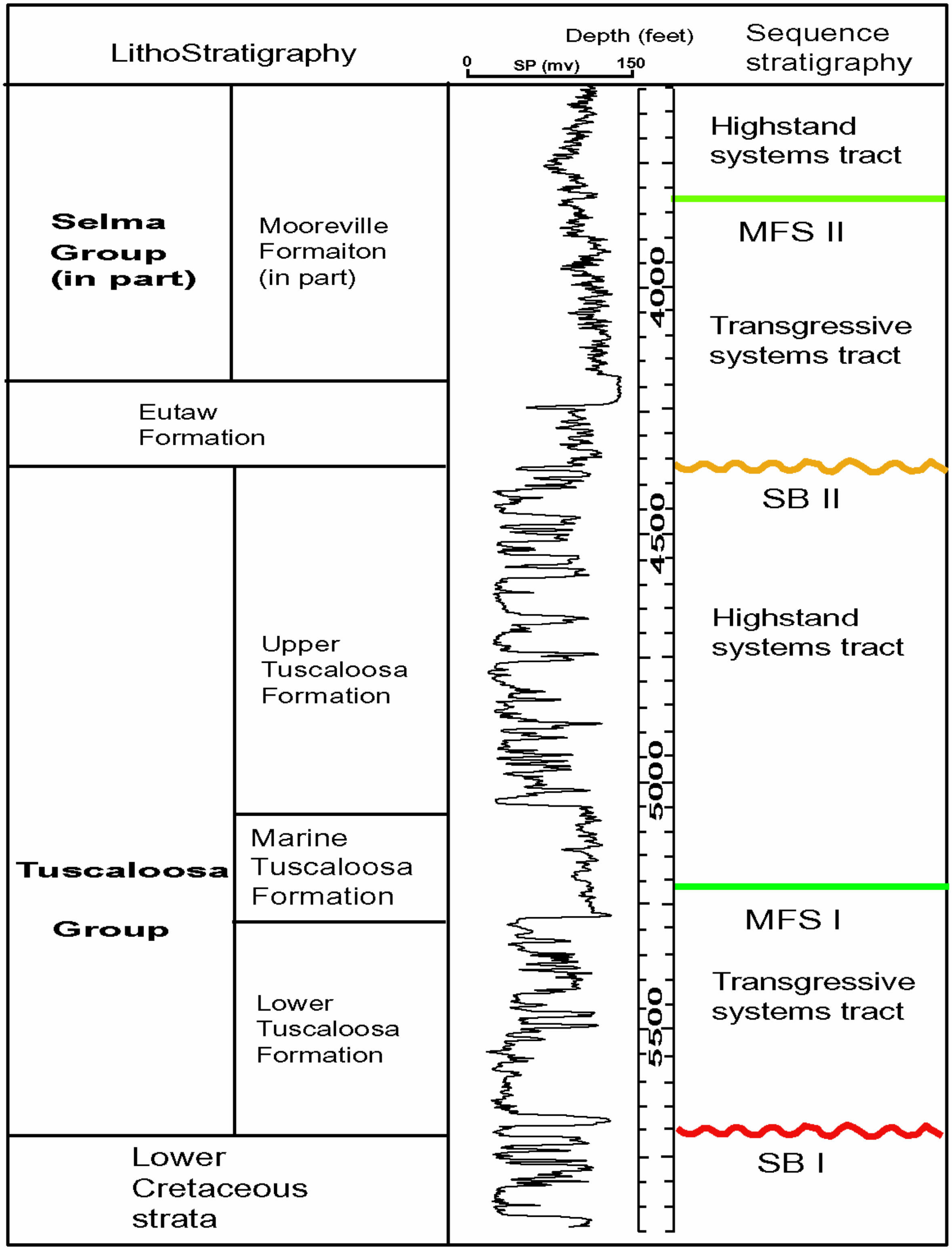


Figure 16. Well log patterns from well 2182, Clarke County, Alabama. The Tuscaloosa Group is divided into three formations in the subsurface according to well log signatures. Sequence stratigraphic interpretation follows Liu (2004). MFS = maximum flooding surface, SB = sequence boundary.

Mancini and Puckett (2003) interpreted the depositional history of the Tuscaloosa Group using an integrated biostratigraphic and transgressive-regressive cycle (sequence) approach. The Tuscaloosa Group was interpreted to represent the Late Cretaceous T-R cycle 5 (transgressive-regressive cycle or sequence) in the northern Gulf of Mexico. The Massive sand of the Lower Tuscaloosa Formation was interpreted to represent the aggrading interval of the transgressive phase (coastal barrier deposits). The marine shale and sandstone beds of the Pilot sand of the Lower Tuscaloosa Formation and the lower beds of the Marine Tuscaloosa Formation were reported to be the backstepping interval of the transgressive phase (marine shelf deposits). The infilling interval of the regressive phase of the T-R 5 cycle was concluded to be represented by the upper beds of the Marine Tuscaloosa Formation (shallow marine deposits) and the Upper Tuscaloosa Formation (fluvial-deltaic deposits).

Eutaw Formation and Selma Group

Hancock (1993) recognized four major transgressive peaks (Peak no. 1 to Peak no. 4) in Campanian-Maastrichtian strata of the northwestern Europe and correlated them to the Upper Cretaceous strata in several areas in North America, such as the Western Interior, New Jersey Coastal Plain and the northern margin of the Gulf of Mexico (Mississippi and Alabama). These transgressive peaks were defined as mid-points between pairs of regressive troughs, which in turn were recognized by identifying nodular chalks and hard grounds in the English Chalk (Hancock, 1990).

According to his trans-Atlantic correlation, Hancock (1993) reported that there were five transgressive peaks in the Santonian-Maastrichtian strata in the northern margin of the Gulf of Mexico in Alabama and Mississippi, including one in the Eutaw Formation (Figure 14). This peak was dated as Santonian in age.

Hancock (1993) reported that the Eutaw Formation represented a marine transgressive peak, because it progressively overlaps the McShan Formation, Tuscaloosa gravels and Ordovician rocks in an updip direction. Hancock (1993) reported that this transgressive peak corresponded to the mid-Santonian peak as recognized in the middle of the European *Uintacrinus socialis* Zone. Hancock (1993) stated that the Tombigbee-Mooreville contact, the layer of phosphatic nodules recorded 21 feet above the bench of Tombigbee sandstone at Plymouth Bluff, Mississippi, represented a regressive event in the earliest Campanian. Hancock (1993) suggested that this regressive event corresponded to the regressive trough recognized in the *Echinocorys tectiformis* Zone in England by Hancock (1990).

Hancock (1993) reported that the Arcola Limestone Member represented a transgressive peak (Peak no. 1) (Figure 14). He reasoned that although rich in calcispheres, the Arcola Limestone Member consists of essentially chalk, which is a good indicator of a transgressive peak in a clastic succession. The Mooreville Chalk was, therefore, interpreted to be transgressive.

Hancock (1993) stated that the transgressive Peak no. 2 should be placed in the lower Demopolis Chalk. However, he did not recognize a physical surface in the lower Demopolis Chalk that can be correlated to the Peak no. 2 in Europe. Hancock (1993) concluded that the disconformity with baculitids in a white phosphate about 5.9 feet (1.8m) above the Arcola Limestone member in the lower Demopolis Chalk, at Tibbee Creek, in Clay County, Mississippi probably represented the transgressive Peak no. 2 (Figure 14). He stated that this disconformity could be the result of a regression but a transgressive peak could have had similar effects in these laminated chalk and marl beds.

Hancock (1993) stated that transgressive Peak no. 3 was represented by the purest chalk section of the Demopolis Chalk (Figure 14). Hancock (1993) stated that this section of the chalk has the lowest clay content and most resembles its European counterpart. The upper Demopolis Chalk above this purest chalk section was interpreted to be regressive. The transgressive Peak no. 4 was interpreted to be represented by the middle part of the Prairie Bluff Chalk (Figure 14).

Mancini et al. (1996) and Puckett and Mancini (2000) studied the Upper Cretaceous strata in the outcrop in central and western Alabama, and in eastern and northeastern Mississippi employing an integrated biostratigraphic and sedimentological approach. Three sequences were recognized in the Santonian to Maastrichtian strata in the eastern Gulf Coastal Plain.

UAZGC 03 Sequence: The Eutaw-Tuscaloosa formation contact was reported to be the sequence boundary of the UAZGC 03 sequence. The lower Eutaw Formation was interpreted to be the lowstand systems tract deposits. The unconformable contact between the lower Eutaw Formation and the Tombigbee Sand Member was reported to be a transgressive surface, which was marked by a one to two inch sandstone bed containing phosphatic pebbles, shark teeth, and reworked fossils (Mancini and Soens, 1994). Therefore, the lower Eutaw Formation was interpreted as lowstand systems tract deposits; and the Tombigbee Sand Member and the lower Mooreville Chalk were reported to be transgressive systems tract sediments.

The Tombigbee-Mooreville contact was described as an unconformity by Conant (1967) and Copeland (1968). Hancock (1993) interpreted this contact to have formed in a marine regression. Mancini et al. (1996), however, interpreted this contact as one of the transgressive surfaces or marine ravinement surfaces in the transgressive systems tract, because they did not observe any physical evidence supportive of placing an unconformity at the base of the Mooreville, as discussed previously.

The maximum flooding event of the UZAGC 03 sequence was recognized based on a change in trend of the relative abundance of planktic foraminifera (P/B ratios). This faunal abundance peak or transgressive peak occurs approximately 100 feet below the top of the Arcola Limestone Member (Puckett and Mancini, 2000). In addition, the high P/B ratio coincides with a particular assemblage of benthic foraminifera which is characteristic of deeper marine water (Gan, 1996; Puckett and Mancini, 2000). This maximum flooding event was, therefore, placed at the level where the deepest water level (maximum bathymetric surface) was interpreted from foraminiferal data. No distinct physical surface has been observed in the Mooreville Chalk at this horizon to delineate a maximum flooding surface.

Puckett and Mancini (2000) also used regional stratigraphic relations to interpret this maximum flooding event or transgressive peak in the UZAGC 03 sequence. They reasoned that the maximum flooding event or transgressive peak should approximate maximum transgression; thereby, separating transgressive facies below from regressive facies above. Therefore, this event should be recognized, particularly in nearshore deposits, as a deeper water marine tongue bounded by shallower water deposits below and above. Puckett and Mancini (2000) recognized two Mooreville tongues (Figure 12): one in northeastern Mississippi and one in eastern Alabama. The Mooreville tongue in eastern Alabama occurred stratigraphically near the Eutaw-Mooreville contact in eastern Mississippi, and the tongue in northeastern Mississippi occurred higher in the Mooreville section (Figure 14).

In northeastern Mississippi, a very thin Mooreville section is present between the Coffee Sand and its Tupelo Tongue in eastern Lee County and northwestern Itawamba County (Figure 12). Puckett and Mancini (2000) concluded that this thin Mooreville bed, which has the lowest sand content, should approximate the maximum flooding surface. Puckett and Mancini (2000) further cited study by Stephenson and Monroe (1940) that showed that the lower Tupelo Tongue is stratigraphically equivalent to the Arcola Limestone Member. Therefore, the maximum flooding event was interpreted to be in the upper middle part of the Mooreville Chalk, slightly below the Arcola Limestone Member. This interpretation is in agreement with the observed changes in P/B ratios and changes in composition in the benthic foraminiferal populations. Therefore, the Coffee Sand proper, which is stratigraphically equivalent to the Mooreville Chalk, was interpreted to be deposits of the transgressive systems tract, and the Tupelo Tongue, which is stratigraphically equivalent to the Arcola Limestone Member, was reported to be deposits of the highstand systems tract.

The stratigraphic position of the Mooreville tongue in eastern Alabama and western Georgia, however, provides additional complexity for sequence stratigraphic analysis. Puckett and Mancini (2000) concluded that this tongue, which occurred between two siliciclastic-dominated tongues of the Blufftown Formation in west central Russell County, Alabama (Figure 12), represented the maximum flooding event of the UAZGC 03 sequence in eastern Alabama. However, biostratigraphic work by Puckett and Mancini (2001) showed that this Mooreville tongue is assigned to the upper part of the *D. asymetrica* foraminiferal zone (latest Santonian according to Caron (1985); therefore, it is older in age than the Mooreville tongue in northeastern Mississippi, which is assigned to the upper portion of the *G. elevata* foraminiferal Zone (late Early Campanian according to Caron (1985). As discussed above, the top of planktic foraminiferal *D. asymetrica* zone occurred immediately above the Tombigbee-Mooreville contact at Plymouth Bluff, eastern Mississippi (Dowsett, 1989; Mancini et al., 1996; Puckett and Mancini, 2000). Therefore, the geological age of the

Mooreville tongue in eastern Alabama approximates the age of the Tombigbee-Mooreville contact in eastern Mississippi (Figure 14). Mancini and Puckett (2003) recognized this stratigraphic relationship and concluded that the UAZGC 03 or T-R 6 cycle consists of two higher order sequences.

The highstand systems tract of the UAZGC 03 sequence was interpreted to include the upper 100 feet of the Mooreville Chalk (including the Arcola Limestone Member) and the lower 7-9 feet of the Demopolis Chalk (Mancini et al., 1996; Puckett and Mancini, 2000).

UAZGC 04 Sequence: The UAZGC 04 sequence includes most of the Demopolis Chalk (including the Bluffport Marl Member) and the lower part of the Ripley Formation. The lower sequence boundary of the UAZGC 04 sequence is represented by an unconformity updip (northern Mississippi) and it becomes conformable downdip in eastern Mississippi and western Alabama (Puckett and Mancini, 2000). This sequence boundary is recognized by an oyster bed (*Pycnodonte convexa*) above the Tupelo Tongue in Lee County, Mississippi. This oyster bed continues to the Frankstown site, where it lies above glauconitic sand beds of the Demopolis Chalk in northern Mississippi (Puckett and Mancini, 2000).

Puckett and Mancini (2000) stated that the unconformable surface between the Coffee Sand and the glauconitic sand beds, which underlies the oyster bed, represented the sequence boundary and the transgressive surface of the UAZGC 04 sequence. This sequence boundary becomes conformable to the south at the Tibbee Creek section in Clay County, eastern Mississippi, where two horizons of abundant phosphatic molds occurred between 4.5 and 7 feet above the Arcola Limestone Member. The upper one was interpreted to be the conformable part of the sequence boundary. As has been discussed above, Hancock (1993) tentatively placed his transgressive Peak no. 2 at this surface (Figure 14).

The maximum flooding event or transgressive peak in this sequence was placed in the middle of the Demopolis Chalk based on a change in trend in relative abundance of planktic foraminifers (P/B ratios) (Mancini et al., 1996; Puckett and Mancini, 2000). No physical surface for this maximum flooding surface was identified; however, this event was located in the purest chalk section, informally named the Muldrow Chalky member, approximately 270 feet above the Arcola Limestone Member in the middle of the Demopolis Chalk (Figure 14). This stratigraphic level corresponds approximately to the transgressive Peak no. 3 of Hancock (1993).

Above the maximum flooding event, there is a marked progressive decrease in planktic foraminiferal percentages and an increase in coarser siliciclastic sediment. This maximum flooding event was, therefore, also placed at the level where the maximum bathymetric surface was interpreted from foraminiferal data.

Puckett and Mancini (2000) used regional stratigraphic relations to assist with the location of the maximum flooding event or transgressive peak of the UZAGC 04 sequence. The transgressive peak of the UZAGC 04 sequence was interpreted to be represented by a marine tongue in the Demopolis Chalk that extended into northeastern Mississippi (Figure 12) and pinched out near Adamsville, Tennessee. Puckett and Mancini (2000) reported that this marine tongue probably represented the highest sea level of the entire Phanerozoic. In eastern Alabama, this transgressive peak is represented by a marine tongue in the middle of the Cusseta Sand Member of the Ripley Formation (Figure 12).

The upper part of the Demopolis Chalk, the Bluffport Marl Member and the lower to middle Ripley Formation represented the highstand systems tract deposits of this sequence. The lithology of the upper UAZGC 04 sequence gradually becomes sandy, grading from the pure chalk section of the Demopolis to the interbedded chalk and marl section of the

Bluffport Marl Member to the calcareous sands of the lower Ripley Formation (Mancini et al., 1996; Puckett and Mancini, 2000). This lithologic trend can be observed at the Rock Hill and Salem Church sections in Oktibbeha County, eastern Mississippi, along the Alabama River at Elm Bluff, Red Bluff, and Rocky Bluff in Dallas County, and in the Braggs area of Lowndes County, Alabama (Puckett and Mancini, 2000).

The UAZGC 04 sequence is capped by an unconformity at the base of the UAZGC 05 sequence. It can be an intraformational unconformity in the Ripley Formation and recognized at the contact between the McNairy Sand Member and the Chiwapa Sandstone Member of the Ripley Formation or the unconformity can be at the contact of the Owl Creek Formation with the Ripley Formation (Mancini et al., 1996).

UAZGC 05 Sequence: The UAZGC 05 sequence is the upper sequence in the Upper Cretaceous strata in the northeastern Gulf of Mexico area. The middle to upper Ripley sandstone beds were reported to represent the lowstand deposits of this sequence (Mancini et al., 1996). The calcareous sandstone and marl beds of the Chiwapa Sandstone Member of the Ripley Formation and the lower marl beds of the Prairie Bluff Chalk were interpreted to represent the transgressive systems tract deposits.

The maximum flooding surface of the UAZGC 05 was recognized within the Prairie Bluff Chalk (Figure 14). A physical surface of low to non-deposition was identified in the middle of the Prairie Bluff Chalk. A decrease in planktic foraminiferal percentages (P/B ratio) was also observed above the surface. The purest chalk section in the middle of the Prairie Bluff section was interpreted to be the condensed section (Mancini et al., 1996).

The top of the UAZGC 05 sequence was marked by the Maastrichtian-Danian unconformity, which is the top of the Upper Cretaceous section in the northeastern Gulf of

Mexico. The length of the hiatus associated with this unconformity is still in debate, as discussed above.

Based on the biostratigraphic and sedimentological work of Mancini et al. (1996) and Puckett and Mancini (2000), Mancini and Puckett (2003) reinterpreted the geohistory of the northern Gulf of Mexico using an integrated biostratigraphic and transgressive and regressive cycle approach discussed by Mancini and Puckett (2002). A T-R cycle is divided into two phases: a transgressive phase that includes an upward deepening event with the creation of the accommodation space and a regressive phase that includes an upward shallowing event with the filling of the accommodation space (Johnson et al., 1985). The transgressive phase of the T-R cycle usually consists of a backstepping interval and may include an aggrading interval; the regressive phase of the T-R cycle usually consists of an infilling interval, but may also include a forestepping interval (Jacquin and de Graciansky, 1998).

The Upper Cretaceous strata were divided into five transgressive-regressive cycles, from T-R 4 to T-R 8 (including the Early Cenomanian part of the Washita Group, T-R 4). As discussed previously, the T-R 5 cycle is represented by the Tuscaloosa Group in the northeastern Gulf of Mexico. The Eutaw Formation and the Selma Group were deposited during the T-R cycles 6, 7 and 8.

The T-R 6 cycle corresponds to the UAZGC 03 sequence of Mancini et al. (1996); however, Mancini and Puckett (2003) concluded that two higher order cycles or sequences probably occurred in the T-R 6 cycle. The Tombigbee-Mooreville contact was interpreted to be a significant marine transgressive and flooding event during the latest Santonian to earliest Campanian. This transgressive peak was also represented by the Mooreville tongue in eastern Alabama. The other transgressive and marine flooding event was represented by the fossil abundance (P/B) peak in the upper part of the Mooreville Chalk (late Early Campanian) and the Mooreville tongue in northeastern Mississippi. The T-R 7 cycle corresponds to the UAZGC 04 sequence of Mancini et al. (1996). The T-R 8 cycle corresponds to the UAZGC 05 sequence of Mancini et al. (1996). However, the glauconitic sandstone beds of the upper Ripley Formation, which were interpreted to be the lowstand systems tract of the UAZGC 05 sequence by Mancini et al. (1996) and Puckett and Mancini (2000), were designated as the aggrading interval of the transgressive phase of the T-R 8 cycle.

Sequence Stratigraphic Interpretation from Seismic Data

The sequence stratigraphy of the Upper Cretaceous strata has been studied by Liu (2004) using seismic data and well log data in offshore Alabama and Mississippi area.

Depositional sequences were interpreted on seismic sections by recognizing horizontal reflection terminations using the concepts and methods defined by Mitchum et al. (1977b) and Vail (1987): sequence boundaries were identified as onlap surfaces and maximum flooding surfaces as downlap surfaces (Figure 17). Important seismic reflections that have correlation implications, such as maximum flooding surfaces and sequence boundaries, were identified and traced across the study area.

Four sequence boundaries were identified on seismic sections and traced across the seismic data coverage area (Figure 18). The Upper Cretaceous strata in the offshore Alabama and Mississippi area were, therefore, divided into three seismic sequences: UK I, UK II and UK III.

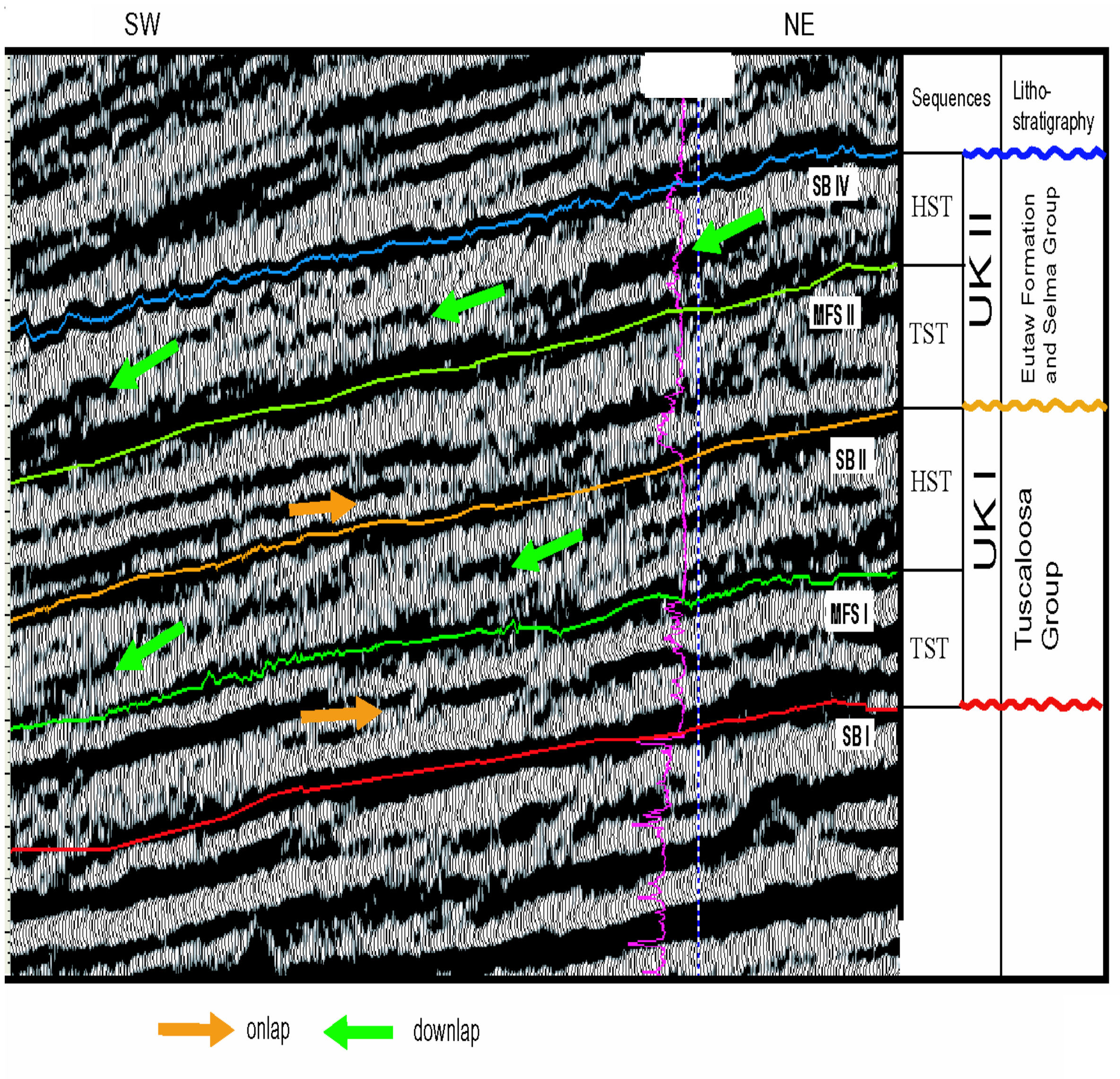


Figure 17. Seismic dip section in the Gulf of Mexico. Sequence boundaries and maximum flooding surfaces are recognized by identifying seismic reflector termination patterns: sequence boundary as onlap surface and maximum flooding surface as downlap surface. SB III is not recognized in this section because the UK III sequence is very thin here. The color of each surface is identical with that in Figures 15, 16, 18. SB = sequence boundary, MFS = maximum flooding surface, TST = transgressive systems tract, HST = highstand systems tract. Seismic line courtesy of WesternGeco.

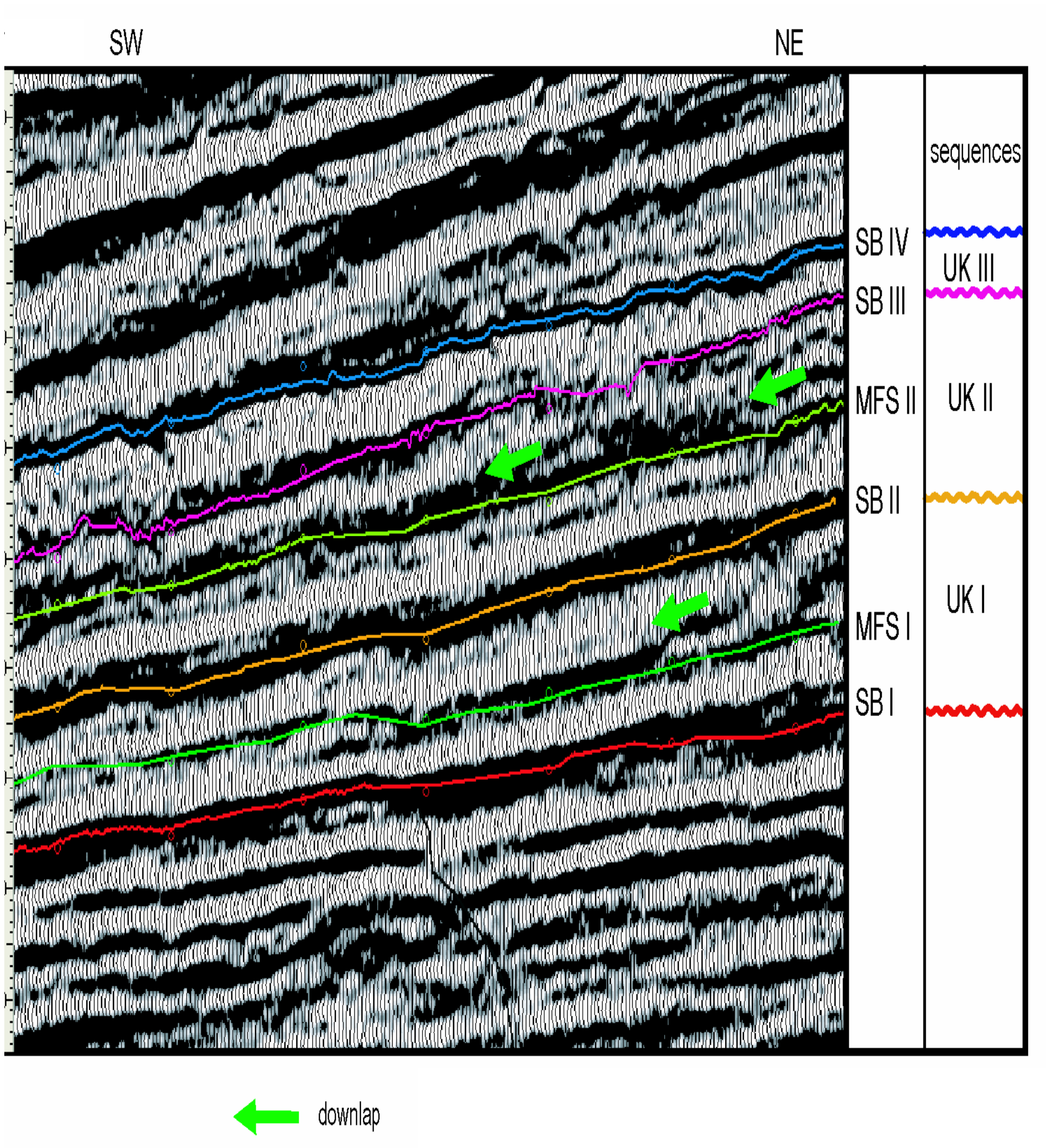


Figure 18. Seismic dip section in the Gulf of Mexico. Four sequence boundaries and two maximum flooding surfaces were identified in the Upper Cretaceous strata in the northeastern Gulf of Mexico area. Three sequences were delineated by these four sequence boundaries, and the lower two sequences were further divided by maximum flooding surfaces into a transgressive systems tract and a highstand systems tract. SB = sequence boundary; MFS = maximum flooding surface. Seismic line courtesy of WesternGeco.

Two maximum flooding surfaces recognized as downlap surfaces were identified in the two lower seismic sequences, therefore, the UK I and UK II sequences were further divided by the two maximum flooding surfaces into a transgressive systems tract and a highstand systems tract, respectively (Figure 18). Seismic sequence boundaries and maximum flooding surfaces identified on the seismic sections were projected onto well logs by using checkshot surveys and checkshot survey calibrated synthetic seismograms (Liu, 2004). Therefore, sequence boundaries and maximum flooding surfaces recognized from seismic data can be correlated to areas outside of the seismic data coverage area.

Correlation from Subsurface to Surface

A cross section based on well log data was established to correlate surfaces identified in offshore Alabama and Mississippi area, where seismic data have been interpreted, to areas near the southern limit of the outcrop belt (Figures 19 and 20).

The sequence boundaries recognized from seismic sections were found to be correlative with major unconformities identified in previous outcrop and subsurface studies: the SB I corresponds to the basal Tuscaloosa unconformity; the SB II corresponds to the unconformity between the Eutaw Formation and the Tuscaloosa Group; the SB III corresponds to the intraformational unconformity in the Ripley Formation in Alabama; and the SB IV corresponding to the unconformity between the Selma Group and the Tertiary Midway Group.

The UK I sequence interpreted from seismic data corresponds to the Tuscaloosa transgressive-regressive cycle or sequence (Mid-Cenomanian to Late Turonian) recognized by previous outcrop and subsurface studies (Conant, 1967; Russell and Keady, 1983; Corcoran et al., 1993; Mancini and Puckett, 2002; Mancini and Puckett, 2003).

The base of this sequence, SB I (the red line on Figures 17 and 18), corresponds to the mid-Cretaceous Sequence Boundary. This sequence boundary is a prominent reflector on most of the seismic lines in the study area, and has been observed by previous authors in the Gulf of Mexico (Shaub et al., 1984; Addy and Buffler, 1984; Faust, 1990). Onlap patterns that terminate against this sequence boundary were observed by Liu (2004) on seismic sections in the outer shelf area near the mid-Cretaceous shelf break (Figure 17). This observation suggests that sea level dropped at least below the onlap point in the outer shelf area. This interpretation agrees with the fluvial-deltaic and marginal marine nature of the Lower Tuscaloosa Formation observed in well cores, logs, and cuttings in southwestern Mississippi, east central Louisiana, and southwestern Alabama (Berg and Cook, 1968; Mancini et al., 1987; Corcoran et al., 1993). Therefore, during the period when the mid-Cretaceous sequence boundary developed, most of the shelf was exposed, and the shelf area was probably subjected to subaerial erosion.

A prominent downlap surface, recognized by Liu (2004) as the MFS I (the dark green line on Figures 17 and 18), divides the UK I sequence into two systems tracts, which have different seismic reflection patterns. Reflectors below the MFS I exhibit a divergent pattern and were interpreted as the transgressive systems tract. The upper part of UK I sequence exhibits a strong prograding pattern on seismic sections and was interpreted as the highstand systems tract (Liu, 2004). Liu (2004) placed the MFS I surface in the middle of the Marine Tuscaloosa Formation by constructing synthetic seismograms and by using checkshot surveys.

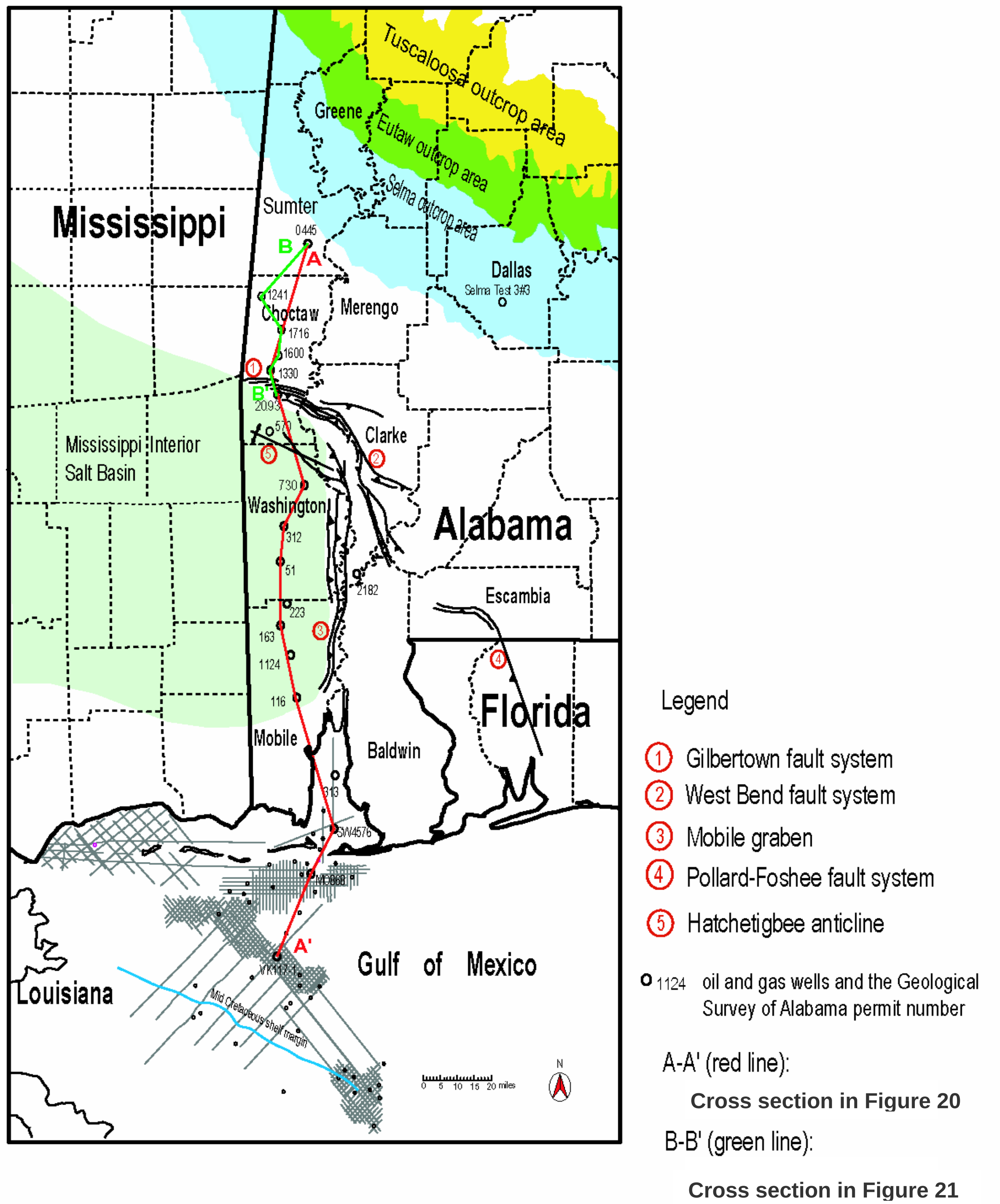


Figure 19. Location of cross sections and seismic data.

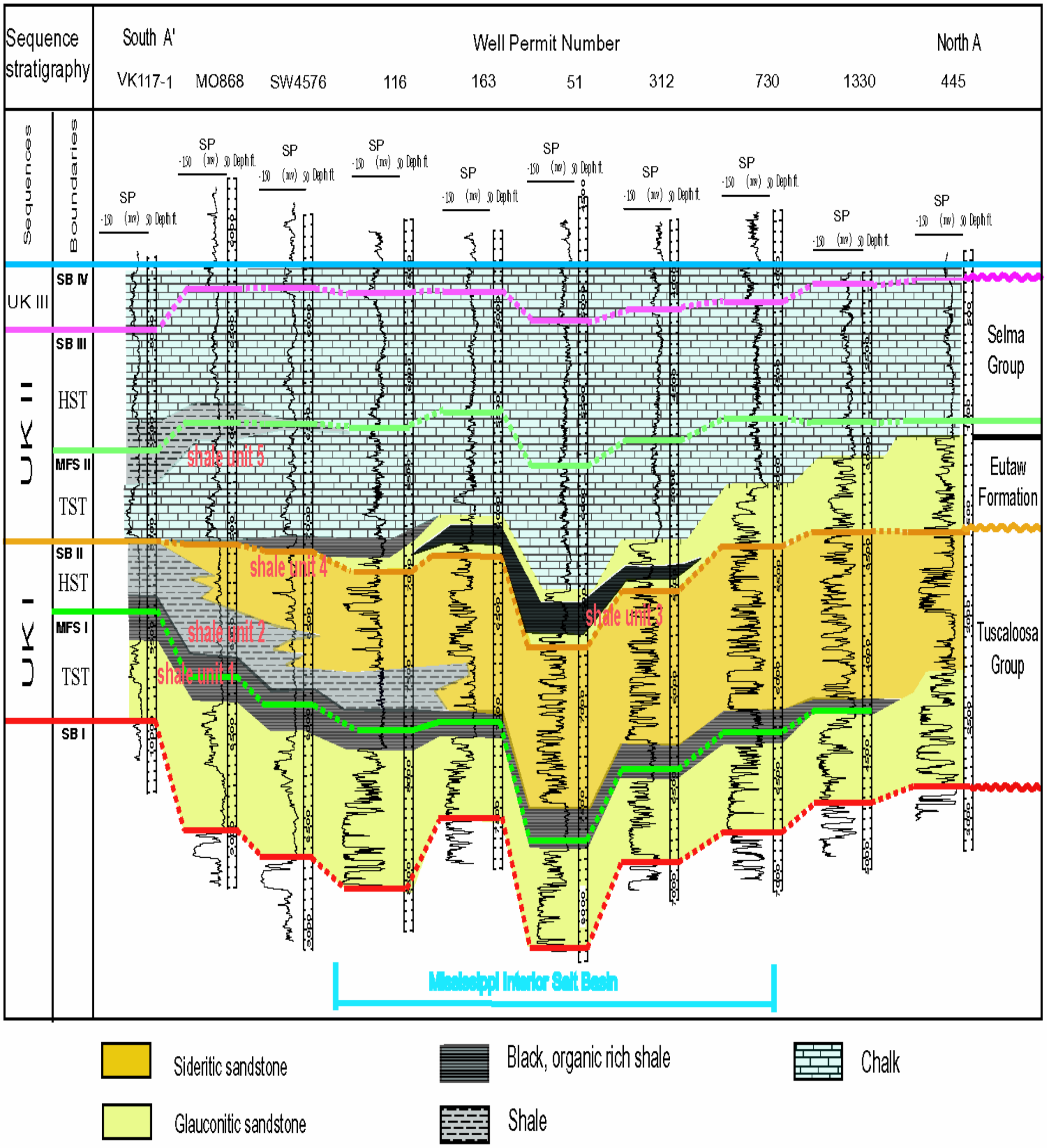


Figure 20. Cross section A-A' from the offshore area to the outcrop belt area showing the facies changes on the continental shelf. See Figure 19 for well locations and the position of the cross section. Sequence boundaries and maximum flooding surfaces were recognized from seismic data (see Figures 17 and 18) and projected onto well logs using synthetic seismograms and check shots (Liu, 2004).

Therefore, the seismic interpretation of the Tuscaloosa Group by Liu (2004) agrees with the T-R cycle (sequence) interpretation of Mancini and Puckett (2003). The transgressive systems tract recognized on seismic data corresponds to the Lower Tuscaloosa Formation and the lower part of the Marine Tuscaloosa Formation; the highstand systems tract corresponds to the upper part of the Marine Tuscaloosa Formation and the Upper Tuscaloosa Formation (Figures 16 and 20).

The seismic reflection termination patterns revealed a fundamental difference between the Lower Tuscaloosa Formation and the Upper Tuscaloosa Formation. Younger sediments of the Lower Tuscaloosa Formation were deposited progressively landward toward the basin margin, therefore, coastal onlap migrated progressively landward against the sequence boundary or initial surface of deposition; whereas, the sediments of the Upper Tuscaloosa Formation prograded progressively downdip onto the maximum flooding surface.

On well logs (Figures 16 and 20), the MFS I, located in the Marine Tuscaloosa Formation, can be traced updip to well 445 in Sumter County. Further updip, the marine shale layer pinched out and the Tuscaloosa Group is divided into the Coker Formation and the Gordo Formation. The maximum flooding surface approximately corresponds to the boundary between the Gordo Formation and Coker Formation (Figure 14).

Facies changes in the Upper Tuscaloosa Formation and Lower Tuscaloosa Formation were revealed by the well log cross section. Both the Lower Tuscaloosa Formation and the Upper Tuscaloosa Formation became sandier and thicker toward the basin margin or updip area, where the siliciclastic input originated. However, depositional patterns in these two formations are different. The Lower Tuscaloosa Formation/Coker Formation exhibits a retrogradational pattern; where as the Upper Tuscaloosa Formation/Gordo Formation exhibits a progradational pattern (Figures 17, 18, and 20). The Upper Tuscaloosa Formation graded essentially into a thick shale unit in the outer shelf area, while the Lower Tuscaloosa Formation remained primarily a sandy unit (Figure 20).

The UK II sequence includes the Eutaw Formation and the lower part of the Selma Group (Mooreville Chalk, Demopolis Chalk, and the lower beds of the Ripley Formation). Therefore, the UK II sequence identified on the seismic data includes the UAZGC 03 and UAZGC 04 sequences of Mancini et al. (1996) and Puckett and Mancini (2000) and the T-R 6 and 7 cycles (sequences) of Mancini and Puckett (2003).

The SB II boundary (the golden line in Figures 17 and 18) separates this sequence from the underlying siliciclastic Tuscaloosa Group. The SB II boundary was observed to truncate the underlying prograding sediment wedges and to be onlapped by the overlying strata on seismic sections in the Gulf of Mexico (Viosca Knoll area). This sequence boundary can be correlated with the unconformity between the Eutaw Formation and the Tuscaloosa Group in the updip area, which was interpreted as the lower sequence boundary of the UAZGC 03 by Mancini et al. (1996) and Mancini and Puckett (2000) or the surface of maximum regression between the TR 5 and 6 cycles (sequences) of Mancini and Puckett (2003). Coastal onlap terminated against SB II were observed on seismic sections in the outer shelf area (Figure 17). It can be inferred that sea level dropped at least below this point when SB II developed during the Late Turonian-Early Coniacian and most of the Late Cretaceous continental shelf area was subaerially exposed.

The UK II sequence is further divided into two systems tracts by a downlap surface, MFS II (the light green line in Figures 17 and 18), recognized by Liu (2004) on seismic sections. Reflectors below the MFS II onlap onto the SB II boundary; these strata were interpreted as part of the transgressive systems tract. Reflectors above the MFS II downlap onto this surface and were interpreted as the highstand systems tract (Figures 17 and 18).

In the outer shelf area, the downlap surface, MFS II, is located in a thick shale unit (250 feet in well VK 117-1; 200 feet in well M0868, Figure 20). This shale bed becomes thin in a landward direction and pinches out in the Mobile Bay area and southern Mobile County (Liu, 2004). However, the unique log signature associated with this pinch-out point can be traced across the Late Cretaceous continental shelf area to near the southern limit of the outcrop belt. This surface was found to be in the lower Mooreville Chalk about 260 feet below the Arcola Limestone Member of the Mooreville Chalk (well 445, Figures 20 and 21). Nannoplankton analysis of the Selma Site Test core in Dallas County indicates that it is latest Santonian-earliest Campanian in age (in the upper CC17 zone, Figure 14). Cyclostratigraphic study of the Milankovitch-scaled cycles from the same Selma Site Test core provided an accurate chronology for the time period represented by the Mooreville Chalk. Sedimentation rate derived from this chronology has shown that sedimentation rate was very low (about 60 inch/ma.) at this level. Therefore, MFS II correspond to a condensed section in the Mooreville Chalk in central Alabama. This downlap surface, MFS II, can also be correlated to the Mooreville tongue in eastern Alabama and the Eutaw-Mooreville contact in eastern Mississippi (Figure 14).

The maximum flooding surface is usually represented by the development of a sediment starvation surface across the shelf (Loutit et al., 1988), whereas in the updip area near the shoreline, the maximum flooding surface is usually represented by a transgressive surface (sometimes with transgressive lags), which is formed by the last major transgression at the top of the transgressive systems tract (Banerjee and Kidwell, 1991; Kidwell, 1991; Hettinger et al., 1994). The Eutaw-Mooreville contact has been interpreted as a diachronous transgressive surface in western Alabama and eastern Mississippi by Mancini et al. (1996), Puckett and Mancini (2000), and Mancini and Puckett (2003). The Tombigbee Sand Member has been interpreted to be the backstepping interval of the transgressive phase of the T-R 6 cycle (sequence) by Mancini and Puckett (2003). The backstepping geometry of the top of the Eutaw Formation or Tombigbee Sand Member can also be identified in subsurface on well log cross sections in southwest Alabama (Figures 20 and 21). Therefore, the Eutaw-Mooreville Chalk contact is interpreted as a series of backstepping transgressive surfaces that formed by a series of major transgressive events. The coincidence of the downlap surface, MFS II, identified on the seismic data with the Eutaw-Mooreville contact in eastern Mississippi (Figure 14) indicates that the transgressive event represented by the Eutaw-Mooreville contact in eastern Mississippi was the last major transgression in the northeastern Gulf of Mexico area, which occurred in latest Santonian-earliest Campanian times.

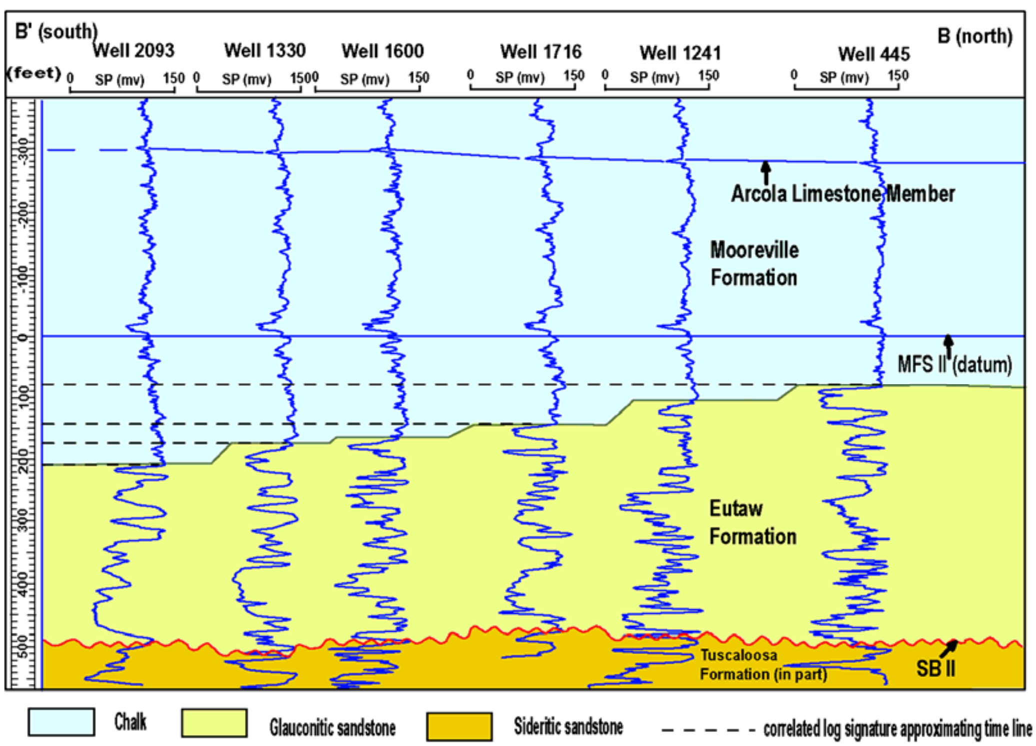


Figure 21. Cross section B-B' showing the backstepping pattern of the Eutaw-Mooreville contact. Sand facies of the Eutaw Formation grade basinward into chalk beds assigned to the Selma Chalk. The MFS II surface identified by Liu (2004) serves as the datum. The Eutaw-Selma formation contact is a time-transgressive surface that intersects with time lines. The top of the Arcola Limestone Member is essentially synchronous. See Figure 19 for location of wells (The distance between well 445 and 2093 is about 41 miles; horizontal distance not in scale). SB = sequence boundary, MFS = maximum flooding surface.

Outcrop studies by Mancini et al. (1996) and Puckett and Mancini (2000) placed the maximum flooding event of the UAZGC 03 sequence at one of the reflection points on the planktic/benthic foraminifer ratio curve, which is about 100 feet below the Arcola Limestone Member (Figure 14). The downlap surface recognized from seismic sections is about 160 feet lower than the maximum flooding event recognized in outcrop. The P/B ratio is a good indicator of paleo-water depth (Gibson, 1989; Van der Zwaan et al., 1990; Van der Zwaan et al., 1999). However, the maximum bathymetric surface in a sequence, represented by the P/B ratio reflection point, does not always coincide with the maximum flooding surface, if the sedimentation rate variation in a strike direction is considered (Catuneanu et al., 1998; Catuneanu, 2002). In addition, Naish and Kamp (1997) suggested that the maximum bathymetric surface identified from foraminiferal or trace fossil paleobathymetry, which is lithologically undeterminable, is usually located in the early highstand systems tract above the maximum flooding surface, although the difference is within 16 feet. This significant distance between the maximum bathymetric surface and the maximum flooding surface is probably caused by variations in siliciclastic sediment input along the coast. According to the sequence stratigraphic model of Vail et al. (1977c), Posamentier and Vail (1988) and Posamentier et al. (1988a), sea level continues to rise during deposition of the sediments of the highstand systems tract, but the rate of sea-level rise slows to a degree that siliciclastic sediment input exceeds the accommodation space provided by the slower sea-level rise. Therefore, sediment begins to prograde out to form clinoforms that downlap onto the maximum flooding surface. However, if variations in sediment input along the coast are considered for areas with relatively lower siliciclastic input, the rising sea level may result in the creation of more accommodation space and the deposition of deeper water sediments in local or regional transgressions. The area where the Mooreville Chalk was deposited, including west and central Alabama and eastern Mississippi, had very low sediment input because it was located between two major sediment supply sources that have been interpreted to have existed in northeastern Mississippi and eastern Alabama during the Late Cretaceous (Mancini et al., 1996). Therefore, the lower sedimentation rate during deposition of the Mooreville Chalk might have resulted in a lag of the timing of the occurrence of the deepest water deposition (maximum bathymetric surface) in the Mooreville Chalk updip and the downlap surface (maximum flooding surface) recognized on seismic data downdip.

However, the maximum flooding surface identified in outcrop is only 160 feet above the correlated log signature associated with the pinch-out point of the outer shelf shale unit. This depth difference is only represented by 0.014 second on seismic sections. Therefore, the possibility cannot be ruled out that the maximum flooding surface identified in outcrop is correlatable to the downlap surface in the outer shelf area at the current seismic resolution.

The Eutaw Formation and the lower Mooreville Chalk were interpreted to represent the transgressive systems tract of the UK II sequence, as interpreted by Mancini and Puckett (2003). The highstand systems tract of the UK II sequence includes the upper Mooreville Chalk (including the Arcola Limestone Member) and the Demopolis Chalk and the lower Ripley Formation.

The sequence boundary identified above the Arcola Limestone Member by Mancini et al. (1996) and Puckett and Mancini (2000) or the surface of maximum regression by Mancini and Puckett (2003) was not identified on seismic data (Figures 17 and 18). As Mancini et al. (1996) and Puckett and Mancini (2000) described, this sequence boundary becomes conformable in east Mississippi and west Alabama. When this sequence boundary formed, most of the shelf was still under sea water and sedimentation continued. Therefore, this sequence boundary was probably formed by a minor sea-level drop or excessive sediment in the updip area during this period, which had no significant impact on the outer shelf areas.

The UK III sequence (Early Maastrichtian to Late Maastrichtian) is the thinnest of the three sequences on seismic data, and it includes the uppermost part of the Selma Group. The sequence is defined by the SB III boundary (the pink line in Figure 18) and the Maastrichtian-Danian unconformity (the blue line in Figures 17 and 18).

This sequence is only resolved on seismic data in areas near the mid-Cretaceous shelf break. No internal structure of the UK III sequence has been recognized from the seismic data, due to lithological uniformity of the Maastrichtian marly chalk in the outer shelf area. Well log data indicate that UK III sequence is about 150 feet thick in the Mobile Bay area, and about 300 feet thick in the Viosca Knoll area (well VK117-1, Figure 20). The greatest thickness of the sequence is observed near the shelf-slope break (about 550 feet thick, estimated on seismic data), where the underlying two sequences nearly pinch out (Liu, 2004).

Since no internal structure has been identified on the seismic data, the position of the coastal onlap and the magnitude of sea-level drop associated with this sequence boundary can not be determined from seismic data. Since the majority of the sequence in the subsurface is composed of chalk, sea-level drop associated with this sequence boundary is probably much less than that associated with the lower two sequence boundaries.

The UK III sequence is overlain by the Maastrichtian-Danian unconformity. On seismic data, the Maastrichtian-Danian unconformity is a high amplitude, high frequency reflector that can be traced across the seismic coverage area (Figures 17 and 18). This sequence boundary is clearly expressed in well log data and can be correlated on log curves throughout the study area (Figure 20). The gamma-ray logs show a large shift to much lower values, and the sonic velocity increases abruptly below this sequence boundary (Liu, 2004).

The lithology contrast between the shale of the basal Midway Group and the chalk of the Selma Group across this sequence boundary is the major reason for these changes.

No coastal onlap against this sequence boundary has been observed in the seismic data coverage area; therefore, the sea-level drop associated with this sequence boundary cannot be determined from current seismic data.

Conclusions

Sequence stratigraphy of the Upper Cretaceous strata in the northeastern Gulf of Mexico was studied independently by previous authors in both outcrop and subsurface. Outcrop studies investigated the upper and middle portions of the Late Cretaceous continental shelf, which were dominated by continental and coastal environments during low stands of sea level and by coastal, inner or middle neritic environments during high stands of sea level, whereas subsurface studies examined the middle and outer portions of the shelf, which were dominated by fluvial-deltaic environments in low stands of sea level and by outer neritic environments in high stands of sea level.

An integrated sequence stratigraphic framework was established by correlating important surfaces that have chronostratigraphic significance such as maximum flooding surfaces and sequence boundaries from subsurface to surface. Facies changes of Upper Cretaceous strata in a dip-oriented direction were determined in the established sequence stratigraphic framework.

Four sequence boundaries recognized on seismic data, SB I to SB IV, in the offshore Alabama and Mississippi area were correlated to areas near the southern limit of the outcrop belt. These sequence boundaries were found to correspond to four major unconformities identified in previous outcrop and subsurface studies. SB I corresponds to the mid-

Cretaceous unconformity/sequence boundary; SB II corresponds to the Late Turonian-Early Coniacian unconformity, which separates the Eutaw Formation from the Tuscaloosa Group; SB III corresponds to the Late Campanian-Early Maastrichtian unconformity, which separates the lower and middle Ripley Formation from the upper Ripley Formation and Owl Creek Formation; and SB IV corresponds to the Late Maastrichtian-Early Danian unconformity, which separates the Prairie Bluff Chalk and Owl Creek Formation from the overlying Tertiary Midway Group.

The UK I and UK II sequences were further divided into a transgressive systems tract and a highstand systems tract by two maximum flooding surfaces, MFS I and MFS II, which were identified as downlap surfaces from seismic data. The MFS I lies in the Marine Tuscaloosa Formation and was correlated updip to the disconformity observed between the Gordo Formation and the Coker Formation. The MFS II was correlated to a major transgressive surface at the base of Mooreville Chalk in eastern Mississippi, a sediment starvation interval in central Alabama and the Mooreville tongue in eastern Alabama. The MFS I was dated as Late Cenomanian, and the MFS II was dated latest Santonian to earliest Campanian by nannoplankton and foraminiferal biostratigraphic data.

Similar internal structures or depositional patterns were found for sediments that belong to the same systems tracts. Sediments of the transgressive systems tract such as the Eutaw Formation and the Lower Tuscaloosa Formation exhibit onlap patterns onto the sequence boundary on seismic data; and they were found to be backstepping/retrogradational in well logs and in the outcrop. Sediments of the highstand systems tract such as the Upper Tuscaloosa Formation exhibit downlap patterns onto the maximum flooding surface on seismic data; and they were found to be progradational in well logs and in the outcrop. No significant depositional pattern was identified for the carbonate dominated Mooreville Chalk and Demopolis Chalk in the updip area. However, these chalk sediments grade into shale and chalky shale in the middle and outer shelf areas where retrograding and prograding patterns were recognized in both well logs and seismic sections.

3. Lower Cretaceous studies involving well logs, cores and seismic data by Ernest Mancini.

Characterization of Lower Cretaceous stratigraphic sequences in this study involved examination of the Lower Cretaceous unconformity-bounded units described by Mancini and Puckett (2002) and Badali (2002). Mancini and Puckett (2002) recognized four transgressive-regressive (T-R) cycles (sequences) and five T-R subcycles in the northeastern Gulf of Mexico, based on well log and core studies (Figure 22); and Badali (2002) recognized eight seismic sequences based on seismic sequence interpretation. Mancini and Puckett (2002) used the following well log responses (Figures 23 and 24) with core information (Figures 25-27) to recognize T-R cycles (sequences). A change from higher to lower gamma ray and/or from more to less positive SP log responses identifies a discontinuity in the log record that can be used to recognize a surface of maximum transgression, which separates the transgressive section from the regressive section in the T-R cycle (sequence). Higher gamma ray and/ or positive SP log signatures are characteristic of shale, clay and argillaceous limestone beds. Lower gamma ray and/or negative SP responses are characteristic of sandstone beds. High resistivity and/or high density log responses are characteristic of carbonate rocks. Very high resistivity and/or very high density are characteristic of anhydrite beds. Badali (2002) used the following generalizations regarding seismic reflection data to recognize stratigraphic sequences, which Mancini and Puckett (2002) used to define T-R cycles (sequences). Thin (one or two seismic cycles), concordant, parallel seismic reflection configurations are characteristic of marine strata of a transgressive backstepping section.

These reflectors are characterized by onlap reflection termination. Thick (several seismic cycles), oblique, progradational seismic reflection configurations are characteristic of prograding clinoforms of a regressive infilling section. These reflectors are characteristic of offlap (downlap) reflection terminations (Figure 28). No lowstand systems tract deposits were observed in these strata; therefore, only transgressive and regressive cycles (sequences) were described. In reviewing these data for this study, we found that in the absence of lowstand deposits, a transgressive–regressive (T-R) sequence characterization is more reasonable than a depositional sequence classification.

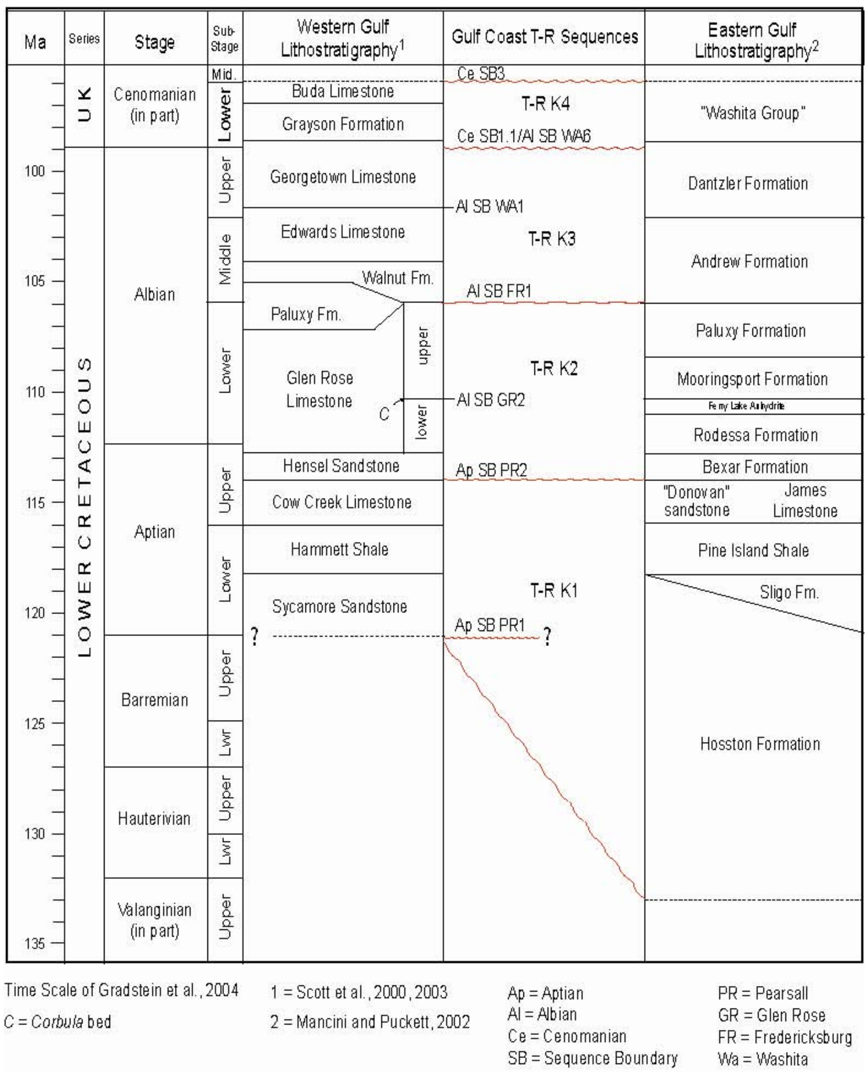


Figure 22. Sequence stratigraphy of Comanchean Cretaceous strata (from Mancini and Scott, 2006a).

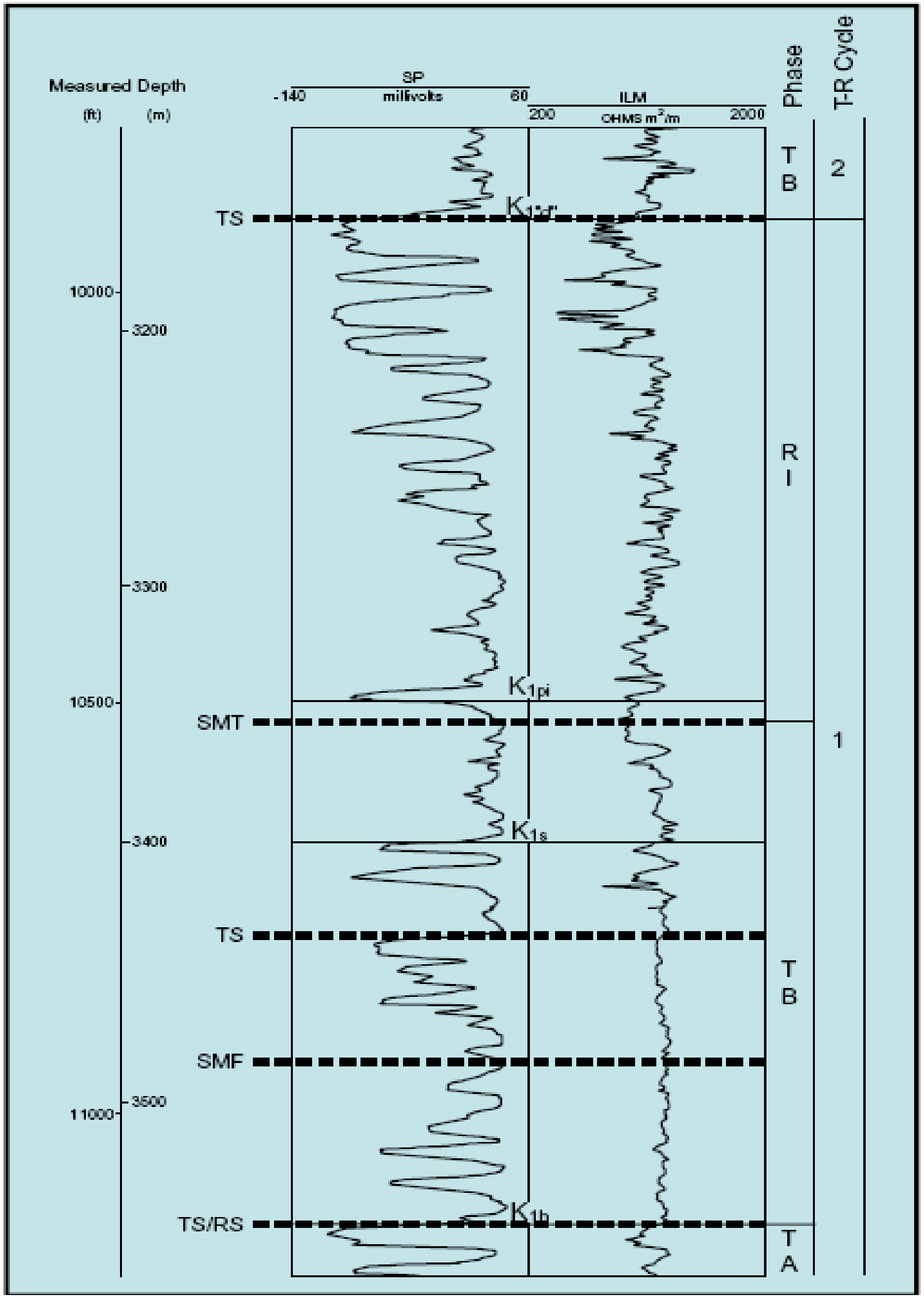


Figure 23. Well log patterns from the Simmons 'A' 1 well, Yazoo Co., MS, showing the well log signature characteristics of the T-R K1 Cycle and associated transgressive-regressive subcycles from the updip area of the Mississippi Interior Salt Basin. SP = spontaneous potential. ILM = medium induction (resistivity). TA = transgressive aggrading interval. TB = transgressive backstepping interval. RI = regressive infilling interval. RS = inferred ravinement surface. SMT = surface of maximum transgression. SMF = surface of marine flooding. K1h = Hosston Fm. K1s = Sligo Fm. K1pi = Pine Island Shale. K1'd' = 'Donovan' sandstone (from Mancini and Puckett, 2002).

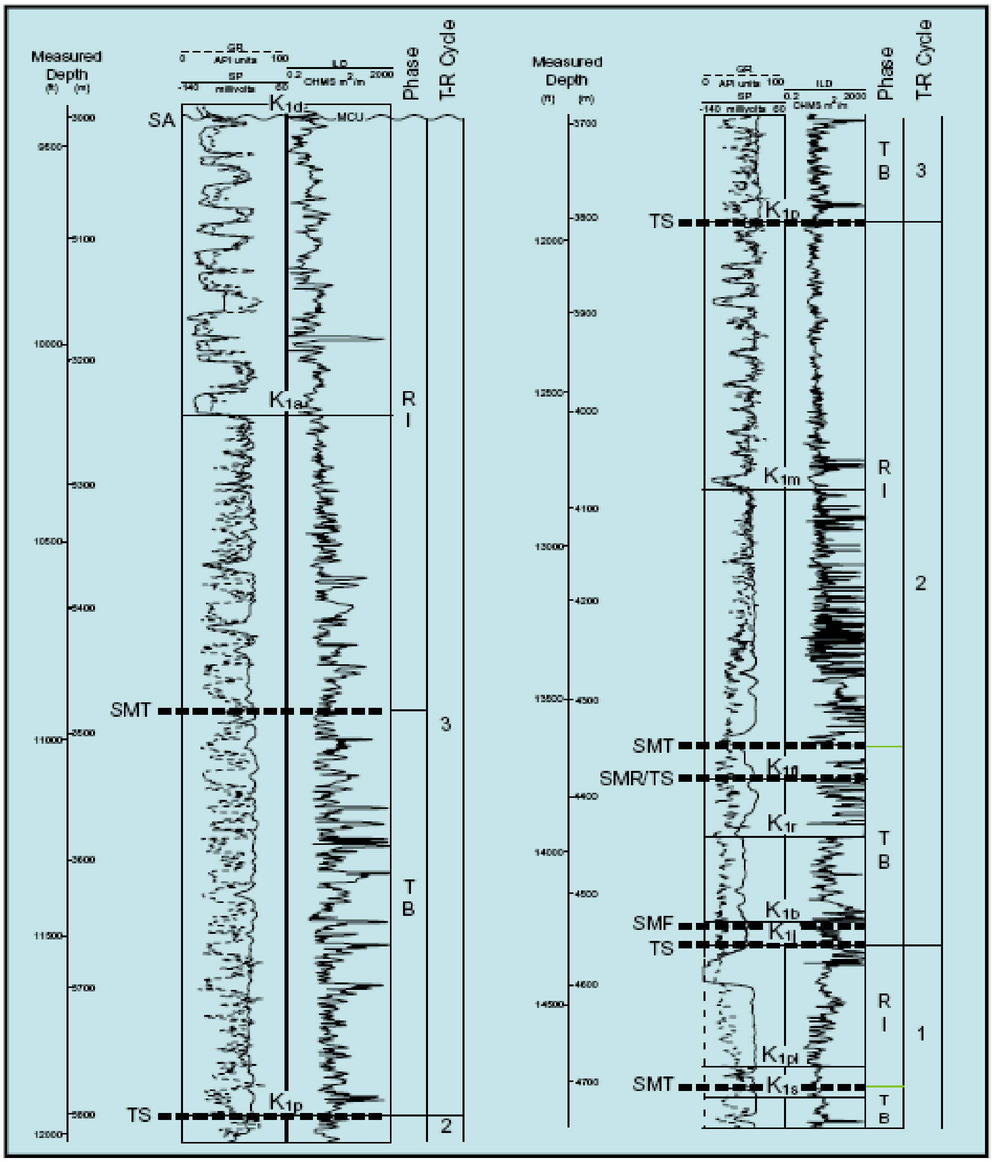


Figure 24. Well log patterns from the Southern Minerals No. 1 well, Pearl River Co., MS, showing the well log signature characteristics of the T-R K1, T-R K2, and T-R K3 cycles and associated transgressive-regressive subcycles from the southern portion of the Mississippi Interior Salt Basin. GR = gamma ray. SP = spontaneous potential. ILD = deep induction (resistivity). TB = transgressive backstepping interval. RI = regressive infilling interval. SA = subaerial unconformity. TS = transgressive surface. SMR = surface of maximum regression. SMT = surface of maximum transgression. SMF = surface of marine flooding. MCU = mid-Cretaceous (mid-Cenomanian) unconformity. K1s = Sligo Fm. K1pi = Pine Island Shale. K1j = James Limestone. K1b = Bexar Fm. K1r = Rodessa Fm. K1fl = Ferry Lake Anhydrite. K1m = Mooringsport Fm. K1p = Paluxy Fm. K1a = Andrew Fm. K1d = Dantzler (from Mancini and Puckett, 2002).

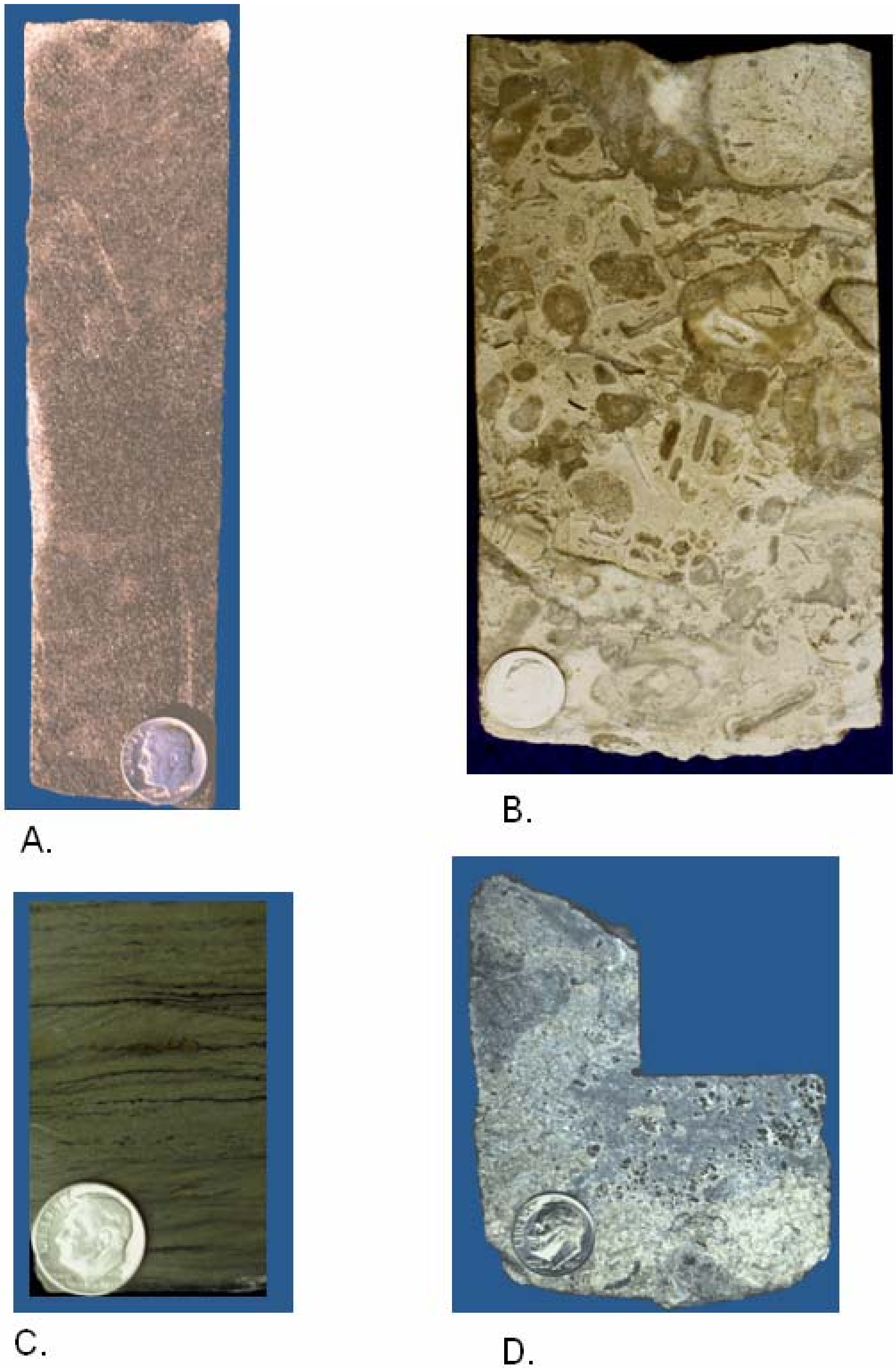


Figure 25. Core photographs for T-R K1 sequence: A. Hosston Sandstone (transgressive aggrading), Reese No. 1-A well, 15,862 ft; B. Sligo Limestone (transgressive backstepping), Main Pass 1654-2 well, 15,610 ft; C. Pine Island Shale (transgressive backstepping), Waveland Gas Unit No. 1 well, 15,679 ft; and D. James Limestone (regressive infilling), Denmiss 24-8 well, 15,915 ft.

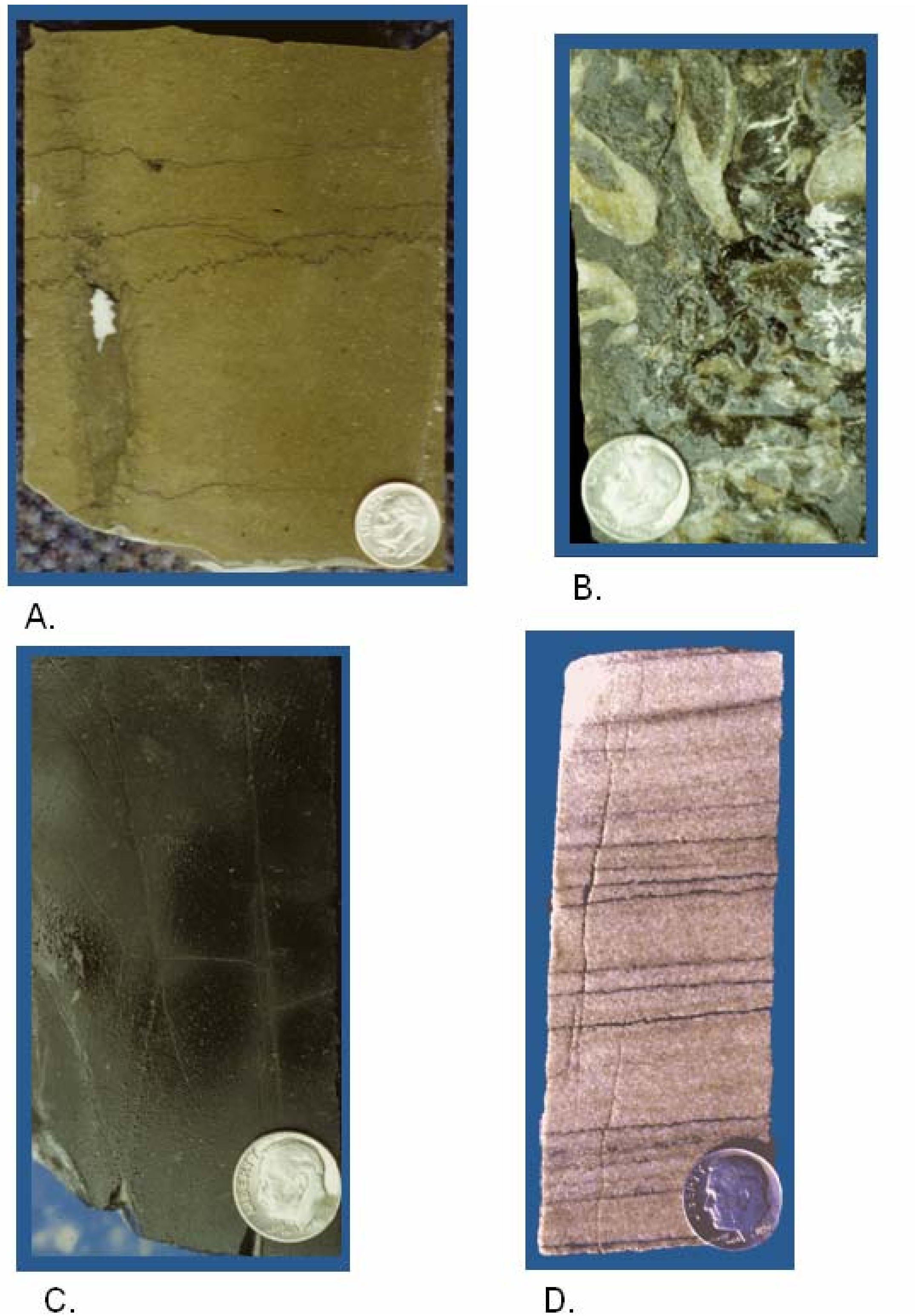


Figure 26. Core photographs for T-R K2 sequence: A. Bexar Shale (transgressive backstepping), Chandeleur Sound Block 61 well, 18,334 ft; B. Rodessa Limestone (regressive infilling phase), Waveland Gas Unit No. 1 well, 14,039 ft; C. Mooringsport calcareous shale (transgressive backstepping), Gex No. 1 well, 13,466 ft; and D. Paluxy sandstone (regressive infilling), Pilgrim No. 1 well, 13,214 ft.

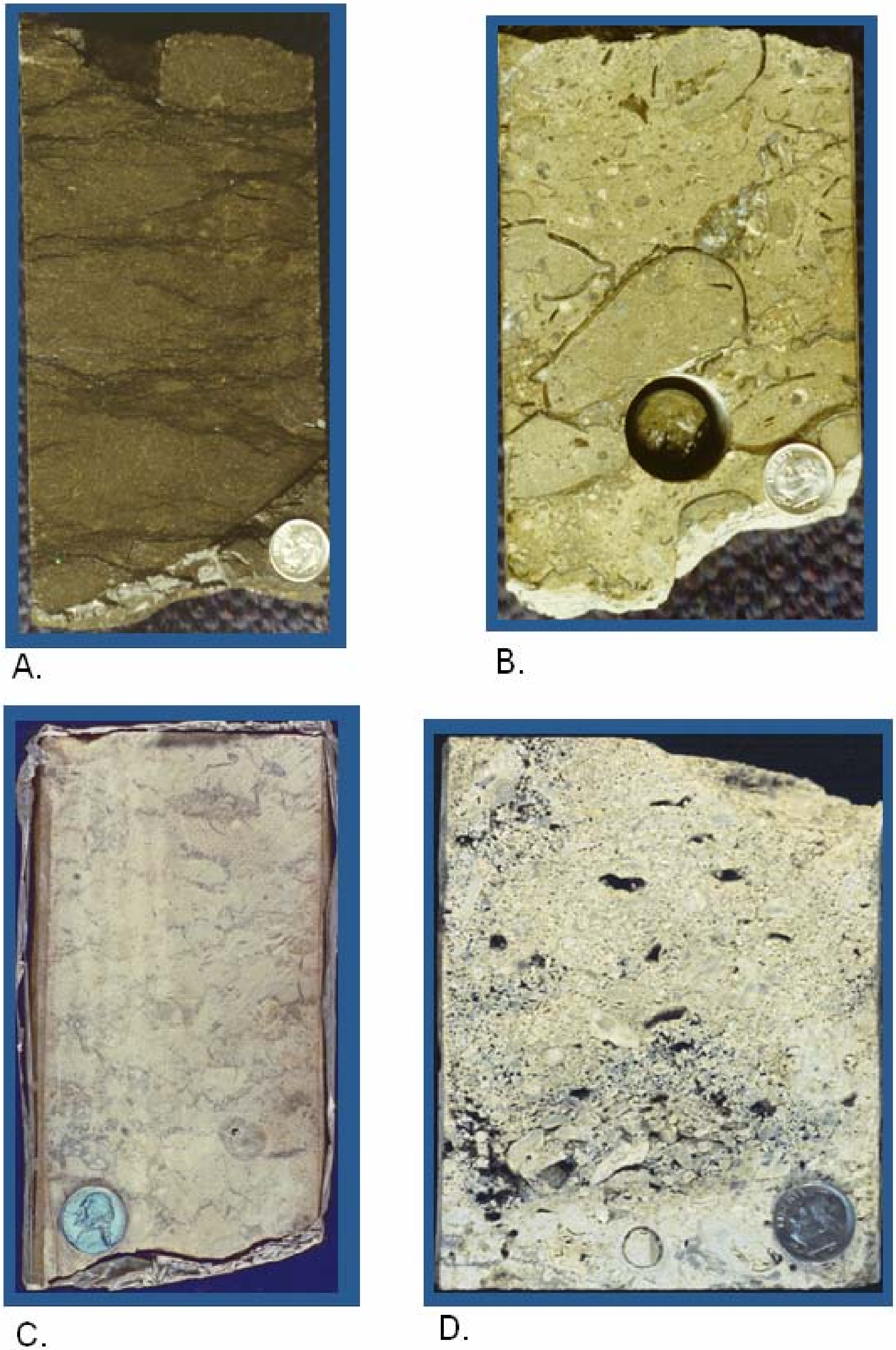


Figure 27. Core photographs for T-R K3 sequence: A. Andrew lime mudstone (transgressive backstepping), Chandeleur Sound Block 61 well, 16,642 ft; B. Andrew rudist boundstone (regressive infilling), Chandeleur Sound Block 61 well, 14,716 ft; C. Washita wackestone (transgressive backstepping), Main Pass 1654-6 well, 8,974 ft; and D. Washita grainstone (regressive infilling), Main Pass 1654-6 well, 8,763 ft.

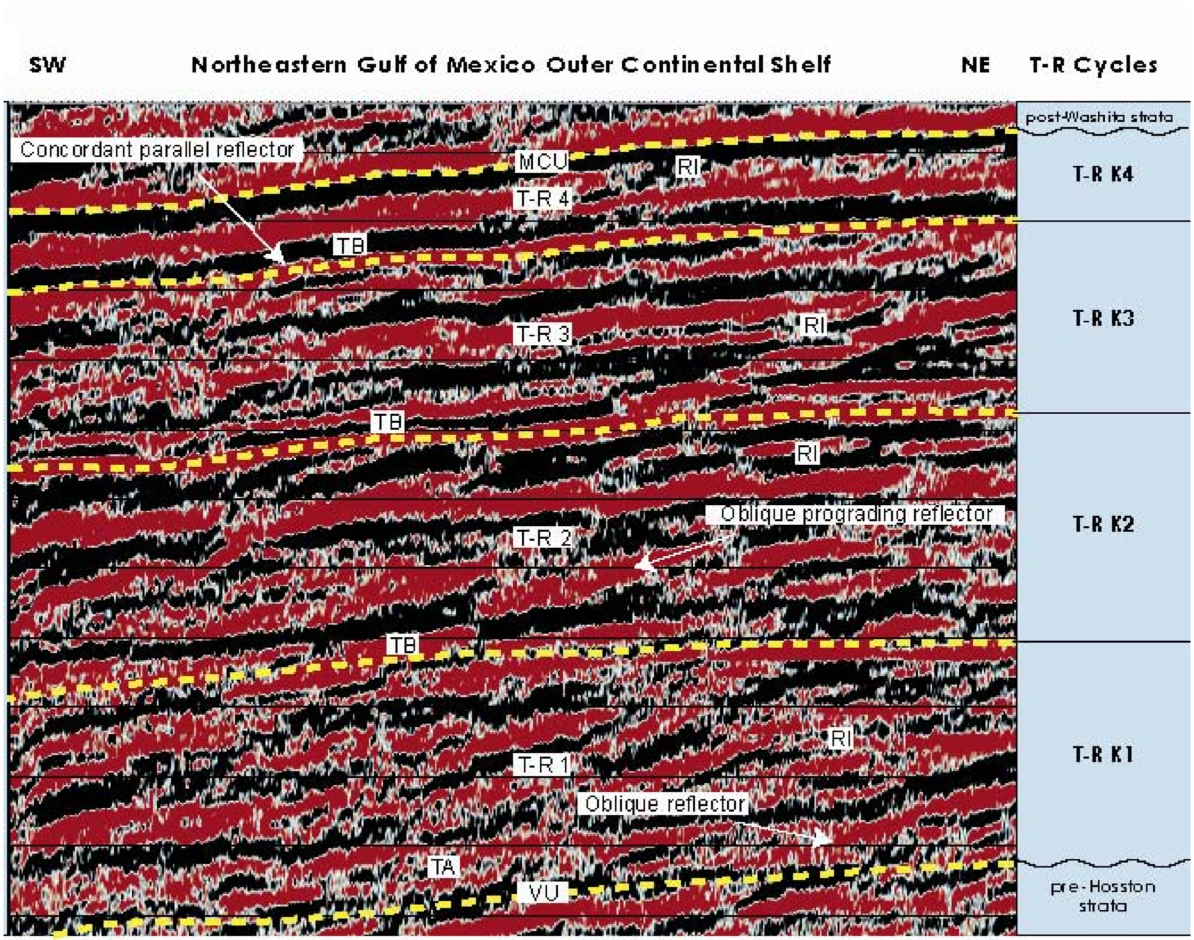


Figure 28. Representative seismic reflection profile from the offshore shelf area of the northeastern Gulf of Mexico showing the seismic reflection configuration of the TR-1, TR-2, TR-3, and TR-4 cycles and the Valanginian (VU) and mid-Cretaceous (MCU) unconformities. TA, transgressive aggrading section: TB, transgressive backstepping section; RI, regressive infilling section (from Mancini and Puckett, 2002). Seismic line courtesy of WesternGeco.

4. Jurassic studies involving well logs, cores and seismic data by Jamal Obid and Ernest A. Mancini.

Characterization of Jurassic stratigraphic sequences in the Gulf of Mexico in this study basically consisted of the dissertation research of Obid (2006), which built on the preliminary work of Mancini et al. (2004).

The following is from the dissertation research of Obid (2006).

Introduction

The Gulf of Mexico is a divergent passive continental margin; with shelfal areas characterized by non-marine to marine siliciclastic and marine carbonate deposits. A stratigraphic analysis, using third-order depositional sequences, as defined by Mitchum et al. (1977b), may provide reliable means for correlating marine shelf deposits with slope and deep marine abyssal deposits. Conversely, studying non-marine deposits of shelfal areas requires an alternate approach using the concepts of transgressive-regressive sequences.

A stratigraphic analysis based on the cyclicity (transgressive-regressive sequences) recorded in the strata and their patterns, which are driven by tectonic-eustatic events, has utility as a tool for constructing a stratigraphic framework for correlation. Moreover, on such passive margins, the stratal patterns are created by a combination of sea level, tectonics, climate, and sediment supply, with a difficulty in distinguishing the role each of these factors may play. The geometry of non-marine strata accumulating above sea level is governed by factors that are controlled by base level changes influenced by sediment supply, tectonics, climate and eustacy. In the shelfal areas of the northeastern Gulf of Mexico, the non-marine and coastal plain deposits of the Jurassic are controlled by changes in stratigraphic base level, which includes changes in sea level.

The purpose of this paper is to analyze seismic sections and well log data from selected wells for the Upper Jurassic section in the study area, recognize stratigraphic surfaces, define transgressive-regressive sequences, and to establish a chronostratigraphic framework for the correlation of strata north and south of the Wiggins Arch.

Geological Setting and Lithostratigraphy

The study area is located in the northeastern Gulf of Mexico, southwest of the state of Alabama (Figure 29). The structural framework of the study area was established by rifted continental margin tectonics associated with the opening of the Gulf of Mexico (Wood and Walper, 1974) and by the extension of the ridges and valleys of the Appalachian structural trend (Salvador, 1987). The resulting paleotopography influenced sedimentation during the Triassic and Jurassic with the presence of positive structures, such as the Wiggins arch and the Conecuh ridge, and negative structures, such as the Mississippi interior salt basin, the Manila subbasin, and the Conecuh subbasin (Mancini et al., 1985) (Figure 30). Differential subsidence of the basement led to a thick buildup of siliciclastic, carbonate, and evaporite deposits in grabens and basins, and thin accumulations of such deposits over pre-Jurassic highs and Jurassic topographic highs (Wilson, 1975; and Mancini et al., 1985).

The Wiggins Arch complex forms a major, east-west basement uplift of Paleozoic age in southern Mississippi and southwestern Alabama. The arch lies between two major Jurassic productive trends: an oil and gas-condensate trend of the Mississippi Interior Salt basin to the north, and a deep natural gas trend to the south. The Wiggins Arch complex covers over 2000 sq. mi. (5180 sq. km.), and has been sporadically explored during the past several years (Montgomery, 2000). The origin of the Wiggins Arch remains undetermined, but appears to date from Triassic rift-related tectonism (Salvador, 1987). Sawyer et al. (1991)

proposed that the arch complex represents an elevated horst block associated with crustal extension and rifting. Cagle and Khan (1983) suggested that the Wiggins Arch might be a remnant of the rifted continental margin of North America. They reported that this basement feature is comprised of pre-rift Paleozoic rocks of metamorphic and granitic nature (Cagle and Khan, 1983).

Figure 29. The study area located in the northeastern Gulf of Mexico. Two wells (1910-A and 1862) north of the Wiggins Arch, and four wells (SW-4576, SW-3840, MO-867, and MO-909) south of the Wiggins Arch were selected for this study.

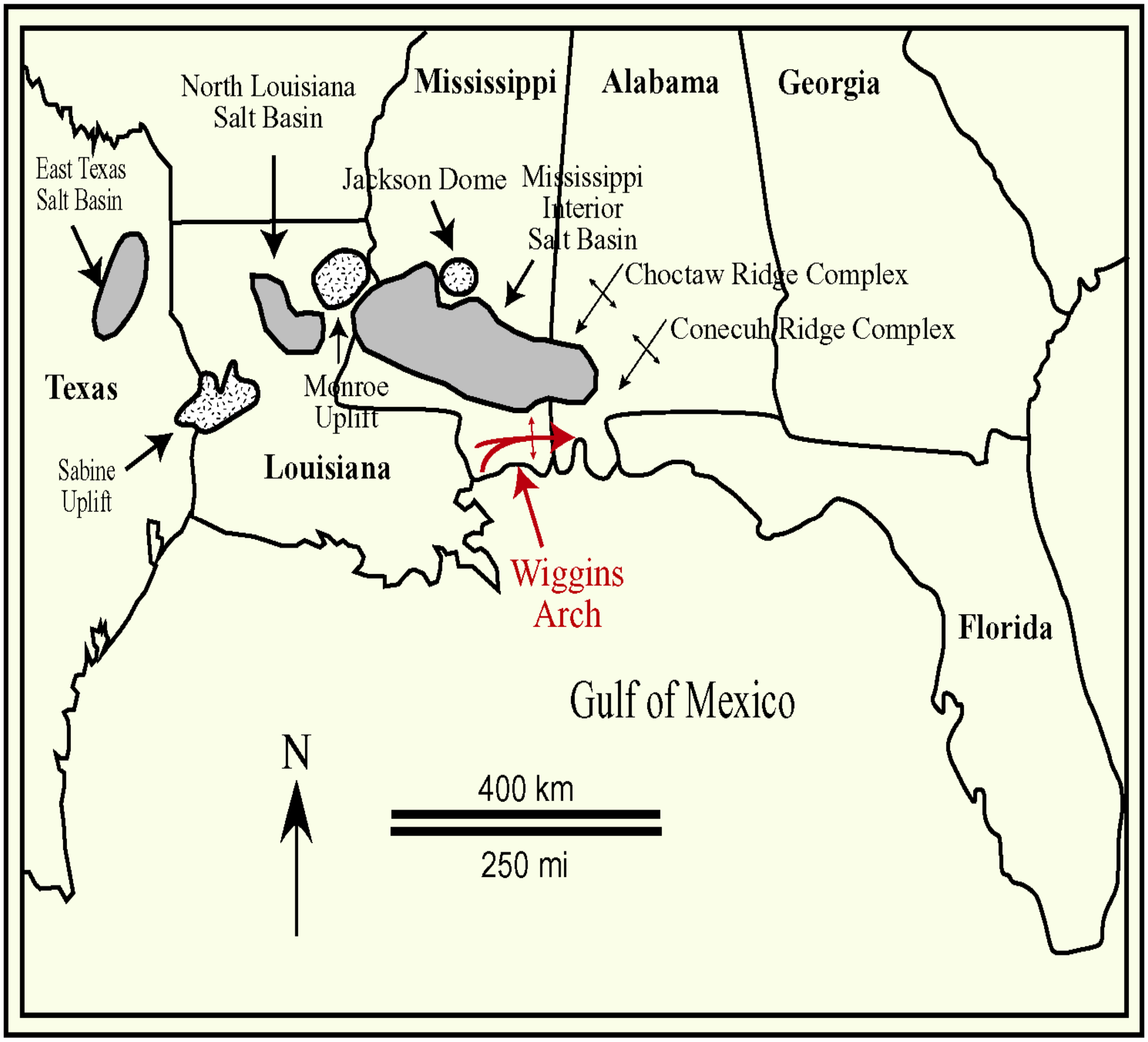


Figure 30. Index map of northeastern Gulf of Mexico Coastal Plain showing major structural features, including the Wiggins Arch (modified from Mancini et al., 2002).

The Upper Jurassic in southwest Alabama (northeastern Gulf of Mexico) consists of a number of lithologic units: the Norphlet Formation (Oxfordian), the Smackover Formation (Oxfordian), the Haynesville Formation (Kimmeridgian), and the Cotton Valley Group (Tithonian to Berriasian/Lower Valanginian) (Mancini et al., 1990a) (Figure 31). The Norphlet Formation is a distinctive stratigraphic unit recognized as the first siliciclastic unit below the limestone of the overlying Smackover Formation. It is regionally extensive, mainly continental, siliciclastic deposits, which accumulated in an arid to semi-arid climate. The

Norphlet deposits, therefore, represent alluvial fan and plain, fluvial (wadi), eolian dune and interdune, and playa lake environments (Mancini et al., 1999).

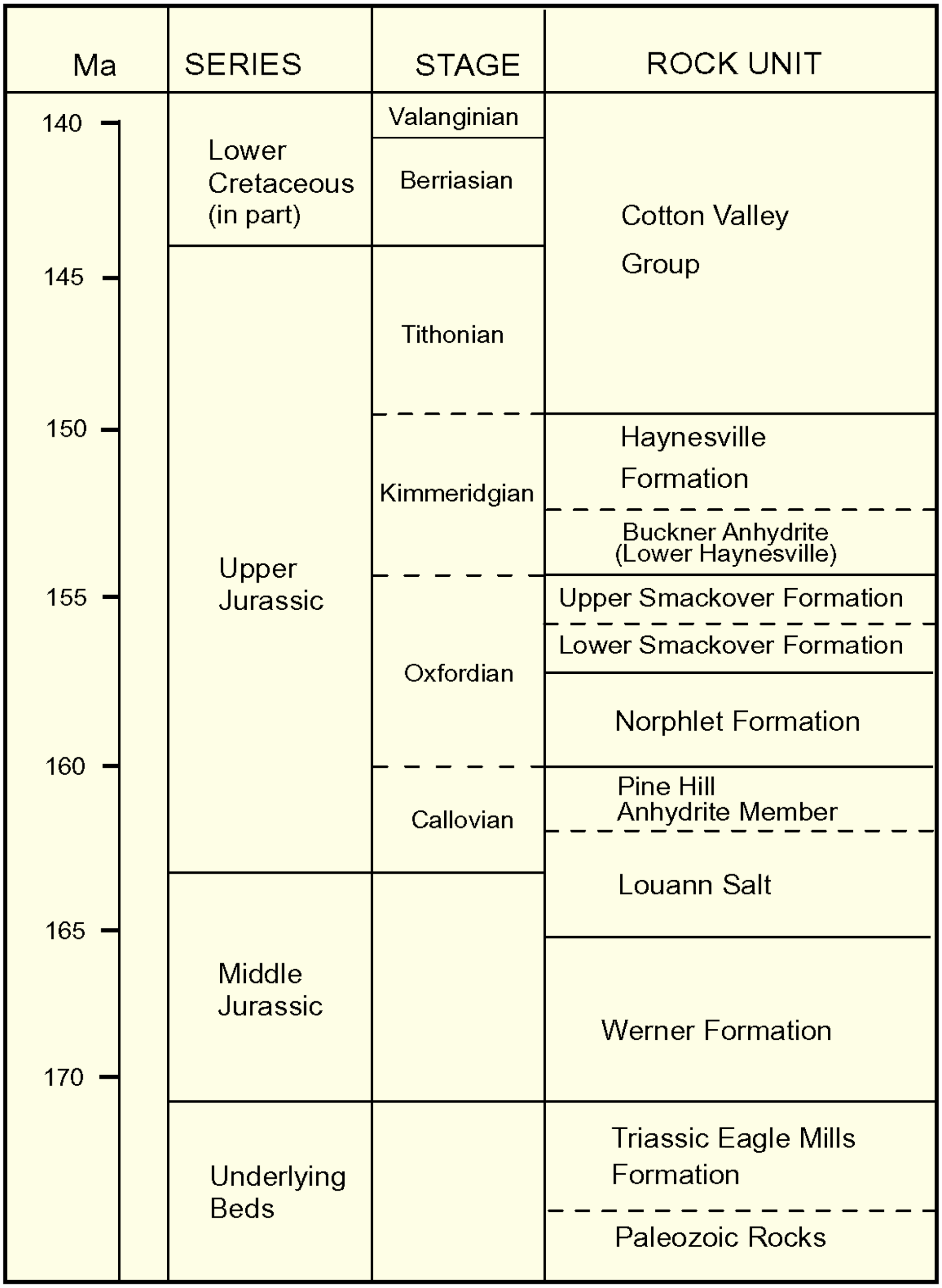


Figure 31. General stratigraphy of the Upper Jurassic section, northeastern Gulf of Mexico area (modified from Mancini et al., 1990a).

The Oxfordian Smackover Formation overlies the Norphlet Formation, and is a regionally extensive Late Jurassic carbonate unit. The Smackover Formation represents the earliest carbonate deposition in the Gulf of Mexico. The deposition of the Smackover Formation was associated with a major Jurassic transgression of marine waters during a major cycle of sea level rise and fall, and was controlled by paleotopography related to basin subsidence and salt tectonics. In general, accumulation of carbonate rocks took place on a carbonate ramp depositional setting in subtidal to intertidal environments (Mancini et al., 1990a). The Smackover lithofacies, recognized in the northeastern Gulf of Mexico, include lower, middle, and upper units. The lower unit is an intertidal to subtidal deposit of lime mudstone and peloidal and oncolitic wackestone and packstone. The middle unit represents subtidal lime mudstone deposits with peloidal and skeletal wackestone and packstone. The upper unit is a subtidal to intertidal oolitic, oncolitic, and peloidal grainstone and packstone interbedded with laminated lime mudstone deposits, chiefly representing moderate to high-energy facies (Mancini et al., 1990a).

The Kimmeridgian Haynesville Formation conformably overlies the Oxfordian Smackover Formation, and includes evaporites, carbonates and terrigenous clastics. In southwest Alabama, the Haynesville Formation is generally comprised of interbedded limestone, anhydrite, sandstone, and shale, with lesser amounts of dolomite. Three units have been identified within this formation: a lower unit of massive anhydrite, recognized onshore as the Buckner Anhydrite Member (the offshore equivalent to this member is the lower Haynesville with its limestone deposits interbedded with shale, dolomite, and sandstone); a middle unit consists of interbedded sandstone, shale, and anhydrite; and an upper unit consisting of interbedded limestone, sandstone, shale and anhydrite (Mancini et al., 1990b, and Mancini et al., 1999).

The Late Jurassic to Early Cretaceous (Tithonian to Berriasian/Lower Valanginian) Cotton Valley Group overlies the Haynesville Formation, and consists of conglomeratic sandstone, shale and coal. The Cotton Valley Group was deposited in marginal marine to continental environments (Mancini et al, 1990c). In the northeastern Gulf of Mexico, the Cotton Valley Group consists of the Schuler Formation, which comprises two members, a lower sandy Shongaloo and an upper shaly Dorcheat Member. Moore (1983) divided the Cotton Valley Group into three intervals, lower (sandy), middle (less sandy) and upper (the least amount of sandstone and more limestone) informal members. The updip limit of limestone occurrence in the upper Cotton Valley was mapped by Moore (1983), and was termed the Knowles Limestone, which is comprised of gray to dark brown dolomitic mudstone and wackestone. Moore (1983) also interpreted the Cotton Valley as being deposited in fluvial, deltaic, strandplain and nearshore marine environments (Moore, 1983).

Dataset and Methodology

Well logs and Cuttings

The dataset consists of well log, mudlog and well cutting data. Well log data used are from wells available in onshore (i.e. north of the Wiggins Arch) and offshore (i.e. south of the Wiggins Arch) Alabama (Figure 29). The onshore wells were selected from the Mississippi Interior Salt Basin of Alabama, while the offshore wells were selected from Mobile Bay and Mobile area. Lithology was described using mudlog and/or well cutting data available for each of the six selected wells. Varieties of well log curves were available for the selected wells. The spontaneous potential (SP) and deep resistivity (ILD) log curves were common for all wells, and therefore were chosen for all six wells. In addition, for the four offshore wells, gamma ray (GR) log curves were also chosen for optimal correlation. The GR log curve was not available for the other two onshore wells. Well log curves were digitized using NEURALOG software. The digitized well log curves were then loaded into PETRA software for the purposes of displaying, preparing cross sections, and correlation and interpretation.

When using well logs, and at the start of the sequence stratigraphic interpretation process, identifying first the predominant sequence stratigraphic surfaces is of great importance. The most important of these surfaces, and the first that was recognized, is the surface of maximum transgression (SMT) (i.e. maximum flooding surfaces (MFS)). According to Posamentier et al. (1999), the SMT surface is a surface of deposition at the time the shoreline is at its maximum landward position. The surface marks the time of maximum flooding or transgression of the shelf, and separates the transgressive and regressive systems tracts in a T-R sequence. A SMT is often distinguished by the presence of radioactive and often organic rich shales, glauconite, and widespread thin-bedded concentrations of fauna (condensed sections) with high abundance and diversity. A SMT can often be the only portion of a sedimentary cycle that is rich in fauna. Such a surface can be recognized on well logs as a sharp to gradational change from sand to shale, with maximum GR (or SP), and minimum resistivity log responses (Figures 32 and 33).

The recognition of SMT is followed, when possible, by the recognition of the transgressive surface (TS). Both SMT and TS coincide and are correlated with radioactive shales (use of the gamma log or SP) that are interpreted to have been deposited across relatively flat surfaces. The transgressive surface (TS) is a marine-flooding surface that forms the first significant flooding surface in a sequence. The transgressive surface, in most siliciclastic and some carbonate successions, marks the onset of the period when the rate of creation of accommodation space is greater than the rate of sediment supply. Where the rate of sediment supply is low, the transgressive surface may merge landward with the surface of maximum transgression. Once the SMT and TS surfaces are established and tied, then the sequence boundaries (SB) of both carbonate and siliciclastic sedimentary strata are identified. The SB can be recognized on well logs simply as a sharp change from shale to sand on SP and/or GR log responses (Figures 32 and 33).

Seismic Data

The dataset for this study consists of seismic reflection data, which were acquired in the offshore Alabama and Mississippi area (Figure 34). It includes about 3500 km, of two dimensional, multi-channel seismic reflection sections. The seismic data are CDP reflection data having 90-fold stacking and post-stacking migration processing. Seismic lines cover the following: Mobile Bay area, Mobile area, Mississippi Sound area, Viosca Knoll area, and Main Pass area. Acquisition parameters were available only for the Mobile area, where seismic data were acquired using LRS-888 recording system and an Aquapulse source with six guns. Western Geophysical Company performed the acquisition and processing of the seismic data that were mainly acquired in 1981 for the Mobile Area. In other areas (e.g. Viosca Knoll, Mississippi Sound), seismic data were acquired between 1984 and 1992. The quality of the 1992 seismic data is higher than those for 1984 and 1981. For the purpose of interpretation, seismic data were loaded into the Kingdom Suite (Version 7.3) software developed by Seismic Micro-Technology. Well log and seismic data were integrated using check shot surveys and synthetic seismograms (Figure 35).

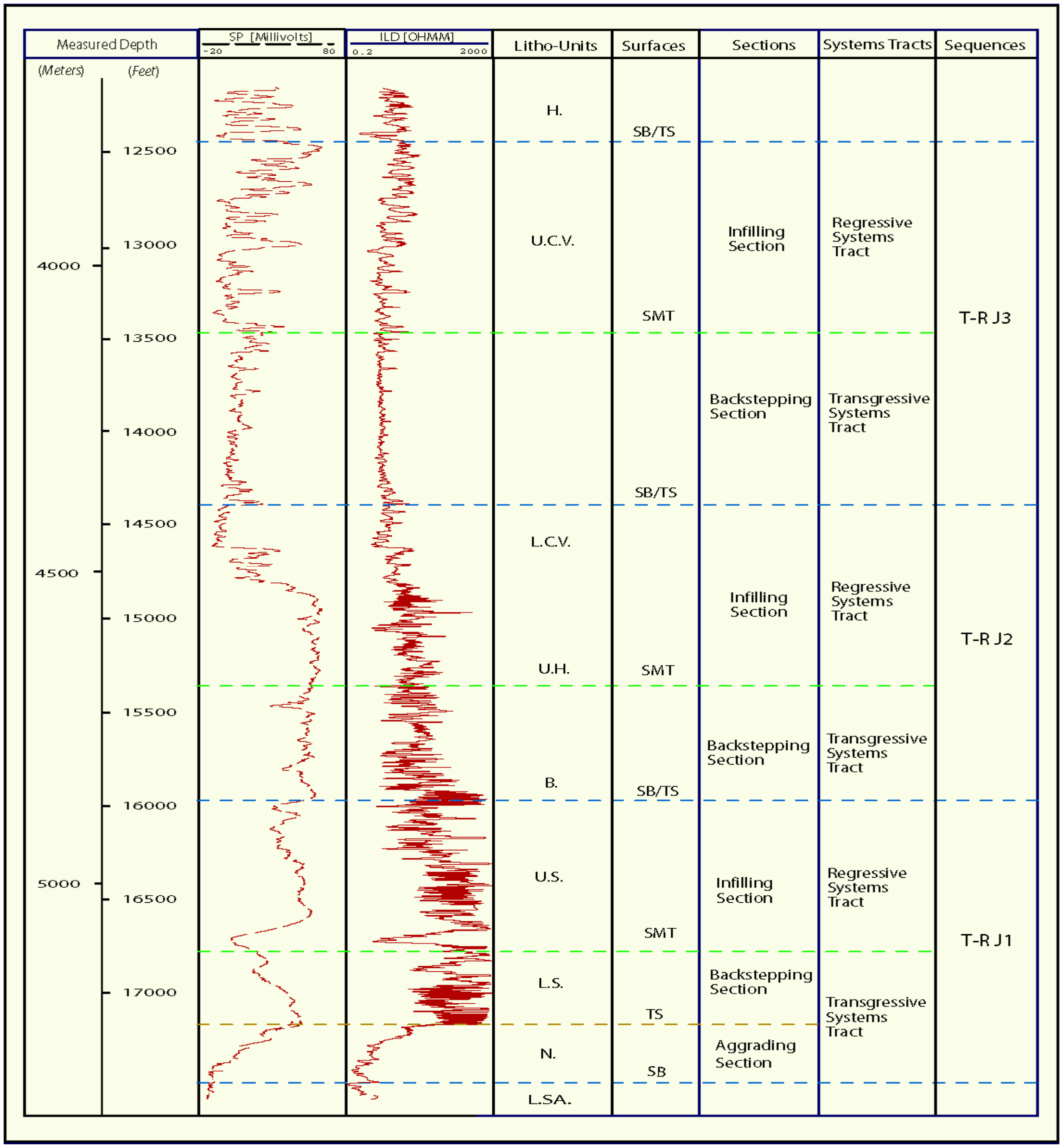


Figure 32. Well log patterns from Well Permit 1910-A, Washington County, AL, showing well log responses characteristic for the Upper Jurassic transgressive-regressive sequences and their related sections. SP=spontaneous potential, ILD=Deep Induction (resistivity). SB=sequence boundary, SMT=surface of maximum transgression, TS=transgressive surface. L.SA.=Louann Salt, N.=Norphlet Formation, L.S.=lower Smackover Formation, U.S.=upper Smackover Formation, B.=Buckner Anhydrite Member, L.H.=lower Haynesville, U.H.=upper Haynesville, L.C.V.=lower Cotton Valley, U.C.V.=upper Cotton Valley, H.=Hosston Formation.

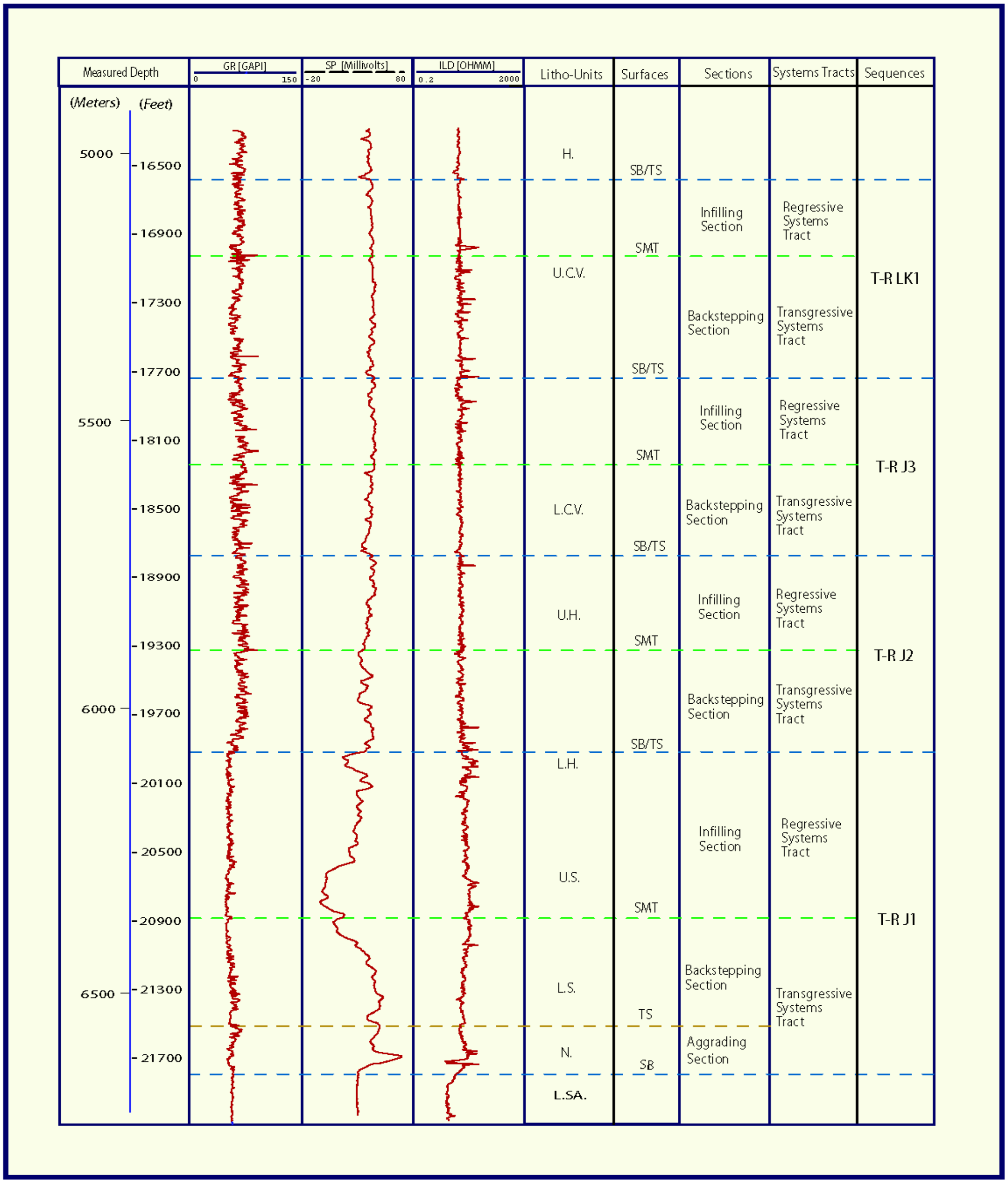


Figure 33. Well log patterns from Well Permit MO-867, Mobile Area, offshore Alabama, showing well log responses characteristic for the Upper Jurassic transgressive-regressive sequences and their related sections. SP=spontaneous potential, GR=gamma ray, ILD=Deep Induction (resistivity). SB=sequence boundary, SMT=surface of maximum transgression, TS=transgressive surface. L.SA.=Louann Salt, N.=Norphlet Formation, L.S.=lower Smackover Formation, U.S.=upper Smackover Formation, B.=Buckner Anhydrite Member, L.H.=lower Haynesville, U.H.=upper Haynesville, L.C.V.=lower Cotton Valley, U.C.V.=upper Cotton Valley, H.=Hosston Formation.

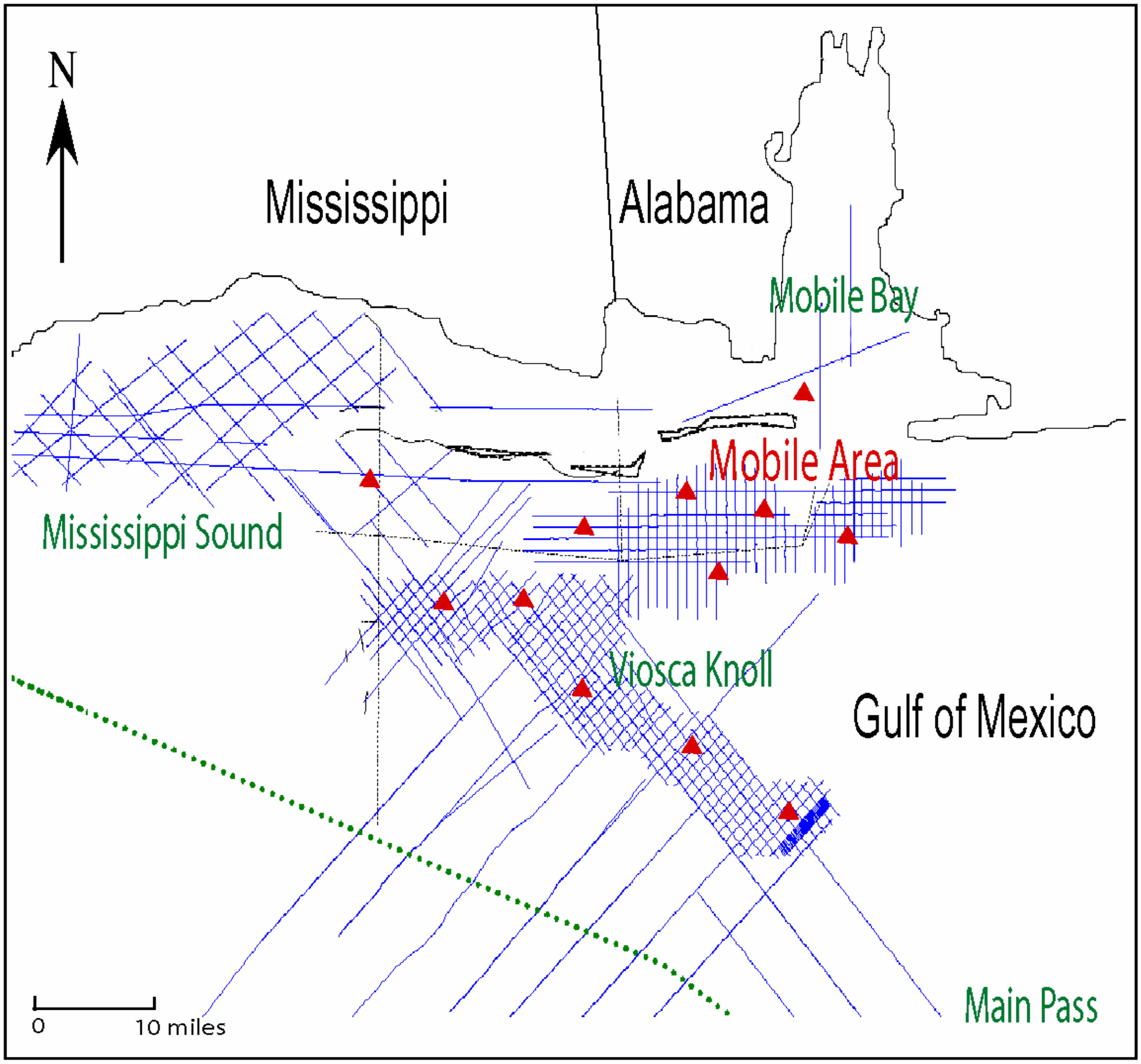


Figure 34. Map of the study area, Mobile Area, offshore Alabama, northeastern Gulf of Mexico. Blue lines represent seismic lines in the area. Wells, within and surrounding the study area, are represented by red triangles.

A variety of bandpass filtering parameters for optimum display of the seismic reflection data at the depths of interest has been applied. Color display was also deemed a factor in enhancing the interpretation process. It has been determined that color schemes display would affect the interpretation. Some color schemes positively improved the interpretation, as opposed to others that seemed to affect interpretation adversely.

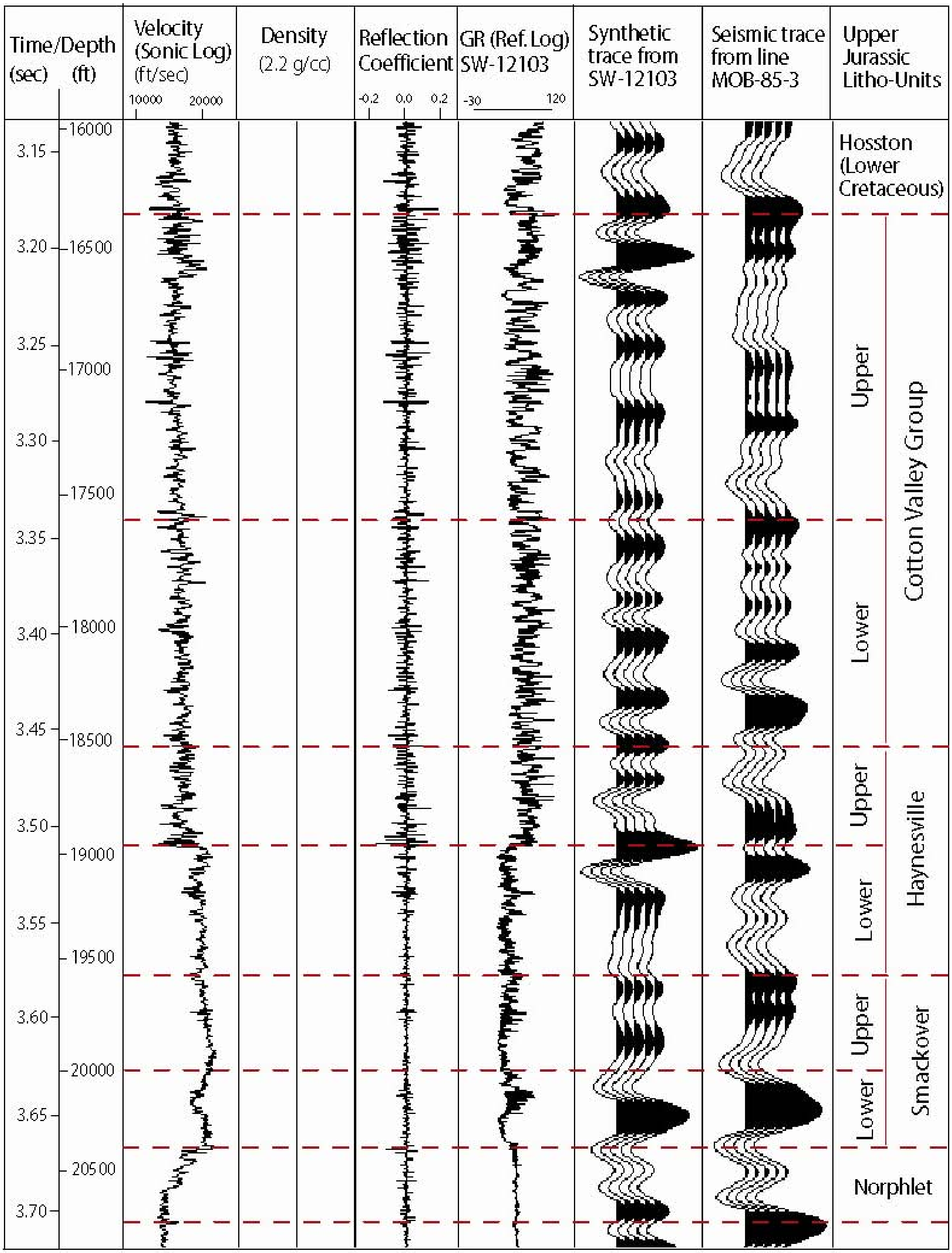


Figure 35. Match between the synthetic trace and the actual seismic trace, well SW-12103.

Using the available reflection seismic data for the Mobile area, offshore Alabama, seismic sequences were outlined (Figure 36) by identifying reflection termination patterns on reflection seismic sections following the methods defined by Mitchum et al. (1977b). Such termination patterns of seismic reflectors include onlaps, downlaps, toplaps, and erosional truncations (Figure 37). Reflection configuration and geometry were also used to identify sequences and to infer seismic stratigraphic surfaces such as, sequence boundaries (i.e. subaerial unconformities, shoreface ravinement surfaces, transgressive surfaces) and downlap surfaces (i.e. surfaces of maximum transgression or maximum flooding surfaces) (Figures 38, 39 and 40).

The method of Mitchum et al. (1977b) continues to be used successfully by seismic stratigraphers to recognize seismic stratigraphic surfaces and in defining third order depositional seismic sequences. However, to date reflection configuration and geometry and termination patterns (Figure 37) have not been used to delineate transgressive-regressive sequences. In this paper, these will be used to recognize the stratigraphic surfaces that delineate transgressive-regressive (T-R) sequences, as defined by Embry (1993, 2002), Jacquin and de Graciansky (1998), and Mancini and Puckett (2002).

In the study area, which is located on the present day inner to middle shelf of the northeastern Gulf of Mexico, seismic reflectors lacked any apparent recognizable significant termination patterns, such as onlaps or downlaps (Figure 36). Therefore, it was impractical to attempt to recognize sequences using only those seismic sections in the Mobile Area alone. Consequently, most of the sequences and inferred stratigraphic surfaces were recognized and delineated using seismic sections in the Viosca Knoll area (mid-outer shelf) (Figure 34), where processing and the quality of seismic data permitted an improved sequence recognition in terms of seismic stratigraphy. In this area, reflection termination patterns, such as toplap/truncation (Figure 38) and downlap (Figure 39) were observed, stratigraphic surfaces identified (Figure 40), sequences delineated and then traced throughout the study area (i.e. Mobile Area), where possible. Seismic lines in the western part of Mobile Area allowed for better recognition of sequences, as opposed to those in the eastern part of the Mobile Area, where sequences could not be reasonably traced and/or recognized.

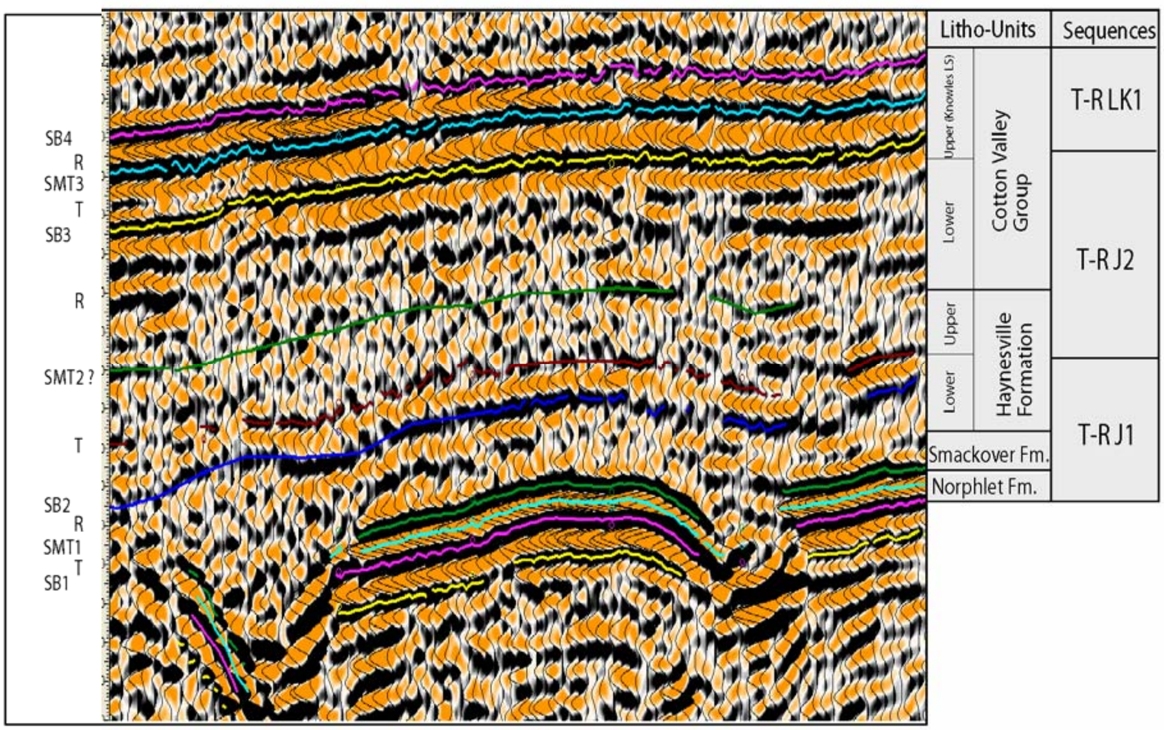


Figure 36. Seismic section from offshore Alabama, showing the three recognized T-R sequences. SB=sequence boundary, SMT=surface of maximum transgression, T=transgressive systems tracts, R=regressive systems tracts. Seismic line courtesy of WesternGeco.

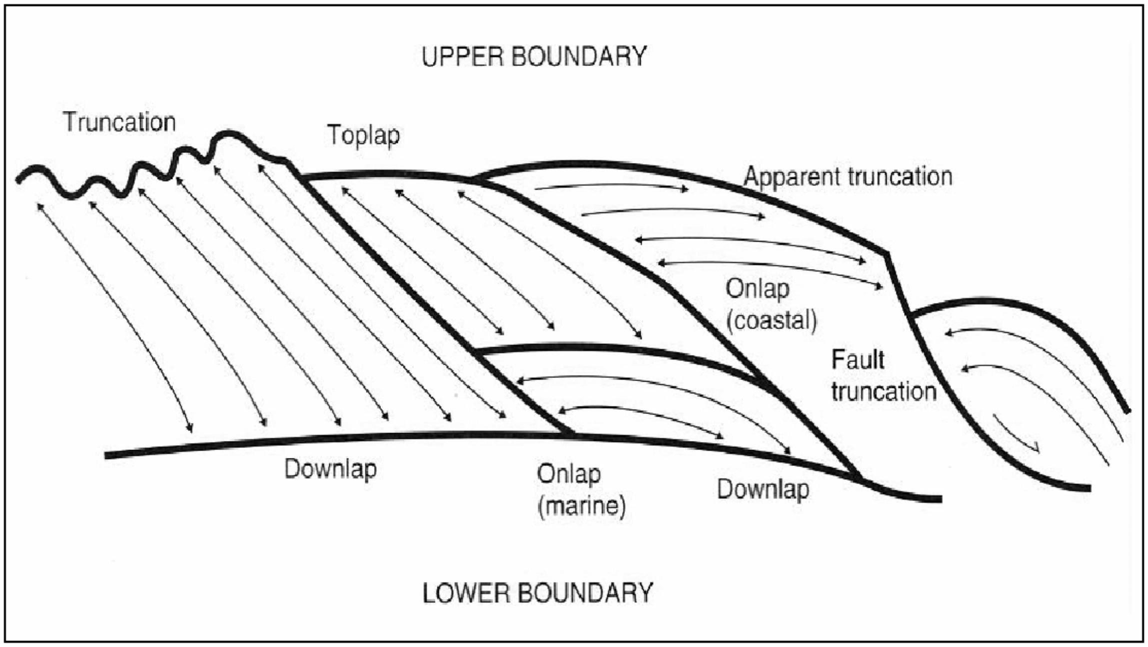


Figure 37. Types of reflection termination patterns that can be observed on reflection seismic sections (figure from Emery and Myers, 1996).

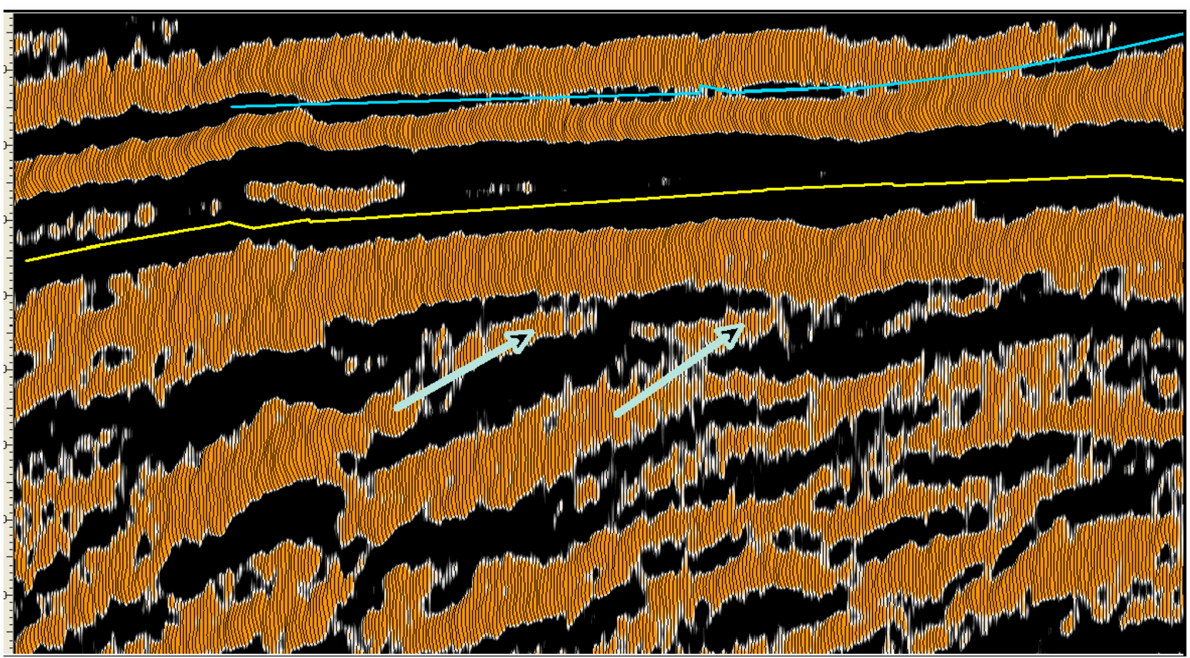


Figure 38. A seismic section from offshore Alabama. Reflection termination patterns (toplap/truncation) are shown by blue arrows, indicating unconformity/sequence boundary (SA) for the T-R LK1 sequence. Seismic line courtesy of WesternGeco.

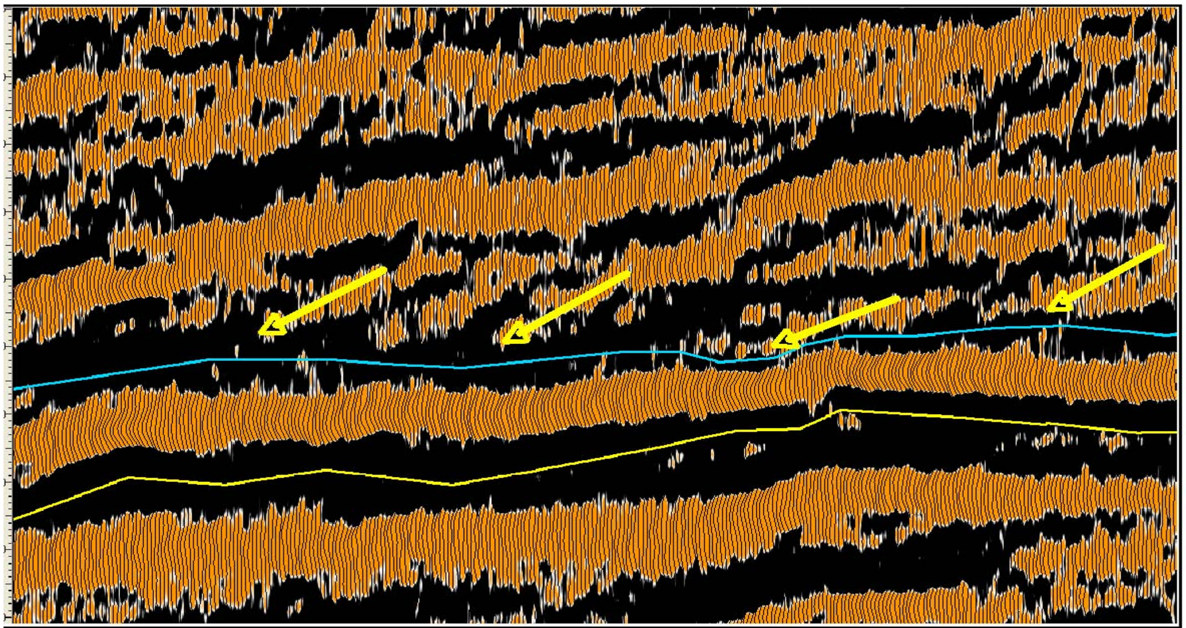


Figure 39. A seismic section from offshore Alabama. Downlap reflection termination patterns are shown by yellow arrows, indicating a surface of maximum transgression (SMT) for the T-R LK1 sequence. Seismic line courtesy of WesternGeco.

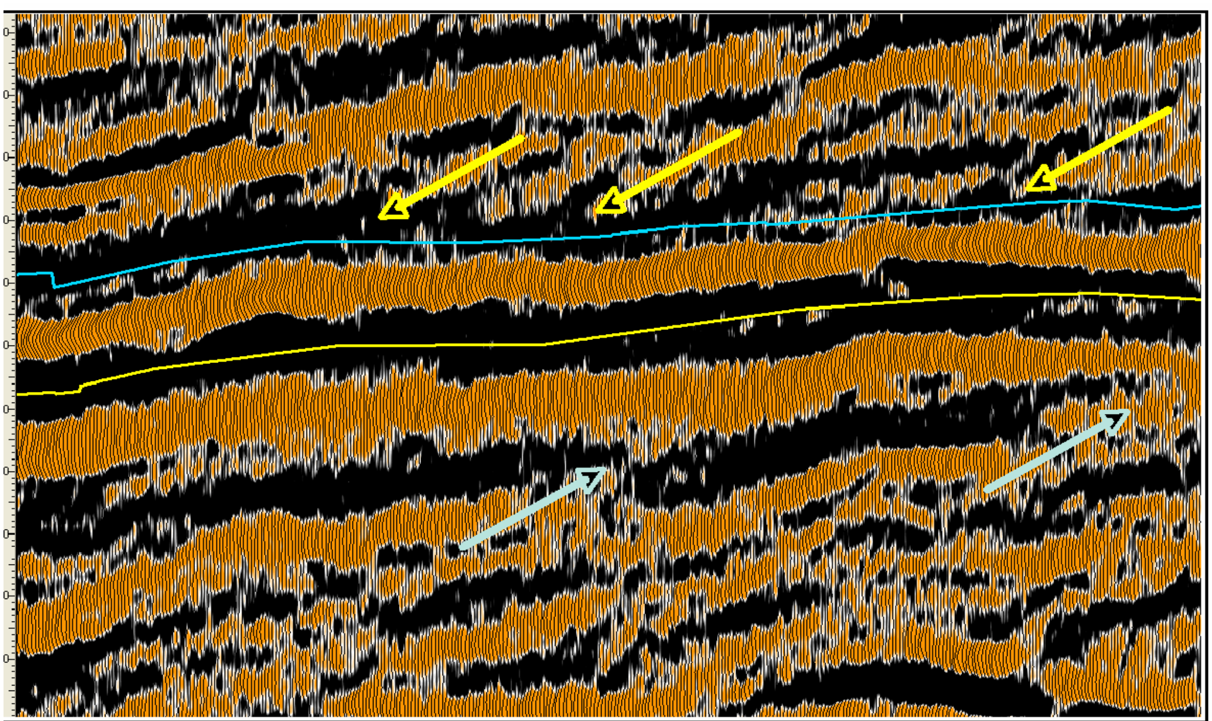


Figure 40. A seismic line from the offshore Alabama, showing seismic reflection termination patterns. Downlaps (yellow arrows) indicate a surface of maximum transgression (SMT), and reflector truncations (blue arrows) indicate a sequence boundary for the T-R LK1 sequence. Seismic line courtesy of WesternGeco.

Seismic Facies Analysis

According to Vail and Mitchum (1977) and Sangree and Widmier (1977), seismic facies analysis involves delineating and interpreting seismic reflection parameters, such as reflection configuration and geometry, continuity, amplitude, frequency, and interval velocity as well as the external form of reflectors within the framework of depositional sequences. Each of the above mentioned seismic reflection parameters contain information of stratigraphic significance. The geologic interpretation of seismic facies involves deciphering the sedimentary environment and lithofacies. This is possible since energy of deposition influences seismic facies. Seismic facies analysis could also be helpful in interpreting sequence boundaries. In certain cases, sequence boundaries may correspond to abrupt changes in facies.

Four seismic facies (A, B, C, and D) have been recognized on seismic reflection sections in the Mobile area, offshore Alabama (Figure 41). Below sequence boundary SB1, the seismic facies appear chaotic, possibly reflecting either basement rocks, or salt deposits, or both. The next interval of seismic reflectors represents the Louann Salt, Norphlet, Smackover and lower Haynesville units. These seismic reflectors appear to be parallel semi-continuous reflectors, showing higher amplitude and lower frequency (seismic facies A), reflecting sharp velocity and density contrasts for the sediments of the Norphlet sandstone and Smackover carbonate. The partial lack of continuity for these reflectors, as shown in Figure 41, is attributed mainly to salt movement that created a faulted and folded antecedent topography structural pattern for these post-rift deposits.

Above seismic facies A, seismic reflectors appear to have a chaotic pattern with a very low amplitude, high frequency, and very poor continuity (seismic facies B) (Figure 41).

This facies reflects the siliciclastic (interbedded shale and sandstone) influence of the deposits of the lower Haynesville Formation (regressive systems tract of the T-R J1 sequence). Overlying seismic facies B, seismic reflectors appear to be parallel semi-continuous to discontinuous with medium amplitude, medium to good continuity and low frequency (seismic facies C) (Figure 41). This seismic facies possibly reflects a facies change in the deposits below sequence boundary SB2.

Above sequence boundary SB2, a chaotic reflection pattern similar to that of seismic facies B is identified, suggesting proximity to the sediment source and significant siliciclastic influence for the conglomeratic sandstone and of the upper Haynesville Formation and sandstone of the lower Cotton Valley Group (regressive systems tract of the T-R J2 sequence). An abrupt seismic facies change occurs at sequence boundary SB3. Above this sequence boundary, seismic reflectors appear to be parallel continuous with medium to high amplitude, low frequency, and very good continuity (seismic facies D) (Figure 41). The change in lithology from siliciclastic strata of the lower Cotton Valley below sequence boundary SB3 to carbonate strata (i.e. Knowles Limestone of the upper Cotton Valley Group) above the sequence boundary produces this distinct seismic facies change (Figure 41).

Sequence boundaries SB3 and SB4 correspond to the lower and upper boundaries of seismic facies D, as shown in Figure 39. Such correspondence suggests a major influence of sea level changes on the character of seismic facies D. Conversely, sequence boundaries SB1 and SB2 do not correspond to seismic facies boundaries, suggesting a combined influence of sea level and tectonic changes on the character of seismic facies A, B, and C (Figure 41).

Upper Jurassic Transgressive-Regressive Sequences

T-R sequences, in this study, are recognized in the onshore/offshore Upper Jurassic strata of the northeastern Gulf of Mexico basin based on wireline logs and seismic data. The following general well log responses were used to delineate the systems tracts and sections of the T-R sequences in the subsurface strata in the study area. The SMT separates the transgressive systems tract, with its backstepping section, from the regressive systems tract, with its infilling section, of a T-R sequence. As a general rule, a transgressive backstepping section of a transgressive systems tract can be identified by an overall increase in gamma ray, or more positive SP log response (i.e. fining upward trend) from top of a discontinuity (unconformity) to base of surface of maximum transgression (Figures 32 and 33). Alternatively, a general decrease in gamma ray, or less positive SP log response (i.e. coarsening upward trend) from top of surface of maximum transgression to base of a discontinuity (unconformity) represents a regressive infilling section of a regressive systems tract. The surface of maximum transgression, therefore, can be defined as the surface between a retrograding unit and an overlying prograding unit. A rectangular gamma ray or SP log pattern is used to recognize the transgressive aggradational section of a transgressive systems tract (Figures 32 and 33).

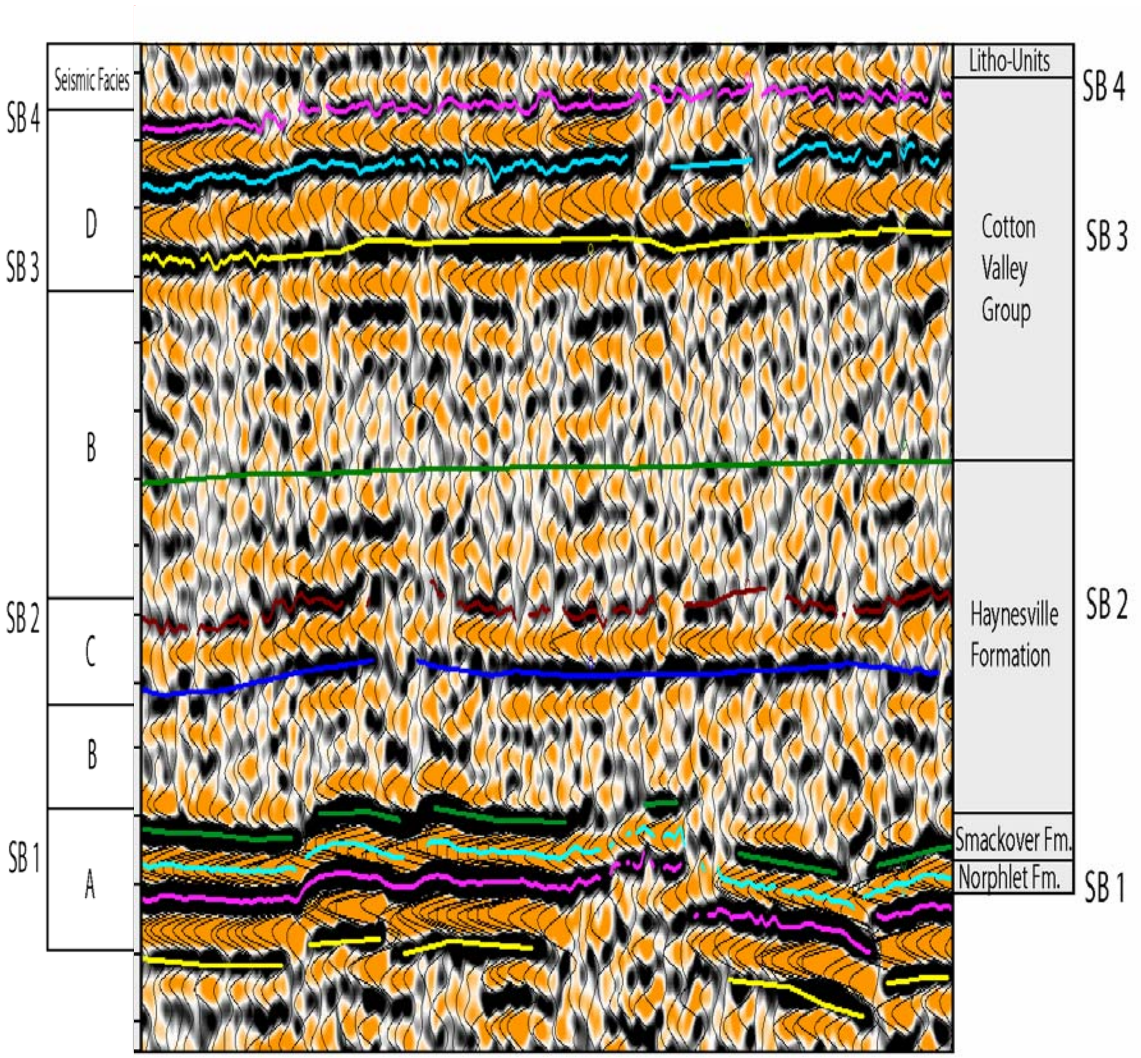


Figure 41. Four Seismic Facies (A, B, C and D) identified on seismic sections in the northeastern Gulf of Mexico. SB=Sequence Boundary. Seismic line courtesy of WesternGeco.

Three, 3-7 million years in duration, T-R sequences (T-R J1, T-R J2, T-R J3) are recognized in the Upper Jurassic onshore and offshore strata of the northern Gulf of Mexico (Figures 32, 42 and 43). In addition, a fourth sequence (T-R LK1) that is 3-4 million years in duration is also recognized only in the offshore strata (Figures 33, 43,44, 45 and 46). These Oxfordian to Berriasian (onshore)/Lower Valanginian (offshore) sequences consist of transgressive backstepping sections and regressive infilling sections.

The Oxfordian to Kimmeridgian (T-R J1) sequence includes the Norphlet Formation, the Smackover Formation, and the lower beds of the Buckner Anhydrite Member of the Haynesville Formation onshore (Figure 32), or the lower Haynesville Formation offshore (Figure 33). The contact between the sandstone of the Norphlet Formation and the underlying Louann Salt is sharp and can be identified by a discontinuity on well log response and in lithology. Such a contact is recorded on well log pattern in low resistivity, negative SP, and low gamma log responses for the Norphlet sandstone, which is interpreted as the aggrading section (continental deposits) of the transgressive systems tract of the T-R J1 sequence. The contact of the carbonate Smackover Formation with the underlying Norphlet sandstone strata is recognized as a discontinuity in well log pattern as well as in lithology, representing an inferred transgressive surface (TS). On well log response, this contact is identified in low resistivity, negative SP, and low gamma log responses for the Norphlet strata. The continental sandstone of the Norphlet is overlain, in places in the region, by marine sandstone shoreface deposits, representing marine reworking of the continental facies of the Norphlet. The contact between the continental Norphlet and the overlying marine Norphlet is disconformable, representing an erosional ravinement surface. The contact between the Smackover carbonates and the underlying shoreface deposits of the Norphlet is gradational.

The backstepping section of the transgressive systems tract of this T-R J1 sequence comprises the Norphlet marine sandstone and lower to middle Smackover intertidal to subtidal packstone, wackestone, and lime mudstone strata. The infilling section of the regressive systems tract of this sequence includes the upper Smackover microbial boundstone, the bioturbated wackestone, packstone and grainstone (shoal complex), and lime mudstone (tidal flat) beds and lower Buckner Anhydrite Member (sabkha deposits) of the

Haynesville Formation (Figure 32). The offshore equivalent of the Buckner Anhydrite Member is the lower Haynesville deposits (Figure 33).

The two systems tracts (transgressive and regressive) of this sequence are separated by a surface of maximum transgression (SMT) that represents a change from an upward deepening (fining) to an upward shallowing (coarsening) sections (Figures 32, 33, 43, 45 and 46). The SMT can be recognized in the middle Smackover by a maximum gamma log response. It can also be recognized by more positive SP and lower resistivity log responses.

The Kimmeridgian to Tithonian (T-R J2) sequence comprises the onshore upper Buckner (subaqueous) Anhydrite Member, the upper Haynesville deposits, and the lower Cotton Valley deposits (Figures 32 and 42). The same sequence occurs offshore (Figures 33 and 44), with the Buckner anhydrite strata being replaced by the lower Haynesville grainstone strata, which directly overlie the Smackover grainstone beds.

The contact of the upper (subaqueous) Buckner anhydrite deposits with the underlying lower Buckner anhydrite deposits is identified on well logs at the top of the blocky resistivity log pattern, characteristic of a massive anhydrite of the lower Buckner deposits, and representative of a transgressive surface with subaqueous anhydrite overlying sabkha anhydrite deposits. Onshore, the bedded anhydrite deposits grade upward into interbedded shale and anhydrite and interbedded shale and limestone deposits of the upper Haynesville Formation.

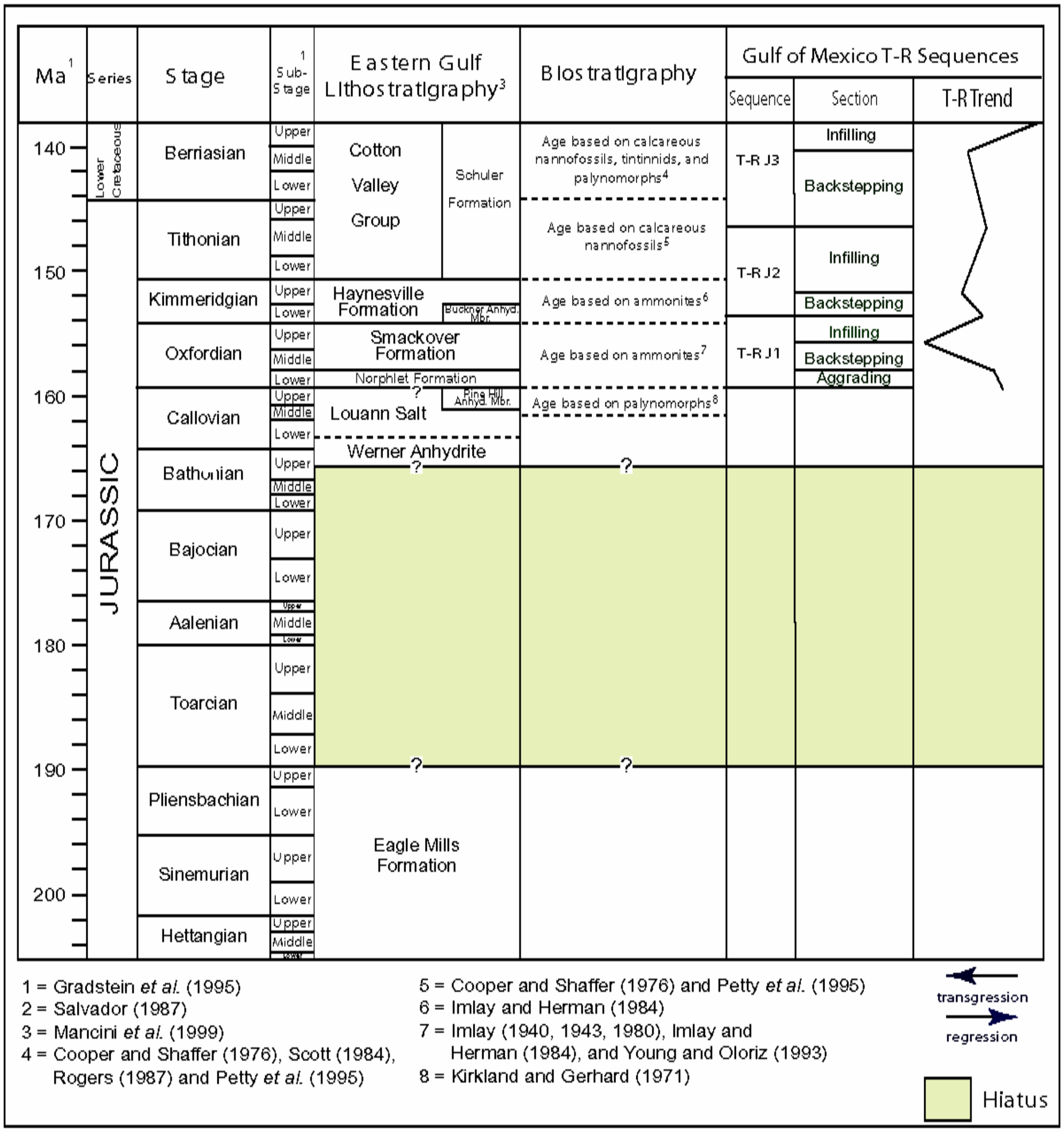


Figure 42. Absolute ages, chronostratigraphic units, lithostratigraphic units, biostratigraphic units, and transgressive-regressive sequences of the Upper Jurassic section, onshore northeastern Gulf of Mexico.

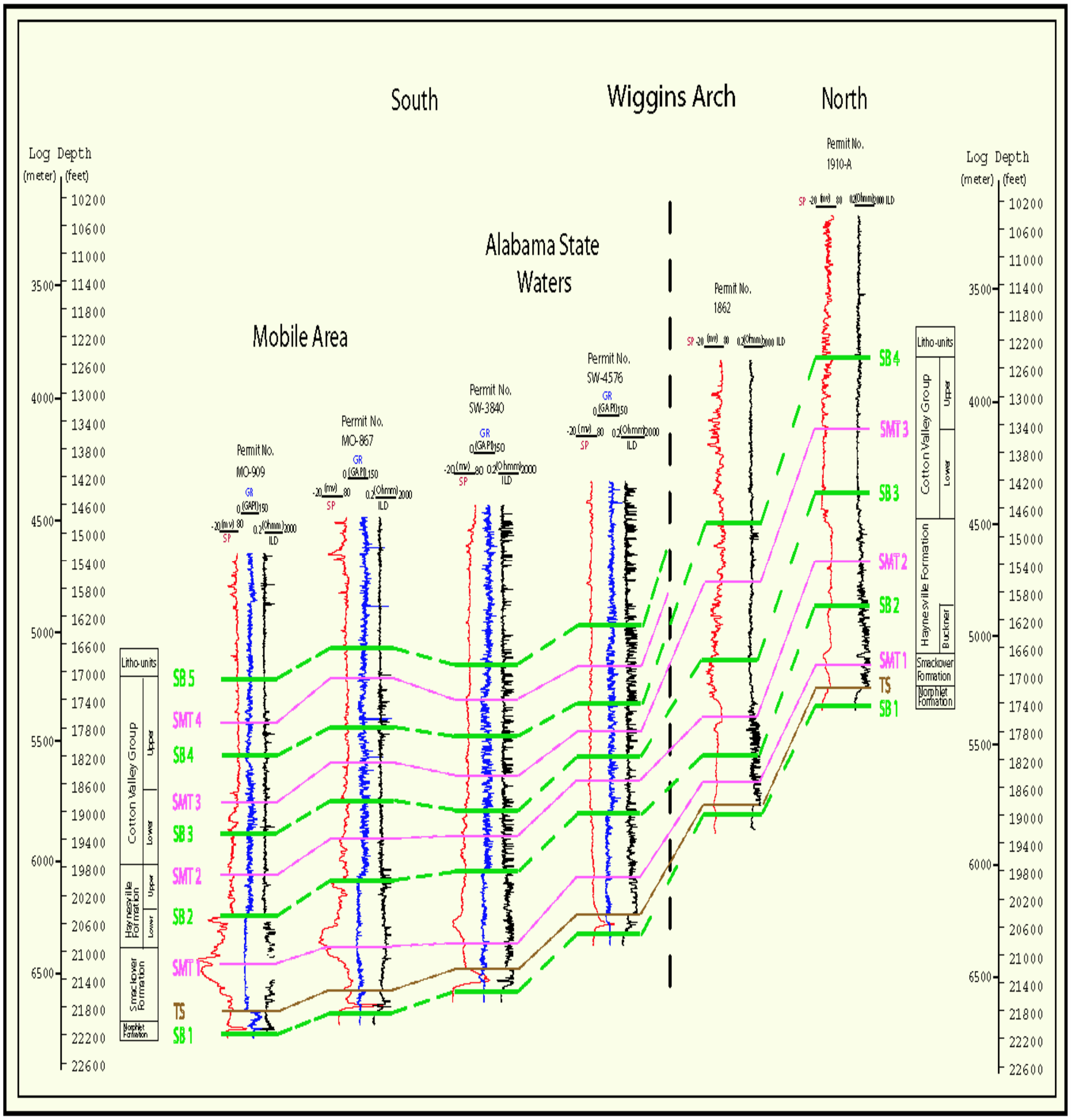


Figure 43. A well log cross section of the selected wells in the study area. Transgressive-regressive sequences, and their associated stratigraphic surfaces, are shown as recognized on well log responses. SB=sequence boundary, SMT=surface of maximum transgression, TS=transgressive surface.

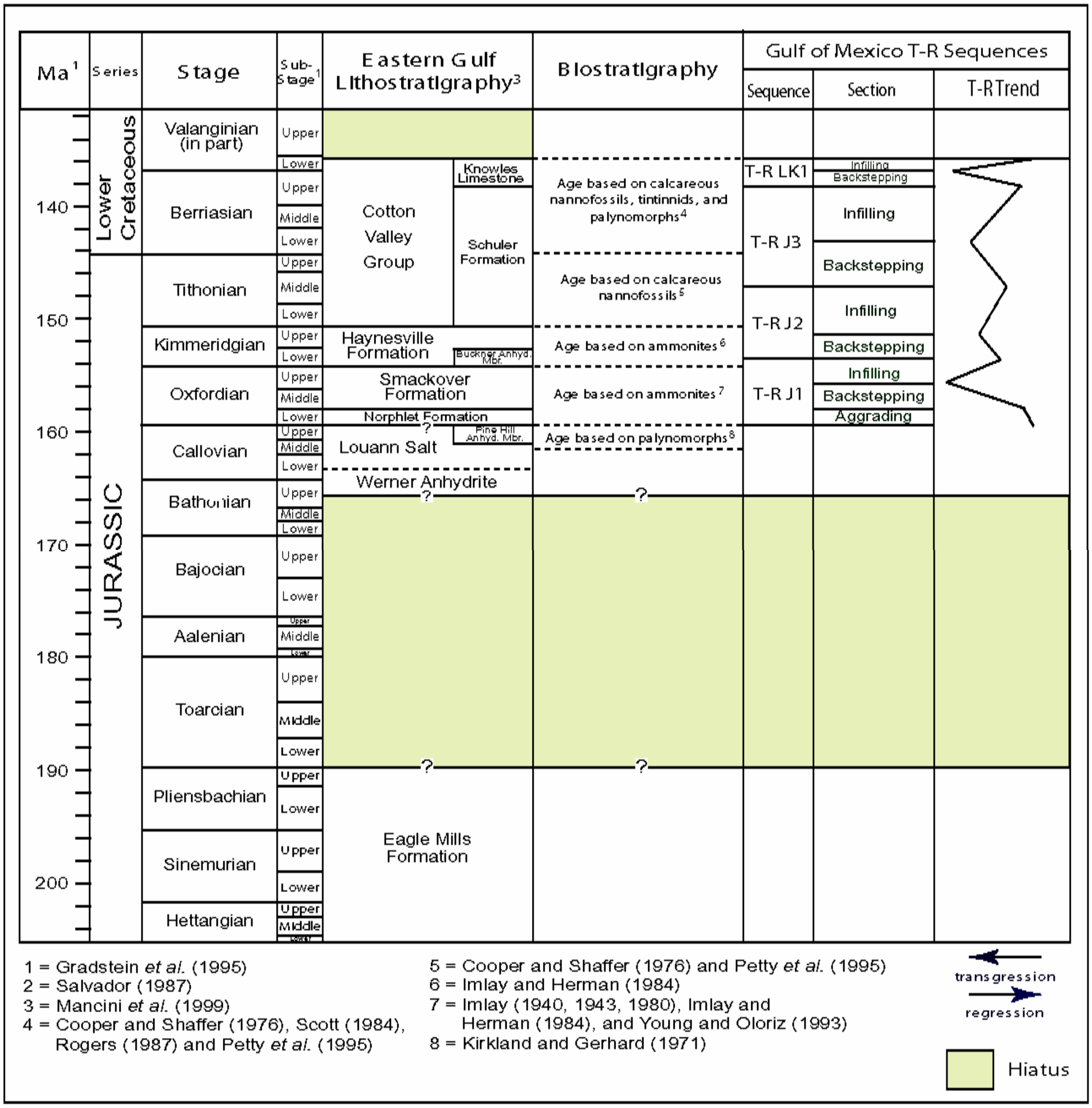


Figure 44. Absolute ages, chronostratigraphic units, lithostratigraphic units, biostratigraphic units, and transgressive-regressive sequences of the Upper Jurassic section, offshore northeastern Gulf of Mexico.

		1910-A	1862	SW-4576	SW-3840	MO-867	MO-909
Sequence 4	R			LS*, Sh, SS*	LS, Sh, Si, SS*	LS, Do*, Sh, SS	LS, Do, Sh, SS*
	T			SS, Si*, Sh, LS*	SS, Si, Sh, LS	SS, Si, Do*, LS	SS, Sh, Do
Sequence 3	R	Sh, SS	Sh, Si, SS	LS*, Sh, Si, SS	LS, Sh, Si*	LS, Sh, Si, SS	LS, Sh, Si, SS
	T	SS, Sh	SS, Si, Sh, LS*	SS, Si, Sh	SS, Si, Sh*, LS*	SS, Si, Do*, LS	SS, Sh, LS
Sequence 2	R	LS, Sh, SS	LS, SS	LS, Sh, Si, SS	LS, Sh, Si*, SS	LS*, Do	LS*, Sh, SS
	T	An, SS*, Sh, LS	An, Sh*, LS	Sh, Si, LS	Si*, An*, LS	Si, Do, LS*	Do, Sh, LS*
Sequence 1	R	LS, Sh*, An	LS, Sh*, An	LS, Do, Sh	LS, Sh, Si*	LS, Si	LS, Do
	T	SS, LS	SS, An, Sh, LS	SS, An*, Do*, LS	SS, An*, Si*, LS	SS, LS	SS, LS

Figure 45. Lithology of the deposits, and associated T-R sequences, from mudlogs and well cuttings for the six selected wells in the study area. SS=Sandstone, LS=Limestone, Do=Dolomite, Sh=Shale, Si=Silt, An=Anhydrite, T=Transgressive systems tract, R=Regressive systems tract.
* denotes small amounts

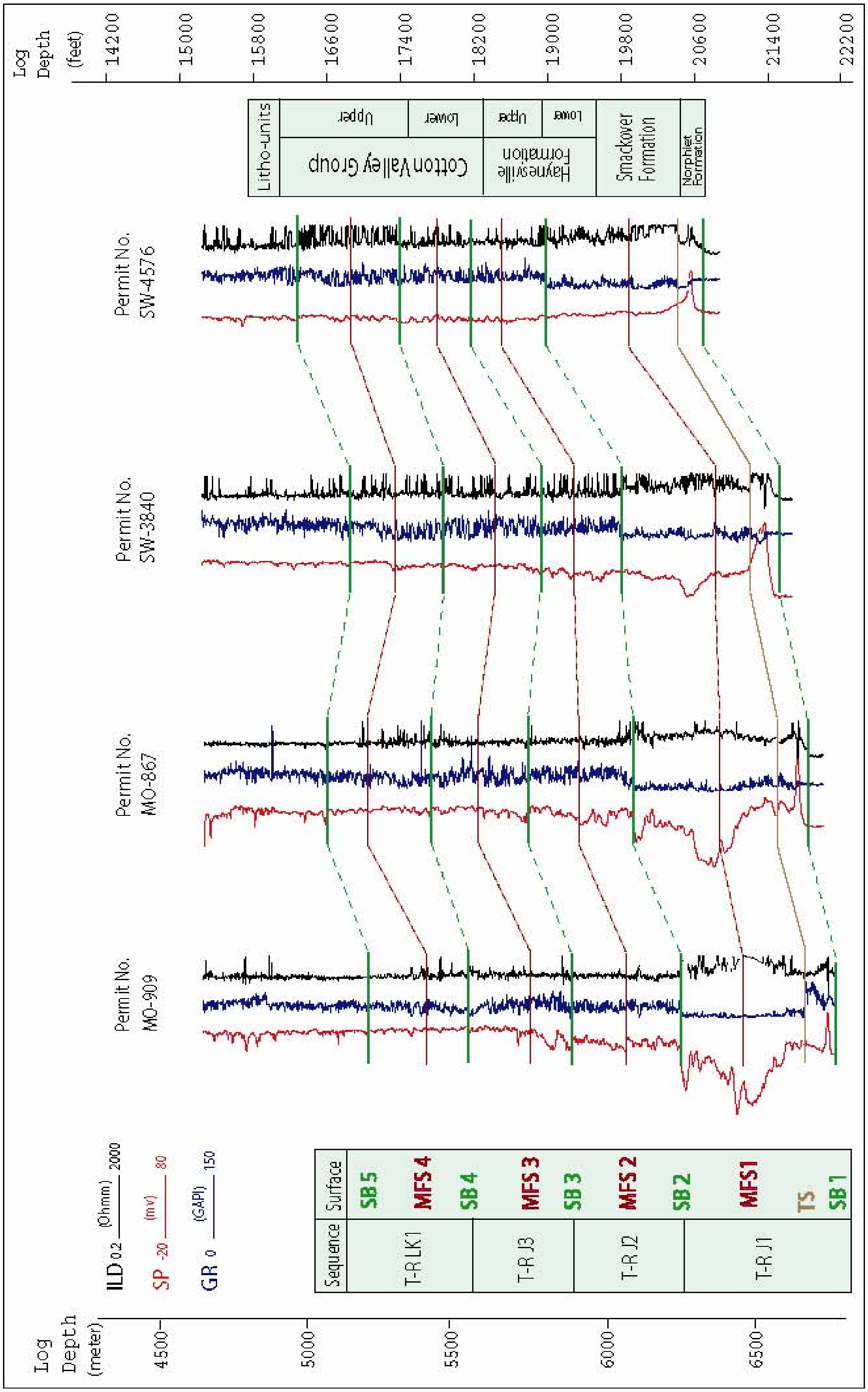


Figure 46. T-R sequences recognized on well log data. Wells are located offshore Alabama, northeastern Gulf of Mexico area. Locations of wells are shown on Figure 29. SB=sequence boundary, TS=transgressive surface, SMT=surface of maximum transgression. (Modified from Obid, 2005a)

The backstepping section of the transgressive systems tract of the T-R J2 sequence includes the bedded (subaqueous) anhydrite, the interbedded anhydrite and shale (lagoonal) deposits, and interbedded shale and limestone (shallow marine) deposits. The interbedded shale and limestone strata grade upward into interbedded shale and sandstone of the upper Haynesville (marginal marine) deposits. The upper Haynesville strata, along with the upper Cotton Valley sandstone (marginal marine and coastal plain) deposits, represent the infilling section of the regressive systems tract of this T-R sequence.

The infilling section of the sequence is separated from the underlying backstepping section by a surface of maximum transgression, which occurs in the interbedded shale and limestone of the lower Haynesville, and interbedded shale and sandstone of the upper Haynesville strata. The SMT separates the two systems tracts of this sequence, and represents a change from an upward deepening (more clay) section to an upward shallowing (less clay) section (Figures 32, 33, 43, 45 and 46). On well logs, the contact of the lower Cotton Valley sandstone deposits with the underlying interbedded shale and sandstone strata (upper Haynesville) is marked by a change in the resistivity log from a serrate signal for the interbedded shale and limestone of the upper Haynesville strata to a more continuous signal for the lower Cotton Valley sandstone strata. The Cotton Valley deposits also are characterized by a more blocky and negative SP and lower resistivity log responses than the Haynesville deposits (Figure 32).

The onshore/offshore Tithonian to Berriasian T-R J3 sequence consists of the upper Cotton Valley Group sand and shale deposits (Figures 42 and 44). On well logs, the contact between the upper Cotton Valley sandy shale strata with the underlying lower Cotton Valley sandstone deposits is recognized by a discontinuity, recorded in a lower resistivity, and more positive SP for the upper Cotton Valley strata, and represents a transgressive surface (Figures

32 and 33). The backstepping section of the transgressive systems tract of this sequence comprises the upper Cotton Valley sandy shale (marine shelf) deposits. The infilling section of the regressive systems tract of this sequence is represented by the sandstone and conglomeratic (nearshore marine and fluvial) deposits of the upper Cotton Valley strata.

The SMT of this sequence occurs in the upper Cotton Valley strata, and is marked by a shift from higher to lower resistivity and from negative to positive SP, and by a higher gamma log responses (Figures 32 and 33). The SMT separates the two systems tracts of this sequence, and represents a change from an upward deepening section to an upward shallowing section (Figures 32, 33, 43, 45 and 46).

In the offshore area, south of the Wiggins Arch, a fourth sequence, T-R LK1, which is Berriasian-Lower Valanginian, was recognized (Figures 33, 43, 44, 45 and 46). This sequence is absent north of the arch, and includes the Knowles Limestone (marine shelf, shoal and reef complex) deposits. The contact of the Knowles with the underlying upper Cotton Valley sandy shale deposits is recognized as a discontinuity on well log pattern. It is marked by a shift from higher to lower gamma ray, and from positive to more negative SP, and a higher resistivity log responses for the Knowles Limestone (Figures 33, 43 and 46).

The Knowles marine shelf shale and limestone beds represent the backstepping transgressive section of this sequence. The shoal and reef complex deposits of the Knowles Limestone represent the infilling regressive section. A SMT occurs in the shale and limestone beds of the Knowles, and is recognized as a shift from lower to higher gamma ray, and more positive SP log responses (Figures 33, 43 and 46). It separates the two systems tracts of this sequence, and represents a change from an upward deepening section to an upward shallowing section (Figures 33, 43, 44, 45 and 46).

North vs. South of the Wiggins Arch Correlation

The Norphlet Formation is a distinctive stratigraphic unit recognized as the first siliciclastic (mainly sandstone deposits) unit below the limestone of the overlying Smackover Formation. It lies unconformably on the salt in relatively downdip locales, and overlie basal black shale, the Pine Hill Anhydrite Member, the Louann Salt, Werner Anhydrite, the Eagle Mills Formation, Mesozoic volcanic rocks, or Paleozoic rocks in updip areas. The uppermost part of the Norphlet section is often massive, indicating marine reworking during the subsequent marine transgression at the end of the Norphlet deposition (Mancini et al., 1999).

The Norphlet Formation in the Mississippi Interior Salt Basin consists of four lithofacies: a basal black shale lithofacies, which occurs in Mississippi and Alabama as well as in the offshore regions of Alabama; a red bed lithofacies, which includes sandstones (subarkose and arkose), siltstones and shales; a cross-bedded sandstone (i.e. Denkman Member), which is also present in Mississippi and Alabama; and a conglomeratic sandstone, occurring in the extreme updip areas of the Norphlet Formation in Mississippi and Alabama (Mancini et al., 1999). In areas adjacent to the Wiggins Arch, Rhodes and Maxwell (1993) examined granite wash in the Norphlet Formation and suggested a source within the granitic basement of the arch.

The Norphlet Formation thickens noticeably in the Mississippi Interior Salt Basin of Mississippi and Alabama. The Norphlet is about 1000 feet thick in Mississippi, and about 800 feet in southwestern Alabama. On the Wiggins Arch itself, the Norphlet is missing. South of the Wiggins Arch, the Norphlet is over 500 feet thick just offshore from Mobile Bay (Mancini et al., 1999). Further offshore, the Norphlet thickness ranges between 600-800 feet and could reach 1000 feet (Mink et al., 1990).

The Smackover Formation in the Mississippi Interior Salt Basin conformably overlies the Norphlet Formation. The Buckner Member (anhydrite beds) of the Haynesville Formation also conformably overlies it. The upper contact of the Smackover Formation, however, can be difficult to recognize in areas south of the Wiggins Arch where the overlying Haynesville Formation is largely carbonate (Mancini et al., 1999). The Smackover Formation in Alabama has been subdivided into lower, middle and upper members (Benson, 1988).

The lower member consists of algal laminate, intraclastic wackestone and packstone, and peloidal-oncoidal packstone and wackestone. The middle member consists of brown to gray skeletal peloidal wackstone interbedded with laminated mudstone. The upper member consists of complex lithologies mainly containing peloidal, oncoidal and oolitic packstone and grainstone (Benson, 1988).

The Smackover Formation in Mississippi differs considerably from the one in Alabama. In Mississippi the Smackover is subdivided only into two members: upper and lower. The upper member is in general coarse grained and quite sandy in certain areas; while the lower member is typically more micritic in lithology, and sandstone is also common (Benson, 1988). South of the Wiggins Arch, the Smackover Formation is little studied. However, the lithology is thought to be more open marine and consists of low-energy, dark gray and dense limestone and of high-energy oolitic and peloidal grainstone shoal deposits (Rhodes and Maxwell, 1993; Tew et al., 1993).

The thickness and facies distribution of the Smackover Formation is influenced by the configuration of the antecedent topography. This is evident in the relatively great thickness of the Smackover in the Mississippi Interior Salt Basin. In contrast, the Smackover thins dramatically, or is missing, over paleotopographic highs such as the Wiggins Arch. The thickness of the Smackover Formation ranges from few hundred feet (onshore and coastal areas of northeastern Gulf of Mexico) to over a thousand feet (south-southwest of coastal areas). It averages around 550-700 feet thick (Mancini et al., 1999; Tew et al., 1993).

The Haynesville Formation in the Mississippi Interior Salt Basin is lithologically variable, and includes shale, anhydrite, sand, conglomerate, and carbonate in varying amounts. The Haynesville is characterized as a mixed siliciclastic-carbonate-evaporitic unit between the Smackover carbonates and the Cotton Valley siliciclastics.

The anhydrite deposits of the Haynesville Formation are often prevailing in the Mississippi Interior Salt Basin and in areas north of the Wiggins Arch, while they are absent in areas south of the arch (Mancini et al., 1999). The Buckner Anhydrite Member of the Haynesville is considered to be the massive anhydrite at the base of the Haynesville Formation, representing deposition in a restricted paleoenvironment landward of a significant barrier, i.e. the Wiggins Arch. It is present in Mississippi as well as in southwest Alabama, except in extreme updip and downdip regions (Tolson et al., 1983). The uppermost part of the Haynesville section is mainly shaly, particularly in southwest Alabama. On paleotopographic highs, the Haynesville sections are often conglomeratic and/or dolomitic in composition. South of the Wiggins Arch, the Buckner anhydrite is absent, and is replaced by interbedded sandstone, limestone, anhydrite and shale deposits of the lower Haynesville (Mancini et al., 1999).

The Wiggins Arch affected the distribution of the various Haynesville lithofacies. During the Jurassic, the arch could have probably defined a platform margin, or steepened ramp, separating dense, dark, micritic limestones offshore from siliciclastic, evaporitic, and carbonate sediments onshore (Cagle and Khan, 1983; and Ericksen and Thieling, 1993). The

Haynesville equivalent beds south of the Wiggins Arch are chiefly dark gray, micritic limestones (Mancini et al., 1999).

The thickness of the Haynesville Formation varies significantly, but averages around 1200-1400 feet. Tolson et al. (1983) suggested that the Haynesville represents a transition between the underlying carbonate deposits of the Smackover Formation and the overlying Cotton Valley Group, with its coarser, continental, siliciclastic deposits.

The Jurassic/partly Lower Cretaceous Cotton Valley Group is mainly paralic deposits between the evaporite, carbonate and siliciclastic sediments of the Jurassic Haynesville Formation below, and the coarse, continental, siliciclastic sediments of the Lower Cretaceous Hosston Formation above (Mancini et al., 1999). Moore (1983) characterized the Cotton Valley Group in Mississippi as predominantly siliciclastic beds. Moore also divided the Cotton Valley Group into three intervals, lower (sandy), middle (less sandy) and upper (the least amount of sandstone, and more limestone) informal members. The updip limit of limestone occurrence in the upper Cotton Valley was mapped by Moore (1983), and was termed the Knowles Limestone. Moore (1983) interpreted the Cotton Valley as being deposited in fluvial, deltaic, strandplain and nearshore marine environments.

The Cotton Valley Group in southern Mississippi was subdivided into three intervals by Ericksen and Thieling (1993). The lower consists of shale, siltstone, and sandstone. The middle consists of shale, limestone, and sandstone. The upper interval consists of sandstone with interbedded limestone. Tolson et al. (1983) described the Cotton Valley Group as consisting of moderate to pale red, light gray and white, fine to very coarse grained sand to conglomeratic sandstone.

In general, in the Mississippi Interior Salt Basin, the Cotton Valley Group is comprised of the Schuler Formation, which consists of coarse siliciclastic sediments that become more conglomeratic updip. The Schuler Formation in onshore northeastern Gulf of Mexico (i.e. in the Mississippi Interior Salt Basin, north of the Wiggins Arch) can be subdivided into two members, a lower Shongaloo Member and an upper Dorcheat Member. The Shongaloo Member consists of red and red-green shale of a darker color than the Dorcheat shale, and of red and white sandstone and conglomerate. The Dorcheat Member, which is partly Lower Cretaceous (Berriasian), is composed of pastel, varicolored shale or claystone, siltstone, and white sandstone (Mancini et al., 1999).

Offshore, south of the Wiggins Arch, the Cotton Valley Group consists of the Schuler Formation (Tithonian to Berriasian) and the Knowles Limestone (lower Valanginian). Unlike the Schuler Formation in the Mississippi Interior Salt Basin, north of the Wiggins Arch, the Schuler Formation south of the arch is undifferentiated (i.e. no Shongaloo or Dorcheat members). The Knowles Limestone is comprised of gray to dark brown dolomitic mudstone and wackestone (Moore, 1983).

Conclusions

In using the concepts of transgressive-regressive sequences, three onshore, and four offshore T-R sequences (T-R J1, T-R J2, T-R J3 and T-R LK1) were recognized in the Upper Jurassic-Lower Cretaceous strata of the northeastern Gulf of Mexico. Each of these T-R sequences consists of a transgressive systems tract, with its backstepping section, and a regressive systems tract, with its infilling section. Recognition of three T-R sequences north of the Wiggins Arch, and four south of the Wiggins Arch, implies that the depositional history of these two areas differ in their geohistories.

Four to five major unconformities/sequence boundaries, identified on reflection seismic data as toplap and erosional truncation surfaces and in well log patterns as discontinuities, and three to four surfaces of maximum transgression, identified on reflection seismic sections as downlap surfaces and in well log patterns as shifts in GR and SP signatures, were recognized as key stratigraphic seismic surfaces representing significant depositional episodes in the geohistory of northeastern Gulf of Mexico. These stratigraphic surfaces were traceable in the study area.

Four seismic facies (A, B, C, and D) were identified on seismic reflection sections in the Mobile Area. Seismic facies D boundaries correspond to sequence boundaries SB3 and SB4 for the T-R LK1 sequence, which implies change in sea level was the major factor influencing the character of seismic facies D. Conversely, the T-R J1 and T-R J2 sequence boundaries do not correspond to seismic facies boundaries, suggesting both tectonic and eustatic influences on the character of seismic facies A, B and C.

Wichita State University Studies-The following is a report from William Parcell on characteristics of Mesozoic stratigraphic sequences of the Bighorn basin of Montana and Wyoming.

Introduction

Wichita State University (WSU) has applied T-R cycle models to describe Middle Jurassic continental and marginal marine units in Wyoming and Montana. This study has encompassed detailed description of Middle Jurassic outcrops in the Bighorn Basin of Wyoming and Montana and has developed a T-R cycle model to characterize stratal architecture and the nature of bounding surfaces of these units.

Initial assessment of outcrops indicated widespread, continuous outcrop belts along the margins of the Bighorn Basin that could be used to examine continuity of bounding surfaces and lateral variation in lithofacies and stratal geometries (Figure 47). Additionally, well log data was collected to further expand the examination of T-R cycles into the subsurface of Bighorn Basin; thereby connecting outcrops on the east and west sides of the Basin. This work involved detailed outcrop descriptions in Wyoming, definition of major lithofacies and their correlation into the subsurface. This work was continued with expansion of outcrop descriptions into southern Montana. With a large and widespread dataset, the interpretation of T-R cycles and the correlation of bounding surfaces was expanded into the subsurface.

Descriptions of Project Objectives

The goals of the study were to integrate outcrop and well log analyses of Middle Jurassic strata in Wyoming and Montana and to view the lateral extent, vertical changes, geometries, and nature of the physical bounding surfaces of the T-R cycles in the field. The purpose of such an undertaking was to support the development of a sequence stratigraphic predictive model for continental and marginal-marine geologic systems.

In order to complete the objectives, WSU was to assess outcrop exposure, accessibility, and completeness, and collect subsurface well log data. Then, detailed outcrop measurements were to be initiated. With outcrop assessment and measurement completed, T-R cycles were to be defined and outcrop measurements to be integrated with well log data through correlation of physical bounding surfaces. All of the objectives were met. The results of this work are described below.

Work Accomplished and Results

Outcrop and Well Log Assessment

The first phase of the project was to assess outcrop exposure, accessibility and stratigraphic completeness. Twenty-four outcrops were chosen (Figure 47) to best represent the variation in lithology while providing as even a distribution of measurement points.

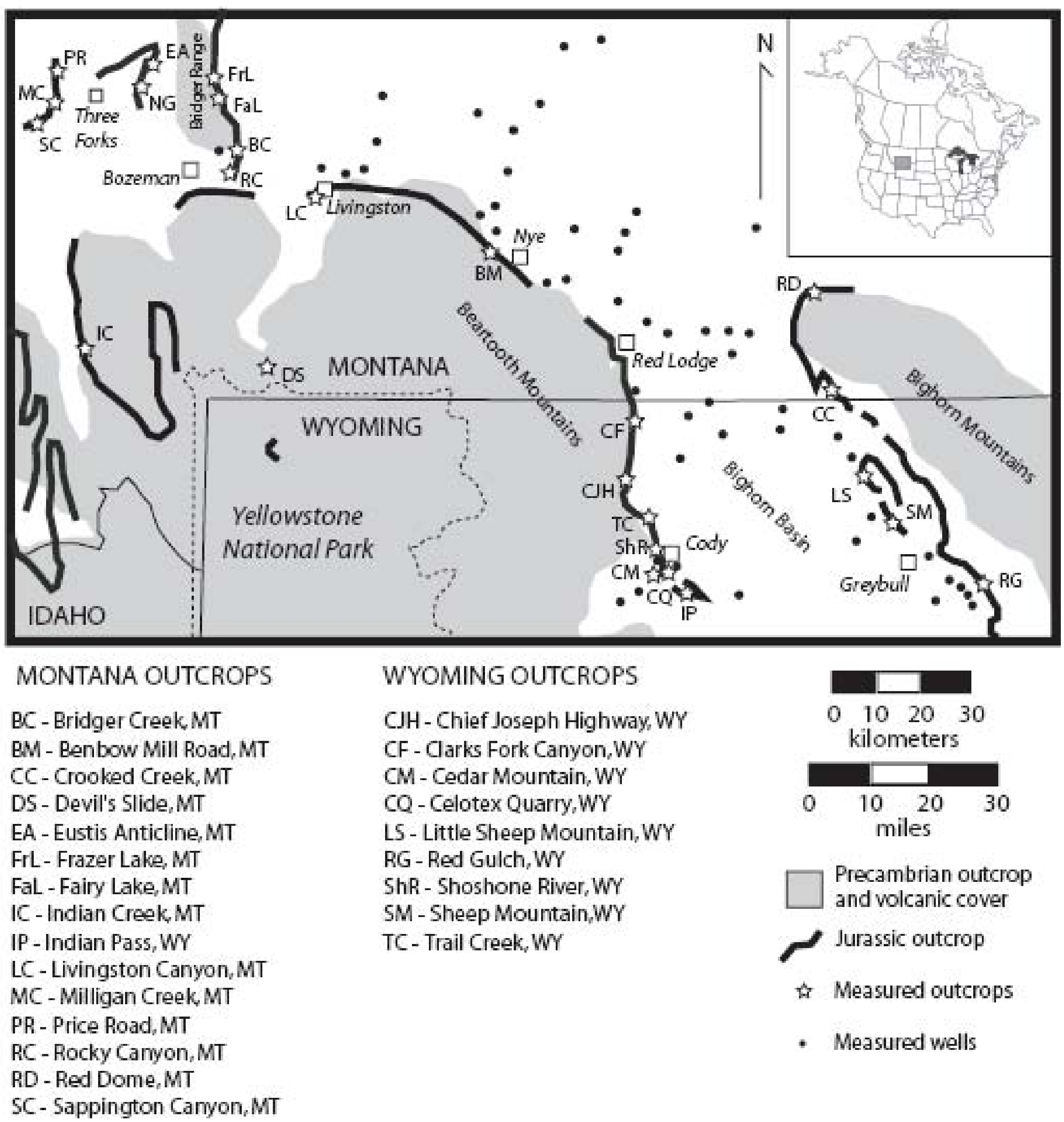


Figure 47. Map of study area showing outcrop and well location.

Eight outcrops were examined in northern Wyoming and 16 outcrops were studied in southern Montana. In northern Wyoming, the outcrops are, (1) Clark's Fork Canyon, State Route 294, (2) Indian Pass, Cody, (3) Chief Joseph Highway, State Route 296, (4) Shoshone River, Cody (Imlay 1956), (5) Trail Creek, Cody, (6) Little Sheep Mountain, Lovell, (7) Sheep Mountain, Greybull, and (8) Red Gulch, Shell. In southern and southwestern Montana, outcrops include, (1) Benbow Mill Road, Limestone, (2) Bridger Creek, Bozeman (Gardner et al. 1946), (3) Crooked Creek, (4) Devil's Slide, Gardiner, (5) Eustis anticline, Manhattan, (6) Fairy Lake, Bridger Mountains, Bozeman, (7) Fraser Lake, Bridger Mountains, Bozeman, (8) Indian Creek, Madison County (Gardner et al. 1946), (9) Livingston Canyon, Park County, (10) Milligan Canyon, Three Forks, (11) Nixon Gulch, Manhattan, (12) Price Road, Three Forks, (13) Red Dome, (14) Rocky Canyon, Bozeman, (15) Sappington Canyon, Three Forks, and (16) Crooked Creek.

General Formation Description

These twenty-four outcrops, supplemented with well logs, provided an opportunity to view the lateral extent, vertical changes, geometries, and nature of the physical bounding surfaces in the field; elements critical to the formulation and application of a T-R cycle model.

The Sawtooth, Piper, and Gypsum Spring Formations represent the Bajocian and Bathonian section (Figure 48) in Wyoming and Montana. The Sawtooth Formation in western Montana varies between limestone, dolomite, shale, siltstone, and sandstone. The Sawtooth Formation is divided into three units: (1) a basal sandstone/siltstone unit, (2) a middle limestone/shale unit, and (3) an upper shale/siltstone unit (Cobban, 1945). Imlay et al. (1948) defined the Piper Formation from exposures near Lewiston, Montana because lithologies in southern and eastern Montana are dominated by carbonates and evaporites. The Piper is likewise divided into three formal members: (1) Tampico Shale Member, (2) Firemoon Limestone Member, and (3) Bowes Member (Nordquist, 1955). Equivalent units in northern Wyoming are called Gypsum Spring Formation. It is also informally divided into three major lithologic units based on lithology and regional continuity of strata. The basal unit contains predominantly white, massive gypsum or anhydrite with interbedded noncalcareous red shale and siltstone. The middle unit contains interbedded green-gray to varicolored shales and gray, black, and brown limestones. The informal upper unit contains primarily red to gray shale and siltstone. The wide variety of member and subunit names in the Sawtooth, Piper, and Gypsum Spring formation is quite confusing and has led to miscorrelations of the Jurassic section. Therefore, for simplicity of discussion, the following informal terms are used for this project: 1) Lower Unit (includes basal unit of Sawtooth Formation, Tampico Member of Piper Formation, and lower unit of Gypsum Spring Formation), 2) Middle Unit (includes middle limestone/shale unit of Sawtooth Formation, Firemoon Member of Piper Formation, and upper limestone and shale member of Gypsum Spring Formation), and 3) Upper Unit (includes upper shale/siltstone unit of Sawtooth Formation, Bowes Member of Piper Formation in Montana, the Piper Formation as commonly denoted in Wyoming, and the informal upper member of the Gypsum Spring Formation).

The Sawtooth, Piper and Gypsum Spring formations are overlain by the Bathonian to Callovian Sundance and Rierdon formations (Figure 48a). The “Lower Sundance” Formation of Wyoming and equivalent Rierdon Formation of Montana consist of interbedded gray-green shale, limestone, and sandstone with some green, slightly glauconitic, ripple-marked siltstone near the top.

Siliciclastics occur throughout the “lower” Sundance but increase frequently towards the top of the formation. They are usually light gray to white or buff, well sorted, dominantly fine-grained sandstones, and occasionally oolitic or glauconitic (Mills 1956). White, gray, and tan argillaceous limestone beds occur throughout the section. Shale predominates over limestone except in a few areas (Imlay 1980). Shale beds are usually gray-green, but some red to maroon, papery, soft varicolored units are present.

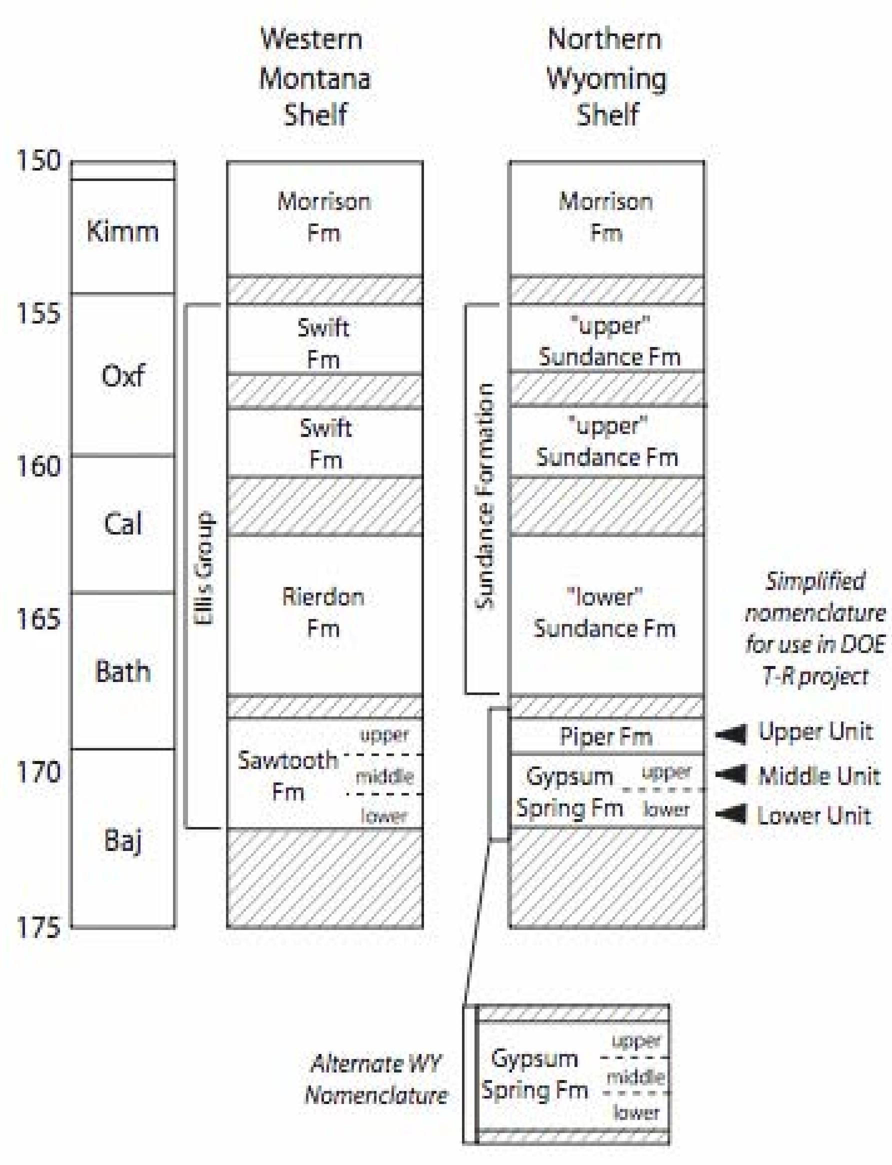


Figure 48a. Stratigraphy of the Middle Jurassic section across western Montana and northern Wyoming. The Sawtooth, Piper and Gypsum Spring formations represent mixed siliciclastic-carbonate –continental deposition.

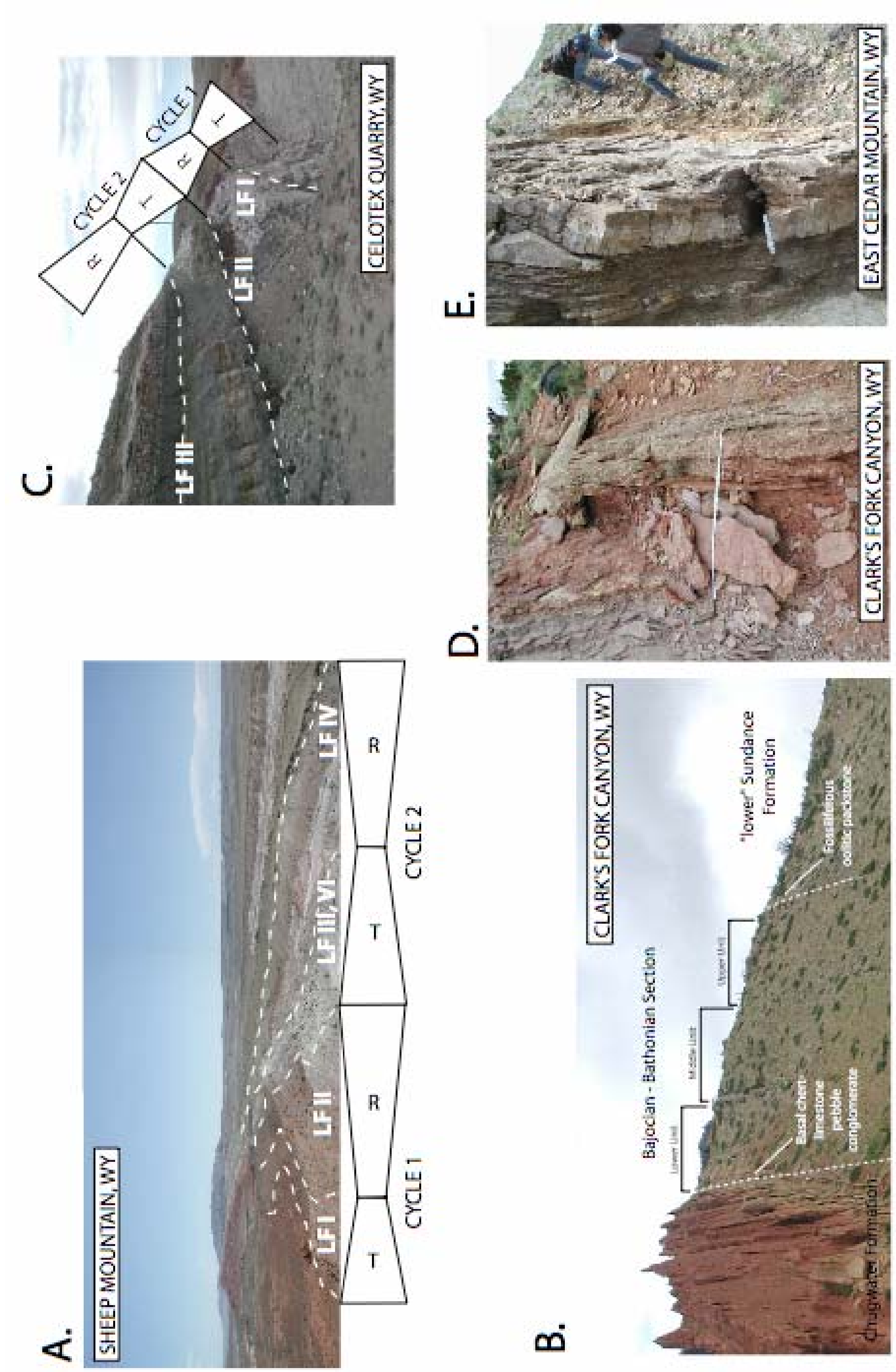


Figure 48b. Outcrop photographs of significant lithofacies, bounding surfaces and T-R cycles in the Bajocian to Bathonian section in Bighorn Basin, Wyoming. Outcrops surrounding Sheep Mountain in the eastern Bighorn Basin (A), exposures at Clark Fork Canyon (B), and near Cody, Wyoming (C) provide complete sections to describe T-R cycles. The base of the Jurassic section is often characterized by a chert-limestone conglomerate (D) marking the beginning of the transgressive phase or T-R cycle 1. The surface of maximum sediment starvation of T-R or T-R cycle 2 is marked by a hardground, recognized by fossil concentrations and developments of microbial buildups (E).

Descriptions of the twenty-four outcrops included the notation of lithology, grain or fossil-fragment size/sorting, mineralogy, nature of physical bounding surfaces, sedimentary structures, macrofossils, and bioturbation. Thin sections were prepared, point-counted, and described; hand samples were analyzed; and macro-, micro-, and trace fossils were noted. In areas where outcrops did not exist, well logs were tied-in to establish 3-D lithofacies and stratigraphic geometries.

Outcrop and subsurface measurements of the Middle Jurassic section in northern Wyoming and southern Montana have resulted in the classification of ten primary lithofacies including: gypsum, varicolored shales, limestones, microbial laminates, dolomites, siltstones, and chert. These ten lithofacies are recognized by outcrop, hand sample, and thin section descriptions of sedimentary texture and structure, mineralogy, and fossil assemblage. Outcrop photographs showing representative examples of T-R cycle bounding surfaces and lithofacies are shown in Figure 48b.

Lithofacies I (LF I) – gypsum

Massively bedded, cliff-forming, white gypsum or anhydrite can dominate the base of the Middle Jurassic section in southern and eastern Montana and northern Wyoming. Individual beds average 2.0 m but some thicker beds (up to ~ 10 m) are present in various locations. At some sites, the basal gypsum can thin to zero in less than a kilometer with chert and gypsum nodules, dolomite, or a siliceous limestone breccia occurring in its place. Thin beds of various lithologies can often be found interbedded with the gypsum/anhydrite. These units are most commonly composed of moderate brown, noncalcareous shale. Gypsum nodules or thin layers or lenses of gypsum are often interbedded with or intergrown with the shale sediments.

Lithofacies II – reddish brown shale

Moderate brown shales dominate the Lower and Upper Units of the Middle Jurassic section. These reddish-brown shales are generally noncalcareous and laterally continuous. Thin units of gypsum or gypsum nodules (usually < 0.5 m, but may be up to 1.5 m) are frequently found interbedded with the shales throughout each section.

Lithofacies III – gray-green shale

Greenish-gray, typically calcareous, shales occur in the Middle Jurassic section. Most beds are continuous over the study area. Argillaceous limestones, varicolored shales and occasional gypsum nodule lenses are often interbedded with the green-gray shales. The oyster, *Gryphaea calceola* var. *nebrascensis*, the crinoid, *Pentacrinus* sp., and the coral, *Coenastraea hyatti* Wells are typical biota characteristic of this facies.

Lithofacies IV – varicolored shale

Varicolored calcareous and noncalcareous shales are found primarily in the Middle Unit across Wyoming and Montana. Contacts between the varicolored shales and the surrounding varicolored, greenish-gray, or reddish-brown shales are gradational. Many of these shales contain gypsum nodules or lenses and some chalcedony may be present locally.

Lithofacies V – siltstone

Few thin siliciclastic beds are found in the southern Montana and northern Wyoming, but are pervasive in northern Montana. Greenish-gray to yellowish-brown units contain subangular to subrounded quartz crystals and are usually calcareously cemented. At some locations, the siltstone is rippled and contains minor pelecypod fragments. Where sandy limestone-chert breccias replace the lower member gypsum, rounded quartz grains are often present as inclusions in the matrix.

Lithofacies VI – chert

Chert in the Middle Jurassic section occurs in two forms: (1) mixed chert-limestone pebble conglomerate or breccia and (2) beds of dark laminated chert. The brecciated chert is found at the base of the Piper and Sawtooth Formations and is mixed with limestone fragments (e.g. the base of section at Clark's Fork Canyon). Laminated chert layers have been reported at multiple stratigraphic intervals in the Middle Jurassic section in the Bighorn Basin (Kvale et al., 2001). Chert horizons have been described in the Gypsum Spring Formation (Imlay, 1956), at the base of the Sundance Formation (Imlay, 1956), and within the Sundance Formation (Imlay, 1956; Kvale et al., 2001).

Lithofacies VII – carbonates

Limestones and microbialites in the study area are found predominantly in the Middle Unit of the Sawtooth, Piper and Gypsum formations and in the "lower" Sundance Formation.

Lithofacies VIIm – mudstone, microbial laminate (VIIml), dolomite (VIId)

Mudstones (LF VIIm) are typically gray to yellow-gray with laminated to thin, wavy/hummocky bedding. Some locations contain minor interbedded gypsum, reddish-brown or gray-green shale, or, rarely, subangular to rounded quartz grains. Outcrop mudstones contain minor pelecypod fragments, occasional small algal heads, minor oncoids, peloids, and burrows. Many locations show signs of bioturbation.

Lithofacies VIIw – wackestone

Wackestones in the study area are laminated to thin, wavy bedded units (< 10 cm) with pelecypods, crinoids, gastropods, foraminifera, oolites, peloids, and mudclasts. These allochems are often found as nuclei for ooids and peloids but some are uncoated grains within the matrix. In addition to fossil nuclei, some subangular to rounded quartz grains are used for nucleation also. Some locations show burrows and bioturbation, and minor amounts of iron are concentrated locally along algal laminations. The matrix is typically calcitic with traces of gypsum.

Lithofacies VIIpg – packstone and grainstone

Packstones and grainstones occur in the Middle and Upper Units and "lower" Sundance Formation. Most of these limestones vary from olive-gray to yellowish gray. Some rippled and cross-bedded units were found but most are typically thin bedded (< 10 cm) to medium bedded (up to 20 cm) with some bioturbation. Peloids and ooids, with fossil fragments or quartz grains for nuclei, make up the majority of the allochems found in these limestones. Fossils, either as nuclei or as uncoated grains, include pelecypods, foraminifera, brachiopods, gastropods, echinoderm fragments, and crinoids, including *Pentacrinus* sp. Other allochems include algal and micrite clasts, chert clasts, minor mud clasts, minor gypsum, and angular to subrounded quartz grains. Many fragments contain micrite envelopes. Fossils and other allochems are often aligned parallel to bedding. Matrix is typically recrystallized calcite with some trace gypsum in several locations.

Lithofacies VIIt – thrombolite

Thrombolites are cryptalgal structures that resemble stromatolites but lack distinct laminations and are characterized by macroscopic clotted fabric. These buildups may have formed through entrapment of detrital grains without layering or organization. In the Middle Jurassic section in the northern Bighorn Basin of Wyoming, thrombolites occur as isolated buildups. The East of Cedar Mountain outcrop, near Cody, WY, contained several thrombolite patches resting on and slightly grown down into a rippled, fossiliferous, oolitic, peloidal packstone to grainstone. The underlying limestone is medium bedded (~ 10 cm) in the lower part and thins upward. Allochems include pelecypod hash, crinoids, echinoderms, some gastropods, and rounded, elongate micritic fragments.

Data Integration and T-R Cycle Characterization

Outcrop descriptions and measurements were correlated to well logs in the Bighorn Basin and southern Montana. This provided a regional picture of the nature of stratigraphic geometries and resulting lithofacies distribution. A stratigraphic cross section combining outcrop and well data are represented in Figure 49.

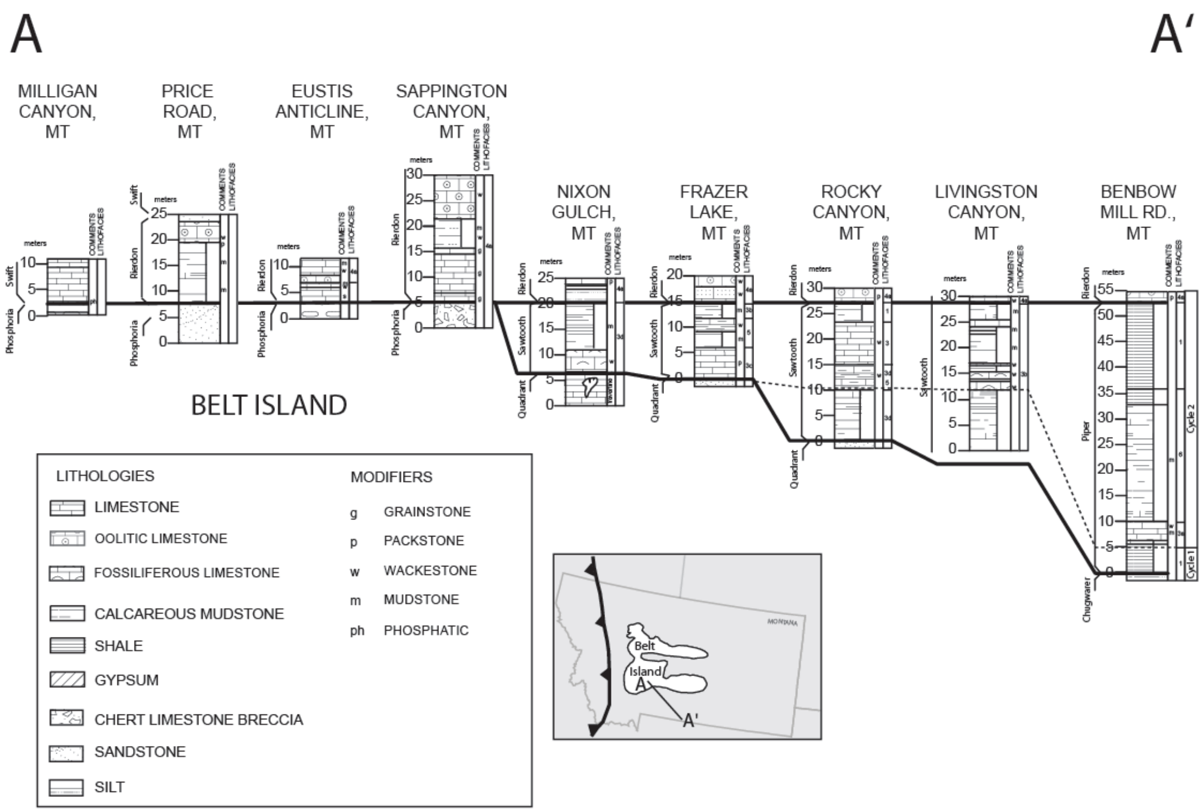


Figure 49. Cross section showing lithostratigraphic relationships along the southern margin of Belt Island.

To permit detailed integration, outcrop descriptions and drill-hole GR log surveys were performed at outcrops. The equipment used for field measurements was a portable 256-channel gamma-ray spectrometer, capable of determining total natural gamma counts as well as concentrations of potassium, thorium, and uranium. For the purposes of this study, total gamma ray measurements were examined. The spectrometer was tested in the lab and in the field to determine its vertical resolution and replicability. All GR logging was in the form of up-section traverses coinciding with the location of field descriptions. Each gamma-ray traverse consisted of measurements at 0.1 to 0.5 m (0.3 ft to 1.5 ft) intervals, depending on access and survey efficiency. Total gamma-ray count (in counts per second or CPS) was averaged over a 10 second interval at each sampling location. The results from field descriptions and outcrop gamma-ray logs were correlated to subsurface drill-hole logs using the GeoPlus software package Petra.

Gamma ray signatures measure the total natural radioactivity from rock formations, of which nearly all is emitted by the radioactive potassium isotope and radioactive elements of the uranium and thorium series. In sedimentary rocks, the log normally reflects the shale content because these radioactive elements tend to concentrate in clays and shales. Field descriptions of the Gypsum Spring and Piper Formations indicate a systematic variation in shale content relative to lithofacies (LF) type and stratigraphic position. In response, GR logs show characteristic and correlatable signatures within the Middle Jurassic section. Representative outcrop descriptions and their associated GR profiles are shown in Figure 50.

These are used to construct synthetic sections for nearby wells that were logged. Well-log readings of LF I (gypsum/anhydrite) are predictably very low, but are clearly punctuated by interbedded shales, which respond as a sharp increase in the gamma-ray reading. LF II (reddish brown shales), and as such much of the Lower and Upper Units, are characterized on gamma-ray logs as either a persistently high reading or a gradual upsection increase in radioactivity. The gray-green shales (LF III) and varicolored shales (LF IV) are typically lower than LF I facies. Therefore, much of the Middle Unit, which is largely composed of this facies, responds lower than the reddish brown shales of Lower and Upper Units. There was not enough of LF V and VI facies (siltstone and chert) across outcrops and wells to make a definitive statement about their gamma ray characteristics. The various limestone facies (LF VII) in general produced a relatively low gamma ray response; however, variation in shale content apparently results in the limestone beds having an increased signal.

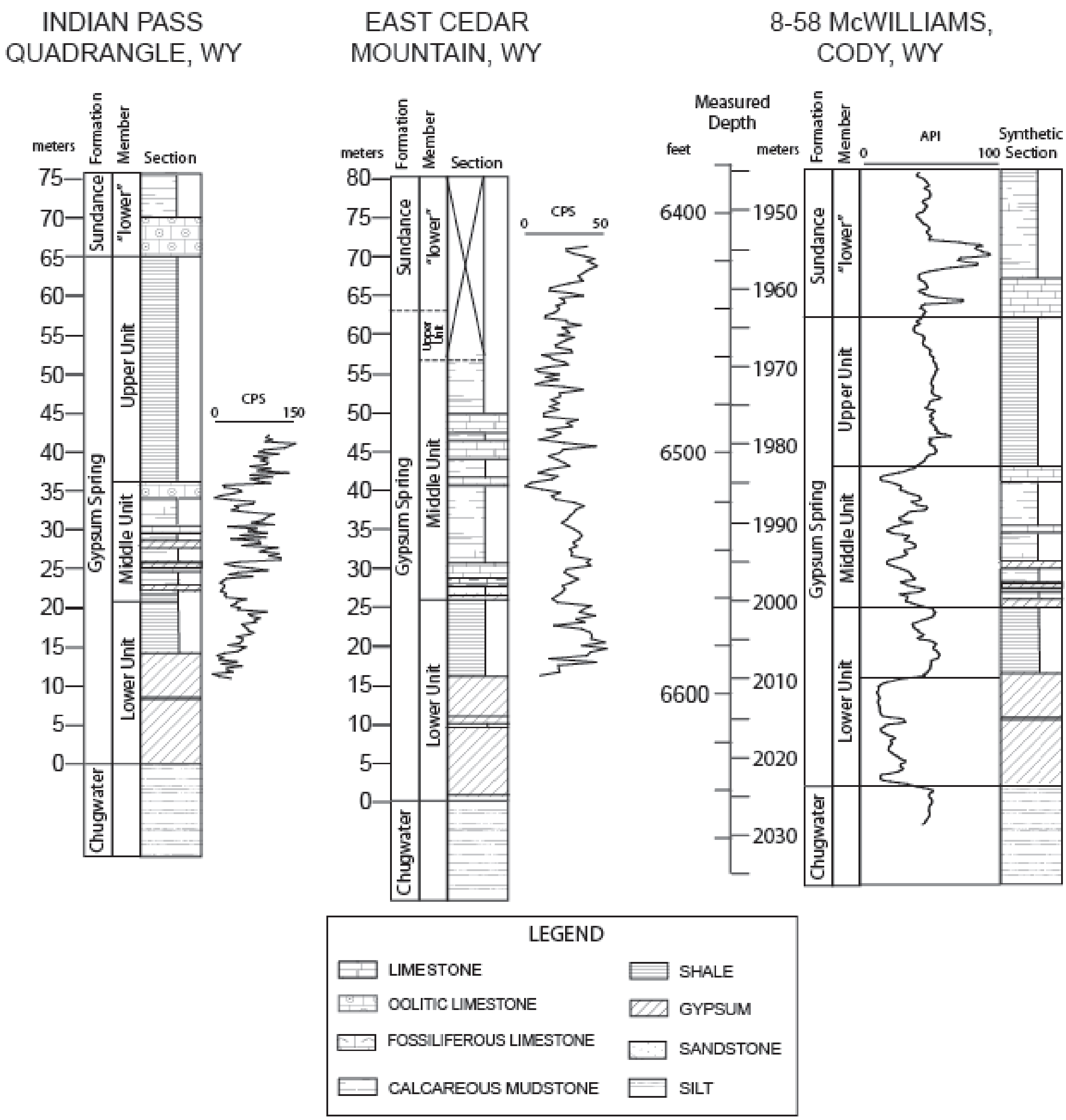


Figure 50. Sections and gamma ray profiles for two outcrops and a well near Cody, Wyoming.

Stratigraphic relationships within the Bajocian to Bathonian section were interpreted from characteristic bounding surfaces, stacking patterns, and lateral facies relationships. Outcrop descriptions, gamma ray measurements and well logs in the Bighorn Basin and southern Montana provided a regional picture of the nature of stratigraphic geometries and resulting lithofacies distribution. Six regionally significant surfaces are recognized in outcrop and wells which separate genetically related strata of two T-R cycles in the Middle Jurassic section (Figure 51). These surfaces are (1) a regional unconformity at the base of the Middle Jurassic section, (2) a gradational boundary between the basal gypsum beds and redbeds of the Lower Unit, (3) a gradational to sharp (and locally unconformable) contact at the base of the Middle Unit, (4) a horizon within the Middle Unit marked by the coral *Coenastraea hyatti* Wells, thrombolite buildups (LF VIIt), and the *Pleuromya compressa* bivalve assemblage, (5) a gradational boundary between the Middle Unit and Upper Unit, and (6) an abrupt (and locally unconformable) contact between the Upper Unit and the “lower” Sundance Formation.

The first major depositional cycle is underlain by a major regional unconformity that separates the Middle Jurassic from Triassic and Paleozoic units below. This cycle represents deposition dominated by restricted marine and sabhka conditions. The subaqueously deposited lower gypsum beds of the Piper and Gypsum Spring formations correspond to the transgressive phase, and the lower redbeds represent the regressive phase of the first cycle. A sharp to gradational contact at the base of the Middle Unit defines the boundary between the first and second T-R cycles. This contact is also unconformable when associated with local paleohighs such as the Sheridan Arch in north-central Wyoming and Belt Island in central Montana. The Lower Unit varies in thickness related to pre-Jurassic topography. The Lower

Unit pinches out against Belt Island and thickens dramatically in subbasins in northern Wyoming.

A second T-R cycle is recorded in the Middle and Upper Units. This cycle represents a wider range of depositional environments ranging from more open marine to sabkha settings. The Middle Unit corresponds to the transgressive and the early regressive phase, while the upper portion of the Upper Unit represents the late infilling regressive episode. A regionally significant horizon marked by the coral *Coenastraea hyatti* Wells, thrombolite buildups (LF VIIt), and the *Pleuromya compressa* bivalve assemblage occurs within the Middle Unit and marks the sediment starvation surface (SSS on Figure 51) of the second cycle. The early regressive phase of the second cycle is characterized by dark green-black, shaly to silty carbonate mudstones of LF VIIm and is recognized in well logs by a gradual gamma-ray increase in the upper portions of the Middle Unit. The aggradational phase of the second T-R cycle is also recognized by an increase in upsection winnowing from LF VIIw to VIIpg facies. The Middle Unit maintains a fairly consistent thickness across the study area but gradually thickens along the margins of Belt Island and the Sheridan Arch.

The Upper Unit represents deposition during the infilling regressive phase of the second T-R cycle. The lower contact of the regressional phase is gradational from the transgressive units below. The upper contact of the regressive phase is sharp against the overlying oolitic packstones and grainstone (LF VIIpg) of the Rierdon and “lower” Sundance formations. The thickness of the Upper Unit also varies in relation to local structures. The Upper Unit thins along the margin of the Sheridan Arch in north central Wyoming and along the southern margin of Belt Island in central Montana.

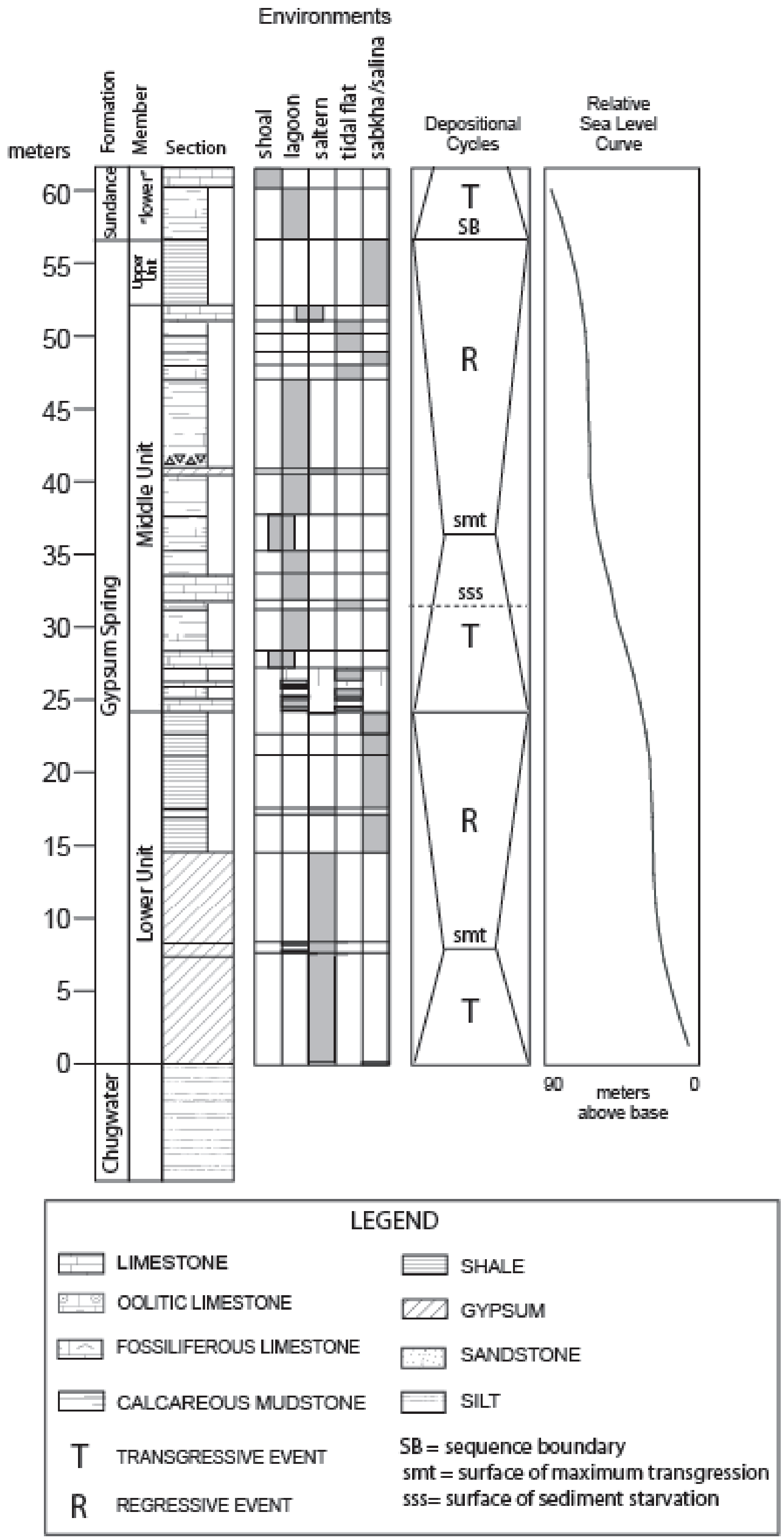


Figure 51. Representative stratigraphy of the Middle Jurassic section across western Montana and northern Wyoming.

Final analysis of the sequence stratigraphy model included testing the T-R cycle and sequence stratigraphic model developed to additional Jurassic sections in southwestern Montana. This area of Montana, represented by the Sawtooth Formation, has an increase in siliciclastic components to the sediments. The stratigraphic model encompasses the Sawtooth Formation in its analysis. Two major cycles are recognizable in the Sawtooth units up to the extreme margin of Belt Island . Near the updip limit of the Middle Jurassic section along Belt Island, it proves difficult to distinguish between the two major depositional cycles, and in fact, only one cycle may be represented. Most likely only the upper cycle is represented along the updip limit of the Middle Jurassic.

McGill University Studies-The following is a report from Bruce Hart on characteristics of Mesozoic stratigraphic sequences of the Atlantic Shelf, Alberta, New Mexico and the Gulf of Mexico.

Seismic Analyses

Seismic analyses undertaken established the reflection character of T-R cycles using data from the Gulf of Mexico (Location 1 on Figure 52). Additional seismic datasets were included to: a) help define the controls (i.e., bed thickness and rock velocity) on recognition of key reflection configurations used to develop seismic stratigraphic models, b) make the T-R cycle model more general by including data from different areas (North American foreland basins and other passive margins), and c) examine the seismic expression of key surfaces using 3-D surveys such as those that are commonly available to small independent producers. Lower and Upper Cretaceous marginal marine clastics are the target intervals for this work.

Key to this work is the inclusion of geologic "ground truth" in the form of measured outcrop or core sections from the intervals of interest.

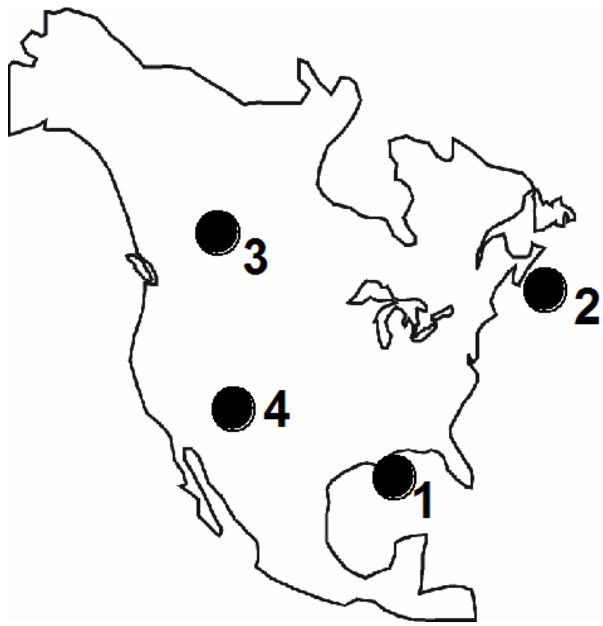


Figure 52. Location of seismic study areas: 1) Gulf Coast, 2) Scotian Shelf, 3) Deep Basin and 4) San Juan Basin.

Database

The seismic database consists of three 3-D seismic surveys and associated well and other data. Two of the 3-D seismic surveys are from the Atlantic margin of North America (Scotian Shelf; Location 2 on Figure 52). They cover areas of approximately 340 km^2 (~130 square miles) and 96 km^2 (~ 38 square miles). Like some Gulf Coast counterparts, wells in this area penetrated Tertiary and Cretaceous clastics drilling to Cretaceous and Jurassic targets. No cores are available from the larger survey area, and so lithologic control is derived using logs and ties to the smaller 3-D survey area located to the northeast (Cummings et al., 2006b). The surveys image the Lower Cretaceous shelf (smaller survey) and shelf margin (larger survey), making them an ideal dataset for studying how stratigraphic surfaces formed on the shelf make their way into deeper water.

The third survey is from the Deep Basin of Alberta (Location 3 on Figure 52). This 3-D dataset covers an area of approximately 460 km^2 (180 square miles) has a 30 x 40 m (98 x 131 ft) bin size and a 2 ms sampling rate. The database includes measured core, wireline logs, and production data. Core sections were measured to provide lithologic control for the seismic interpretation. Like productive, time-equivalent rocks of the Rocky Mountain area to the south, the Cretaceous clastics analyzed in this study were deposited along the western margin of the Western Interior Seaway, with T-R cycles developing in response to interactions between subsidence, sediment supply and eustatic sea-level change.

The San Juan Basin (Location 4 on Figure 52) produces gas from Upper Cretaceous T-R cycles, primarily from unconventional reservoirs in the Dakota Formation and Mesaverde Group (both "tight-gas" reservoirs) and the Fruitland Formation (coalbed methane). Long seismic lines show dip sections that are longer to view than can be seen in 3-D data. As such, they help to examine large-scale stratigraphic geometries that cannot be imaged in even large 3-D surveys like those employed in this study. Outcrop sections were measured in the San Juan Basin in order to provide lithologic control for the seismic interpretation.

Results

We discuss each study area separately.

Atlantic Shelf Dataset

This area shares many similarities with the U.S. Gulf Coast. Jurassic carbonates and overlying Cretaceous and Tertiary clastics are drilling targets. Lower Cretaceous (Berriasian to Cenomanian) marine, marginal marine, and continental clastics of the Missisauga and

Logan Canyon formations are imaged in the two 3-D seismic data volumes from the Scotian Shelf. The general stratigraphy of this area was established by Wade and MacLean (1990). Cummings et al. (2006b) examined the stratigraphy of the "Upper Member" of the Missisauga, and the overlying Naskapi and Cree members of the Logan Canyon Formation using 3-D seismic data, logs and core from an area that was situated on the paleoshelf. A strike-oriented section through their dataset (Figure 53a) shows incision that is easily recognized being caused by fluvial incision during lowstand. In fact, two such sequence boundaries may be present. Fluvial sands directly overlie the sequence boundary and marginal-marine deposits (e.g., hummocky cross-stratified sandstones) underlie it. This seismic transect is flattened on the O Marker, a mixed carbonate-siliciclastic unit that generates a strong seismic reflection in proximal parts of the shelf and which separates the Upper Member of the Missisauga Formation from the underlying units.

We extended the seismic-based stratigraphic analyses to a 3-D seismic data volume located SW of the dataset shown in Figure 53a. This volume images the Missisauga and Logan Canyon shelf margin (Figure 53b), and together the two seismic volumes provide a unique opportunity to examine the relationships between shelf incision and continental margin progradation. Two uncored (in the Cretaceous section) wells are located in the survey area, and the stratigraphy of these wells was established by correlations with wells studied by Cummings et al. (2006b). Stratigraphic analyses of this dataset have resulted in the identification of one, and possibly two unconformities in the Upper Missisauga that probably correlate to the features identified in Figure 53a. In Figure 53b, the unconformities can be seen to truncate the O Marker near the shelf margin. Unfortunately shelf-margin clinoforms are not well developed in the Missisauga, possibly because of synsedimentary slumping. A "hot shale" (condensed section) in logs at the top of the Naskapi shale can be correlated basinward to a downlap surface below the Cree Member, and therefore, can be recognized as a maximum flooding surface.

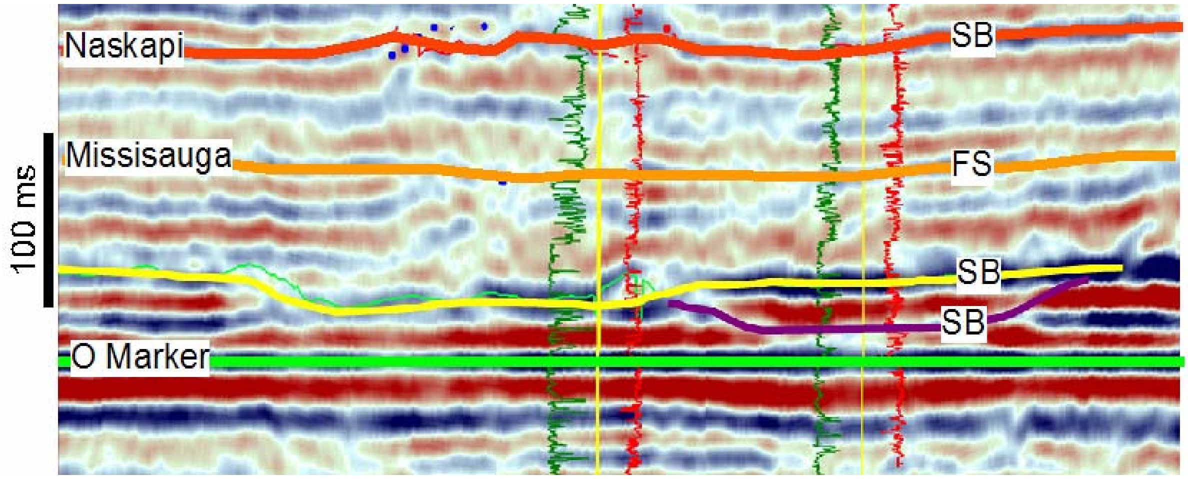


Figure 53a. Strike-oriented seismic transect showing seismic expression of a subaerial erosion surface/sequence boundary (yellow) in the Missisauga Formation on the Scotian Shelf (Location 2, Figure 52). A second sequence boundary (purple) may be present at this level, implying relatively short-lived (e.g., fourth order) sea-level fluctuations superimposed on a longer fall of relative sea level.

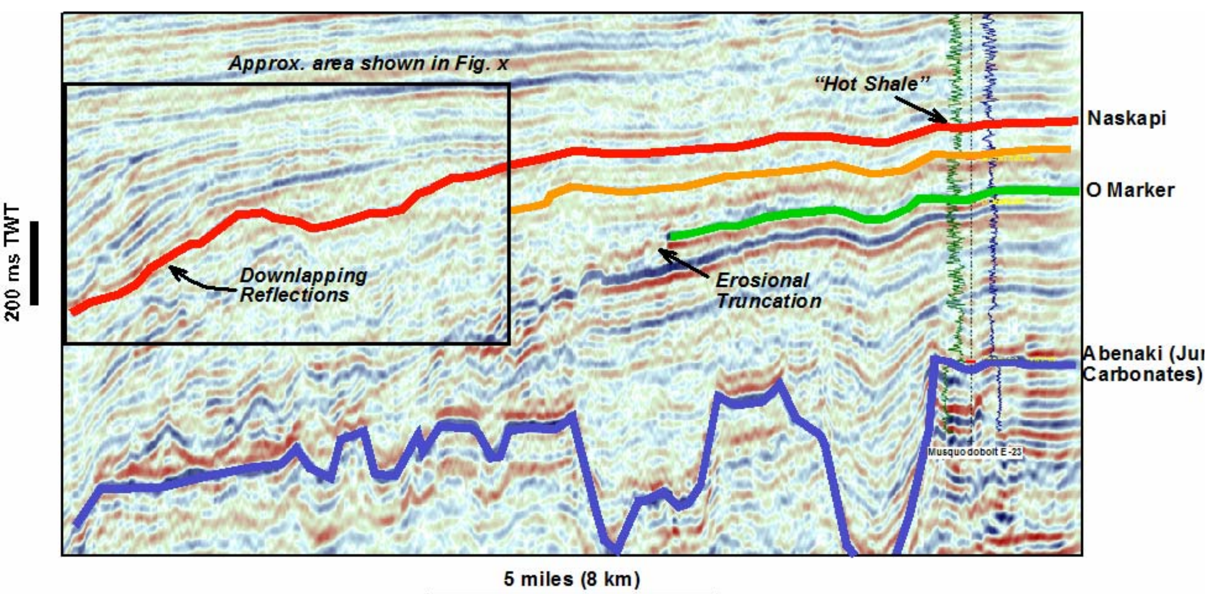


Figure 53b. Dip-oriented seismic transect showing stratal geometries at the paleo shelf edge for strata equivalent to those displayed in Figure 53a. Lower Cretaceous rocks of interest to this study are those above the O Marker.

Extending the mapping of the major unconformity to the new 3-D seismic data volume located SW of the dataset examined by Cummings et al. (2006b), the relief that is present on the sequence boundary at the shelf margin is observed (Figure 54). That surface illustrates an approximately V-shaped incision into the shelf margin, with smaller tributaries to the sides. The surface probably formed by mass-wasting during fall of relative sea level. Another possibility is that it formed by fluvial incision during lowstand of sea level. However, it formed, the surface is overlain by chaotic facies that show a general progradational pattern. These undrilled deposits probably represent failed shelf-margin deltaic deposits, based on analogy with other parts of the Missisauga Formation (Cummings et al., 2006a).

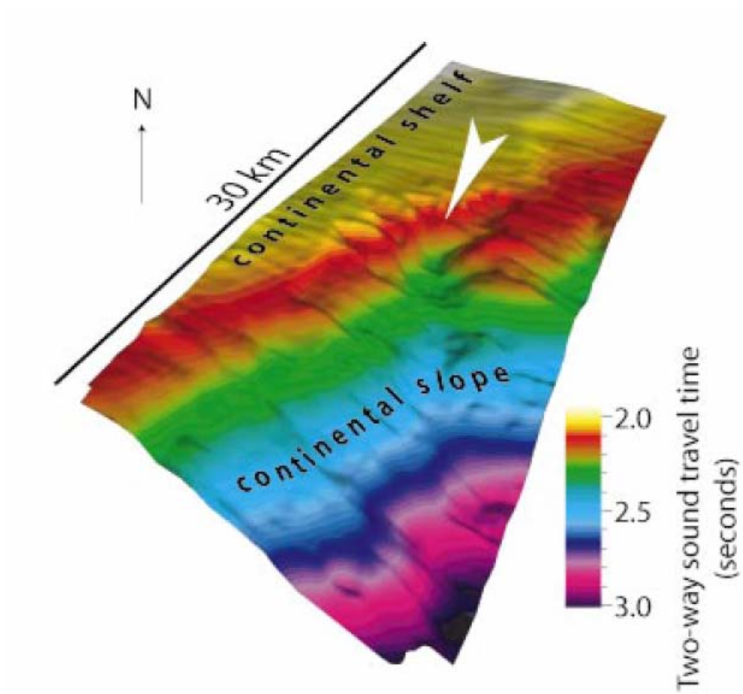


Figure 54. Time-structure map of an erosion surface beneath the Upper Missisauga Formation, Scotian Shelf. Note the prominent incision into the shelf margin (arrow). As shown in Figure 55, similar erosional relief is present at the base of the overlying Cree Member. From Cummings et al. (2006a).

A similar stratigraphic style, consisting of an erosion surface capped by prograding deposits, was recognized as being present at the level of the overlying Cree Member. Near the shelf margin this surface incises into underlying strata (Figure 55). Note that, despite the morphology that is suggestive of being a sequence boundary, the surface is overlain by downlapping reflections that, by definition, identify it as being a maximum flooding surface.

Also, recognized is an undated, un-named deltaic package at the base of the Upper Cretaceous to Tertiary Banquereau Formation. As shown in Figure 56, that unit displays clear downlap onto the underlying Wyandot Formation (a chalk), thus identifying a maximum flooding surface. Erosional truncation is apparent in the seismic data at the top of the delta, thus indicating the presence of a sequence boundary. A timeslice through the seismic data at the level of the incision shows the plan-form outline of a channel that was incised near the delta front/shelf margin during sea-level lowstand.

Seismic criteria for recognizing key seismic stratigraphic surfaces (sequence boundaries, maximum flooding surfaces) were not observed in the strata overlying and underlying this deltaic package in the available 3-D seismic dataset. As such, it is not possible to define T-R sequences. However, we note that the interval between the downlap surface and the sequence boundary can confidently be assigned to a regressive systems tract in T-R terminology.

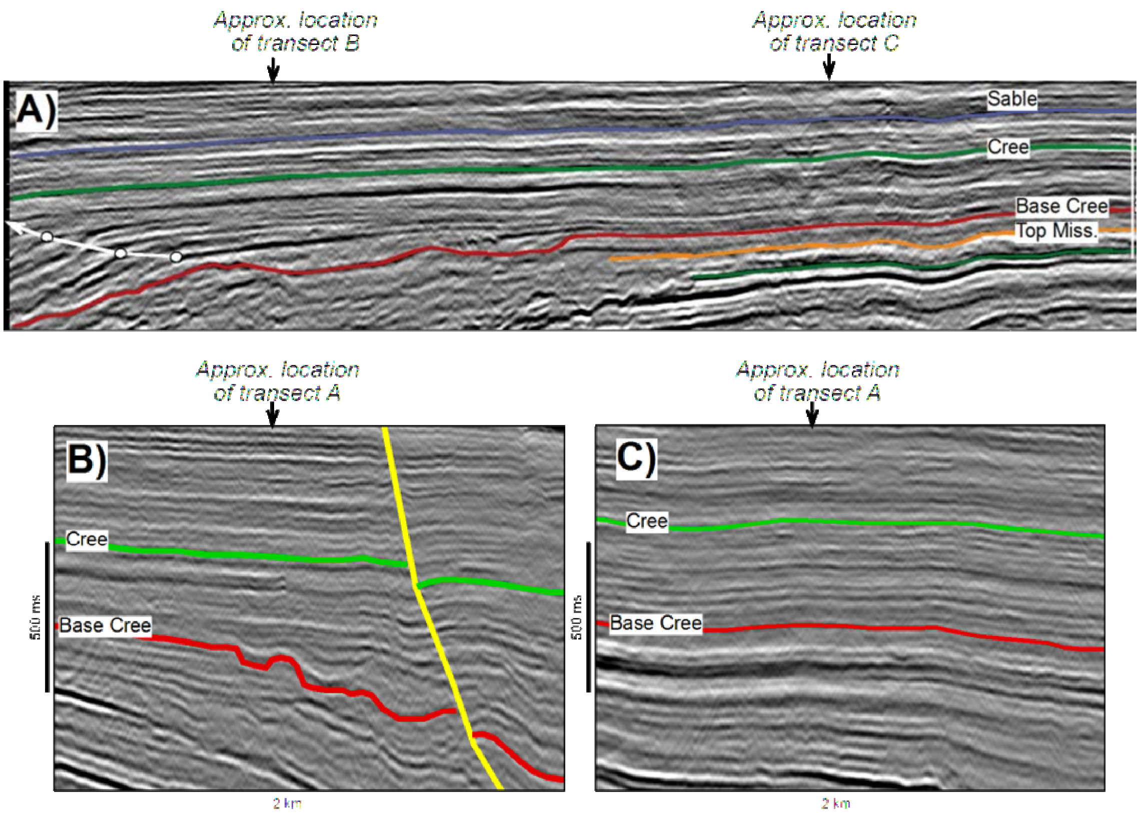


Figure 55. A) Dip section through the Cree Member near the paleo-shelf margin. The base of the Cree is a downlap surface (red) at and beyond the shelf margin (left) that resembles the unconformity shown in Figure 54. B) Strike section through showing incision at the base of the Cree near the shelf margin. C) Strike section showing absence of erosion further landward. In part A, note that the shelf margin continues to prograde (white arrow/dots) above the unconformity. No seismic criteria can be observed in this dataset for separating the Cree Member from the overlying Sable Member.

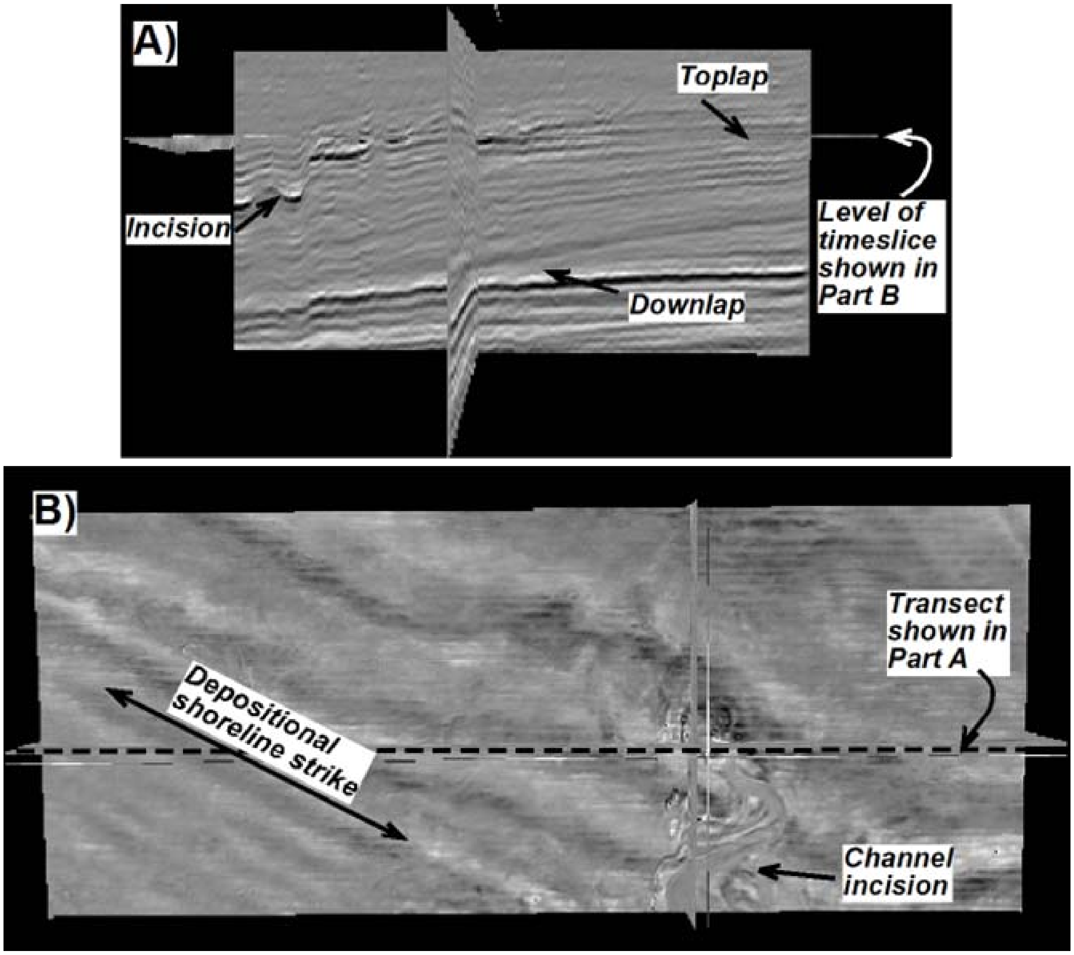


Figure 56. Seismic transects through an un-named deltaic succession in the Tertiary Banquereau Formation, Scotian Shelf. A) Dip section showing downlap surface (designated as a maximum flooding surface) onto underlying Wyandot Formation, and erosional truncation/toplap (sequence boundary). B) Timeslice from upper part of deltaic succession. The interval between the downlap surface and the sequence boundary can be assigned to a regressive systems tract in T-R terminology. The timeslice cuts through toplapping reflections to show the NW-SE depositional strike. Note meandering channel

Western Interior Seaway

Three different stratigraphic levels have been identified for analysis in the Deep Basin study area. In stratigraphically ascending order, these are: a) the Lower Albian Notikewin Member of the Spirit River Formation, b) the Middle Albian Harmon and Cadotte members, and Upper Albian Paddy members of the Peace River Formation, and c) the Turonian – Coniacian Cardium Formation. These rocks were deposited in a foreland basin setting, where accommodation increased towards the thrust belt.

The Peace River Formation (Harmon, Cadotte and Paddy members) directly overlies the Notikewin Member and had a similar shoreline orientation. For that reason, we studied these units together. We measured core and generated log cross-sections that show the stratigraphic relationships in an approximately N-S orientation that is nearly parallel to depositional dip (Figure 57). The base of the Notikewin Member is a basin-wide unconformity, with non-marine and marine rocks of the Notikewin overlying non-marine rocks of the Falher Member of the Spirit River Fm (Hayes et al., 1994).

The juxtaposition of marine rocks (Notikewin) above the Falher indicates the presence of a transgression surface, and Schmidt and Pemberton (2003) showed that a transgressive systems tract, bounded below and above by a transgression surface and a maximum flooding surface respectively, can be mapped using core and logs in an area immediately west of our study area. We identified their stratigraphic units in our data. Above the maximum flooding surface, the Notikewin consists of a series of northward prograding to slightly aggrading parasequences, with interfingering of marine, shoreface and coastal plain deposits. In T-R Cycle terminology, these parasequences form a progradational systems tract. No subaerial unconformity is present within, or at the top of, the Notikewin, at least in our study area.

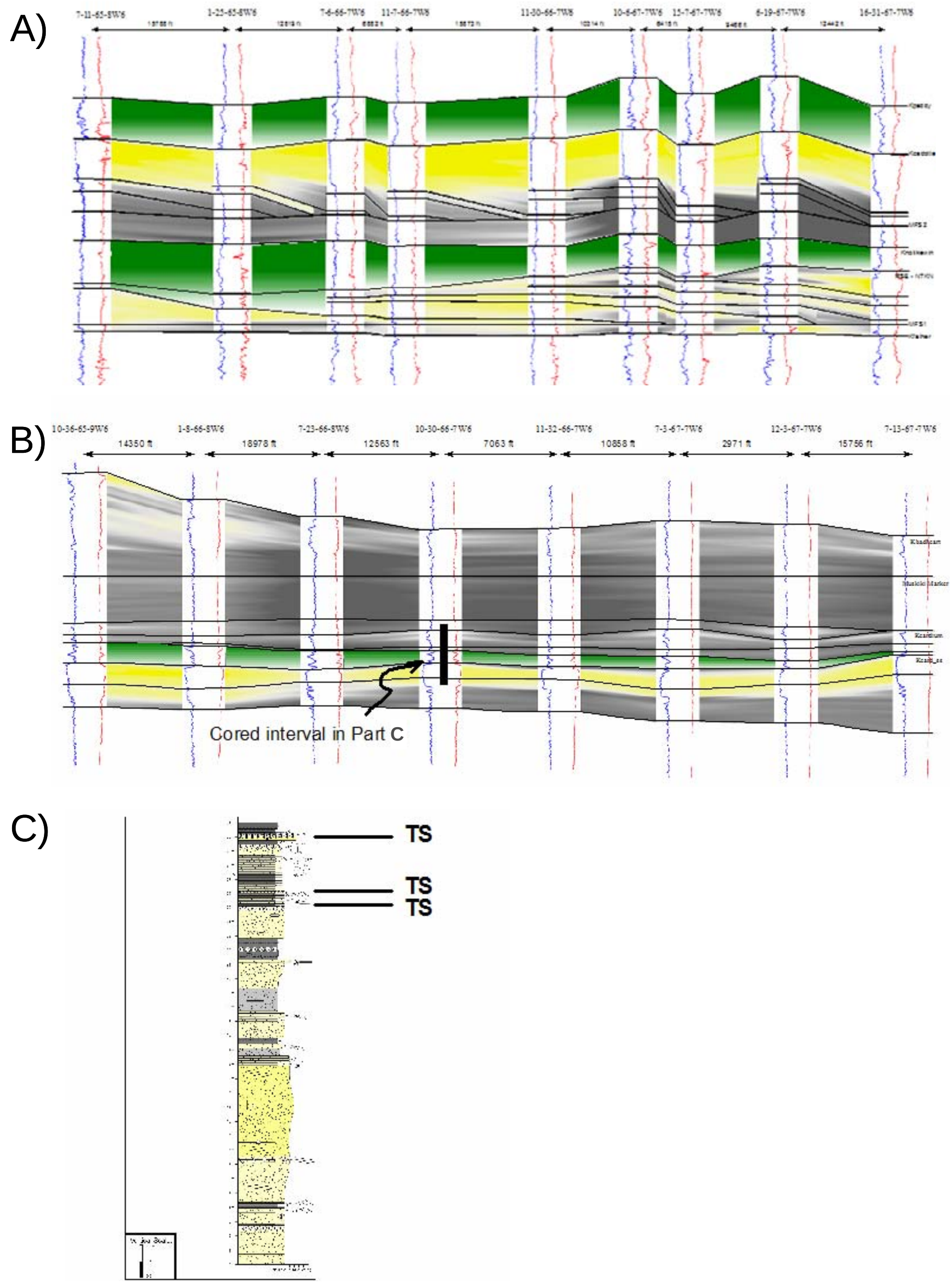


Figure 57. A) Dip-oriented log cross section showing stratigraphic relationships in the Notikewin to Paddy interval of the Deep Basin (Study area 3, Fig. 52). Grey=marine shale, yellow=shoreface/delta front sands, green=coastal plain deposits. Note the prograding geometries in the Notikewin and Cadotte intervals. Transect ~ 12 miles long. B) Dip-oriented log cross section of the Cardium Formation and stratigraphically adjacent units. A main shoreface sandstone body (yellow) is overlain by coastal plain deposits (green) that are, in turn, overlain by marine parasequences. Stratigraphic surfaces correspond to those defined by Hart and Plint (1993). C) Measured core showing lithologic expression of facies and surfaces identified in Part B. Corresponding logs shown in Part A. TS-Transgression Surface.

A transgression surface caps the Notikewin, with marine shales of the Harmon Member overlying that surface. A maximum flooding surface within the Harmon is recognizable based on gamma ray signature ("hot shale") and stratal geometry (downlap surface on log cross-sections; Figure 57). As such, the lower part of the Harmon can be identified as a transgressive systems tract in T-R Cycle terminology. Above the MFS, the lithostratigraphically defined Harmon and Cadotte members show prograding relationships. Shoreface sandstones of the Cadotte appear to be conformably overlain by non-marine deposits of the Paddy Member. However, regional work has shown that a significant unconformity is present either within the Paddy or at the Paddy/Cadotte contact (Leckie et al., 1994). This unconformity appears to correspond to a Middle to Upper Albian eustatic sea level drop of approximately 50 m (Haq et al., 1987). In our area, the unconformity is difficult to locate because it either separates non-marine from non-marine strata (i.e., it is within the Paddy), or it separates foreshore deposits (Cadotte) from overlying non-marine deposits (Paddy). In either case the contact is easily misidentified as a normal facies transition, and so some operators place the unconformity at the top of the Cadotte whereas others place it at the base of a channelized sandbody in the upper part of the Paddy. To date, palynology data have not been employed, or have not been available, to locate the unconformity in our area. Because of this uncertainty, the top of the progradational systems tract that includes the Cadotte Member is not adequately defined in our study area. Another transgression surface caps the Paddy, separating it from the overlying Shaftsbury Shale.

Stratal geometries and systems tracts defined using log and core data are compared to the seismic data. To do so, we have generated synthetic seismograms to tie the logs to the seismic data, and we have also used log cross-sections to generate seismic models of this interval. Figure 58 shows a sample synthetic seismogram generated using a range of frequencies that is comparable to those in the 3-D seismic data at the Cadotte/Notikewin level. Figure 59A shows a seismic model of the cross-section shown above and Figure 59B shows an arbitrary transect from the seismic data that goes through all of the wells used to construct the cross-section. From the synthetic seismogram and the seismic model, we make the following observations: A) The flooding surface at the top of the Paddy (Kpaddy) is imaged as a peak. B) The lithologic break at the top of the Cadotte (shoreface/foreshore sands below, coastal plain deposits above; Kcadotte) is imaged as a trough. This could be a surface of maximum regression in T-R terminology. C) The maximum flooding surface in the Harmon Shale (MFS2) is imaged as a relatively low-amplitude peak. D) The flooding surface at the top of the Notikewin (FS – Top Notikewin) is imaged as a high-amplitude trough. This flooding surface generates a stronger reflection than the overlying maximum flooding surface (MFS2). E) The “Regressive Surface of Erosion” (as defined by Schmidt and Pemberton, 2003) at the top of the prograding Notikewin shoreline (RSE – NTKN) is imaged as a peak. F) The flooding surface/unconformity at the base of the Notikewin (TSE) is imaged as a peak. The details of the stratigraphic geometries seen in the log cross-section (Figure 57) are not visible in the seismic model, and only subtle variations in amplitude, related to changes in lithology and stratigraphic geometry, are evident. The seismic data show similar geometries to the seismic model results. It is clear that the seismic data do not image all of the stratigraphic complexity that is mappable using dense well control, and that the unconformity in, or at the base of, the Paddy cannot be imaged.

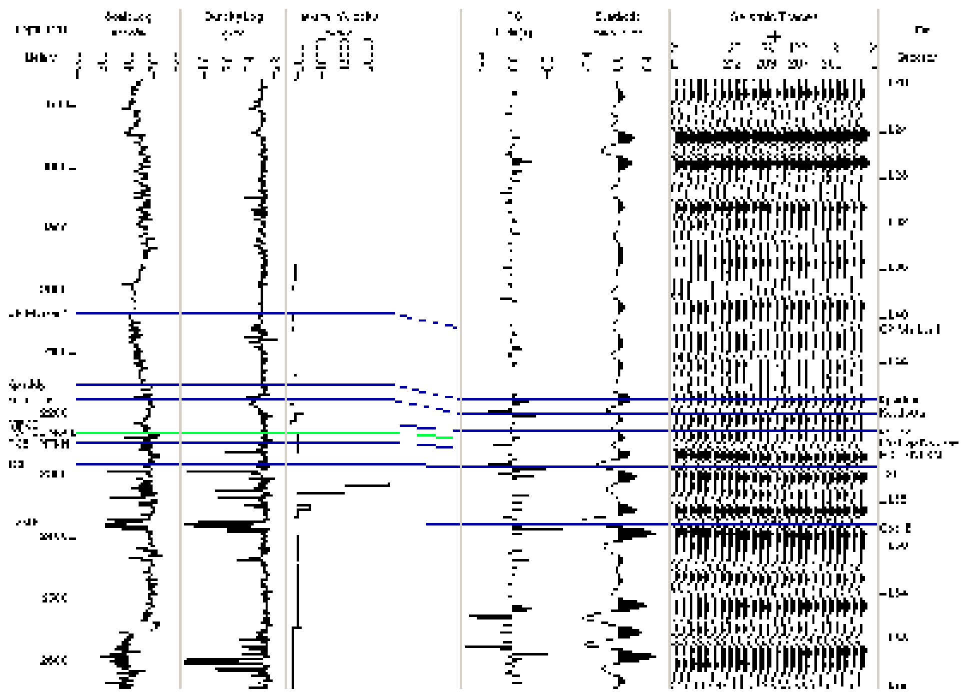


Figure 58a. Sample synthetic seismogram showing suggested tie to the seismic data for the Notikewin to Paddy interval.

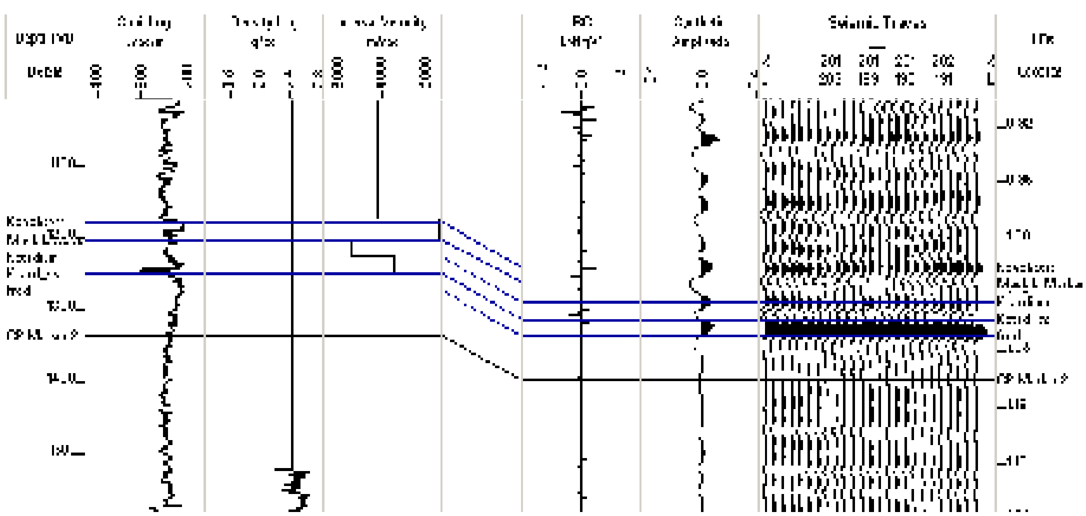


Figure 58b. Synthetic seismogram showing predicted seismic response of Cardium Formation and adjacent strata.

The stratigraphy of the Cardium Formation in this area was studied by Hart and Plint (1993). The formation is particularly interesting in our study area because of the presence of “sharp-based” shoreface sands that have been interpreted by some authors to indicate shoreline progradation during a fall of relative sea level (“forced regression”). The base of the sharp-based shoreface has been called a “regressive surface of marine erosion” (RSME) and has been identified by some authors with a sequence boundary in Exxon-style sequence stratigraphy. Embry (2002) explained why the RSME is a poor candidate for a sequence boundary.

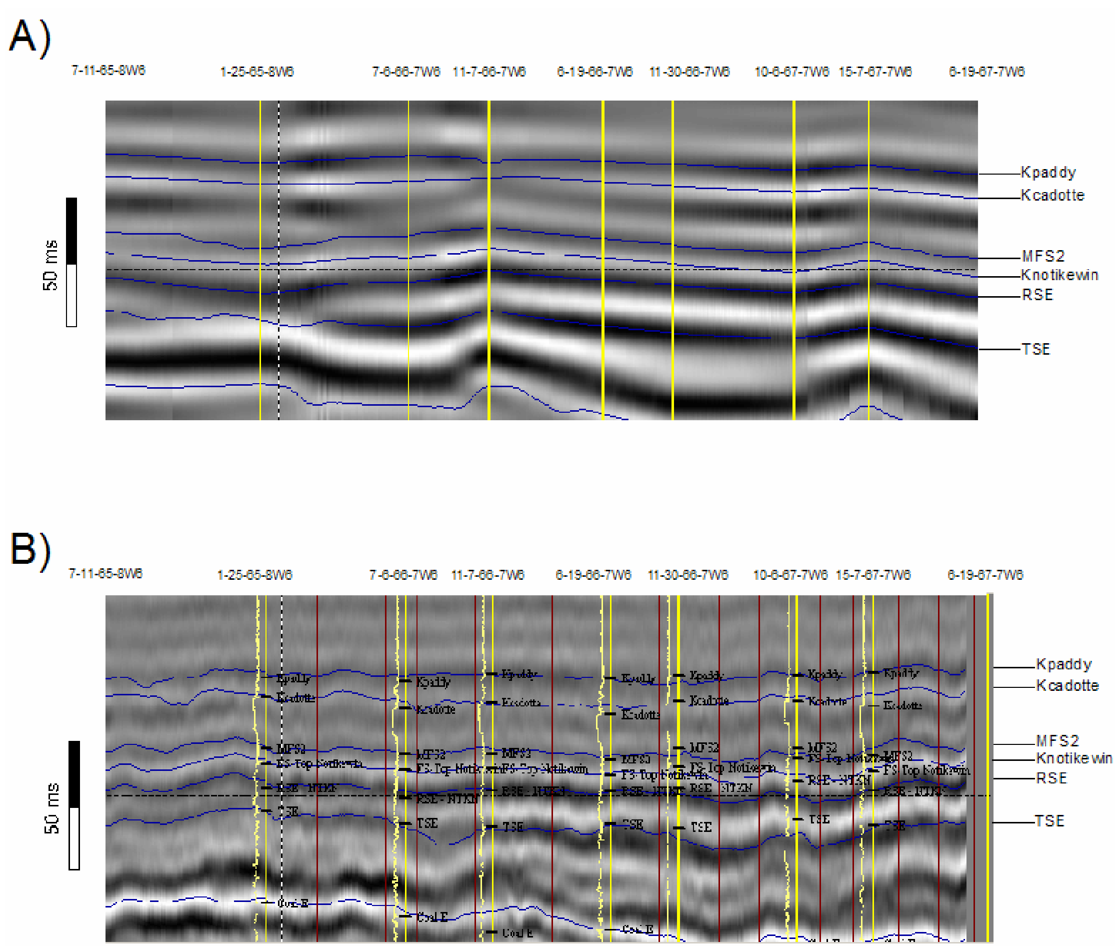


Figure 59. A) 2-D seismic model based on log cross section shown in Figure 57. B) Arbitrary transect through 3-D seismic volume that corresponds to seismic model shown in Part A.

A dip-oriented (SW-NE) log cross-section of the Cardium and stratigraphically adjacent units is presented in Figure 57b. In this area the formation consists of a progradational package of shoreface sandstones that are overlain by non-marine/coastal plain deposits and finally by a succession of thin, dominantly shaly (in this area), marine parasequences (Figure 57c). Like many other foreland basin deposits, well-developed subaerially formed erosion surfaces (accompanied by major channel incision) developed during lowstands are not present in the Cardium.

A synthetic seismogram from this area is shown in Figure 58b, and a seismic model and seismic transect corresponding to the log cross-section are shown in Figure 60a and 60b, respectively. Low-amplitude detachment folds affect the Cardium in this area and so the seismic data have been flattened on an upper horizon. Reverse faults affect the shales below the Cardium, obscuring some of the stratigraphic relationships in the shale in both log cross-sections and seismic data. Additionally this interval is in the upper part of the seismic data, and the data quality is reduced at this level. Despite these issues, and like the stratigraphically lower Notikewin to Paddy level, it is clear that the seismic character does not show the same level of detail as the log cross-section. The seismic images show that the "Muskiki Marker", a downlap surface (i.e., MFS in the marine shales overlying the Cardium) is imaged as a trough. The top of the Cardium (Kcardium), a flooding surface corresponding to the transition from the small parasequences of the upper part of the Cardium to the overlying transgressive shales of the Muskiki Fm. is represented by a peak in the data. Counter intuitively, because it corresponds to an increase in acoustic impedance, the top of the shoreface sandstones of the Cardium (Kcard_ss) is imaged as a trough.

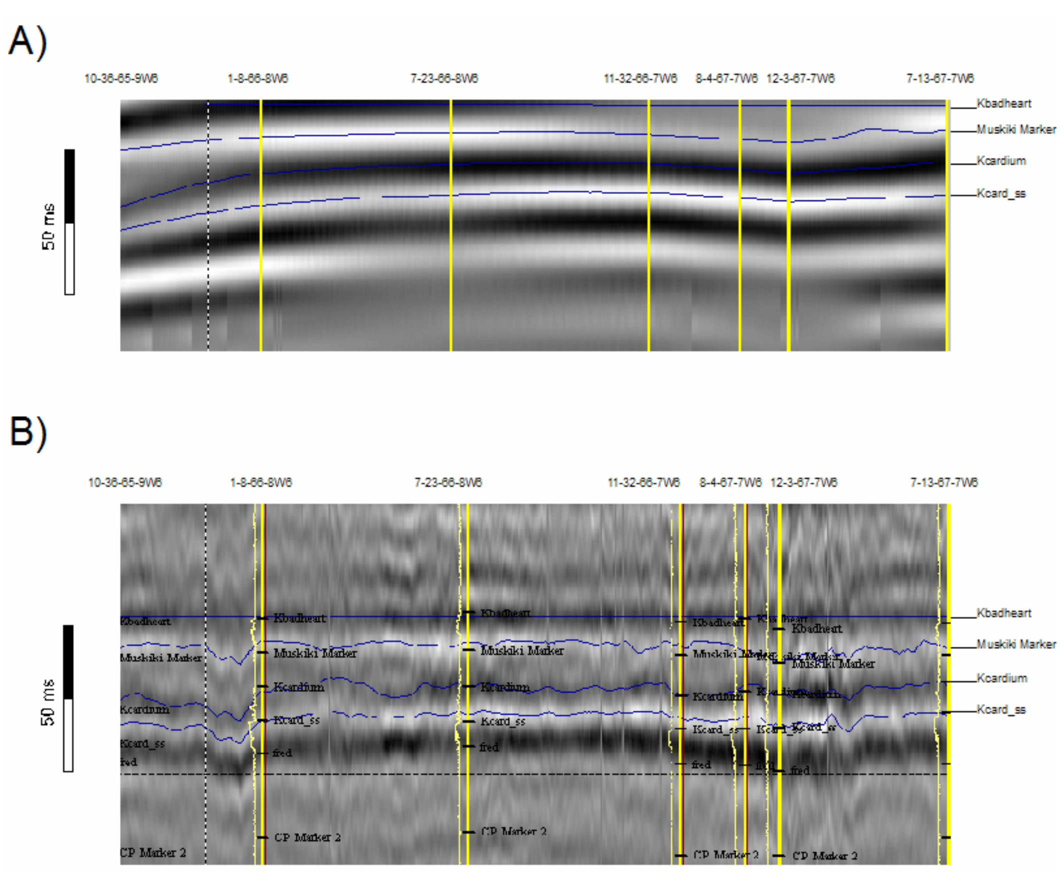


Figure 60. A) 2-D seismic model based on log cross section shown in Figure 59a. B) Arbitrary transect through 3-D seismic volume that corresponds to seismic model shown in Part A. Marked horizons correspond to log picks shown in Figure 59a. Details are described in the text, but like the underlying Notikewin/Cadotte interval (Figure 58), it is clear that the seismic images cannot capture all of the stratigraphic details evident in the log cross section.

We also studied the Cenomanian Dunvegan Formation, a relatively thick deltaic succession that prograded to the south-southeast. Plint (2000) correlated outcrop and subsurface data to study the stratigraphy of the Dunvegan over an area of approximately 80,000 km^2. His allostratigraphic analyses (based on the identification and mapping of surfaces that include unconformities, omission surfaces, ravinement surfaces, flooding surfaces, "event beds" such as ash layers, etc.) showed that only two of the ten mappable "allomembers" correspond to Exxon-style sequences.

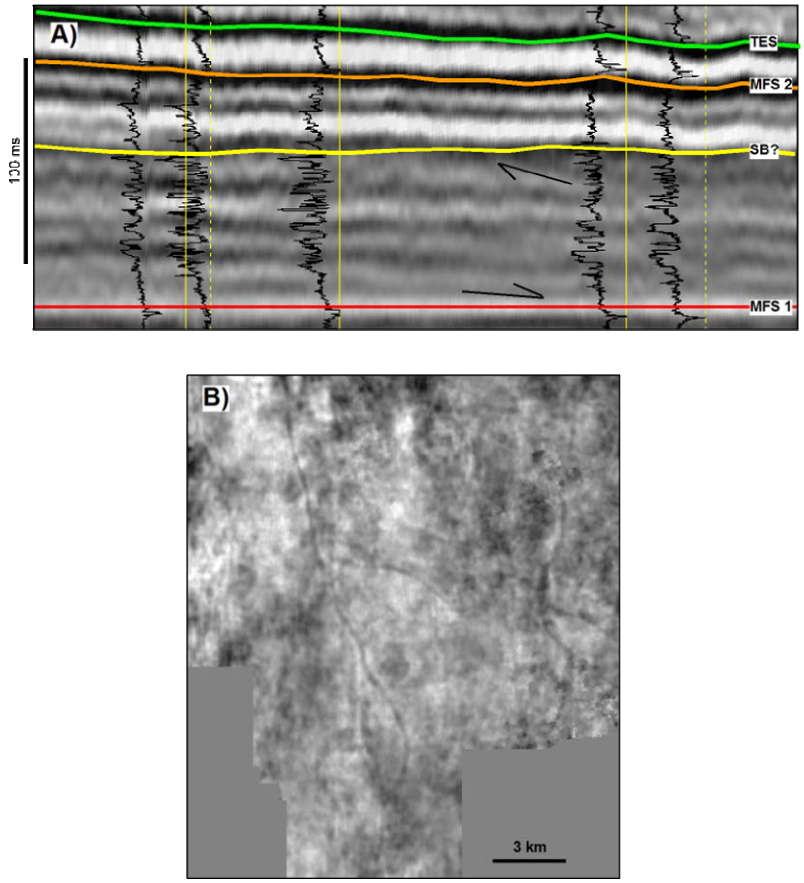


Figure 61. A) Transect through 3-D seismic volume showing downlap onto the FSU horizon (MFS 1) and toplap at a potential sequence boundary (SB?). An overlying maximum flooding surface (MFS 2) is a prominent seismic reflection that corresponds to a radioactive ("hot") shale. The surface marked "TES" is a tectonic erosion surface (Plint, 2000; Hart et al., *submitted*). Transect shows gamma ray log overlays for five wells. B) Slice through the seismic volume 54 ms above the MFS 1 horizon. Note the presence of channels (dark) that bifurcate in an offshore direction (to bottom). These are probably deltaic distributaries.

Figure 59a shows a dip section through the Dunvegan Formation in the 3-D seismic volume. The section has been flattened on the underlying "Fish Scales Upper" (FSU) horizon (MFS 1), a radioactive shale that corresponds to a downlap surface in long wireline log cross sections. The seismic transect is shorter than those log cross sections, but still shows downlap of seismic reflections onto the FSU horizon. Subtle toplap is present at a seismic surface that corresponds to a marine flooding surface that separates lagoonal deposits from overlying marine rocks. That marine flooding surface corresponds to the top of Plint's (2000) Dunvegan Alloformation. Based on seismic truncations, this surface (labeled SB? in Figure 59) represents a potential sequence boundary. Two overlying horizons correspond to another radioactive shale/Maximum Flooding Surface (MFS2) and a surface corresponding to a tectonic erosion surface (TES). Unlike the Banquereau example shown in Figure 4, no incised valley is present at the top of the Dunvegan, either in the seismic data or the cross-sections of Plint (2000). Channels are traceable in slices through the data parallel to the FSU downlap surface, and some of those channels show bifurcation toward the paleoshoreline that suggests that they are deltaic distributaries (Figure 59b).

San Juan Basin Dataset

The Mesaverde Group of the San Juan Basin consists of a progradational to retrogradational package of shelf, paralic and non-marine clastic deposits thought to represent a third-order succession. Progradational shoreface to deltaic sandstones at the base of the Group are included in the Point Lookout Formation, whereas retrogradational paralic sandstones at the top of the Mesaverde are included in the Cliff House Formation. Coastal plain deposits between these two formations are included in the Menefee Formation. The Mesaverde Group is Santonian to Campanian in age. Previous studies (e.g., Hollenshead and Pritchard, 1961; Cross and Lessenger, 1997) have shown that the Point Lookout and Cliff House interfinger with coastal plain deposits of the Menefee Formation to the southwest, and with heterolithic shelf deposits of the underlying Mancos Shale and overlying Lewis Shale respectively.

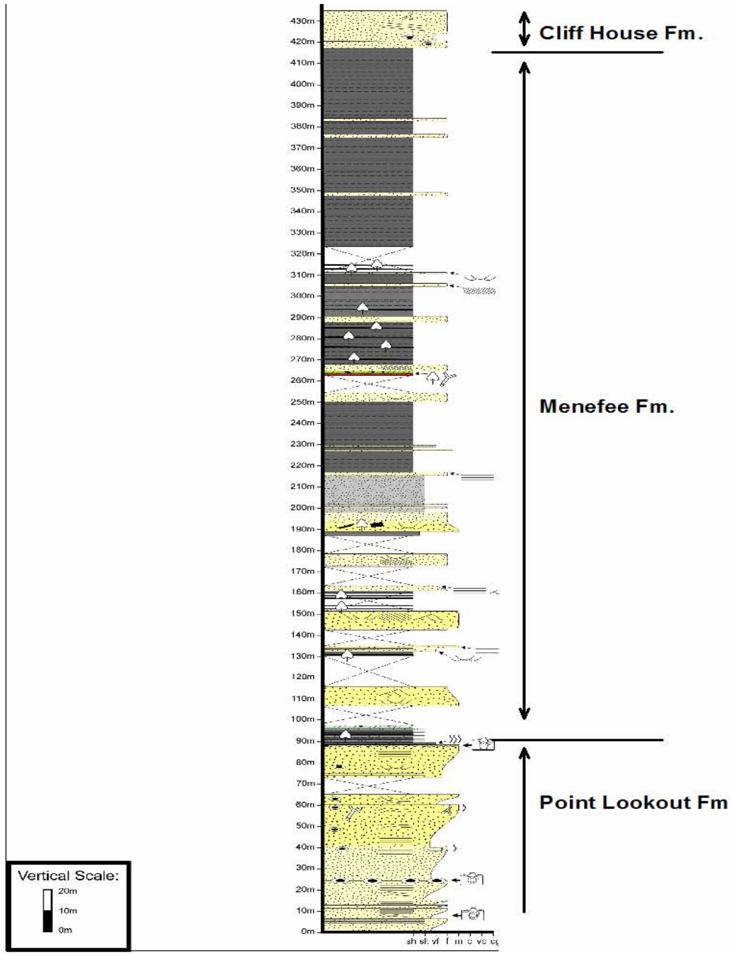


Figure 62a. Measured outcrop section through the Mesaverde Group at the Hogback Monocline, west of Farmington (Location 4, Figure 52). Note the abundance of channel sandstones in the lower portion of the Menefee Formation.

We measured a section through the Point Lookout, Menefee and basal Cliff House formations at the Hogback Monocline west of Farmington (Figure 62a). The Point Lookout consists of a succession of shelf-to-shoreface capped by flooding surfaces (i.e., parasequences). The Menefee is dominantly sandy in the lower portion but becomes mud dominated in its upper part. Cross and Lessenger (1997) suggested that these divisions could correspond to the progradational and retrogradational portions (Point Lookout, Menefee) of the Mesaverde Group respectively (Figure 62b). If this is true, then the change from the upper to lower Menefee corresponds to the surface of maximum regression for this third-order cycle, and is a sequence boundary. The 2-D seismic data we seek will allow us to look for a seismic expression of this surface.

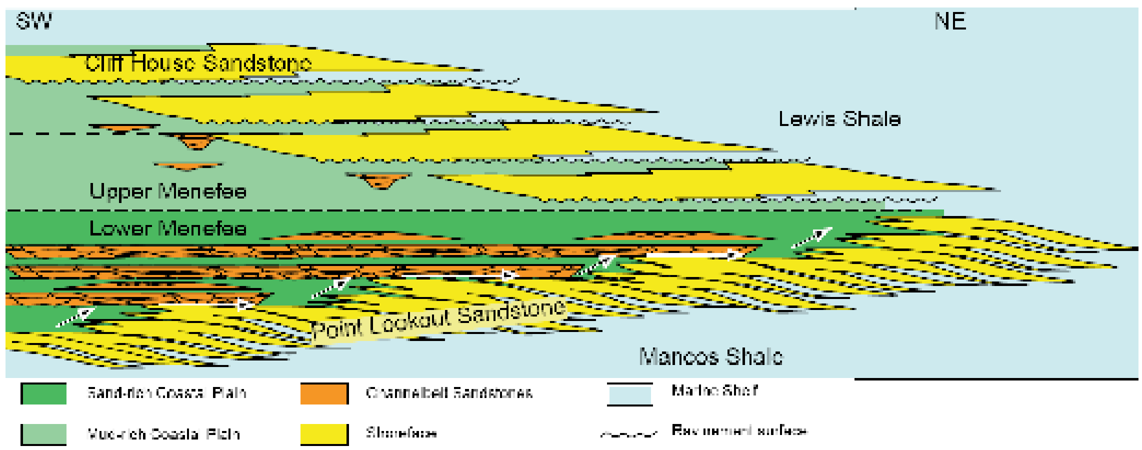


Figure 62b. Schematic dip-oriented cross section through the Mesaverde Group in the San Juan Basin. The contact between the Lower and Upper Menefee corresponds to a surface of maximum regression, i.e. a sequence boundary, in T-R cycle terminology. The transition from sand- to shale-dominated section in the Menefee is visible in outcrop (Figure 61) and may be detectable using seismic data.

Summary

Through seismic-based analyses, we have confirmed that traditional seismic stratigraphic analyses, involving the identification of key surfaces and stratal terminations to define unconformities, flooding surfaces and maximum flooding surfaces, can be successfully employed in passive-margin settings where sequences are relatively thick. In these settings, T-R sequences, as defined by Embry (2002) can be defined with confidence. On the other hand, subaerial erosion surfaces associated with lowstands of relative sea level are commonly not developed in foreland basin settings, and they are not seen in the log cross-sections or the core and outcrop sections constructed and measured for this study. As such seismic data from foreland basin deposits may not show clear evidence for erosional truncation (sequence boundaries) at least in the size of 3-D surveys that are commonly available to operators. Other commonly used reflection geometries (onlap, downlap) may not be visible in seismic data through the T-R cycles because those cycles are too thin. As such, the utility of seismic data to define T-R cycles in these and similar settings is diminished. Other factors that affect an interpreter's ability to identify key stratigraphic surfaces include: data quality, and location and length/extent of the seismic transect. Stratal terminations are best developed in some settings (shelf margins) than in others (fluvial settings), and therefore, seismic data that sample the former settings will be more useful for definition of T-R cycles. Larger 3-D seismic surveys, or 2-D seismic grids, are more helpful for identifying the stratal terminations needed to identify T-R sequences. Where only limited seismic coverage is available, but logs are available for many wells (mature basins), log-based correlations can be integrated with seismic data to identify depositional geometries at sub-seismic scale.

An enigma can be found in some shelf-margin deltaic successions in the Scotian Shelf. 3-D seismic data allow the mapping of erosion surfaces landward and basinward of the shelf margin. On the shelf the surfaces appear to represent channel incison (sequence boundaries) because of their geometry. At and beyond the shelf break, they could have formed by mass wasting as sea level fell, and so might be considered as regressive surfaces of marine erosion. However, based on the observation of downlap in the seismic data they would be classified as maximum flooding surfaces. Most stratigraphers consider these surfaces to be sequence boundaries on the shelf, but in the examples shown here, at and seaward of the shelf break the surfaces are overlain by aggradationally prograding deltaic strata. The location of these prograding strata above the sequence boundary automatically places them in the transgressive systems tract, and therein lies the enigma. Similar stratigraphic relationships were noted by Hart et al. (1997) in their study of a Pleistocene shelf-margin delta from the offshore Gulf of Mexico (Figure 63a, b).

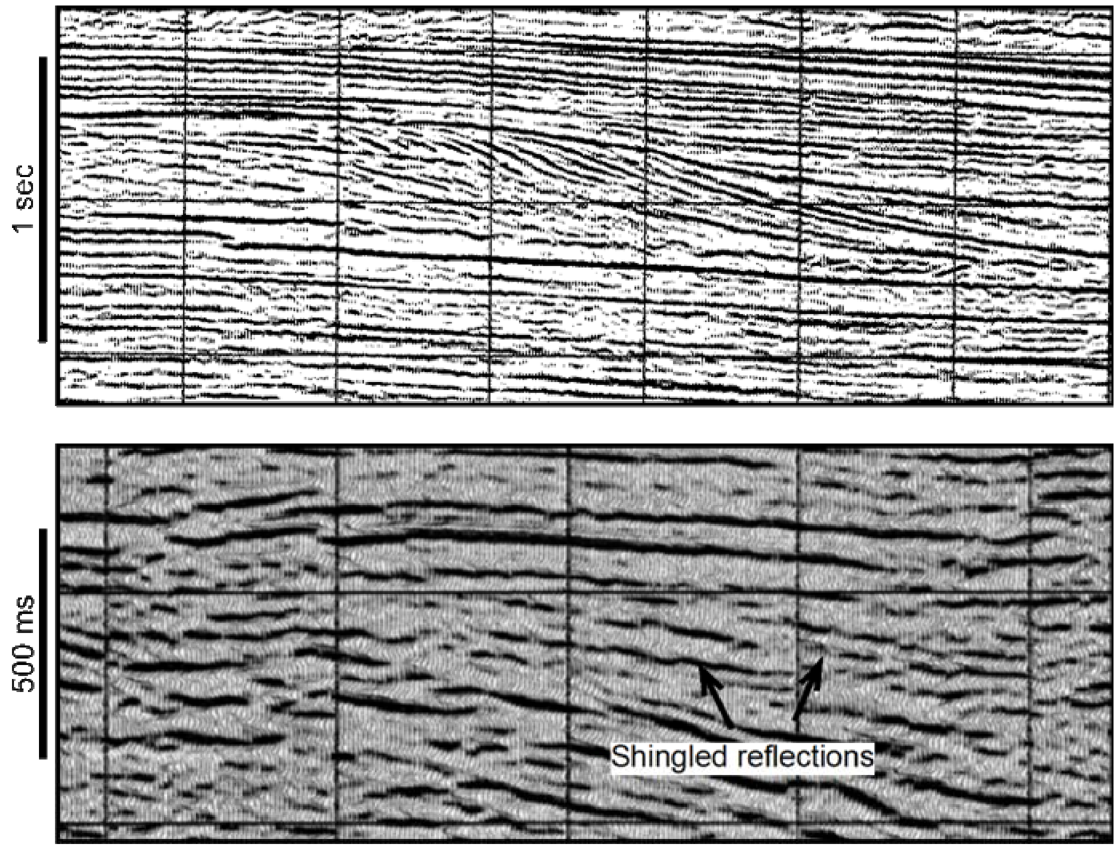


Figure 63a. Comparison of prograding deltas from two different stratigraphic levels in the same 2-D seismic dataset. Top: prograding clinoforms of the same deltaic succession in the Banquereau Formation. Below: shingled reflections in the Upper Member of the Missisauga Formation. It is more difficult to identify stratal terminations and surfaces in the lower example because of the lower frequency content and lower signal-to-noise ratio. The strata are also affected by faulting near the left of the section. Nevertheless, the shingled reflections correspond to a shelf-margin delta that produces from Alma Field (initial production December 2003).

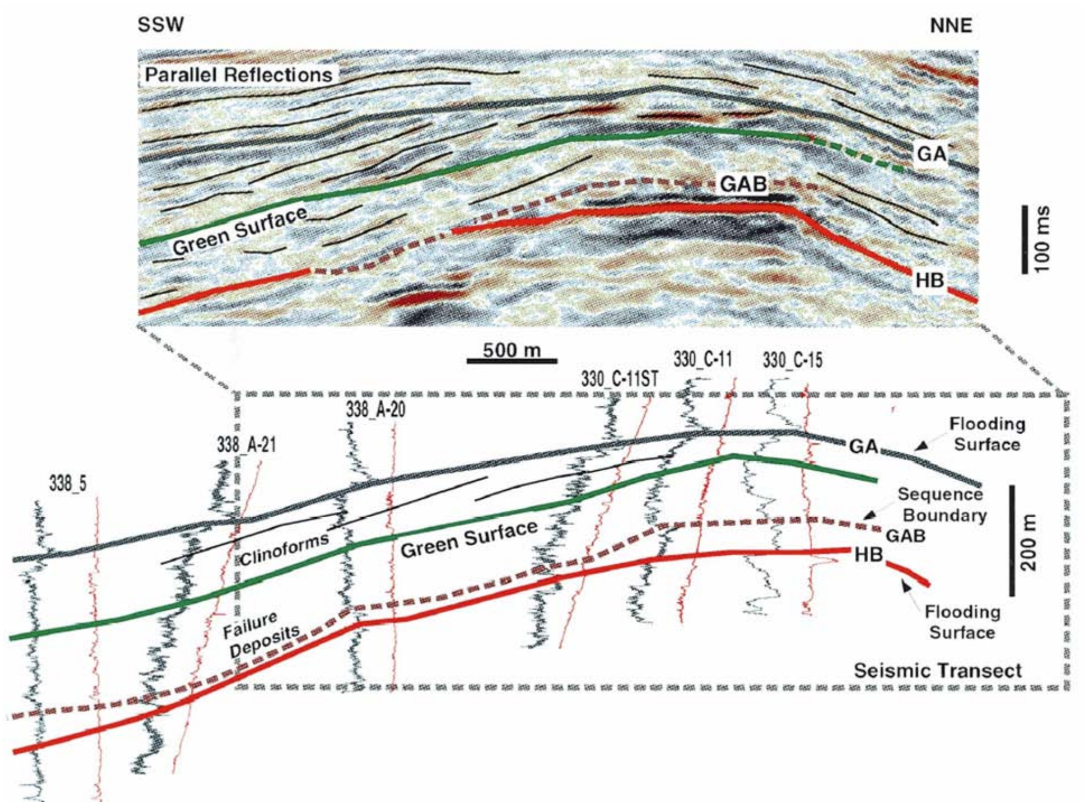


Figure 63b. Seismic (top) and log cross-section through a Pleistocene shelf margin delta, Eugene Island Block 330. An erosion surface at the base of the succession (surface "GAB") is overlain by two stacked prograding delta lobes. Based on its geometry in cross section (not shown) the surface is identified as a sequence boundary. In both T-R sequences and Exxon-style depositional sequences, this places the overlying prograding succession in the transgressive systems tract. From Hart et al. (1997).

The formation of these successions is not difficult to explain. Sediment supply must have been high enough following lowstand and during initial relative sea level rise to allow the shoreline to prograde, albeit in an aggradational manner. The problem arises because, like facies models, sequence stratigraphic principles cannot be general enough to encompass all combinations of variables, and yet concise enough to be useful. The stratigraphic record is shaped by the interplay between basin physiography, changes in sediment supply and relative changes in sea level (tectonics and eustacy). Unfortunately these variables can combine in a virtually infinite number of ways, and no universally applicable model for sequence development has emerged.

Data integration-The data, information and observations resulting from the outcrop, well log, and seismic characterization studies were compiled, integrated and used in developing the depositional, T-R and sequence stratigraphy models.

Depositional, ***T-R and sequence stratigraphy model development***-The outcrop, well log and seismic characterization studies, in addition to published sequence stratigraphy models, have been used to construct a depositional sequence model, a T-R sequence model, and a sequence stratigraphy model. Geoscientists have used third-order (1 to 10 million years in duration) unconformity-bounded depositional sequences as recognized in seismic reflection sections (Mitchum et al., 1977b; Vail et al., 1977b; Posamentier et al., 1988a; and Van Wagoner et al., 1988) for stratigraphic correlation and sedimentary basin studies. The principal factor controlling stratal architecture was interpreted as changes in global sea level (Posamentier et al., 1988a). As mentioned earlier, two types of depositional sequences have been used, type 1 and type 2 (Figures 1 and 2). A type 1 sequence can include lowstand, transgressive and highstand systems tracts, and a type 2 sequence can include shelf margin, transgressive and highstand systems tracts (Posamentier et al., 1988a). The unconformity at the base of the type 1 sequence is as subaerial unconformity or ravinement surface, and the unconformity at the base of the type 2 sequence is a transgressive surface (Figures 1 and 2). A maximum flooding surface separates the transgressive and highstand systems tracts. As discussed earlier, Mancini and Tew (1991), found the use of the depositional sequence model to be appropriate for the classification and correlation of Tertiary (Paleogene) strata of the Gulf Coast region. Although Mancini et al. (1996) utilized the depositional sequence model to classify and correlate Upper Cretaceous strata of the Gulf Coast area, Mancini and Puckett (2003) concluded that the use of a transgressive-regressive (T-R) model was more useful for interpreting the architecture of these strata. They (2003) concluded that stratal patterns in these strata were driven by low-frequency, tectonic-eustatic events.

The following discussion is from Mancini and Puckett (2005).

Some geoscientists working in the non-marine realm (Schumm, 1993; McCabe, 1994; Currie, 1997; Martinsen et al., 1999) have concluded that stratigraphic base level is the key factor driving non-marine stratal architecture. For non-marine sediments to accumulate, base level must be at a higher elevation than sea level. To illustrate this point, sea level is held constant in Figure 64 to determine the behavior of strata relative to the sediment surface, sea level and stratigraphic base level. In this case, stratigraphic base level, sea level and the sediment surface intersect at the shoreline. This convergence produces an erosional ravinement or transgressive surface. In a direction seaward of the shoreline, base level and sea level are converged and accommodation space is created and is defined as the interval between the sediment surface and sea level. Landward of the shoreline, sea level and base level diverge, with base level rising to some elevation above sea level. This divergence and the rise of stratigraphic base level above the sediment surface produces accommodation space and results in the accumulation of sediments as part of the transgressive phase of the cycle. This early portion of a T-R cycle is the aggrading interval. Thus, in the non-marine realm, accommodation space is defined as the interval between the sediment surface and stratigraphic base level. Tectonics, sea level, sediment supply, and climate are factors affecting the partitioning of these sediments.

Using the concept of stratigraphic base level, deposition of non-marine strata above a subaerial unconformity is explained. With an increase in accommodation space and continuing siliciclastic sediment influx into an area, aggradational and progradational processes remain active. With a reduction in accommodation space and where sediment input is insufficient to support continued progradation, the agents of erosion shift the sediment in a seaward direction resulting in the development of an unconformable surface. This shift represents a drop in stratigraphic base level below the sediment surface and results in a loss of accommodation space. As long as stratigraphic base level remains below the sediment surface over a large geographic area, a regional subaerial unconformity results. With renewed sediment influx, stratigraphic base level rises above the sediment surface, accommodation space is created and sediments are deposited. As the sediment surface remains between sea level and stratigraphic base level, non-marine deposits accumulate. With a sea-level rise above the sediment surface, marine sediments are deposited.

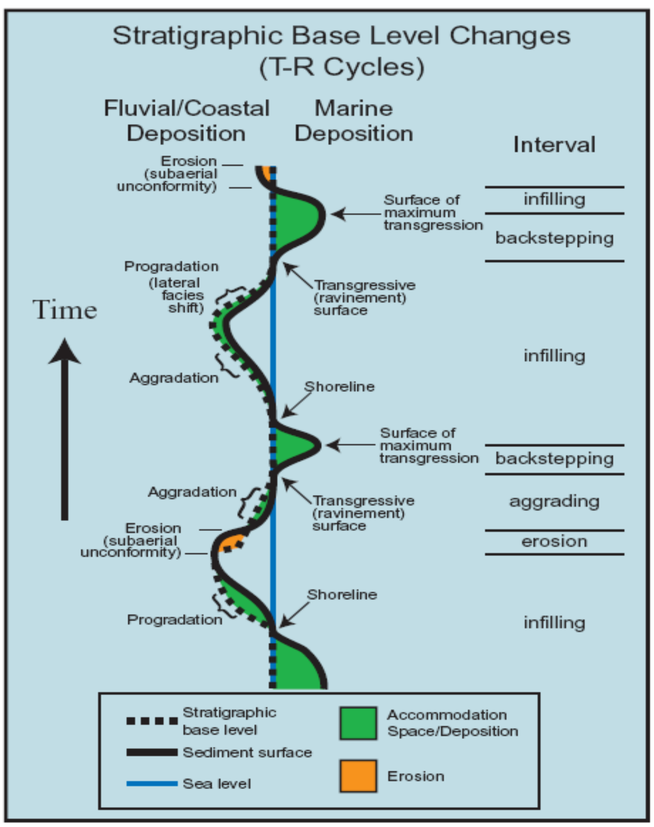


Figure 64. Diagram illustrating conceptual model of factors affecting stratal architecture. The model is based on stratigraphic base level changes controlling T-R cycle development in the non-marine and marine realm. In this model, sea-level is held constant to determine the behavior of strata relative to the sediment surface, sea level, and stratigraphic base level (from Mancini and Puckett, 2005).

The T-R sequence (cycle) model, as discussed earlier, builds on the work of Johnson et al. (1985), Steel (1993), Embry (1993, 2002), Jacquin and de Graciansky (1998) and Mancini and Puckett (2002). The T-R sequence consists of an upward deepening event (transgressive section) and an upward shallowing event (regressive section) separated by a surface of maximum transgression (Embry, 2002; Mancini and Puckett, 2002). Jacquin and de Graciansky (1998) recognized four intervals in T-R sequences, including aggrading, backstepping, infilling and forestepping. Mancini and Puckett (2002) identified aggrading, backstepping and infilling intervals in Gulf Coast strata and used these intervals in their interpretation of stratal architecture. They (2002) observed that a T-R sequence was bounded by an unconformable surface at the base, subaerial unconformity, ravinement surface or transgressive surface. The transgressive aggrading and transgressive backstepping sections were separated by a transgressive surface, and the transgressive backstepping and regressive infilling sections were separated by a surface of maximum transgression. The contact between the regressive infilling section of an underlying sequence can be conformable with the transgressive backstepping section of an overlying sequence. This conformable surface has been termed a surface of maximum regression by Mancini and Puckett (2002). Embry (2002) was the first to describe these surfaces, and he used somewhat different terminology.

The following comparison of the depositional sequence model, the T-R sequence model and the genetic stratigraphic sequence model of Galloway (1988) is from the dissertation research work of Obid (2006).

Introduction

Sequence stratigraphy is the study of rock relationships within a time-stratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or non-deposition, or their correlative conformities (Posamentier et al., 1988a, b; and Van Wagoner et al., 1988). Sequence stratigraphy was established as a discipline and is based on the work of Sloss et al. (1949), who first used the term sequence to define a stratigraphic unit bounded by unconformities. Sloss et al. (1949) defined a sequence as “an assemblage of strata and formations bounded by prominent interregional unconformities”. Later Mitchum et al. (1977a, b) modified Sloss’s definition by including the concept of “correlative conformity” that implied sequence boundaries can be traced further basinward into the central regions of a sedimentary basin. A sequence refers to a package of sediments deposited during one significant cycle of rise and fall of base-level. In marine settings, base-level corresponds to sea-level.

According to Mitchum et al. (1977a, b), a sequence is “a stratigraphic unit composed of a relatively conformable succession of genetically related strata bounded on top and base by unconformities or their correlative conformities”. This modified definition had significant implications on sequence stratigraphy in the sense that sequences could be potentially mapped across the entire basin, and not only the margins of basins, where most unconformities would form. Furthermore, the definition of Mitchum et al. established that a sequence boundary is made of two parts, unconformable and conformable.

The unconformable part of a sequence boundary coincides with a subaerial unconformity or a shoreface ravinement surface, which occurs mainly on the basin margin and tends to disappear or becomes difficult to trace towards the center of a basin (Mitchum et al., 1977a, b).

The modified definition of a sequence by and Mitchum et al. (1977a, b) resulted in three main different schools of thought in terms of sequence stratigraphic analysis, with four different types of sequence boundaries, each with a particular combination of unconformable and conformable parts, and consequently, the establishment of four different types of sequences. These are type 1 depositional sequence and type 2 depositional sequence (Vail and Mitchum, 1977; Vail et al., 1977a; Posamentier et al., 1988a, b), genetic stratigraphic sequence (Galloway, 1989a, b) and T-R (transgressive-regressive) sequence (Embry and Johannessen, 1992; Embry, 2002).

The Vail et al. (1977a, b) depositional sequence approach, also known as the Exxon model (Figures 65-67), was based primarily on reflection seismic data and was later extended to well log, core and outcrop data. Vail's approach defines two types of depositional sequences; type 1 and type 2. The boundary of the type 1 depositional sequence, as defined by Posamentier et al. (1988a, b), is characterized by unconformable and conformable portions. The unconformable portion is a subaerial unconformity on the basin margin, while the conformable portion of the sequence boundary (i.e. correlative conformity) is represented by a time line equivalent to the start of a basinward base-level fall.

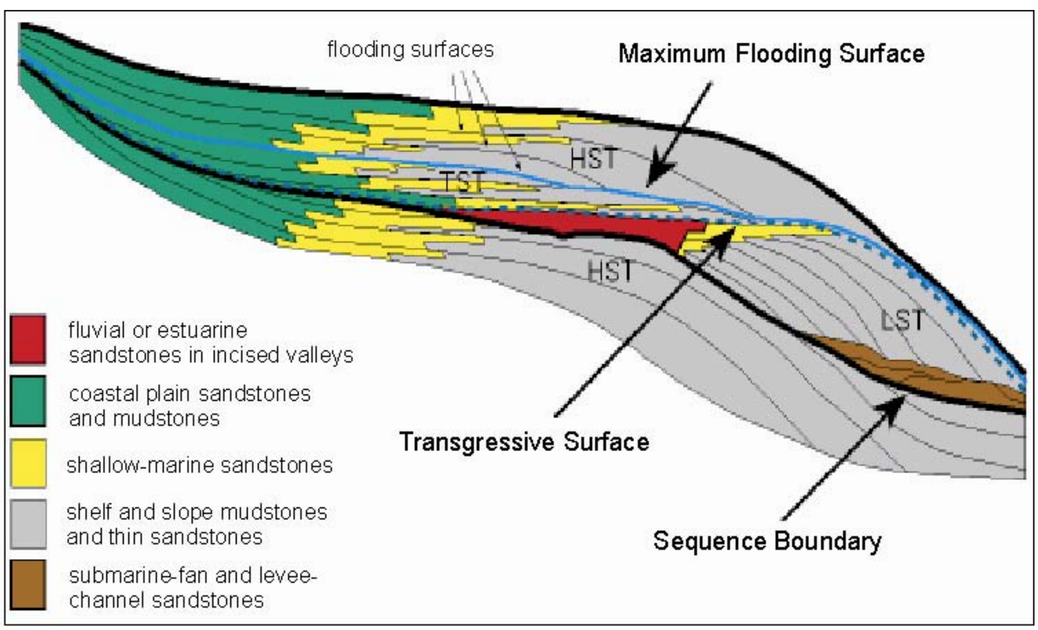


Figure 65. Type 1 depositional sequence model, with its systems tracts and stratigraphic surfaces. HST: highstand systems tract, LST: lowstand systems tract, TST: transgressive systems tract. (from Van Wagoner et al., 1988).

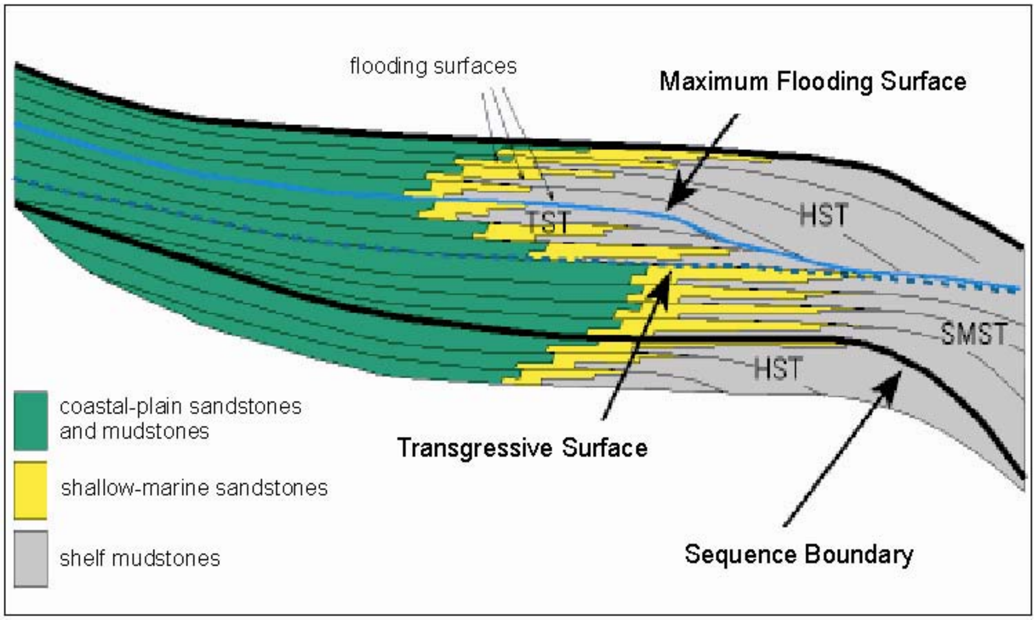


Figure 66. Type 2 depositional sequence model, with its systems tracts and stratigraphic surfaces. HST: highstand systems tract, LST: lowstand systems tract, TST: transgressive systems tract, SMST: shelf margin systems tract (from Van Wagoner et al., 1988).

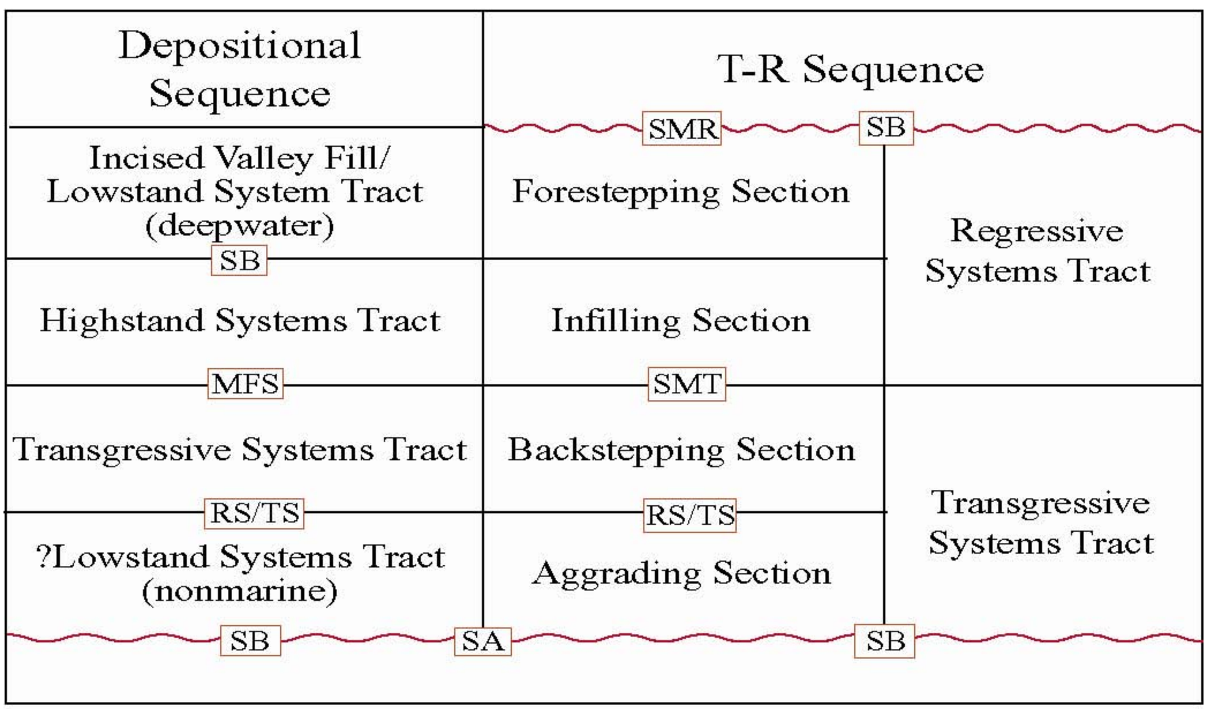


Figure 67. Chart comparing concepts of the third order depositional sequence concept and the T-R sequence, and their associated important stratigraphic surfaces. SB=sequence boundary, SA=subaerial unconformity, RS=shoreface ravinement surface, TS=transgressive surface, MFS=maximum flooding surface, SMT=surface of maximum transgression, SMR=surface of maximum regression (modified from Mancini et al., 2004).

Embry (1993; 1995) argues that the conformable portion of such a sequence boundary, as described by Posamentier et al. (1988a, b), has no distinguishing characteristics, and cannot be recognized with scientific objectivity. Embry (2002) points out that although in this type of sequence all strata deposited during base-level fall are placed above the sequence boundary, the basinward portion (i.e. correlative conformity) of the sequence boundary is placed within the sequence and not at the sequence boundary (Embry, 2002).

Posamentier et al. (1988a, b) describes the boundary of the type 2 depositional sequence as distinguished by a subaerial unconformity on the basin margin, representing the unconformable portion of the boundary. The correlative conformity of this boundary is a time line that is equivalent to the start of base-level rise basinward; where the unconformable portion of the sequence boundary is no longer present (Posamentier et al., 1988). According to Embry (2002), the problem associated with this type of sequence is again the lack of scientific objective criteria for the recognition of the conformable portion of the sequence boundary. Moreover, all strata deposited during base-level rise are placed directly below the sequence boundary (Embry, 1995; 2002).

Sequences can be subdivided into smaller units, called systems tracts, that are genetically related and that form during different stages of a single sea-level cycle (Posamentier et al., 1988a, b) (Figures 65 and 66). For instance, a package of sediments deposited during an interval of relative sea-level fall, and the subsequent slow relative sea-level rise would be termed “lowstand systems tract”. However, a package of sediments deposited during a stage of relative sea-level rise would be referred to as “transgressive systems tract”. A “highstand systems tract” describes deposition during the late stage of relative sea-level rise and the early stage of relative sea-level fall (Posamentier et al., 1988a, b; Van Wagoner et al., 1988).

According to Van Wagoner et al. (1988), the type 1 depositional sequence of Vail consists of three systems tracts: lowstand, transgressive and highstand. A type 2 depositional sequence includes shelf margin, transgressive and highstand systems tracts. Many workers (e.g. Prather, 1992; Baria et al., 1993; etc.) have used the Vail approach, particularly the type 1 depositional sequence concept, for years in their sequence and stratigraphic interpretations.

In 1989, Galloway introduced a third type of sequence, termed the genetic stratigraphic sequence, which is also known as a regressive-transgressive (R-T) sequence. Galloway developed his methodology utilizing well log data in defining the bounding surfaces of the genetic stratigraphic sequence, and in recognizing other important stratigraphic surfaces. Unlike the type 1 and type 2 depositional sequences of Vail, Galloway advocates using maximum flooding surface (MFS), rather than unconformities, as bounding surfaces of his type of sequence (Figure 68).

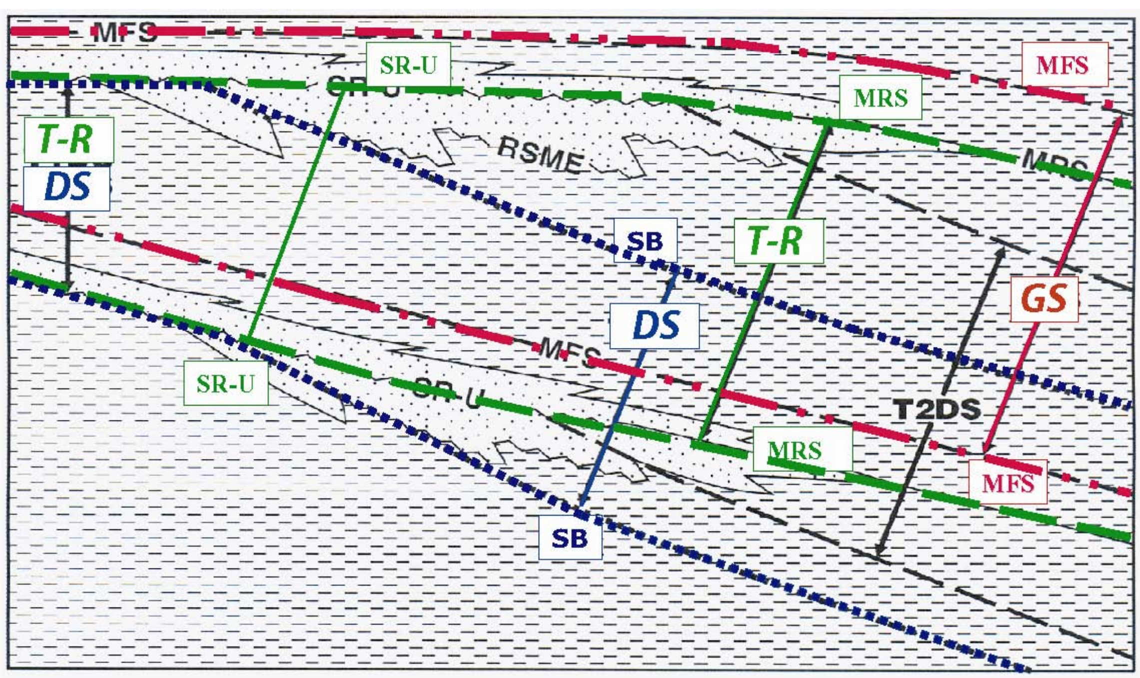


Figure 68. A schematic cross section illustrating the surfaces of sequence stratigraphy and the sequence boundaries of the three main concepts of sequence stratigraphy. T-R=transgressive-regressive sequence. DS=depositional sequence. GS=genetic stratigraphic sequence. MRS=maximum regressive surface. MFS=maximum flooding surface (also known as surface of maximum transgression "SMT". SB=sequence boundary (Modified from Embry, 2002).

A maximum flooding surface is defined as a surface separating the underlying older strata, representing the transgressive systems tract, from the overlying younger strata, representing the highstand systems tract. This surface also approximates the deepest water facies within a sequence (i.e. maximum transgression). This flooding surface lies at the turning point that marks the shift from retrogradational to progradational parasequence stacking, although this shift may be gradational and characterized by aggradational stacking. In this case, a single surface defining the point of maximum flooding may not be identifiable, and a maximum flooding "zone" is recognized instead. The maximum flooding surface commonly, but not always, displays evidence of condensation or slow deposition, burrowing, hardgrounds, mineralization, and fossil accumulations. Galloway (1989a, b) argues that the MFS consists of both unconformable (at the basin margin) and conformable (basinward) portions, and as such, his genetic stratigraphic sequence is similar to the Mitchum et al. (1977a, b) definition of a sequence.

The advantage of the Galloway's genetic stratigraphic model is that only one type of surface is defined, i.e. the maximum flooding surface. The maximum flooding surface (MFS) can easily and objectively be recognized by scientific analysis on well logs, seismic, as well as cores. It also is a stratigraphic surface that has low diachroniety. This makes the MFS a good candidate for usage as a sequence boundary. Nevertheless, Embry (2002) argues that the fact that the genetic sequence is bound on top and base by a maximum flooding surface (MFS) would mean placing the subaerial unconformity within the sequence and not at its boundaries. This would have significant sequence stratigraphic implications in delineating sequences particularly on the margin of a basin such that a genetic stratigraphic sequence would consist of two different, genetically unrelated stratigraphic units separated by a subaerial unconformity. This represents a major drawback to this type of sequence and appears at odds with the original Mitchum et al. (1977a, b) definition of a sequence, as well as the objective of sequence stratigraphy in recognizing and identifying separate, genetically related stratigraphic units (Embry, 2002).

Galloway (1989a) argues that his genetic stratigraphic sequence approach offers an alternative to the depositional sequence model of Vail et al. (1977a, b), and the two models use many of the same stratigraphic surfaces. Earlier, Vail and Mitchum (1977) identified a MFS on a seismic section as a downlap surface, and considered it a sequence boundary. However, soon after, they discontinued designating a MFS as a sequence boundary.

Embry and Johannessen (1992) and Embry (1993; 1995; 2002) define a fourth type of sequence termed the transgressive-regressive (T-R) sequence. The T-R sequence (Figure 68) is bound on top and base by a sequence boundary. The sequence boundary has an unconformable portion, which is the subaerial unconformity or shoreface ravinement unconformable surface. The subaerial unconformity forms during base-level fall and regression, whereas the shoreface ravinement forms during the interval of base-level rise when transgression begins, resulting in a landward shift of the shoreline. As such, the shoreface ravinement surface is cut by shoreface wave action, which removes sediments basinward as a result of the landward shift of the shelf equilibrium profile (Embry, 1995).

The correlative conformity of the sequence boundary is the maximum regressive surface (MRS), which represents the conformable portion of the sequence boundary basinward (Embry, 2002). A maximum regressive surface is the stratigraphic horizon that marks the change from shallowing-upward, regressive strata below to deepening-upward, transgressive strata above.

At the margin of a basin, the T-R stratigraphic sequence resembles the type 1 and type 2 depositional sequences in terms of the unconformable portion of the sequence boundary. Basinward, towards the central regions of a basin, the conformable portion of the sequence boundaries of these sequences diverge (Figure 68).

The T-R stratigraphic sequence of Embry was developed using outcrops and core data analyses. Embry divides the T-R sequence into a transgressive systems tract (TST) below and a regressive systems tract (RST) above with a maximum flooding surface (MFS), an equivalent to surface of maximum transgression (SMT), as a mutual boundary separating the two systems tracts (Figures 67 and 68). Embry suggests using the regressive systems tract (RST) in lieu of the lowstand systems tract (LST) and highstand systems tract (HST) of Vail's depositional sequence, which he incorporates in the RST of his T-R sequence (Embry, 2002).

Embry (2002) promotes using the T-R sequence arguing that it is in agreement with the Mitchum et al. (1977a, b) definition of a stratigraphic sequence. Moreover, the T-R sequence is composed of two genetically related units, which are bound by a maximum flooding surface (MFS). In addition, all of the bounding stratigraphic surfaces of this sequence (i.e. the unconformity, the MFS, and the MRS) can be objectively and scientifically recognized (Embry, 1995; 2002).

Comparative Sequence Stratigraphic Analysis of the Upper Jurassic Section

In terms of sequence stratigraphy, there are various schools of thought that have developed and evolved since Sloss et al. (1949). There has also been conflicting opinions concerning which is the most appropriate and applicable for sequence stratigraphic analysis. In general, sequence stratigraphic concepts and models have been applied mainly to marine strata and have used the concepts defined by Mitchum et al. (1977a, b). This project attempted to establish a stratigraphic framework for the Upper Jurassic continental, marginal marine and marine strata in the northeastern Gulf of Mexico by using a combined sequence and seismic stratigraphic approach.

The sequence stratigraphic analysis of the Upper Jurassic section in the study area (Figure 69) is illustrated in Figures 70-72. These figures show comparative sequence stratigraphic interpretations utilizing the three main approaches in the sequence stratigraphy discipline; namely the depositional sequence concept of Vail el al. (1977a, b), the genetic stratigraphic sequence concept of Galloway (1989a, b) and the transgressive-regressive (T-R) sequence concept of Embry (2002).

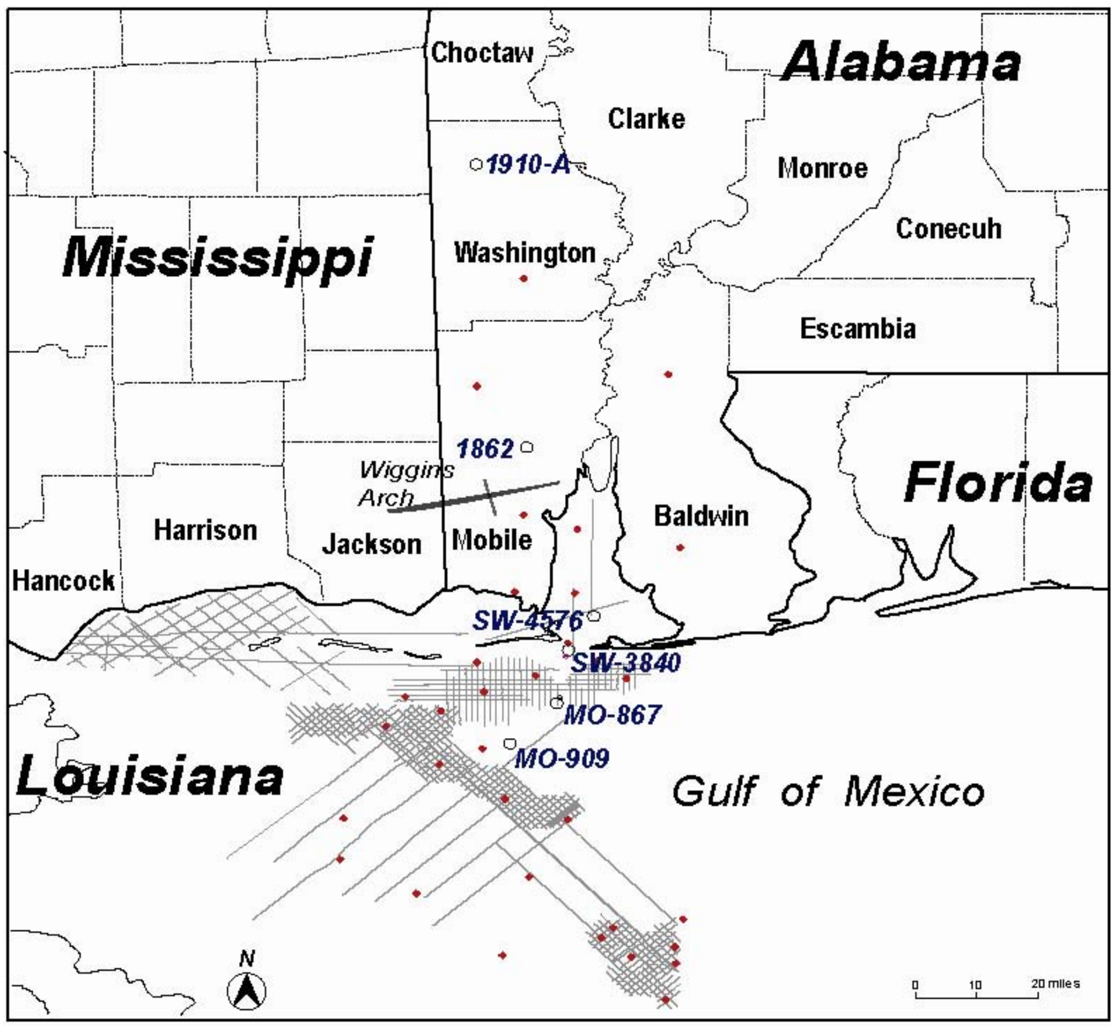


Figure 69. Map of study area, located in the northeastern Gulf of Mexico, showing locations of wells (red circles) and seismic data (grey lines).

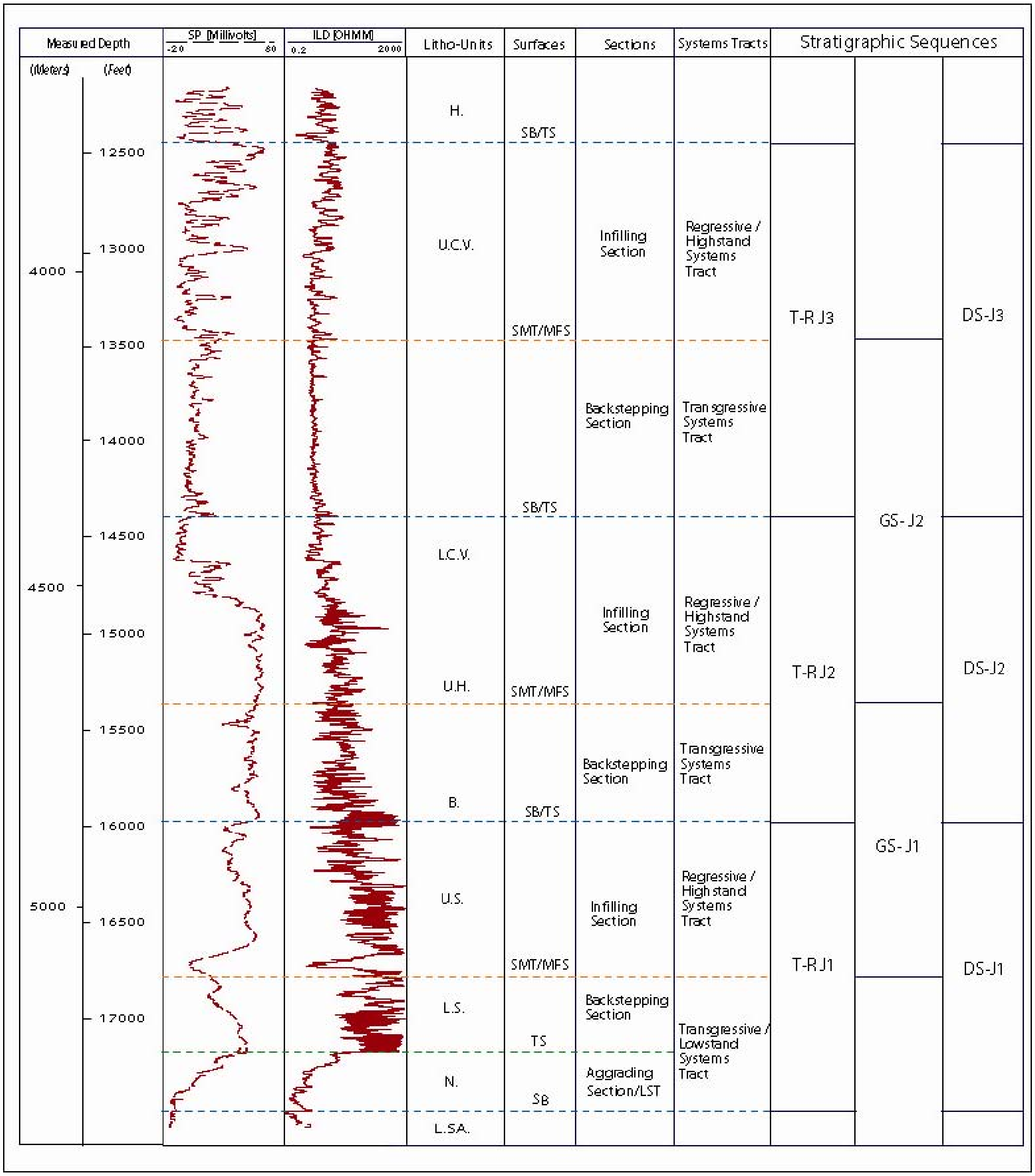


Figure 70. Well log patterns from Well Permit 1910-A (location shown on figure 1), Washington County, AL, showing well log responses characteristic for the Upper Jurassic transgressive-regressive, genetic and depositional sequences. SP=spontaneous potential, ILD=Deep Induction (resistivity). SB=sequence boundary, MFS=maximum flooding surface, TS=transgressive surface. L.SA.=Louann Salt, N.=Norphlet Formation, L.S.=lower Smackover Formation, U.S.=Upper Smackover Formation, B.=Buckner Anhydrite Member, L.H.=lower Haynesville, U.H.=upper Haynesville, L.C.V.=lower Cotton Valley, U.C.V.=upper Cotton Valley, H.=Hosston Formation (modified from Obid, 2005a).

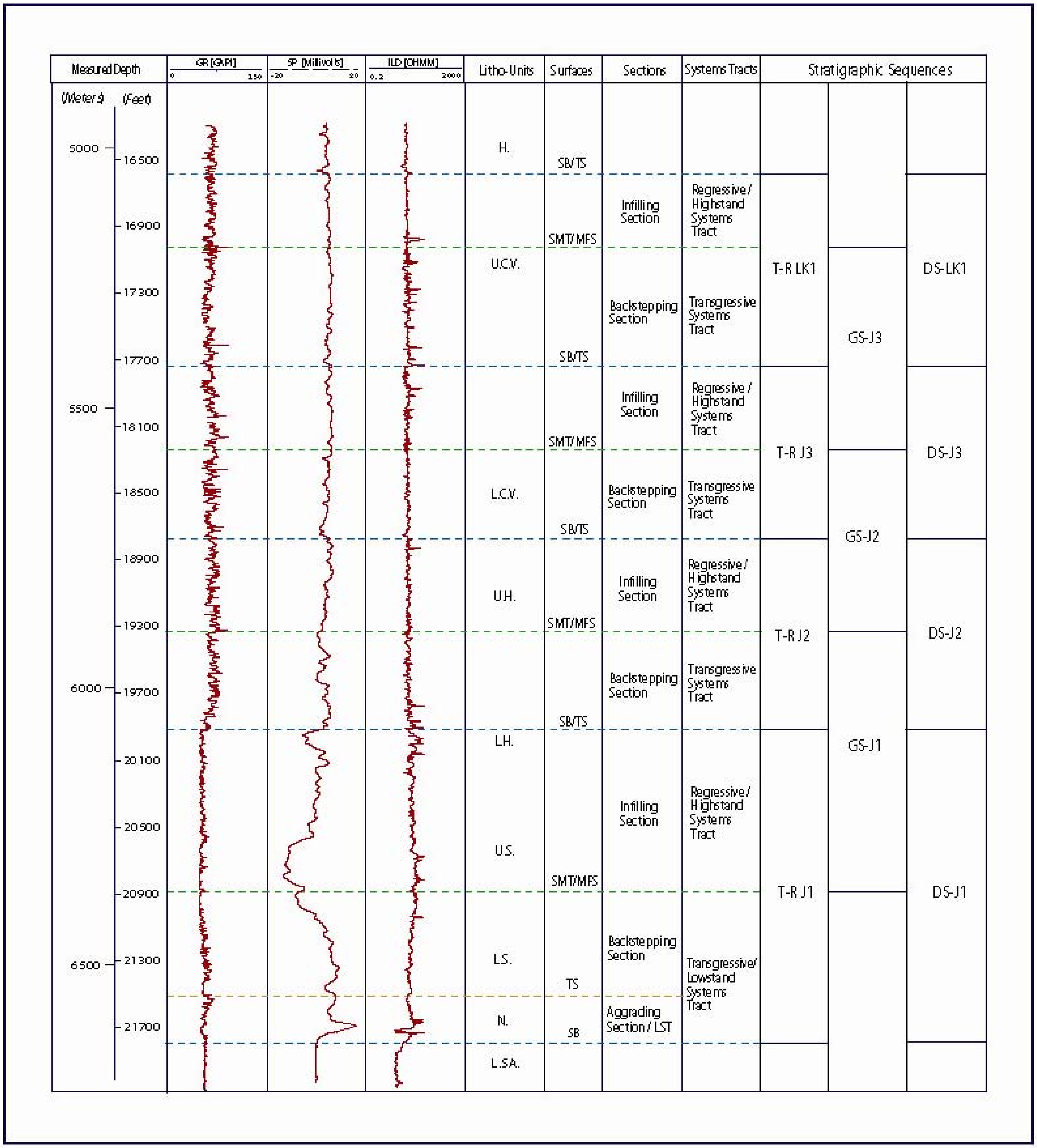


Figure 71. Well log patterns from Well Permit MO-867 (location shown on figure 1), Mobile Area, offshore Alabama, showing well log responses characteristic for the Upper Jurassic transgressive-regressive, genetic and depositional sequences. SP=spontaneous potential, GR=gamma ray, ILD=Deep Induction (resistivity). SB=sequence boundary, MFS=maximum flooding surface, TS=transgressive surface. L.SA.=Louann Salt, N.=Norphlet Formation, L.S.=lower Smackover Formation, U.S.=upper Smackover Formation, B.=Buckner Anhydrite Member, L.H.=lower Haynesville, U.H.=upper Haynesville, L.C.V.=lower Cotton Valley, U.C.V.=upper Cotton Valley, H.=Hosston Formation (modified from Obid, 2005a).

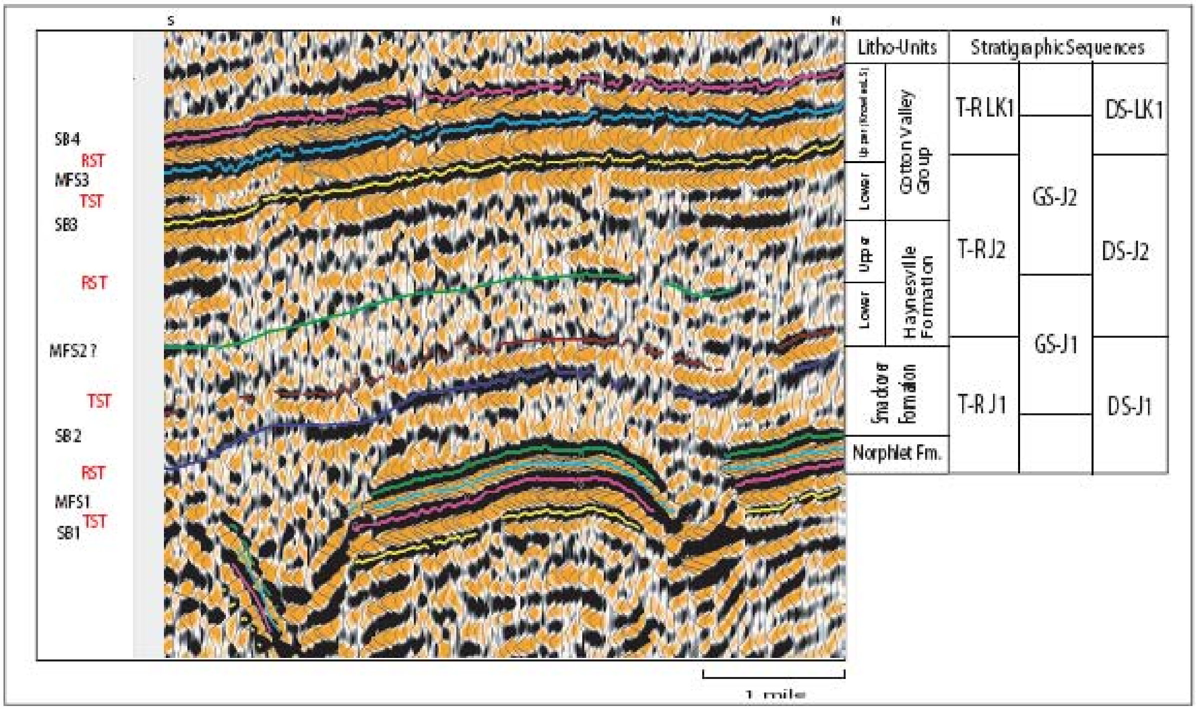


Figure 72. A typical seismic section from offshore Alabama, showing the three recognized T-R sequences. SB=sequence boundary, MFS=maximum flooding surface, T=transgressive systems tracts, R=regressive systems tracts. Seismic line courtesy of WesternGeco.

Based on the depositional sequence approach presented by Vail et al. (1977a), three depositional stratigraphic sequences (DS-J1, DS-J2, and DS-J3) can be recognized on well logs in the onshore Alabama area, north of the Wiggins Arch (Figure 70). Offshore Alabama, south of the Wiggins Arch, four depositional stratigraphic sequences (DS-J1, DS-J2, DS-J3, and DS-LK1) can be recognized (Figure 71). On reflection seismic sections, Vail's approach yields three depositional stratigraphic sequences; DS-J1, DS-J2 and DS-LK1 for the offshore area (Figure 72).

The DS-J1 sequence includes the Norphlet Formation, which represents deposits of the late lowstand systems tract (continental eolian, alluvial fan and plain, fluvial and marine reworked deposits) of the sequence. These strata are overlain by a transgressive surface (TS). The contact between the continental sandstone of the Norphlet Formation and the underlying

Louann Salt is sharp and can be identified as a discontinuity on well log responses (Figures 70 and 71). The marine sandstone of the Norphlet Formation and the lower and middle marine lime mudstone of the Smackover Formation represent the transgressive systems tract deposits of the sequence. The highstand systems tract consists of upper Smackover nearshore and shoal packstone and grainstone and sabkha anhydrite deposits of the Buckner Anhydrite Member of the Haynesville Formation. The maximum flooding surface occurs within the lime mudstone beds of the middle Smackover Formation.

The DS-J2 sequence includes subaqueous anhydrite beds of the Buckner Anhydrite Member, and interbedded anhydrite and shale (lagoonal) and interbedded shale and limestone (shallow marine) of the lower Haynesville Formation. These deposits overlie the sequence boundary and represent deposits of the transgressive systems tract of this sequence. The maximum flooding surface occurs in the interbedded shale and limestone of the lower Haynesville. The highstand systems tract consists of interbedded shale and sandstone (marginal marine) deposits of the upper Haynesville Formation and sandstone (marginal marine and coastal plain) deposits of the lower Cotton Valley. Offshore, the Buckner Anhydrite is absent and is replaced by lower Haynesville shale and limestone (shallow marine) strata.

The DS-J3 sequence onshore includes sandstone and shale (marine shelf) deposits of the upper Cotton Valley Group. The transgressive systems tract of this sequence consists of upper Cotton Valley sandy shale (marine shelf) deposits. The highstand systems tract of this sequence is represented by the sandstone and conglomeratic (nearshore marine and fluvial) deposits of the upper Cotton Valley. The maximum flooding surface occurs in the upper Cotton Valley shale deposits.

The DS-LK1 sequence, which is recognized only offshore, consists of the Knowles Limestone (marine shelf, shoal and reef complex deposits) of the upper Cotton Valley Group. The transgressive systems tract consists of marine shelf shale and limestone beds of the Knowles Limestone. The shoal and reef complex deposits of the Knowles represent the highstand systems tract of this sequence. The maximum flooding surface occurs in the marine shelf shale and limestone.

Using the genetic stratigraphic sequence approach presented by Galloway (1989a) to the same datasets available in this paper and focusing on utilizing maximum flooding surfaces (MFS) as defining sequence boundaries as identified on well logs, two genetic stratigraphic sequences (GS-J1, and GS-J2) can be delineated in the onshore Alabama area, north of the Wiggins Arch (Figure 70). In the offshore area, south of the Wiggins Arch, three genetic stratigraphic sequences (GS-J1, GS-J2, and GS-J3) can be recognized (Figure 71). On reflection seismic sections, two genetic stratigraphic sequences, GS-J1 and GS-J2, can be delineated (Figure 72).

Figures 70-72 illustrate the transgressive-regressive (T-R) sequences recognized on reflection seismic profiles and well logs, both onshore and offshore, following the approach of Embry and Johannessen (1992) and Embry (1993; 2002). Using available well log data, three sequences, T-R J1, T-R J2 and T-R J3, were recognized onshore (Figure 70), while four sequences, T-R J1, T-R J2, T-R J3 and T-R LK1, were identified in the offshore part of the study area (Figure 71). On reflection seismic data, only three sequences, T-R J1, T-R J2 and T-R LK1, were recognized (Figure 72). The description of these sequences and their systems tracts is presented in previous chapters after Obid (2005a, b).

The Vail model was originally based on the premise that eustacy (global sea-level) is the main driver behind the depositional sequence, with less emphasis on local/regional tectonics and climate. Moreover, the depositional sequence model was applied mainly to marine strata, as defined by Mitchum et al. (1977a, b). The Upper Jurassic section in the study area is a mixed siliciclastic and carbonate section that represents continental, marginal marine and marine environments. Therefore, the Vail approach may have limitations when applied to the Upper Jurassic stratigraphic section in this area of study.

The Norphlet Formation, for instance, was interpreted as a highstand systems tract by Mancini et al. (1990), using Vail's approach. In this paper, following the transgressive-regressive approach of Embry (2002), the Norphlet Formation is interpreted on well log and seismic data to be the aggrading section of the transgressive systems tract of the T-R J1 sequence. However, following the concept of Vail, the Norphlet Formation in the study area is interpreted on well log and seismic data as being a lowstand systems tract because this unit occurs above a sequence boundary and below a transgressive surface (Figures 70 and 71). The depositional patterns and trends of the Norphlet continental deposits are not consistent with the definition of lowstand systems tract deposits. The Norphlet deposits are widespread and continuous and do not show the characteristics of regional incision.

The Galloway approach does not seem to honor the widely accepted definition of a sequence. As shown in Figures 70 and 71, the Smackover Formation is divided into two separate and different, not genetically related, sequences using this approach. The lower to middle Smackover is assigned to an undefined sequence below the GS-J1 sequence, below the maximum flooding surface. The upper Smackover is assigned to the GS-J1 sequence. These assignments are not consistent with the original definition of a sequence by Sloss et al. (1949) and the later modified definition by Mitchum et al. (1977a, b), in which a sequence is defined as "a stratigraphic rock unit composed of "genetically" related strata…". Moreover, the Galloway approach places the sequence boundary (the subaerial unconformity) within the sequence, not at its boundaries. This is a potential problem with Galloway's approach, and appears inconsistent with the Mitchum et al. (1977a, b) definition of a sequence, in which it states that "a sequence…is bounded on top and base by unconformities…" (Mitchum et al., 1977a, b).

Given the above discussion, the transgressive-regressive (T-R) approach to sequence stratigraphic analysis seems more applicable, considering the location of the study area and type of data available. It appears to be probably the most direct approach to establish a sequence stratigraphic framework for this area, and adheres to the basic fundamentals of the discipline. It also seems to be the more favorable to be applied, especially in mixed siliciclastic and carbonate settings, with the least amount of complications. Moreover, it has a minimum amount of terminology, particularly in terms of surfaces and systems tracts. In the absence of lowstand deposits, the T-R approach and the depositional sequence approach yield the same sequence stratigraphic assignment.

Conclusions

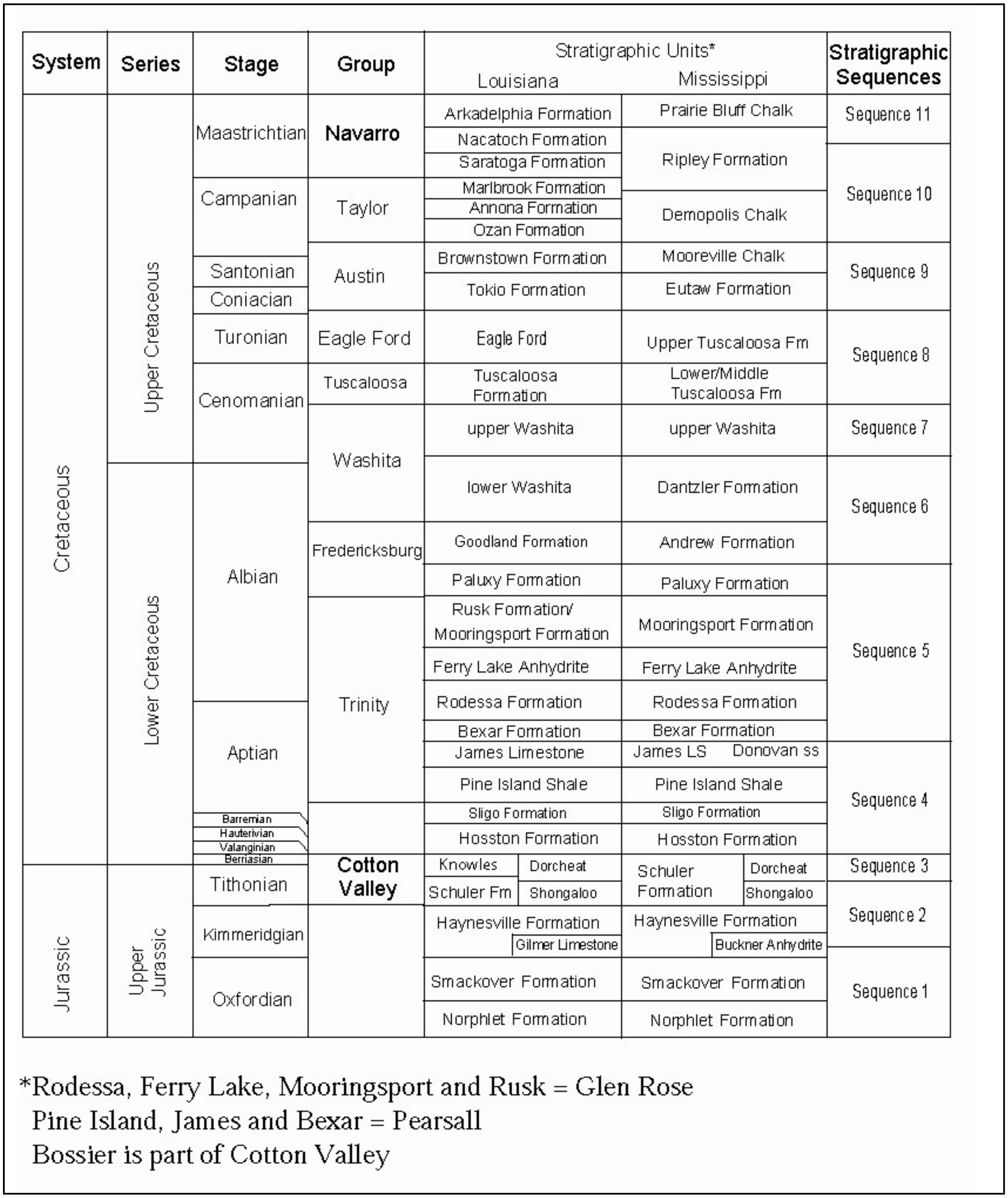
Sequence stratigraphy is useful for recognition of changes in depositional trends during a relative sea-level cycle. These changes in trends are represented by stratigraphic surfaces that can be utilized for correlation of sequences and their associated systems tracts. Several sequence stratigraphic approaches have been developed. These include the Vail depositional sequence approach, the Galloway genetic stratigraphic sequence approach and the Embry transgressive-regressive (T-R) sequence approach. Each of these approaches has defined sequence boundaries, systems tracts and key stratigraphic surfaces.

For the Upper Jurassic section in the northern Gulf of Mexico, the transgressive-regressive (T-R) approach of Embry seems to have the greatest utility for establishing a framework for sequence stratigraphic analysis given the available dataset, tools utilized and the nature of stratigraphic section. This approach is straightforward and has application for a mixed carbonate and siliciclastic stratigraphic section characterized by continental, marginal marine and marine deposits.

In the absence of lowstand systems tract deposits, the T-R approach and the depositional sequence approach produce the same stratigraphic interpretation. Whereas the genetic stratigraphic sequence approach of Galloway has limitations for application in this area for its use results in placing genetically related stratigraphic units into different sequences.

In conclusion, as demonstrated by Obid (2006), it is clear that all three sequence stratigraphic models are useful. The key in selecting the preferred model for the classification and correlation of strata in a given basin is dependent on the conditions, such as the changes in tectonics, sea level, sediment supply, and climate for that particular basin. However, the surfaces bounding the strata are common to all three models. Therefore, in developing a sequence stratigraphy model, the best approach is to refer to the sequences as stratigraphic sequences that are bounded and subdivided by distinctive surfaces and recognize the subdivisions within the sequences as system tracts.

Discovered reservoir classification-As a demonstration of the usefulness of sequence stratigraphy in petroleum exploration, the known petroleum reservoirs of the Mississippi Interior and North Louisiana Salt Basins are grouped and classified as stratigraphic sequences (Figure 73) and in T-R sequences (Tables 3 and 4).



System	Series	Stage	Group	Stratigraphic Units* Louisiana	Stratigraphic Units* Mississippi	Stratigraphic Sequences
Cretaceous	Upper Cretaceous	Maastrichtian	Navarro	Arkadelphia Formation	Prairie Bluff Chalk	Sequence 11
				Nacatoch Formation	Ripley Formation	
				Saratoga Formation		Sequence 10
		Campanian	Taylor	Marlbrook Formation	Demopolis Chalk	
				Annona Formation		
				Ozan Formation		
		Santonian	Austin	Brownstown Formation	Mooreville Chalk	Sequence 9
		Coniacian		Tokio Formation	Eutaw Formation	
		Turonian	Eagle Ford	Eagle Ford	Upper Tuscaloosa Fm	Sequence 8
		Cenomanian	Tuscaloosa	Tuscaloosa Formation	Lower/Middle Tuscaloosa Fm	
			Washita	upper Washita	upper Washita	Sequence 7
	Lower Cretaceous	Albian		lower Washita	Dantzler Formation	Sequence 6
			Fredericksburg	Goodland Formation	Andrew Formation	
				Paluxy Formation	Paluxy Formation	Sequence 5
			Trinity	Rusk Formation/ Mooringsport Formation	Mooringsport Formation	
				Ferry Lake Anhydrite	Ferry Lake Anhydrite	
		Aptian		Rodessa Formation	Rodessa Formation	
				Bexar Formation	Bexar Formation	
				James Limestone	James LS / Donovan ss	Sequence 4
				Pine Island Shale	Pine Island Shale	
		Barremian		Sligo Formation	Sligo Formation	
		Hauterivian / Valanginian		Hosston Formation	Hosston Formation	
		Berriasian	Cotton Valley	Knowles / Dorcheat	Schuler Formation / Dorcheat	Sequence 3
Jurassic	Upper Jurassic	Tithonian		Schuler Fm / Shongaloo	Shongaloo	Sequence 2
		Kimmeridgian		Haynesville Formation / Gilmer Limestone	Haynesville Formation / Buckner Anhydrite	
		Oxfordian		Smackover Formation	Smackover Formation	Sequence 1
				Norphlet Formation	Norphlet Formation	

*Rodessa, Ferry Lake, Mooringsport and Rusk = Glen Rose
Pine Island, James and Bexar = Pearsall
Bossier is part of Cotton Valley

Figure 73. Stratigraphy and sequence stratigraphy of the North Louisiana and Mississippi Interior Salt Basins (from Mancini et al. 2006b).

Table 3. Mississippi Interior Salt Basin Oil and Gas Production.

Reservoir	Oil (Bbls)	Gas (Mcf)	T-R Sequence
Selma	39,205,424	224,393,889	TB/RI
Eutaw	301,449,711	1,754,506,272	TA/TB
Upper Tuscaloosa	26,338,415	19,226,238	RI
Lower Tuscaloosa	610,702,463	1,805,166,543	TA/TB
Dantzler	783,201	72,450,931	RI
Washita-Fredericksburg	56,943,318	255,821,157	TB/RI
Paluxy	56,544,588	568,991,732	RI
Mooringsport	11,633,767	215,885,662	RI
Ferry Lake	7,381	8,175	TB
Rodessa	235,162,019	341,331,628	RI
Pine Island	543,856	676,027	TB
Sligo	30,927,220	157,859,597	TB
James	902,320	80,356,905	RI
Hosston	54,887,990	995,065,210	TA
Cotton Valley	106,461,276	146,163,240	RI
Haynesville	6,421,491	349,786,844	RI
Smackover	522,979,535	4,069,721,819	TB/RI
Norphlet	12,664,335	331,269,443	TA
Others	562,883,419	641,775,162	
Total	**2,637,441,729**	**12,030,456,474**	

TA=transgressive aggrading, TB=transgressive backstepping, RI=regressive infilling. Production data from State Oil and Gas Boards of Mississippi and Alabama.

Table 4. North Louisiana Salt Basin 0il and Gas Production.

Reservoir	Oil (Bbls)	Gas(Mcf)	T-R Sequence
Arhadelphia/Monroe	44,038	7,452,904,183	RI
Nacatoch	758,374,196	4,431,274,239	TB
Ozan/Buckrange	265,037,353	1,007,534,243	TB
Tokio/Blossom	128,817,273	1,718,406,462	TB
Tuscaloosa/Eagle Ford	3,971,873	75,601,381	TB/RI
Fredericksburg	1,643,190	34,409,159	TB/RI
Paluxy	6,206,760	88,408,279	RI
Mooringsport/Ferry Lake	312,309	1,171,999	TB/RI
Rodessa/Hill/Kilpatrick	198,858,232	5,615,080,804	RI
James	12,409	2,869,335	RI
Pine Island	8,745,072	545,229,418	TB
Sligo/Pettet	140,715,109	3,557,065,945	TB
Hosston	12,896,970	1,641,948,296	TA
Cotton Valley	114,348,835	2,223,486,076	RI
Haynesville	13,923,298	152,081,744	RI
Smackover	33,800,601	271,765,406	TB/RI
Others	25,388,311	130,564,541	
Total	**1,713,324,029**	**28,949,890,852**	

TA=transgressive aggrading, TB=transgressive backstepping, RI=regressive infilling. Production data based on information from International Oil Scout Association, Yearbook 2002.

Exploration strategy development-Exploration strategies are identified based on the developed sequence stratigraphy predictive model and the results from the classification of discovered reservoirs using T-R sequence terminology. These strategies include the use of outcrop, well log and seismic data in identifying specific facies that have reservoir potential and in identifying potential stratigraphic traps. The sequence stratigraphy model is based on the recognition of stratigraphic sequences bounded by key surfaces. In Jurassic and Cretaceous strata of the Gulf Coastal Plain, the stratigraphic sequences are T-R sequences, including a transgressive systems tract (aggrading and backstepping sections) and a regressive systems tract (infilling section). In Tertiary (Paleogene) strata these sequences are depositional sequences, including a lowstand systems tract, transgressive systems tract and highstand systems tract. The specific facies with reservoir potential in the Jurassic and Cretaceous strata are found chiefly in the aggrading section of the transgressive systems tract, and in the infilling section of the regressive systems tract. In the aggrading section, these continental and coastal plain facies include: alluvial, fluvial, eolian, coastal and tidal. These aggrading facies can be recognized by their characteristic well log signature and seismic reflection configuration; that is a smooth cylinder-shaped gamma ray or SP well log pattern and by a thick (several seismic cycles) interval of seismic reflectors exhibiting an aggradational reflection configuration. In the backstepping section, this marine facies include: nearshore marine, barrier bar and marine shelf. These backstepping facies are recognized by an overall increase in gamma ray or change to a more positive SP log response (bell-shaped or fining upward trend in well log pattern) and by a thin (one or two seismic cycles) interval of seismic reflectors exhibiting a concordant, parallel reflection configuration with onlap stratal terminations. In the infilling section, these non-marine, transitional, and marine facies include: fluvial, deltaic, coastal plain, tidal, and marine shelf.

These infilling facies are recognized by an overall decrease in gamma ray or change to a more negative SP log response (funnel-shaped or coarsening upward trend in well log pattern and by a thick (several seismic cycles) interval of seismic reflectors exhibiting an oblique, progradational reflection configuration with offlap (downlap) stratal terminations.

Stratigraphic traps (depositional traps, diagenetic traps, and/or unconformities) are defined by Biddle and Wielchowsky (1994) as traps, in which the requisite geometry and reservoir-seal combination were formed by any variation in the stratigraphy that is independent of structural deformation. These petroleum traps can be recognized in the Gulf Coast region through well log and seismic studies, cross section preparation, correlation and subsurface mapping. On seismic data, onlap and offlap seismic terminations can be recognized. From well log studies, in combination with the preparation of stratigraphic and structural cross sections, potential unconformities and stratigraphic pinchouts can be identified.

For example, in southwest Alabama, Upper Jurassic and Lower Cretaceous strata terminate against basement features (Mink and Mancini, 1995). Facies associated with these combination (stratigraphic and structural) traps include: transgressive aggrading (Norphlet alluvial, fluvial, eolian; Haynesville alluvial, fluvial, eolian, beach, nearshore marine, and Hosston fluvial and coastal); and infilling (Smackover nearshore and inner ramp). Delineation of topographic anomalies using seismic reflection data is the key to detecting these combination traps. The paleohighs are identified using 2D seismic data; and with the advent of 3D seismic reflection technology, the prediction as to whether potential reservoir facies are present on the crest and flanks (Figure 74) or restricted to the flanks (Figure 75) of a particular paleohigh can be made. The 3D technology also provided the opportunity to explore for the updip pinchout of potential reservoir facies (Figures 76 and 77).

A new Upper Jurassic play in southwest Alabama is developing, and this play has been described as a stratigraphic trap. As an example of an application of the sequence stratigraphy model and developed exploration strategies, the following discussion of this new stratigraphic trap (Little Cedar Creek) from Mancini et al. (2006c) is provided below. The sequence stratigraphic interpretation of the Smackover and associated strata (Figure 78) is from Mancini et al. (2004) and Llinas (2004), and their interpretation is based on the T-R sequence model developed as part of this study.

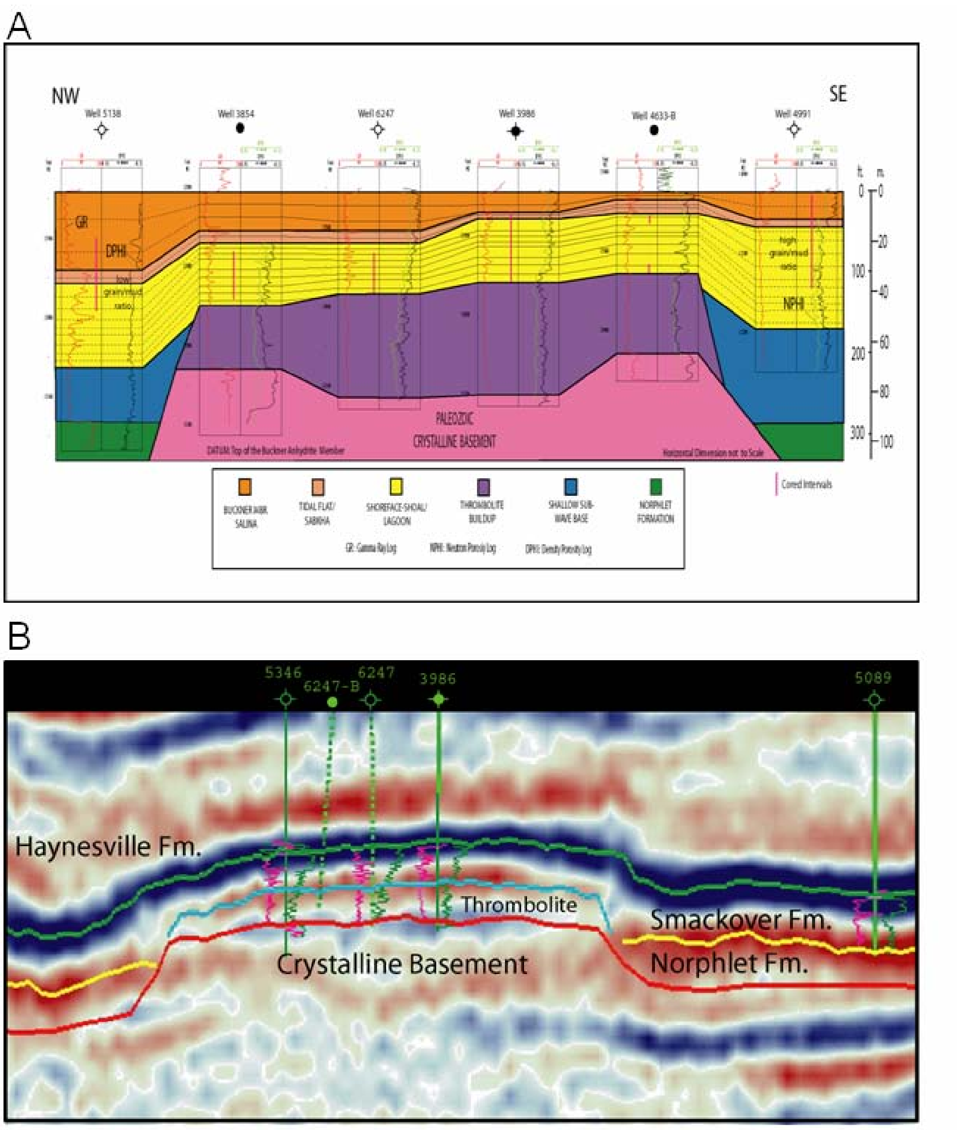


Figure 74. Appleton Field NW-SE cross section (A) and seismic line (B) (from Mancini et al., 2004).

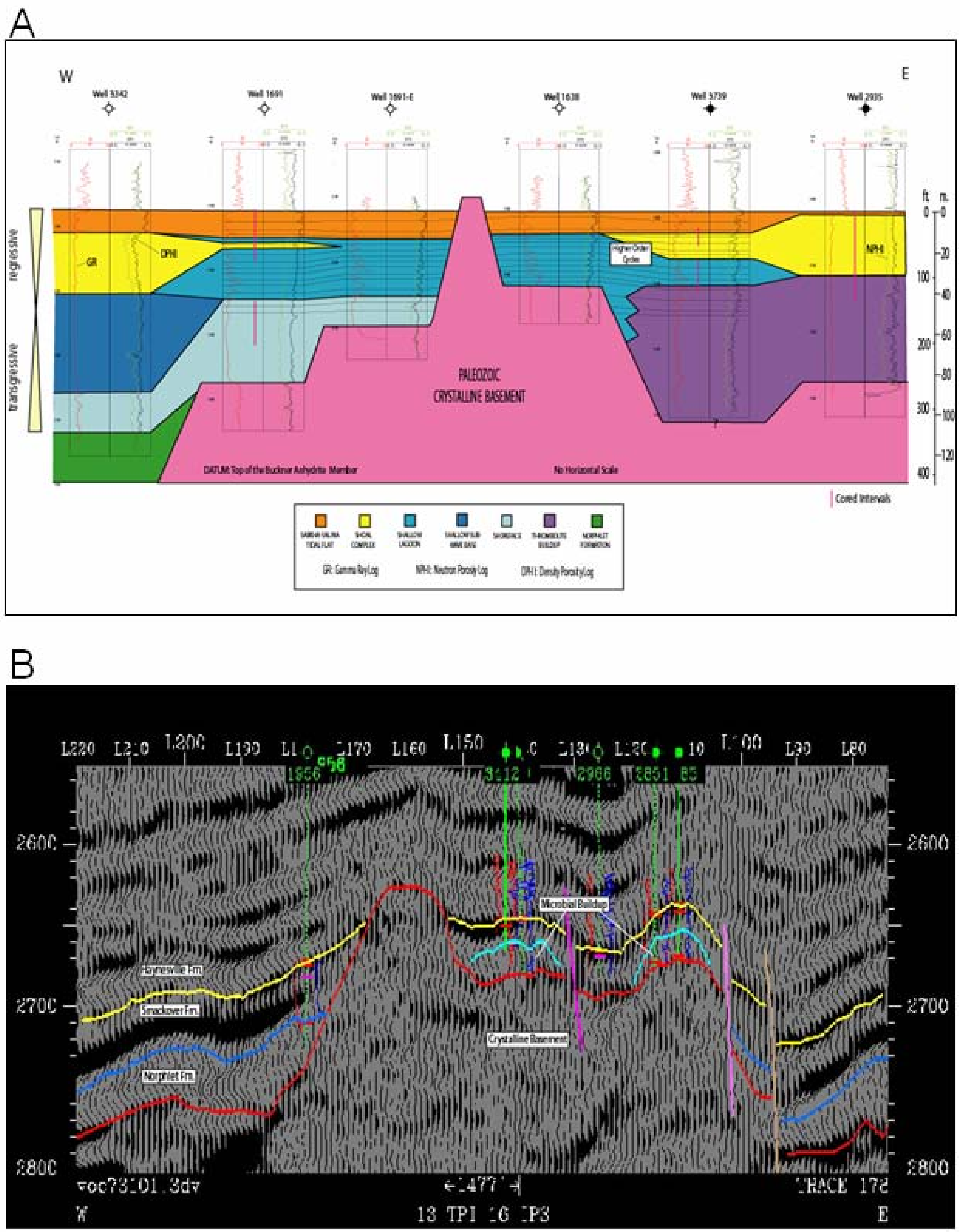


Figure 75. Vocation Field W-E cross section (A) and seismic line (B) (from Mancini et al., 2004).

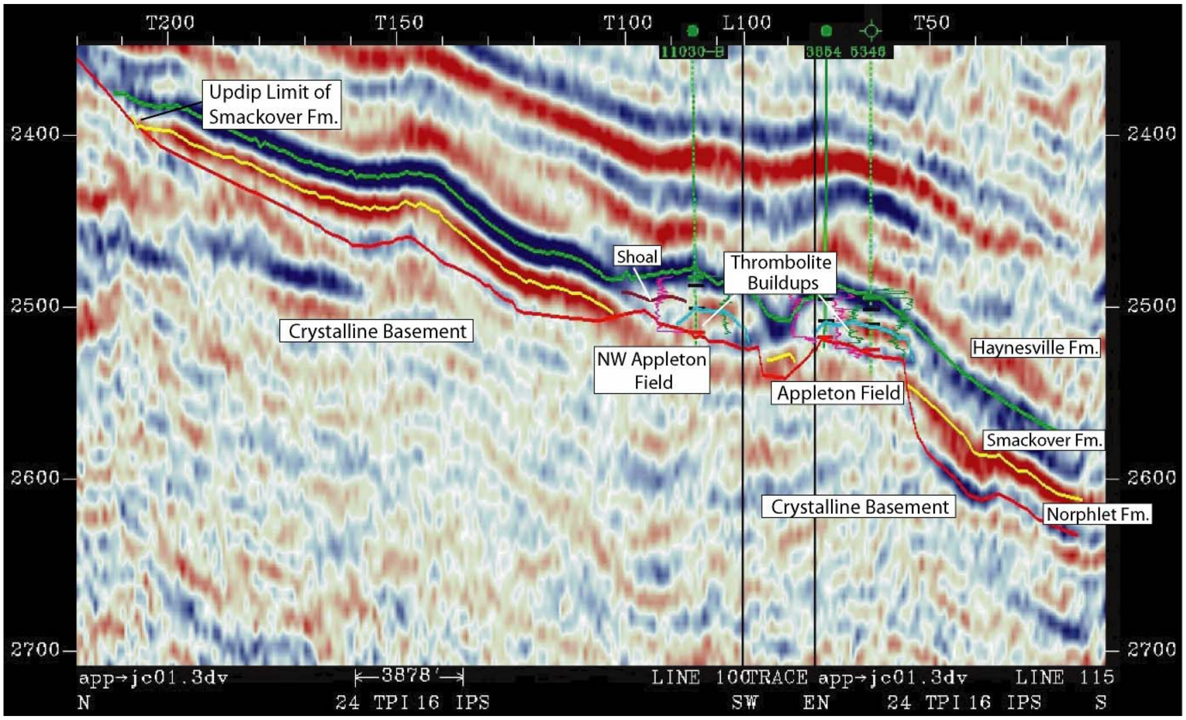


Figure 76. 3D seismic line illustrating the expression of potential stratigraphic traps and proven combination traps (from Mancini et al., 2004).

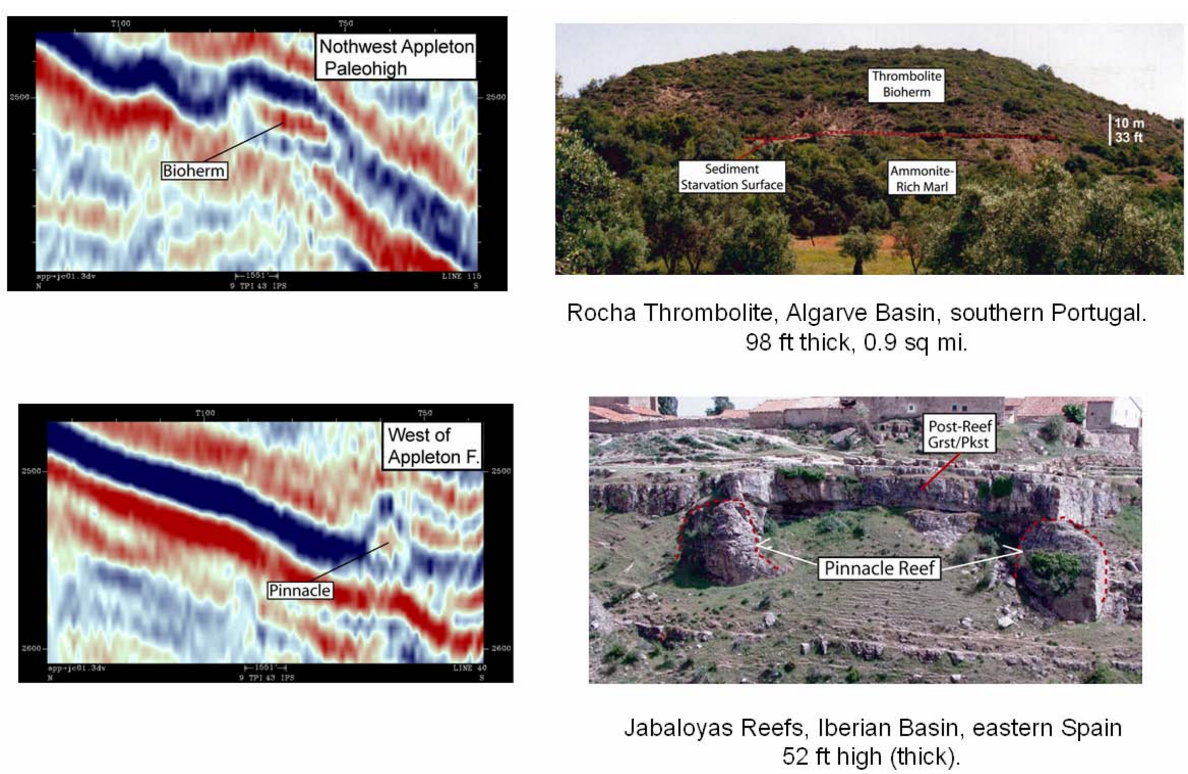
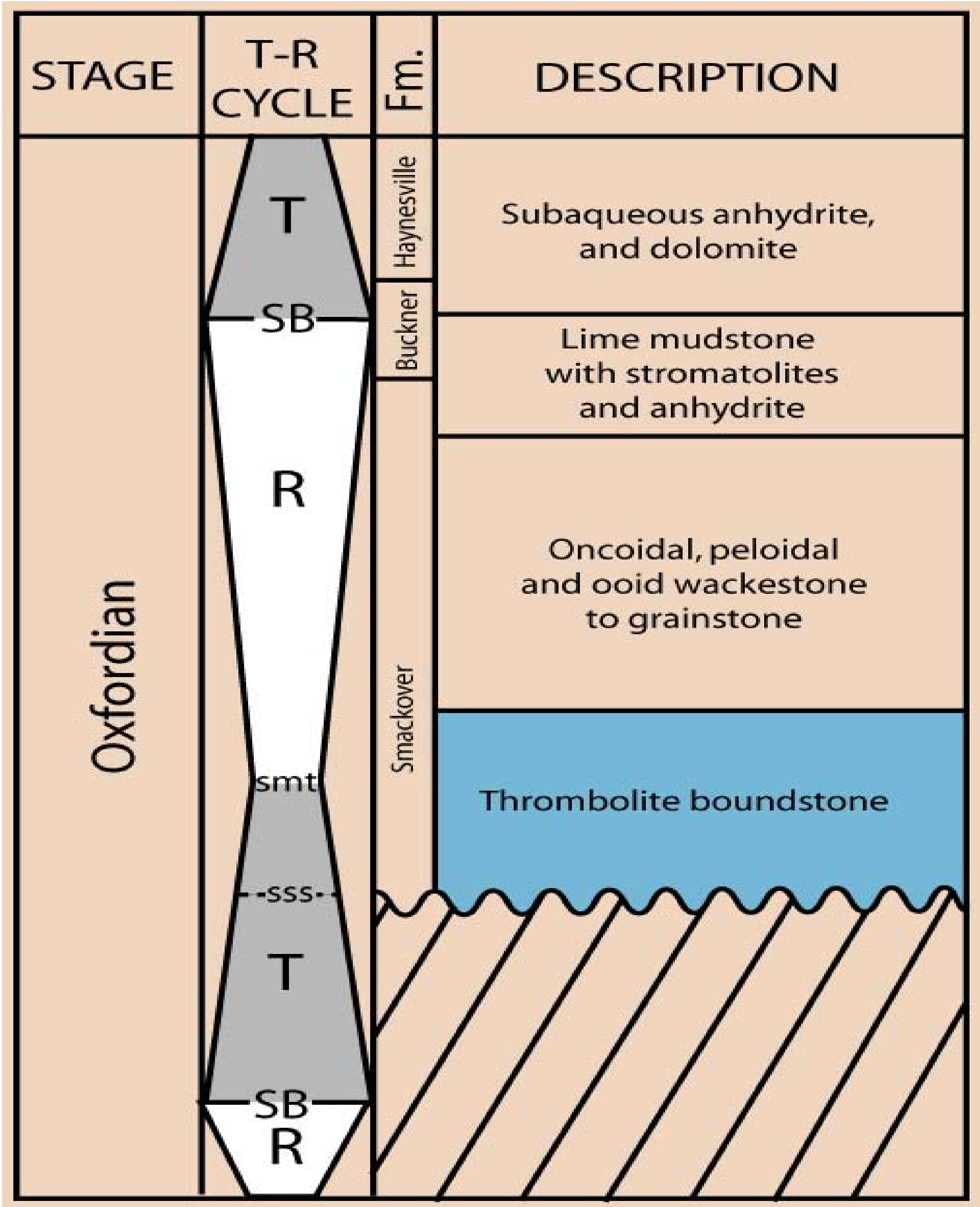


Figure 77. 3D seismic and outcrop expression of stratigraphic-structural traps (from Mancini et al., 2004).



SB=sequence boundary, SSS=surface of sediment starvation, SMT=surface of maximum transgression

Figure 78. Sequence stratigraphy interpretation of Smackover and associated strata (Llinas, 2004; Mancini et al., 2004).

Little Cedar Creek Field

The following discussion about the stratigraphic trap at Little Cedar Creek Field is from Mancini et al. (2006c).

Introduction

Upper Jurassic Smackover microbial buildups have proven to be hydrocarbon reservoirs in the eastern Gulf Coastal Plain. Typically, these buildups are associated with Paleozoic basement paleohighs, which has made them detectable through the use of seismic reflection data. These microbial buildups have been characterized by Baria et al. (1982), Crevello and Harris (1984), Kopaska-Merkel (1998), Parcell (2000), Llinas (2004) and Mancini et al. (2004). With the development of Little Cedar Creek Field, Conecuh County, Alabama, geologists now recognize that Smackover microbial buildups have developed in bathymetric settings other than on Paleozoic basement paleohighs, including updip, nearshore, and shallow subtidal environments.

Field History

Little Cedar Creek Field, Conecuh County, Alabama, was discovered in 1994 with the drilling and testing of the Cedar Creek Land and Timber Company 30-1 #1 well (Permit #10560) by Hunt Oil Company (Figure 79). The well tested at 108 barrels of 46 degree API gravity oil from the Upper Jurassic Smackover Formation. The field was officially established in 1995. A second well was drilled and tested successfully in 2000, and a third well was drilled and tested successfully in 2003. Both wells were drilled by Midroc Operating Company. In 2004, Midroc drilled and tested an additional 13 wells in the field area, and the field was unitized in December, 2004 (effective date of January, 2005) with prospects for secondary recovery by waterflood. Through September 2005, there were 23 producing wells in the field with a cumulative production of 1.4 million barrels of oil and 1.2 Bcf of gas.

Petroleum Geology

The petroleum trap at Little Cedar Creek Field has been interpreted as a stratigraphic trap near the updip limit of Smackover deposition (State Oil and Gas Board of Alabama, 2004). Figures 80-82 show that the upper grainstone/packstone and lower boundstone/packstone reservoirs are interbedded with three lime mudstone units (upper peritidal, middle subtidal and lower transgressive) throughout the field serving to encase these reservoirs vertically, and to the northeast and updip in well 13976, the Smackover section essentially consists of lime mudstone. This lime mudstone section has the potential to serve as an updip seal rock, thus providing a critical element to this apparent stratigraphic trap (Figures 81 and 82). The structural maps prepared on top of the Smackover Formation (Figure 79), thrombolite horizon, and Norphlet Formation show no indication of structural closure in this field area.

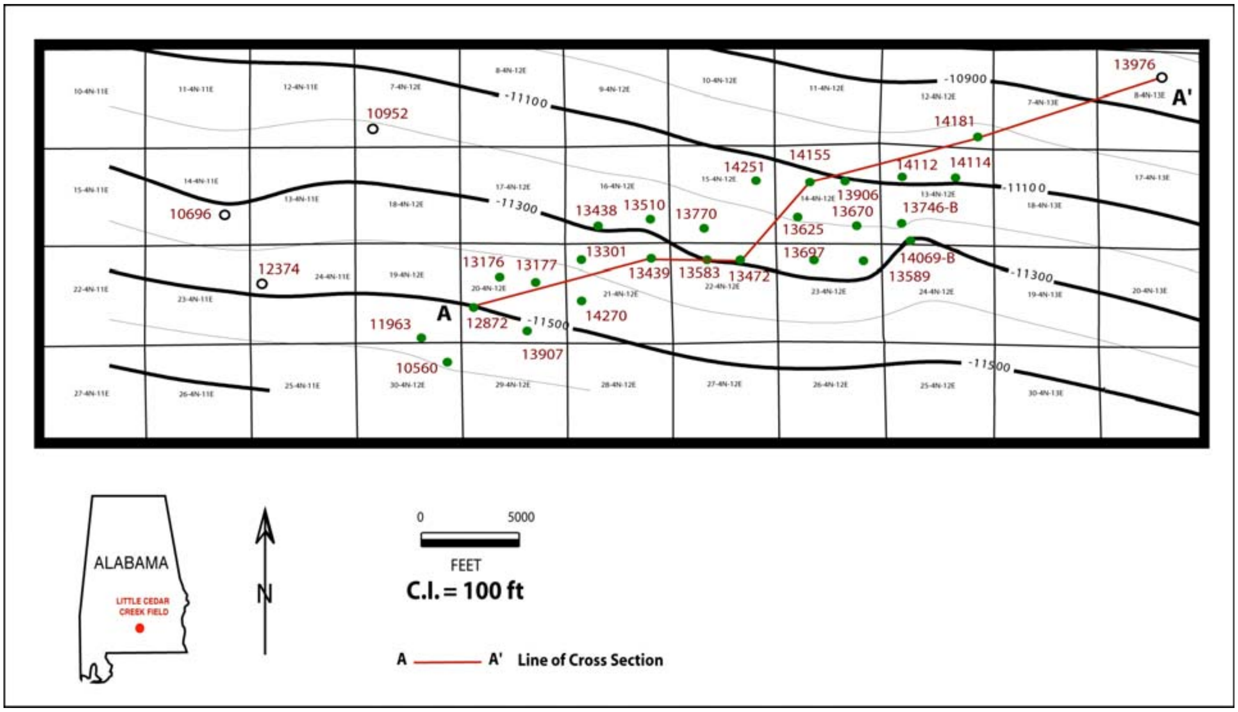


Figure 79. Structure map on top of the Smackover Formation, Little Cedar Creek Field area, Conecuh County, southwest Alabama, illustrating the absence of structural closure in the field.

Petroleum source rock analyses indicate that although the total organic carbon content and thermal alteration of the microbial and herbaceous kerogen of the lime mudstone and dolomudstone beds are adequate to be a potential source rock, the thickness of these beds is not sufficient to generate significant amounts of commercial hydrocarbons. Therefore, the oil in this field probably migrated updip from the basin center of the Conecuh sub-basin to this field area.

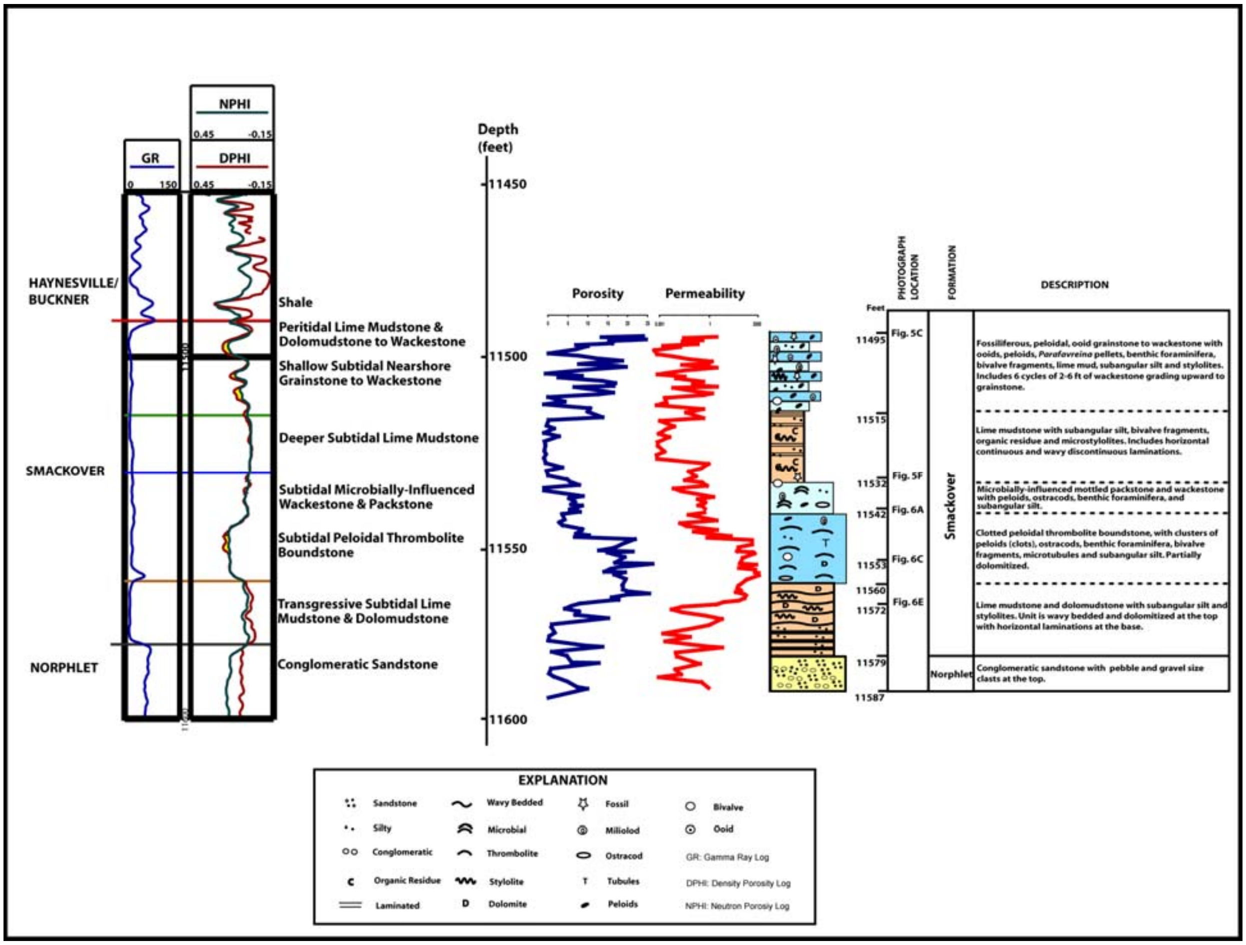


Figure 80. Correlation of well log response, vertical trends in porosity and permeability, and core description for well 13472, Little Cedar Creek Field. Grainstone and packstone constitute the upper reservoir, and boundstone and packstone constitute the lower reservoir. The Smackover lime mudstone separating these two reservoirs and the argillaceous beds of the Haynesville (Buckner) are the vertical seal rocks. Heydari and Baria (2005) have provided an interpretation of the lithofacies they have observed in this core.

Although Haynesville (Buckner) anhydrite beds are present in the Little Cedar Creek Field area, these anhydrite beds are thin, discontinuous and have not been found to directly overlie the Smackover reservoirs in this field (Figure 80). Therefore, the petroleum seal rocks at Little Cedar Creek Field are interpreted to include the Haynesville (Buckner) argillaceous beds that overlie the nearshore grainstone and packstone and the subtidal lime mudstone that overlies the microbially-influenced wackestone and packstone and thrombolite boundstone (Figures 80 and 81). Reservoir pressure and fluid data indicate there exist separation of the upper high energy nearshore reservoir from the lower thrombolite reservoir in this field (State Oil and Gas Board of Alabama, 2004).

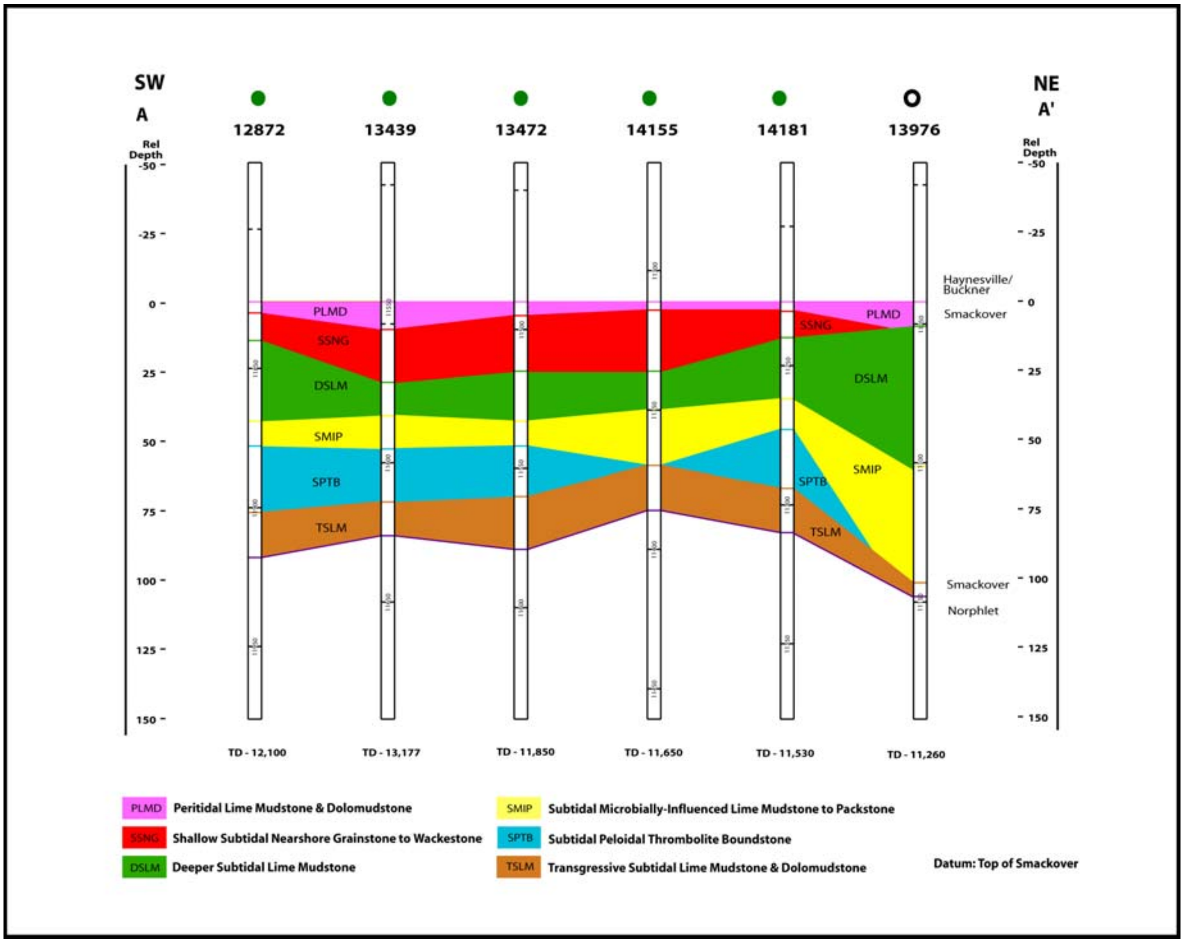


Figure 81. Stratigraphic cross section A-A', illustrating the vertical and lateral lithofacies recognized in the Little Cedar Creek Field area. Note that the upper grainstone/packstone reservoir and lower boundstone/packstone reservoir are interbedded with three lime mudstone and dolomudstone units (upper peritidal, middle subtidal, and lower transgressive) throughout the field; and to the northeast and updip in well 13986, the Smackover section essentially consists of only lime mudstone/dolomudstone, supporting the interpretation that the petroleum trap for this field is stratigraphic. See Figure 79 for line of cross section.

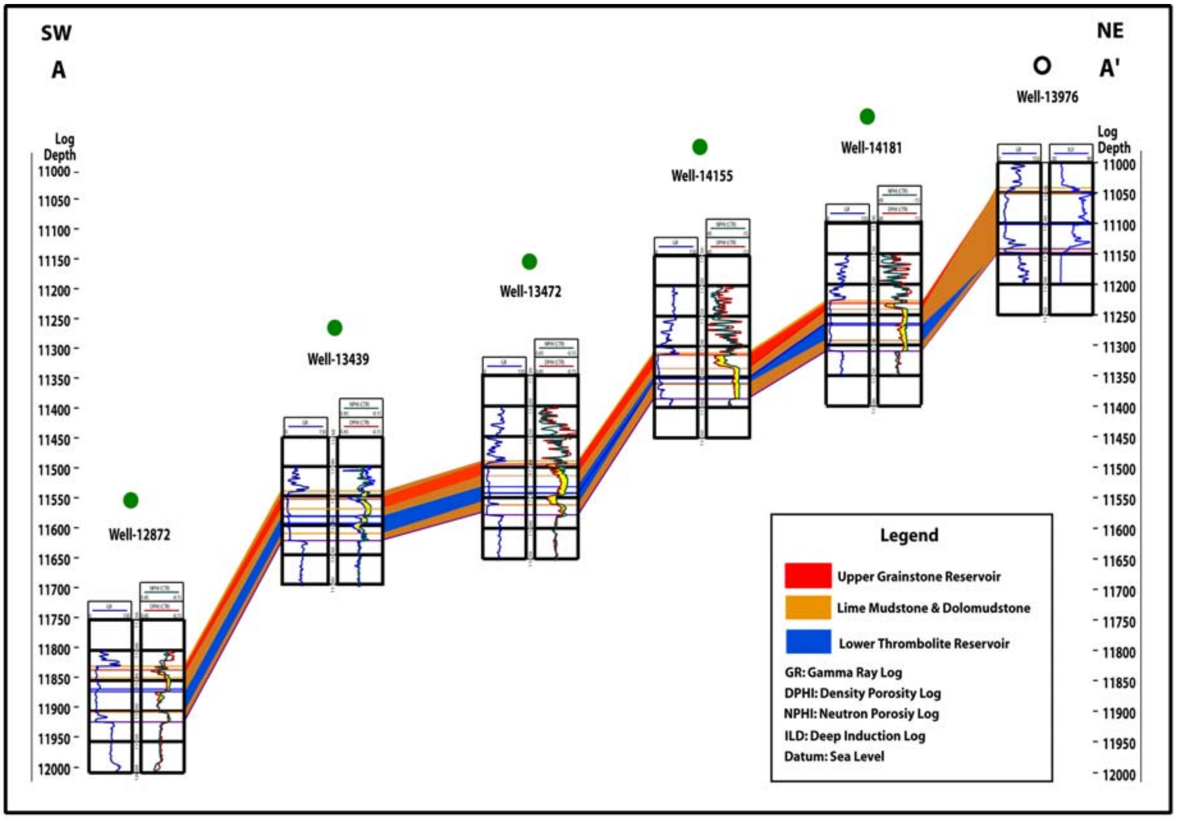


Figure 82. Structural cross section A-A', illustrating elevation changes in the Little Cedar Field area in a southwest to northeast direction. See Figure 79 for line of cross section.

The upper and lower reservoirs at Little Cedar Creek are similar to those described for other Smackover fields associated with thrombolite buildups in the Conecuh sub-basin (Mancini et al., 2004), for they include high energy grainstone/packstone and Thrombolite boundstone. However, the upper grainstone/packstone and lower thrombolite reservoirs in Little Cedar Creek Field are separated by a lime mudstone. This stratigraphy differs from other described fields, for in these other fields the grainstone/packstone directly overlies thrombolite boundstone (Mancini et al., 2004). The grainstone/packstone and thrombolite reservoir facies vary in thickness in Little Cedar Creek Field and are absent in some wells. Along the eastern and western parts of the field area, the grainstone/packstone reservoir is absent (Figure 83). This reservoir attains a maximum thickness in the central part of the field area. The thrombolite reservoir is absent along the northern margin of the field area and exhibits a southwest to northeast thickness trend in the southern part of the field area (Figure 84). The distribution for these reservoir facies in other Smackover fields associated with thrombolite buildups has been reported as continuous (Mancini et al., 2004).

In further contrast to Smackover fields in the Conecuh sub-basin, Little Cedar Creek Field reservoirs are mainly limestone and are not capped directly by the Buckner anhydrite seal. Porosity in the thrombolite boundstone reservoir chiefly consists of secondary vuggy pores, and porosity in the nearshore grainstone and packstone reservoir mainly includes moldic diagenetic pore types. The predominance of diagenetic pore types in the productive intervals at Little Cedar Creek Field highlights the importance of post-depositional diagenesis in reservoir formation. The proximity of the Little Cedar Creek reservoir facies to the Smackover paleoshoreline suggests that pore-forming and pore-enhancing diagenesis occurred early in the burial history of the rocks.

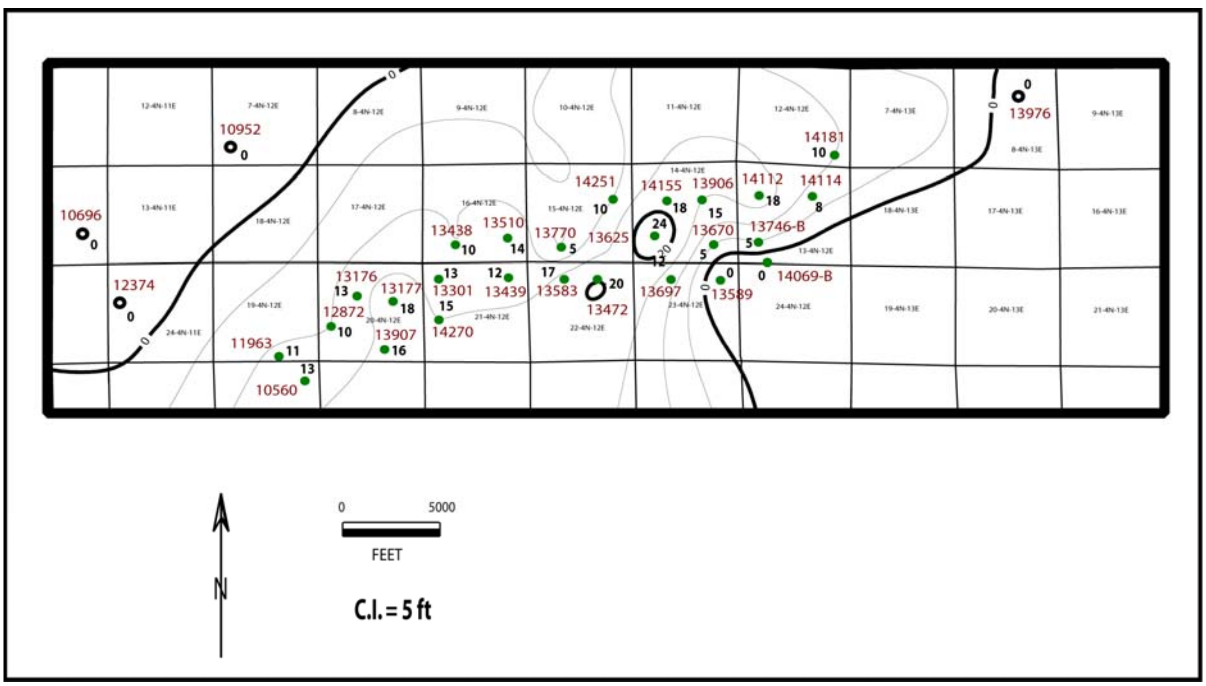


Figure 83. Isopach map of the shallow subtidal nearshore grainstone to wackestone facies. Note this facies varies in thickness across the field and is absent in wells along the eastern and western margins of the field area and attains a maximum thickness in the central part of the field area.

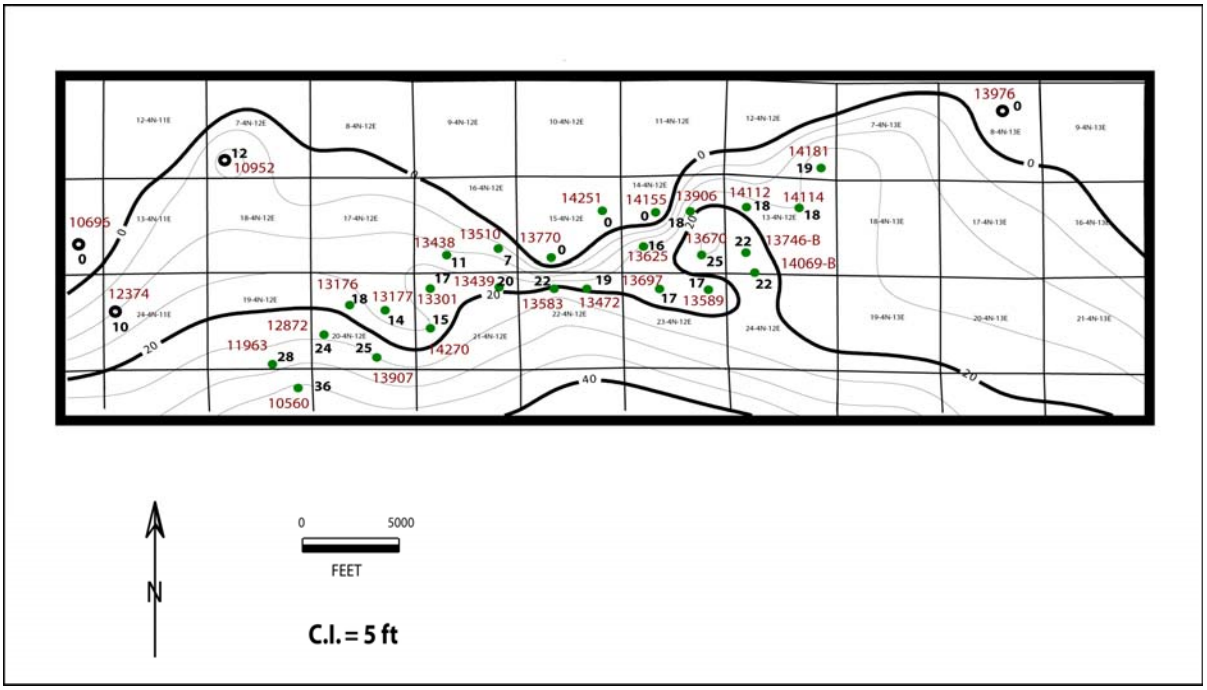


Figure 84. Isopach map of the subtidal peloidal thrombolite boundstone facies. Note this facies varies in thickness across the field and shows a southwest to northeast thickness trend in the southern part of the field area.

Smackover Facies

The Smackover section in Little Cedar Creek Field ranges from 70 to 110 feet in thickness and is interpreted to be equivalent to the upper Smackover in more downdip locations (Figures 80-82). In this field, Haynesville (Buckner) argillaceous beds disconformably overlie upper Smackover carbonates (Figure 85A), and lower Smackover carbonates unconformably overlie Norphlet conglomeratic sandstone beds (Figure 86F).

Six Smackover lithofacies have been identified from the study of wireline logs, cores and thin sections from the field. These facies include, in descending order, (1) peritidal lime mudstone and dolomudstone to wackestone (Figures 85A, B), (2) shallow subtidal nearshore grainstone to wackestone (Figures 85C, D, E), (3) deeper subtidal lime mudstone (Figure 85F), subtidal microbially-influenced lime mudstone to packstone (Figure 86A), (5) subtidal peloidal thrombolite boundstone (Figures 86B, C, D), and transgressive subtidal lime mudstone and dolomudstone (Figures 86E, F). These facies accumulated in water depths of less than 10 feet and within 3 miles of the paleoshoreline. Petrographic microfacies analysis in conjunction with meso- and macro-scale core description has defined the following major facies.

1) Peritidal lime mudstone and dolomudstone to wackestone (Figures 85A, B)

Constituents of this facies are abundant lime mud with some dolomite replacement and siliciclastic subangular silt. Dolomite typically occurs in laminae that alternate with dolomite-free lime mud. These rocks have low porosity (3-4 %) and permeability (<0.02 md) as reported in the core analysis for well 12872. This facies is 3-13 feet thick in the field area.

2) Shallow subtidal nearshore grainstone to wackestone (Figures 85C, D, E)

Constituents of this higher energy facies include ooids, peloids, lime mud, subangular silt, bivalve fragments, Parafavreina [Flag: Italicize Parafavreina] pellets, and benthic foraminifera. This facies is highly leached, and porosity includes mainly diagenetic moldic pores (Figure 87A). This reservoir averages 16.3 % porosity and 7.6 md in permeability in this field (State Oil and Gas Board of Alabama, 2004). In well 13472, these rocks have high porosity (up to 20.9 %) and moderate permeability (up to 9.31 md) (Figure 80). This facies ranges in thickness from zero to 24 feet across the field (Figure 83).

3) Subtidal lime mudstone (Figure 85F)

Constituents of this deeper subtidal facies include abundant of lime mud, subangular silt, and bivalve fragments (Figure 87B). The lime mud fraction may be dolomitized in this facies. In well 13472, these rocks have generally low porosity (0.1-4 %) and permeability (<0.01 md), however, thin layers of less than 1 foot at the base of this interval can have higher porosities (up to 7.2 %) and permeabilities (up to 2.33 md) (Figure 80). This facies is 18 to 35 feet in thickness in the field area.

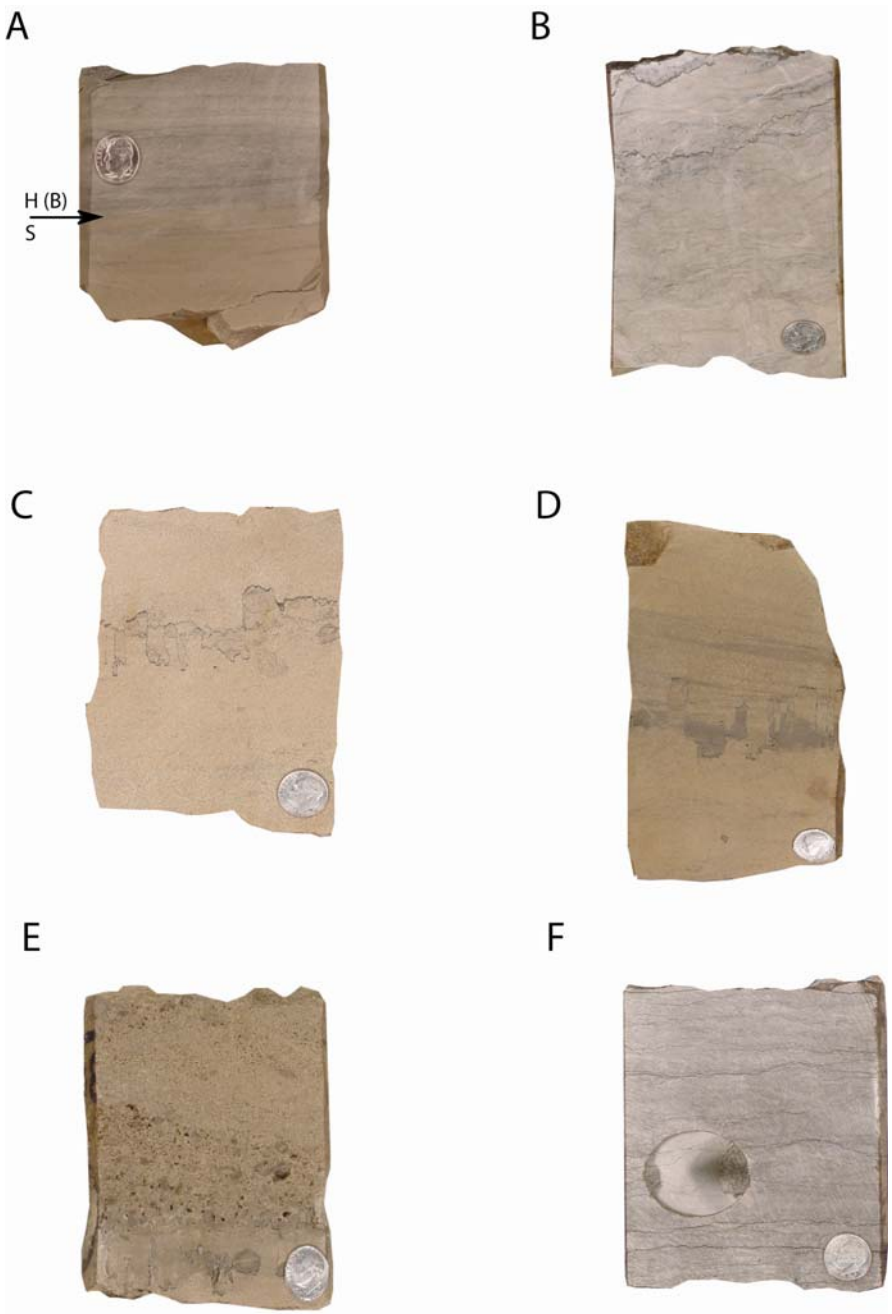


Figure 85. Core photographs of Smackover lithofacies in the Little Cedar Creek Field area: (A) contact of the upper Smackover (S) with the argillaceous beds of the Haynesville (Buckner) (H/B), well 13770, depth 11,455; (B) lime mudstone to dolomudstone from the peritidal lime mudstone and dolomudstone to wackestone facies, well 12872, depth 11,826 ft; (C) ooid grainstone from the shallow subtidal nearshore fossiliferous, peloidal, ooid grainstone to wackestone facies, well 13472, depth 11,495 ft; (D) cross bedded grainstone from the shallow subtidal nearshore fossiliferous, peloidal, ooid grainstone to wackestone facies, well 14181, depth 11,237 ft; (E) fossiliferous beds in the grainstone from the shallow subtidal nearshore fossiliferous, peloidal, ooid grainstone to wackestone facies, well 14181, depth 11,238 ft; and (F) lime mudstone from the deeper subtidal lime mudstone facies, well 13472, depth 11,532 ft.

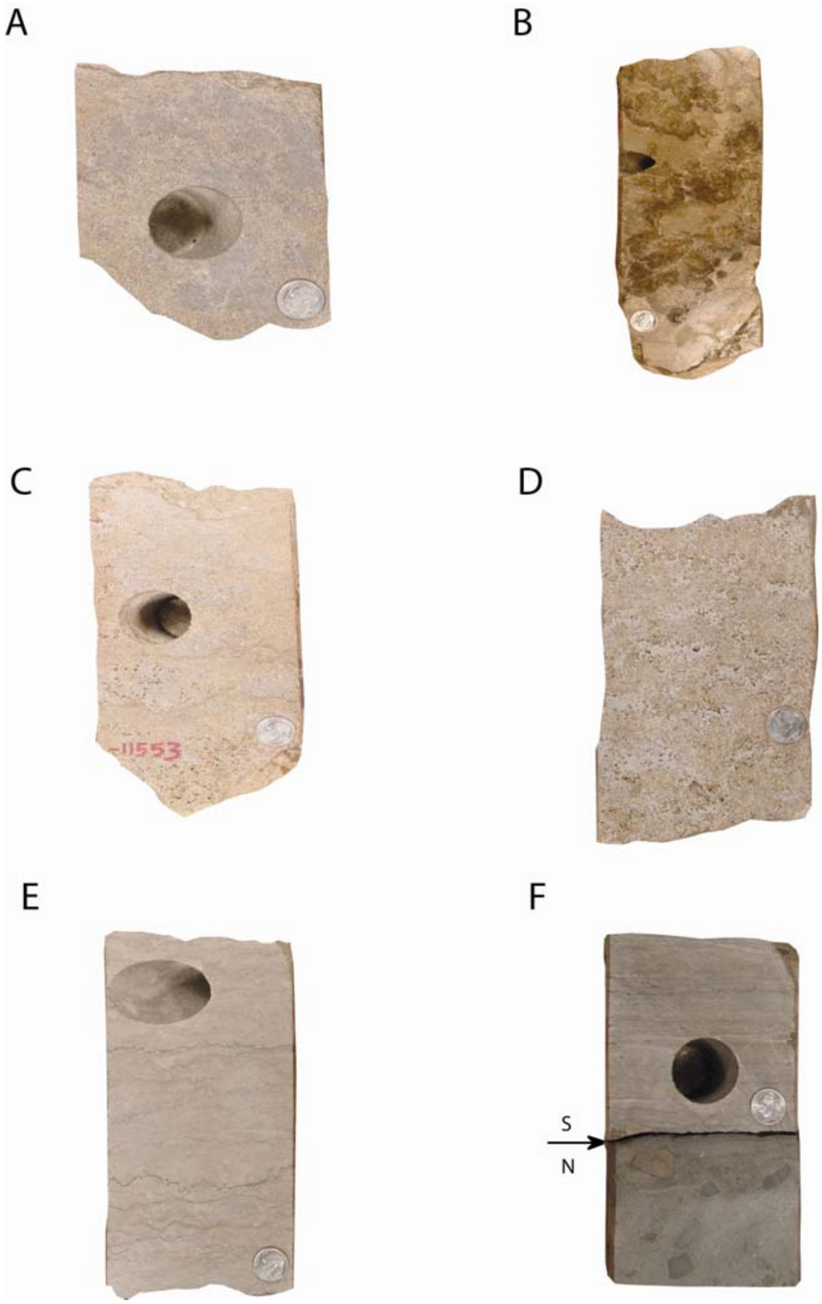


Figure 86. Core photographs of Smackover lithofacies in the Little Cedar Creek Field area: (A) packstone from the subtidal microbially-influenced lime mudstone to packstone facies, well 13472, depth 11,542 ft; (B) thrombolite boundstone from the subtidal peloidal thrombolite boundstone facies, well 14181, depth 11,282 ft; (C) leached boundstone from the peloidal thrombolite boundstone facies illustrating vuggy pore types, well 13472, depth 11,553 ft; (D) highly leached boundstone from the peloidal thrombolite boundstone facies, well 12872, depth 11,880 ft; (E) wavy bedded lime mudstone to dolomudstone from the transgressive subtidal lime mudstone to dolomudstone facies, well 13472, depth 11,572 ft; and (F) contact of the Smackover (S) with conglomeratic sandstone of the Norphlet Formation (N), well 13589, depth 11,497 ft.

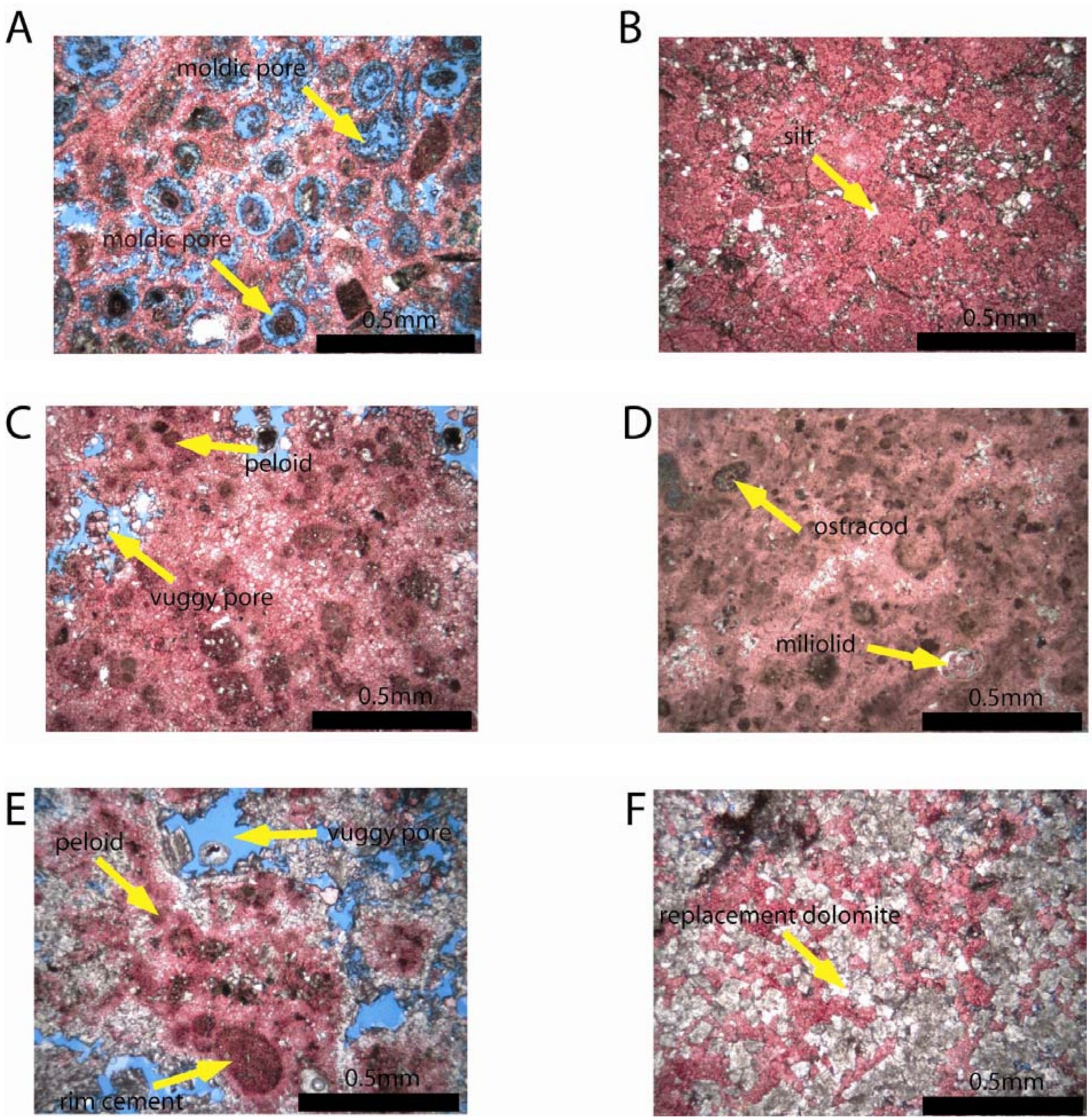


Figure 87. Photomicrographs of the Smackover lithofacies: (A) ooid grainstone from the shallow subtidal nearshore fossiliferous, peloidal, ooid grainstone to wackestone facies showing moldic pores, well 13472, depth 11,495 ft; (B) lime mudstone from the deeper subtidal lime mudstone facies, well 13472, depth 11,532 ft; (C) packstone from the subtidal microbially-influenced lime mudstone to packstone facies showing vuggy pores, well 13472, depth 11,542 ft; (D) peloidal thrombolite boundstone from the subtidal peloidal thrombolite boundstone facies showing microfossil content of this facies, well 13439, depth 11,609 ft; (E) peloidal thrombolite boundstone from the subtidal peloidal thrombolite boundstone facies showing vuggy pores, well 13472, depth 11,000 ft; and (F) lime mudstone to dolomudstone from the transgressive subtidal lime mudstone to dolomudstone facies showing replacement dolomite, well 13472, depth 11,572 ft.

4) Subtidal microbially-influenced lime mudstone to packstone (Figure 86A)

Constituents of this facies include clusters of peloids, ostracods, benthic foraminifera and subangular silt (Figure 87C). This facies has a mottled appearance. In well 13472, these rocks consist of packstone and wackestone having porosities of up to 8.0 % and permeabilities of up to 9.07 md (Figure 80). In areas of the field where thrombolite buildups are not present, this facies is the dominant facies in the middle part of the Smackover section (Figure 81). In these areas, these rocks essentially have low porosity (0.1-5) and permeability (<0.3) as reported in the core analysis for well 13976. The thickness of this facies is highly variable ranging from 2 to 36 feet in the field area.

5) Subtidal peloidal thrombolite boundstone (Figures 86B, C, D)

Constituents of this facies include clotted peloidal boundstone (thrombolite) with fine, subangular silt. This facies contains a low diversity fauna, including benthic foraminifera, ostracods, bivalve fragments and microtubules (Figure 87D). Sparsely- and densely-packed clotted fabrics characterize the rocks included this facies. Dolomite in this facies both replaces lime mud in some samples and/or fills void space. In some samples, dolomite appears to be concentrated around microbial clots, while in others; dolomite is only filling void space. Although there is variation in the degree of dolomitization, no samples are completely dolomitized. This facies is highly leached, and porosity chiefly consists of vuggy pore types (Figure 87E). This reservoir averages 10.8 % porosity and 196 md in permeability in this field (State Oil and Gas Board of Alabama, 2004). In well 13472, these rocks have high porosity (up to 22.2 %) and permeability (up to 2834 md) (Figure 80). This facies ranges in thickness from zero to 36 feet across the field (Figure 84).

6) Transgressive subtidal lime mudstone and dolomudstone (Figure 86E, F)

Constituents of this transgressive facies include abundant lime mud (some with pervasive well-formed dolomite rhomb overprint) and subangular silt (Figure 87F). One sample contains “needles” which may be sponge spicules. These rocks have relatively low porosity (1-6 %) and permeability (<1.89 md) (Figure 80). This facies is 16 to 22 feet in thickness in the field area.

Comparison to Other Thrombolites

Smackover inner ramp, shallow water (less than 30 feet) thrombolite buildups typically developed on Paleozoic crystalline paleohighs and occasionally on Jurassic salt features in the eastern Gulf Coastal Plain. Such thrombolites attained a thickness of over 100 feet and occurred over an area of up to 2.4 square miles (Mancini et al., 2004). Calcimicrobes, red algae, foraminifera, sponges, echinoids and bivalves were part of these buildups (Baria et al., 1982). These buildups developed directly on igneous and metamorphic basement rocks in a low energy paleoenvironment under low background sedimentation rates. Cessation of thrombolite growth appears to correspond with regressions of the Smackover sea. The buildups were usually overlain by higher energy, nearshore and shoal grainstone and packstone facies.

The thrombolite facies is highly leached and dolomitized, suggesting that the growth patterns of the buildups made them favorable candidates for early diagenetic dissolution and dolomitization. Depositional porosity typically is a mixture of primary shelter and fenestral pores overprinted by dolomite intercrystalline and vuggy diagenetic pore types (Mancini et al., 2004).

Although the thrombolites at Little Cedar Creek Field area may be associated with Paleozoic basement paleotopography, these buildups were not developed directly on crystalline rocks, nor can they be demonstrated to occur on the crest of a particular paleohigh. These buildups are further up depositional dip than other previously described thrombolites in the eastern Gulf. They developed within 3 miles of the Smackover paleoshoreline, suggesting that thrombolite growth probably occurred in water depths of less than 10 feet. The thrombolites consist of clotted peloidal boundstone and include a microfauna, including benthic foraminifera, ostracods, bivalves and microtubules. The buildups are not directly overlain by strandplain or shoal deposits but rather by microbially-influenced lime mudstone, wackestone and packstone, suggesting thrombolite demise was a result of an overall deterioration of environmental conditions or an influx of freshwater and/or siliciclastic or carbonate sediment. Productive thrombolite reservoirs are highly leached but not pervasively dolomitized. Pore types are mainly diagenetic rather than depositional and include chiefly vuggy pores.

Conclusions

Recent drilling in Little Cedar Creek Field, Conecuh County, southwest Alabama, has shown that hydrocarbon productive thrombolite and associated nearshore grainstone and packstone facies were deposited in shallow water near the Smackover paleoshoreline. The Smackover Formation consists of six lithofacies in Little Cedar Creek Field: peritidal lime mudstone and dolomudstone to wackestone, shallow subtidal nearshore fossiliferous, peloidal, ooid grainstone to wackestone, deeper subtidal lime mudstone, subtidal microbially-influenced lime mudstone to packstone, subtidal peloidal thrombolite boundstone, and transgressive subtidal lime mudstone and dolomudstone.

The predominance of diagenetic pore types (moldic and vuggy) in the productive thrombolite and high energy nearshore facies at Little Cedar Creek Field illustrates the importance of post-depositional processes, such as dissolution, in reservoir formation. The proximity of the Little Cedar Creek reservoir facies to the Smackover paleoshoreline suggests that pore-forming and pore-enhancing diagenesis occurred early in the burial history of these rocks.

The occurrence of hydrocarbon productive Smackover thrombolites at Little Cedar Creek Field demonstrates that these buildups developed in bathymetric settings other than on Paleozoic basement paleohighs, including updip, nearshore, shallow subtidal environments. Future exploration and development strategies, therefore, should search for these potential reservoir facies in an array of bathymetric settings from inner ramp paleoenvironments near the paleoshoreline to paleoenvironments associated with the mid-ramp, which is punctuated with antecedent paleotopographic highs. Exploration successes will depend on direct observation of wireline logs, cores and cuttings because these stratigraphic traps and associated thrombolite and nearshore reservoir rocks are not easily recognized by studying seismic reflection data.

Identification of underdeveloped and undiscovered resources**-**Mancini et al. (2006b) utilized the sequence stratigraphy predictive model and exploration strategies developed during this study to evaluate the underdeveloped and undiscovered resources of the North Louisiana and Mississippi Interior Salt Basins. The following discussion is from Mancini et al. (2006b). Although not emphasized in the Mancini et al. (2006b) paper, the regional unconformity on top of the Monroe Uplift, (which results in onlap of Upper Cretaceous reservoir facies onto this feature) is a major combination stratigraphic and stratigraphic petroleum trap in this area.

The key component of this trap is stratigraphic and involves a regional unconformity (Figures 88-92). The stratal patterns observed are characteristic of those described in this study as being typical of a stratigraphic trap (unconformity). Continental and nearshore marine facies are major reservoirs associated with this stratigraphic trap. These facies can be recognized by their characteristic well log signatures as described in this current study.

The origin of the interior salt basins, North Louisiana and Mississippi Interior Salt Basins, in the central and eastern Gulf Coastal Plain is closely linked to the evolution of the Gulf of Mexico. Upper Jurassic lime mudstone beds of the Smackover Formation are the effective regional petroleum source rocks in the North Louisiana and Mississippi Interior Salt Basins. In the Upper Jurassic and Cretaceous strata in these basins, eleven stratigraphic sequences are recognized: three Upper Jurassic, three Lower Cretaceous and five Upper Cretaceous sequences. Upper Jurassic and Cretaceous continental (alluvial, fluvial and eolian), transitional (deltaic, tidal, beach, coastal and marginal marine), and marine (nearshore, barrier bar, shelf and deeper water) sandstone facies that accumulated in association with siliciclastic depositional systems are major petroleum reservoirs. Upper Jurassic and Cretaceous limestone facies that were deposited in peritidal, nearshore, shoal, shelf and reef environments associated with carbonate depositional systems are also major petroleum reservoirs in these basins. Potential undiscovered reservoirs in the North Louisiana Salt Basin are subsalt Triassic Eagle Mills sandstone facies and deeply buried Upper Jurassic limestone and sandstone facies of the Smackover and Haynesville Formations and Cotton Valley Group. Potential underdeveloped reservoirs in this basin include Lower Cretaceous sandstone facies of the Hosston and Paluxy formations and limestone facies of the Sligo, James, Rodessa and Mooringsport (Glen Rose) formations and Fredericksburg and Washita groups. Upper Cretaceous sandstone facies of the Tokio, Ozan and Nacatoch formations also have potential as underdeveloped reservoirs in this basin. In the Mississippi Interior Salt Basin, potential undiscovered reservoirs are subsalt Triassic Eagle Mills sandstone facies and Lower Cretaceous limestone facies of the James, Rodessa, Mooringsport and Andrew formations. Potential underdeveloped reservoirs in this basin include Lower Cretaceous sandstone facies of the Hosston, Paluxy and Dantzler formations and Upper Cretaceous sandstone facies of the Tuscaloosa Group and Eutaw Formation.

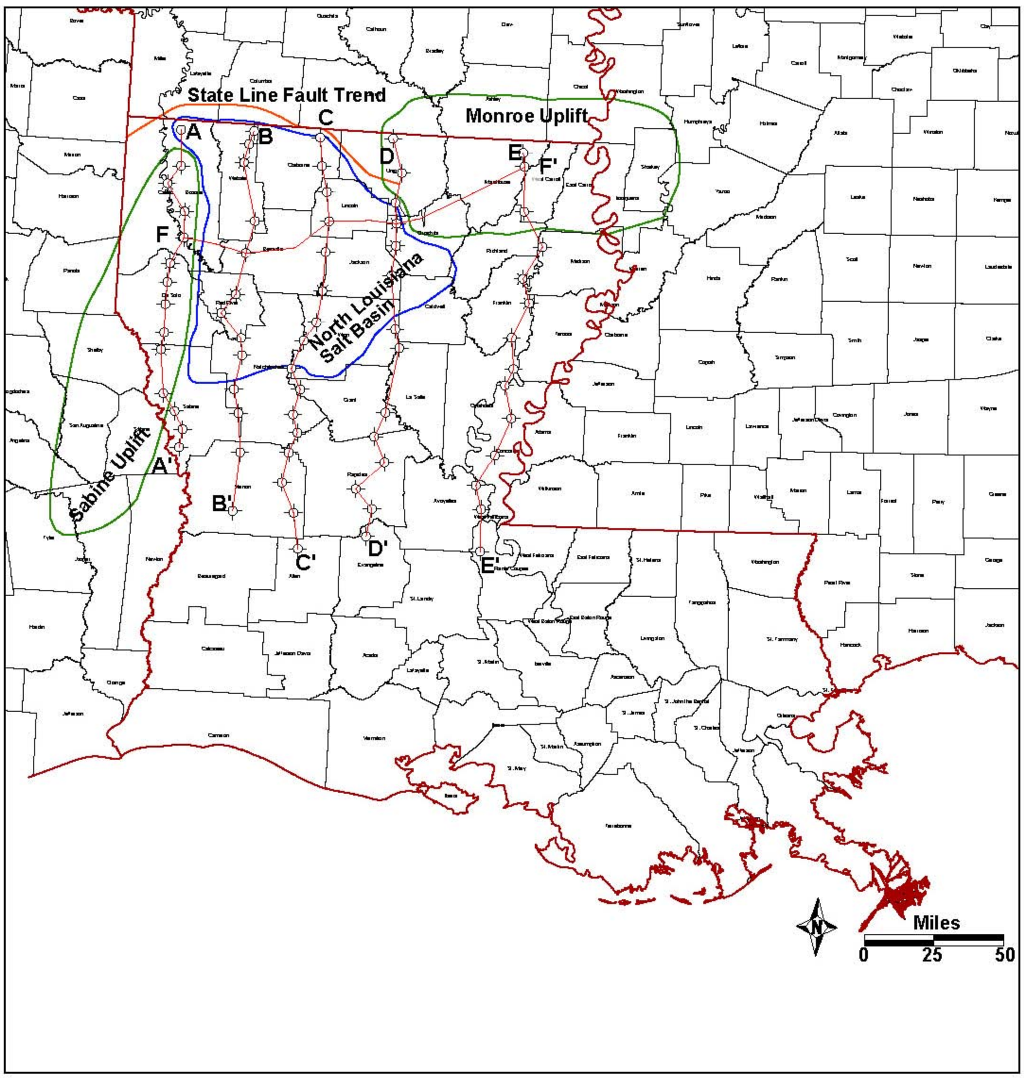


Figure 88. Location map of cross sections, North Louisiana Salt Basin.

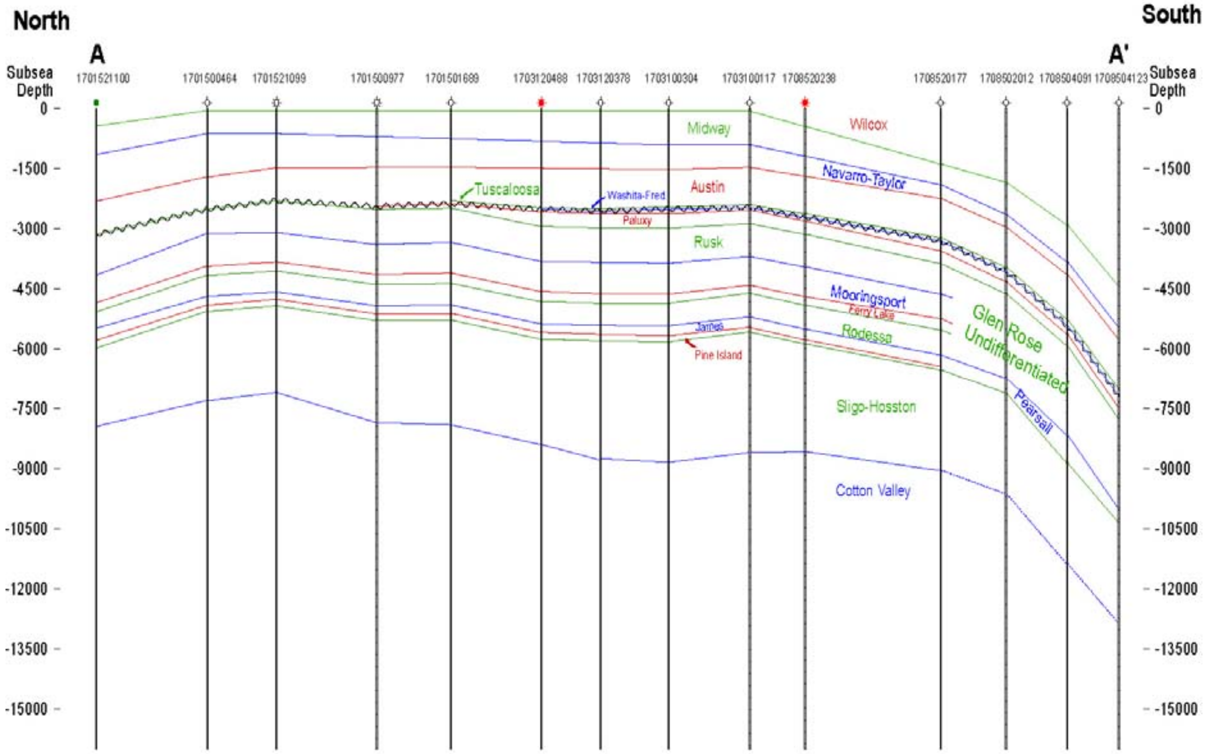


Figure 89. North-south cross section A-A', across the Sabine Uplift, VE: 22X.

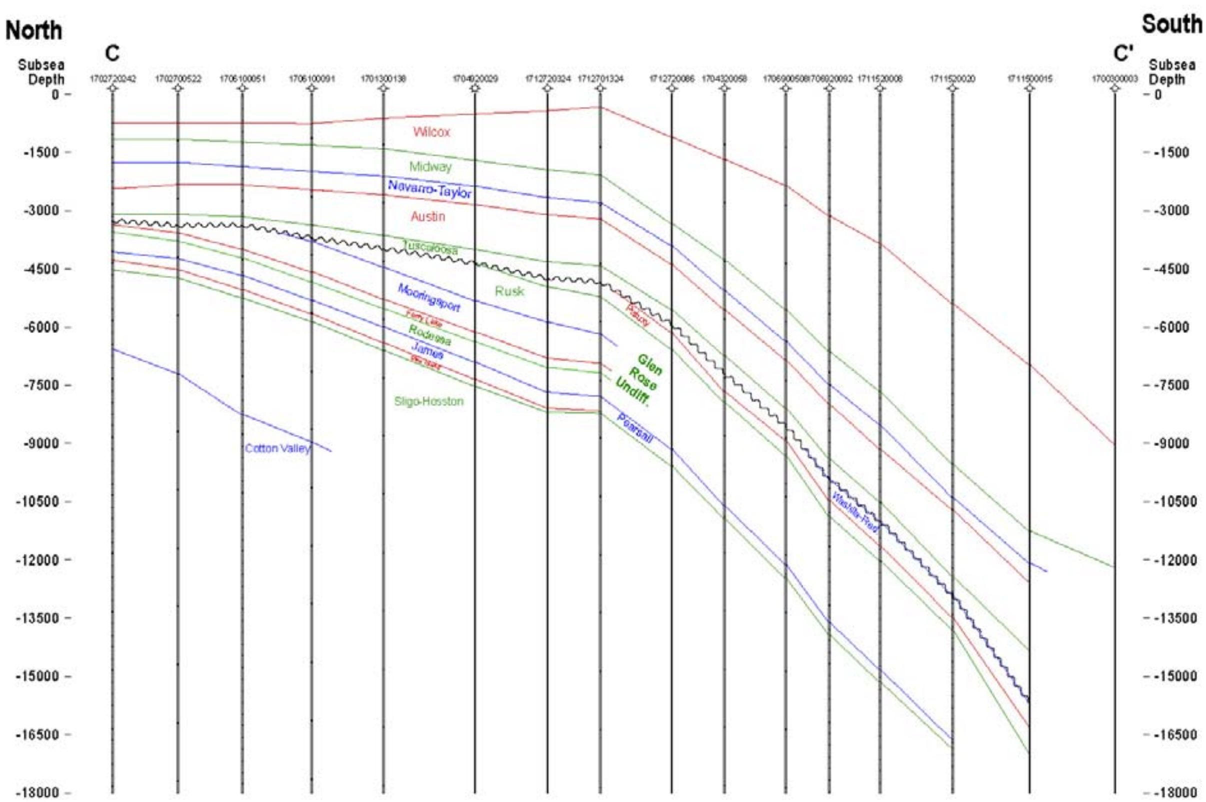


Figure 90. North-south cross section C-C', North Louisiana Salt Basin, VE: 34X.

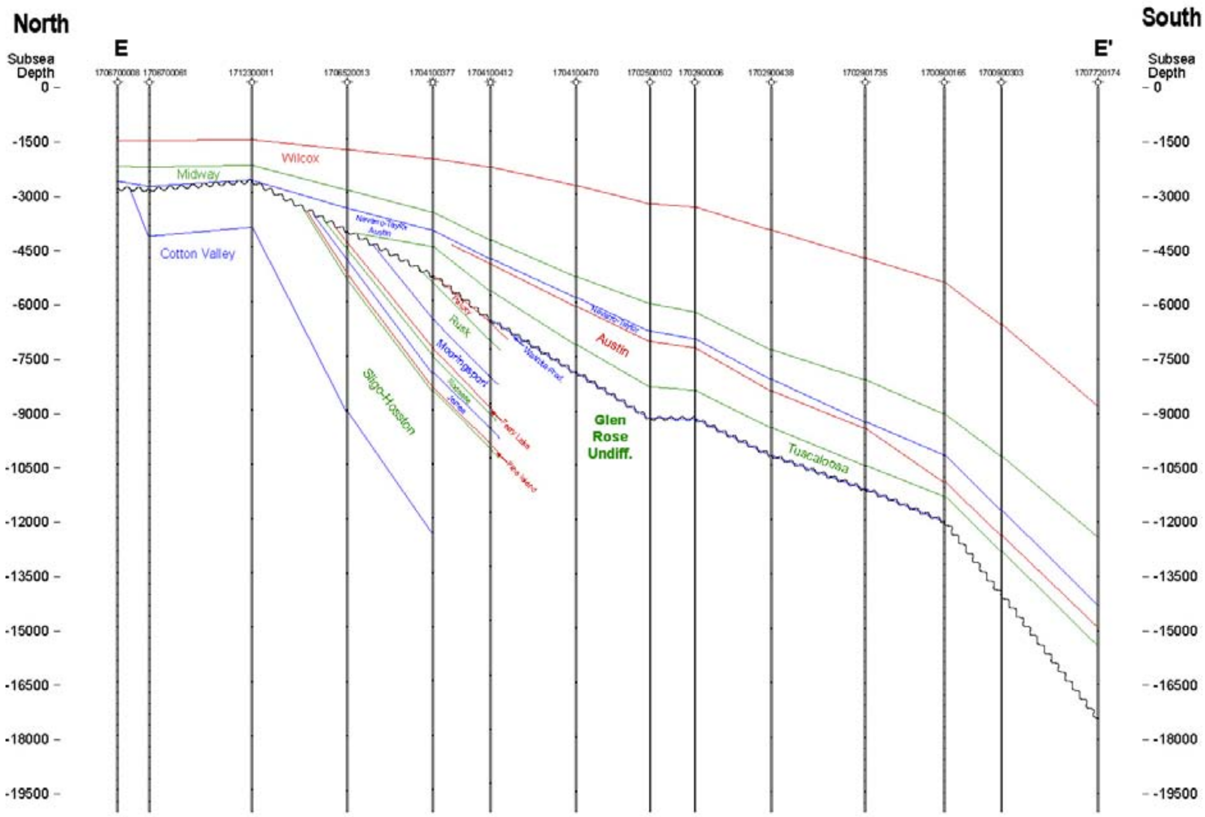


Figure 91. North-south cross section E-E', across the Monroe Uplift, VE: 30X.

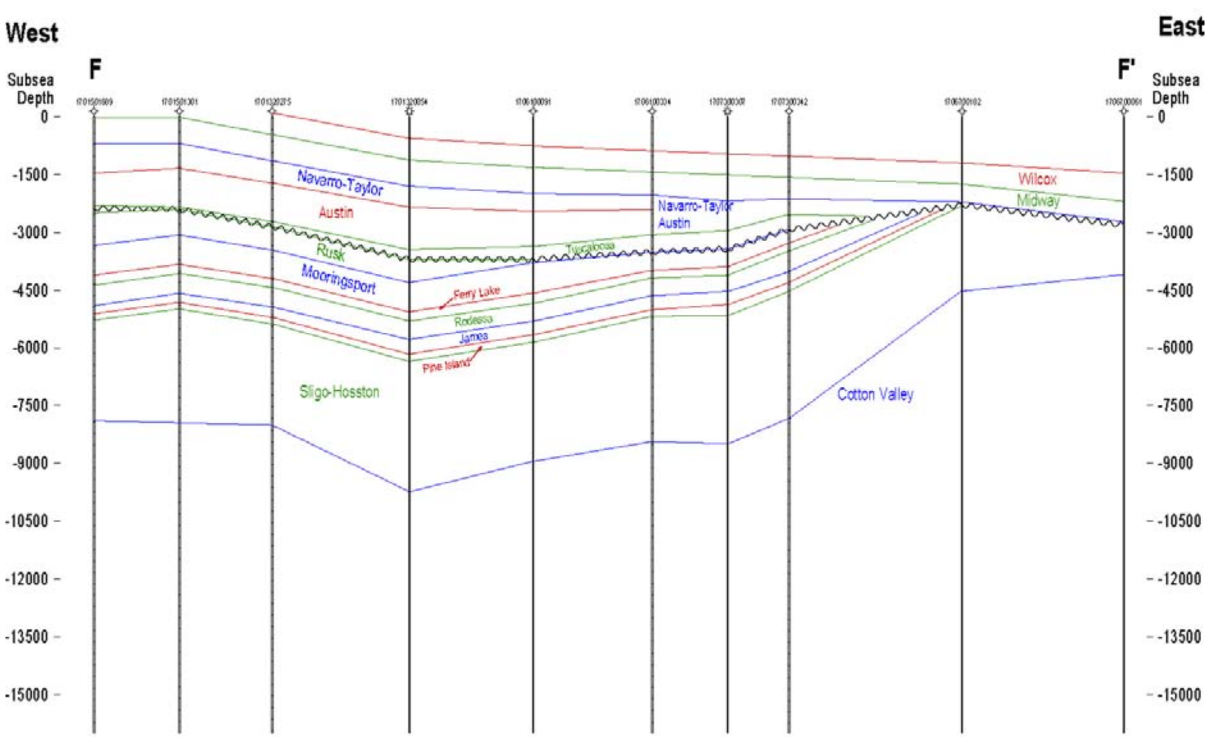


Figure 92. West-east cross section F-F', across the Monroe Uplift, VE: 22X.

Sequence Stratigraphy

In the strata of the onshore interior salt basins of the central and eastern Gulf Coastal Plain, 11 stratigraphic sequences have been reported by Mancini and Puckett, 2002, 2003; Mancini et al., 2004). Specifically, three Upper Jurassic sequences, including Norphlet, Smackover, Haynesville and Cotton Valley strata, have been recognized (see Figure 73). Three Lower Cretaceous sequences, including Hosston, Sligo, Pine Island, James/Donovan, Bexar, Rodessa, Ferry Lake, Mooringsport/Rusk, Paluxy, Goodland, Andrew, Fredericksburg, lower Washita and Dantzler strata, have been described. Five Upper Cretaceous sequences, including Tuscaloosa, Eagle Ford, Eutaw, Austin, Mooreville, Demopolis, Taylor, Ripley, Prairie Bluff and Navarro strata, have been identified. These genetic stratigraphic sequences form the foundation for the facies and petroleum reservoir analysis reported in this paper.

Depositional Systems and Facies Analysis

Upper Jurassic

The discussion, which follows regarding deposition during the Late Jurassic in the North Louisiana and Mississippi Interior Salt Basins, is from Mancini et al. (1999, 2004c, 2006).

During the early Oxfordian, alluvial, fluvial, wadi, eolian and nearshore sandstone deposits of the Norphlet Formation accumulated primarily in the Mississippi Interior Salt Basin. In the late Oxfordian, Smackover peritidal, nearshore, inner to outer ramp and reef sediments were deposited in the North Louisiana and Mississippi Interior Salt Basins. Buckner sabkha anhydrite beds accumulated in the early Kimmeridgian. Deposition of subaqueous anhydrite beds of the Buckner Anhydrite Member of the Haynesville Formation followed in the Mississippi Interior Salt Basin, while Gilmer Limestone deposition occurred in the North Louisiana Salt Basin. In the middle Kimmeridgian, lagoonal shale, evaporite beds and shallow marine sandstone and limestone of the Haynesville Formation accumulated. During the late Kimmeridgian, marginal marine shale and sandstone beds of the upper Haynesville accumulated, and during the early Tithonian, marginal marine and coastal plain deposits of the Cotton Valley Group (Shongaloo Member of the Schuler Group) were deposited. Cotton Valley fluvial-deltaic sandstone deposition occurred in the Mississippi Interior Salt Basin in the Tithonian to middle Berriasian. During this time in the North Louisiana Salt Basin, marine shelf shale beds of the Dorcheat Member of the Schuler Formation of the Cotton Valley Group and marine shelf, shoal and reef deposits of the Knowles Limestone accumulated. Bossier Shale was deposited in marine basinal environments.

Lower Cretaceous

The discussion, which follows regarding deposition during the Early Cretaceous in the North Louisiana and Mississippi Interior Salt Basins, is from Mancini and Puckett (2002) and Mancini et al. (1999, 2006d).

Coastal and fluvial-deltaic deposits of the Hosston Formation were deposited during the late Valanginian to earliest Aptian. In the early to early late Aptian Sligo and Pine Island lagoonal and marine shelf shale and nearshore sandstone beds accumulated in the Mississippi Interior Salt Basin. Nearshore, marine shelf and reef deposits of the Sligo Formation and the marine shelf shale and sandstone of the Pine Island shale were deposited in the North Louisiana Salt Basin. Nearshore, marine shelf and reef deposition of the James Limestone followed, except in the easternmost part of the Mississippi Interior Salt Basin where Donovan fluvial sandstone deposits accumulated. In the late Aptian, marine shelf shale of the Bexar Formation was deposited. During the latest Aptian to early Albian marginal marine shale and sandstone beds of the Rodessa Formation accumulated in the Mississippi Interior Salt Basin; while in the North Louisiana Salt Basin, Rodessa nearshore, marine shelf and reef limestone, marine shale, and evaporite beds accumulated at this time. Ferry Lake Anhydrite deposition followed. During the late early Albian marginal marine and marine shelf shale and nearshore sandstone beds of the Mooringsport Formation accumulated in the Mississippi Interior Salt Basin. During this time in the North Louisiana Salt Basin, nearshore, marine shelf and reef limestone, marine shale, and nearshore and marginal marine sandstone beds of the Mooringsport-Rusk (Upper Glen Rose) accumulated. Paluxy nearshore and marine shelf sandstone deposition followed. In the middle Albian, marine shelf limestone and shale beds of the Goodland Formation and the Fredericksburg Group were deposited in the North Louisiana Salt Basin, and marine limestone and shale beds of the Andrew Formation accumulated in the Mississippi Interior Salt Basin. During the late Albian, fluvial-deltaic sandstone deposition associated with the Dantzler Formation occurred in the Mississippi Interior Salt Basin, while in the North Louisiana Salt Basin marine shelf marl and limestone beds of the lower Washita Group accumulated.

Upper Cretaceous

The discussion, which follows regarding deposition during the Late Cretaceous in the North Louisiana and Mississippi Interior Salt Basins, is from Mancini and Puckett (2003) and Mancini et al. (1999, 2006d).

In the North Louisiana Salt Basin, marine shelf shale, marl and limestone of the upper Washita Group were deposited during the early Cenomanian. During the middle Cenomanian, coastal sandstone deposits of the lower part of the Tuscaloosa Group accumulated in the central and eastern Gulf Coastal Plain. Marine shelf shale of the Tuscaloosa Group was deposited during the late Cenomanian to early Turonian in the Mississippi Interior Salt Basin. In the middle to late Turonian, fluvial sandstone deposits of the upper part of the Tuscaloosa Group accumulated. In the North Louisiana Salt Basin, marine shelf and marginal marine shale beds of the Eagle Ford Group accumulated during the Turonian. Eutaw tidal and shallow marine sandstone and shale deposition occurred in the Mississippi Interior Salt Basin during the middle Coniacian to middle Santonian. In the North Louisiana Salt Basin, marginal marine and marine sandstone and shale beds of the Tokio Formation accumulated at this time. Nearshore sandstone beds of the Eutaw Formation and marine shelf and marl and chalk beds of the Mooreville Chalk (Selma Group) were deposited in the Mississippi Interior Salt Basin during the late Santonian to early middle Campanian. In the North Louisiana Salt Basin, marine shelf marl and chalk of the Brownstown Formation accumulated during this time. Marine shelf chalk and marl deposits of the Demopolis Chalk (Selma Group) and marine shelf marl and lagoonal shale of the Ripley Formation were deposited during the middle to late Campanian in the Mississippi Interior Salt. In the North Louisiana Salt Basin, nearshore sandstone of the Ozan Formation, marine shelf chalk and marl beds of the Annona, Marlbrook and Saratoga formations, and marine shelf and marginal marine shale of the lower part of the Nacatoch Formation accumulated in this time period. During the early to early late Maastrichtian, nearshore sandstone and limestone of the Ripley Formation and marine shelf marl and chalk of the Prairie Bluff Chalk were deposited in the Mississippi Interior Salt Basin. In the North

Louisiana Salt Basin, nearshore sandstone of the Nacatoch Formation and marine shelf chalk and marl of the Arkadelphia Formation accumulated during this time.

Petroleum Reservoirs

Petroleum reservoirs include Upper Jurassic and Cretaceous fluvial-deltaic, shoreline, marine bar and shallow shelf sandstone facies, and carbonate shoal, shelf and reef facies (Tables 3 and 4). Reservoir parameters described below are, in part, from Goddard in Mancini et al. (2006).

Upper Jurassic Norphlet alluvial and fluvial, eolian dune and interdune, and marine sandstones are reservoirs in the Mississippi Interior Salt Basin. Porosities average 20% with permeabilities of 300 md in this basin.

Upper Jurassic Smackover peritidal, nearshore, shoal and reef limestones and dolostones are reservoirs in the North Louisiana and Mississippi Interior Salt Basins. Porosities are 2 to 28% with permeabilities of 1 to 100 md in the North Louisiana Salt Basin.

Upper Jurassic Haynesville fluvial, eolian, beach and marine sandstones and nearshore and reef limestones and dolostones are reservoirs in the North Louisiana and Mississippi Interior Salt Basins. Porosities are of 9 to 16% with permeabilities of 50 to 400 md in the North Louisiana Salt Basin.

Upper Jurassic/Lower Cretaceous Cotton Valley fluvial-deltaic, nearshore and barrier bar sandstones and nearshore and reefal limestones are reservoirs in the North Louisiana and Mississippi Interior Salt Basins. Porosities are of 9 to 18% with permeabilities of 1 to 300 md in the North Louisiana Salt Basin.

Lower Cretaceous Hosston fluvial-deltaic, tidal, nearshore and deeper water sandstones are reservoirs in the North Louisiana and Mississippi Interior Salt Basins.

Porosities are of 3 to 17% with permeabilities of 1 to 300 md in the North Louisiana Salt Basin.

Lower Cretaceous Sligo nearshore, shelf and reef limestones are reservoirs in the North Louisiana Salt Basin. Porosities are of 16 to 20% with permeabilities of 9 to 100 md in this basin.

Lower Cretaceous Pine Island nearshore marine sandstones are reservoirs in the North Louisiana and Mississippi Interior Salt Basins. Porosities are of 10 to 15% with permeabilities of 10 to 200 md in the North Louisiana Salt Basin.

Lower Cretaceous James nearshore, shelf and reefal limestones are reservoirs in the North Louisiana and Mississippi Interior Salt Basins. Porosities are of 10 to 15% with permeabilities of 0.1 to 100 md in the North Louisiana Salt Basin.

Lower Cretaceous Donovan fluvial sandstones are reservoirs in the Mississippi Interior Salt Basin. Porosities are of 10 to 16% with permeabilities of 0.5 to 75 md in this basin.

Lower Cretaceous Rodessa nearshore, shelf and reef limestones are reservoirs in the North Louisiana Salt Basin. Porosities are of 10 to 26% with permeabilities of 10 to 650 md in this basin. In the Mississippi Interior Salt Basin, Rodessa marginal marine and nearshore sandstones are reservoirs. Porosities average 16% with permeabilities of 150 md in this basin.

Lower Cretaceous Mooringsport marine shelf limestones are reservoirs in the North Louisiana Salt Basin, porosities are of 10 to 20% with permeabilities of 10 to 500 md. In the Mississippi Interior Salt Basin, Mooringsport marine shelf and reefal limestones and marginal marine and nearshore sandstones are reservoirs. Porosities average 16% with permeabilities of 150 md in this basin.

Lower Cretaceous Paluxy fluvial, nearshore and shelf sandstones are reservoirs in the Mississippi Interior Salt Basin. Porosities average 16% with permeabilities of 150 md in this basin. Paluxy nearshore sandstones are reservoirs in the North Louisiana Salt Basin. Porosities are of 10 to 30% with low permeabilities in this basin.

Lower Cretaceous marine shelf limestones of the Goodland Formation are reservoirs in the North Louisiana Salt Basin, and Andrew marine shelf limestones are reservoirs in the Mississippi Interior Salt Basin. Porosities are of 20 to 30% with low permeabilities in the North Louisiana Salt Basin.

Lower Cretaceous Dantzler fluvial-deltaic sandstones are reservoirs in the Mississippi Interior Salt Basin. Porosities average 25 to 30% with permeabilities of 50 to 150 md in this basin.

Upper Cretaceous Tuscaloosa fluvial, coastal and marine shelf sandstones are reservoirs in the North Louisiana and Mississippi Interior Salt Basins. Porosities are of 25 to 30% with permeabilities of 200 to 2,000 md in the North Louisiana Salt Basin.

Upper Cretaceous Eutaw tidal, nearshore and marine shelf sandstones are reservoirs in the Mississippi Interior Salt Basin. Porosities average 27% with permeabilities of 0.1 to 4000 md in this basin.

Upper Cretaceous Tokio, Ozan and Nacatoch nearshore sandstones are reservoirs in the North Louisiana Salt Basin. Porosities are 20 to 33% with permeabilities of 100 to 2,500 md in this basin.

Upper Cretaceous Annona and Saratoga marine shelf chalks are reservoirs in the North Louisiana Salt Basin. Porosities are of 20 to 33% with permeabilities of 100 to 2,500 md in this basin.

Upper Cretaceous Selma marine shelf chalks and Woodruff sandstones are reservoirs in the Mississippi Interior Salt Basin. Porosities are 18% with low permeabilities in this basin.

Upper Cretaceous Monroe Gas Rock marine shelf sandy chalks are reservoirs in the North Louisiana Salt Basin. Porosities are 5 to 25% with permeabilities of 500 md.

Future Reservoirs

According to Puckett et al. (2000) potential undiscovered reservoirs in the Mississippi Interior Salt Basin are subsalt Triassic Eagle Mills sandstone facies and Lower Cretaceous carbonate facies of the James, Rodessa, Mooringsport and Andrew formations. Lower Cretaceous sandstone facies of the Hosston, Paluxy and Dantzler formations and Upper Cretaceous Eutaw and Tuscaloosa sandstone facies are potential underdeveloped reservoirs in this basin.

According to Mancini et al. (2006d), potential undiscovered reservoirs in the North Louisiana Salt Basin are subsalt Triassic Eagle Mills sandstone facies and deeply buried Upper Jurassic sandstone and limestone facies of the Smackover and Haynesville formations and Cotton Valley Group. These Upper Jurassic units account for 20% of the current cumulative oil production and 38% of the current cumulative gas production in the Mississippi Interior Salt Basin (Table 5), and only account for some 10% of the current cumulative oil and gas production in the North Louisiana Salt Basin (Table 6) (Mancini et al., 2006). Based on petroleum system characterization and modeling, gas should be preserved in these potential reservoirs to depths of 30,000 feet in the North Louisiana Salt Basin, and the depositional and diagenetic histories of these strata in the North Louisiana Salt Basin are interpreted to be similar to those of the Mississippi Interior Salt Basin. Potential underdeveloped reservoirs in the North Louisiana Salt Basin include Lower Cretaceous sandstone facies of the Hosston and Paluxy formations and limestone facies of the Sligo, James, Rodessa and Mooringsport (Glen Rose) formations and Fredericksburg and Washita groups and Upper Cretaceous Tokio, Ozan and Nacatoch sandstone facies.

Table 5. Mississippi Interior Salt Basin Oil and Gas Production (from Mancini et al., 2006d).

Reservoir	**Oil (Bbls)**	**Gas (Mcf)**
Selma	39,205,424	224,393,889
Eutaw	301,449,711	1,754,506,272
Upper Tuscaloosa	26,338,415	19,226,238
Lower Tuscaloosa	610,702,463	1,805,166,543
Dantzler	783,201	72,450,931
Washita-Fredericksburg	56,943,318	255,821,157
Paluxy	56,544,588	568,991,732
Mooringsport	11,633,767	215,885,662
Ferry Lake	7,381	8,175
Rodessa	235,162,019	341,331,628
Pine Island	543,856	676,027
Sligo	30,927,220	157,859,597
James	902,320	80,356,905
Hosston	54,887,990	995,065,210
Cotton Valley	106,461,276	146,163,240
Haynesville	6,421,491	349,786,844
Smackover	522,979,535	4,069,721,819
Norphlet	12,664,335	331,269,443
Others	562,883,419	641,775,162
Total	**2,637,441,729**	**12,030,456,474**

Table 6. North Louisiana Salt Basin Oil and Gas Production (from Mancini et al., 2006d).

Reservoir	Oil (Bbls)	Gas(Mcf)
Arhadelphia/Monroe	44,038	7,452,904,183
Nacatoch	758,374,196	4,431,274,239
Ozan/Buckrange	265,037,353	1,007,534,243
Tokio/Blossom	128,817,273	1,718,406,462
Tuscaloosa/Eagle Ford	3,971,873	75,601,381
Fredericksburg	1,643,190	34,409,159
Paluxy	6,206,760	88,408,279
Mooringsport/Ferry Lake	312,309	1,171,999
Rodessa/Hill/Kilpatrick	198,858,232	5,615,080,804
James	12,409	2,869,335
Pine Island	8,745,072	545,229,418
Sligo/Pettet	140,715,109	3,557,065,945
Hosston	12,896,970	1,641,948,296
Cotton Valley	114,348,835	2,223,486,076
Haynesville	13,923,298	152,081,744
Smackover	33,800,601	271,765,406
Others	25,388,311	130,564,541
Total	**1,713,324,029**	**28,949,890,852**

Conclusions

The origin of the interior salt basins, North Louisiana and Mississippi Interior Salt Basins, in the central and eastern Gulf Coastal Plain is closely linked to the evolution of the Gulf of Mexico.

Upper Jurassic lime mudstone beds of the Smackover Formation are the effective regional petroleum source rocks in the North Louisiana and Mississippi Interior Salt Basins. In the Upper Jurassic and Cretaceous strata in these basins, eleven stratigraphic sequences are recognized: three Upper Jurassic, three Lower Cretaceous and five Upper Cretaceous sequences.

Upper Jurassic and Cretaceous continental (alluvial, fluvial and eolian), transitional (deltaic, tidal, beach, coastal and marginal marine), and marine (nearshore, barrier bar, shelf and deeper water) sandstone facies that accumulated in association with siliciclastic depositional systems are major petroleum reservoirs. Upper Jurassic and Cretaceous limestone facies that were deposited in peritidal, nearshore, shoal, shelf and reef environments associated with carbonate depositional systems are also major petroleum reservoirs in these basins.

Potential undiscovered reservoirs in the North Louisiana Salt Basin are subsalt Triassic Eagle Mills sandstone facies and deeply buried Upper Jurassic limestone and sandstone facies of the Smackover and Haynesville formations and Cotton Valley Group. Potential underdeveloped reservoirs in this basin include Lower Cretaceous sandstone facies of the Hosston and Paluxy formations and limestone facies of the Sligo, James, Rodessa and Mooringsport (Glen Rose) formations and Fredericksburg and Washita groups. Upper Cretaceous sandstone facies of the Tokio, Ozan and Nacatoch formations also have potential as underdeveloped reservoirs in this basin.

In the Mississippi Interior Salt Basin, potential undiscovered reservoirs are subsalt Triassic Eagle Mills sandstone facies and Lower Cretaceous limestone facies of the James, Rodessa, Mooringsport and Andrew formations. Potential underdeveloped reservoirs in this basin include Lower Cretaceous sandstone facies of the Hosston, Paluxy and Dantzler formations and Upper Cretaceous sandstone facies of the Tuscaloosa Group and Eutaw Formation.

Technology transfer-Listed below are the publications and presentations resulting from this research project to date.

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Work Planned

Technology transfer-Technology transfer workshops on T-R sequence characterization and modeling and on exploration strategies will be combined into a single workshop scheduled for February 20, 2007 in Tuscaloosa, Alabama.

RESULTS AND DISCUSSION

The characterization of T-R cycles (sequences) was achieved through studies by Wichita State University, McGill University and the University of Alabama.

Wichita State University (William Parcell) described T-R cycles (sequences) observed in middle Jurassic continental and marginal marine units in outcrops in Wyoming and Montana. A T-R cycle (sequence) method to characterize stratal architecture and the nature of bounding surfaces of these units has been developed. In addition, well log data were used to facilitate the correlation of the outcrop information.

McGill University (Bruce Hart) demonstrated that traditional seismic stratigraphic analyses, involving the identification of key surfaces and stratal terminations to define unconformities, flooding surfaces, and maximum flooding surfaces, can be used to identify T-R cycles (sequences) and depositional sequences in passive margin settings such as the Gulf Coast and offshore Atlantic (Scotian shelf). However, subaerial erosion surfaces associated with lowstands of relative sea level have not been observed in seismic, well logs, or outcrop sections from foreland basins, and therefore, appear to be not developed in foreland basin settings. Reflection geometries, such as onlap and downlap, associated with T-R cycles (sequences), were not commonly visible in seismic data because the sections were too thin in thickness. Seismic attributes, in particular instantaneous phase, is useful in recognizing key surfaces because it is an indicator of reflection continuity.

University of Alabama (Ernest Mancini, Jamal Obid, Kaiyu Liu, Juan Carlos Llinas and Victor Ramirez) characterized Jurassic, Cretaceous and Tertiary (Paleogene) stratigraphic sequences of the Gulf of Mexico using outcrop, well logs and seismic data. Mancini showed that the uses of deposition system terminology of Posamentier et al. (1988a, b) was reasonable for categorizing Paleogene sequences as type 1 or type 2 depositional sequences. A type 1 depositional sequence consists of lowstand, transgressive and highstand systems tracts, bounded at the base by a subaerial unconformity, ravinement surface, or transgressive surface. A type 2 depositional sequence consists of transgressive and highstand systems tracts bounded at the base by a transgressive surface or ravinement surface. A condensed section generally occurs between the transgressive and highstand regressive systems tracts, and a surface of maximum sediment starvation or maximum flooding surface can be present in the condensed section.

Obid has demonstrated that the Upper Jurassic-Lower Cretaceous mixed siliciclastic and carbonate section in the northeastern Gulf of Mexico includes three to four T-R sequences. Using selected onshore (north of the Wiggins Arch) and offshore (south of the Wiggins Arch) well log data, three T-R sequences were recognized in the Upper Jurassic-Lower Cretaceous onshore and offshore sections. A fourth sequence was recognized only in the offshore section, south of the Wiggins Arch. Three T-R sequences have been recognized on two dimensional reflection seismic data in the Mobile Area, offshore Alabama, northeastern Gulf of Mexico. The three T-R sequences (T-R J1, T-R J2, and T-R LK1) are of

Upper Jurassic (Oxfordian) to Lower Cretaceous (Lower Valanginian) in age, ranging from 3-12 million years in duration. These sequences represent continental, coastal, marginal marine and marine strata of the shelfal areas of the Gulf of Mexico basin, in which low frequency, tectonic-eustatic events are the main driver behind such stratal patterns. Each sequence consists of a backstepping transgressive section and an infilling regressive section. A surface of maximum transgression (SMT) separates the two systems tracts. Four sequence boundaries and three surfaces of maximum transgression were recognized on seismic sections. These Upper Jurassic to Lower Cretaceous T-R sequences and their associated sequence boundaries and surfaces of maximum transgression (downlap surfaces) have utility for regional correlation across the northeastern Gulf of Mexico.

Liu has shown the merits of establishing an integrated sequence stratigraphic framework for correlating Upper Cretaceous strata in the northeastern Gulf of Mexico area, particularly for correlations from updip areas to downdip areas and for interpreting the depositional history of these strata. Surfaces that have chronostratigraphic significance, such as maximum flooding surfaces and sequence boundaries, were used in conjunction with biostratigraphic data for correlation. Sequence stratigraphic interpretations from seismic studies were found to be in general agreement with interpretations from outcrop studies. Sequence boundaries identified as onlap surfaces from seismic sections were found to correspond to prominent unconformities observed from outcrop studies. Maximum flooding surfaces recognized as downlap surfaces on seismic sections in the downdip area were found to correlate with transgressive surfaces in marginal marine areas and with sediment starvation surfaces in pelagic areas. Strata of transgressive systems tracts were recognized as reflectors that onlap against sequence boundaries. These strata exhibit a retrogradational and backstepping geometry in well log patterns and in surface deposits. Strata of highstand systems tracts were recognized as reflectors that downlap on maximum flooding surfaces. These strata were observed to be progradational in well log patterns and in surface deposits. Facies changes in a dip-oriented direction were determined using the established stratigraphic framework. The depositional history and relative sea-level changes in Upper Cretaceous deposits in the northeastern Gulf of Mexico area were interpreted from stratal geometry and facies stacking patterns. Differences in interpretations of changes in relative sea level based on outcrop studies versus seismic studies were attributed to variations in sedimentation rates in a strike orientation.

Mancini, Llinas and Ramirez used T-R sequences to classify the stratigraphic sequences recognized in the Jurassic and Cretaceous strata of the Mississippi Interior Salt Basin and North Louisiana Salt Basin. They recognized 11 stratigraphic sequences from well log studies and correlation. The sequences recognized in these basins had good correlation with these described by Mancini and Puckett (2002), Liu (2005b), and Obid (2006) for the Mississippi-Alabama area.

Stratigraphic sequence models (depositional sequence, T-R sequence and sequence stratigraphy), were evaluated, modified and/or developed. The depositional sequence model of Mitchum et al. (1977a, b), Vail et al. (1977a, b), Posamentier et al. (1988a, b) and van Wagoner et al. (1988, 1990) was evaluated and was found to be a reasonable model for classifying Tertiary (Paleogene) strata in the Gulf Coastal Plain. The term shelf margin systems tract was not useful in describing a type 2 depositional sequence. Thus, the depositional sequences consisted of two types, sequences including lowstand systems tract deposits (type 1) and sequences where lowstand deposits were not present or recognizable (type 2).

The T-R sequence (cycle) model builds on the work of Johnson et al. (1985), Steel (1993), Embry (1993, 2002), Jacquin and deGraciansky (1998) and Mancini and Puckett (2002). The T-R sequence consists of an upward deepening event (transgressive systems tract) and an upward shallowing event (regressive systems tract) separated by a surface of maximum transgression. This model was modified to divide the transgressive systems tract into an aggrading section and a backstepping section and to divide the regressive systems tract into an infilling section and a forestepping section. Only the aggrading, backstepping and infilling sections were recognized in Jurassic and Cretaceous strata of the Gulf Coastal Plain. The T-R sequence model was found to be the most appropriate model for classifying Jurassic and Cretaceous strata of the Mississippi Interior and North Louisiana Salt Basins.

The sequence stratigraphy predictive model used in this study was based primarily on the modified T-R sequence model. The T-R sequence model was the most useful for categorizing the Jurassic and Cretaceous continental, coastal and marine strata of the Gulf Coastal Plain. The stratal patterns of these deposits were affected by changes in sediment supply, climate and tectonics in addition to sea level changes. The preferred approach in using a sequence stratigraphy model is to begin by identifying the surfaces bounding the stratigraphic sequences and recognizing the systems tracts. The next step is to determine which specific model (depositional sequence, T-R sequence or genetic stratigraphic sequence) is appropriate for classifying the strata being studied. The developed sequence stratigraphy predictive model based on T-R sequences was found to be the most effective for improving petroleum stratigraphic trap and reservoir facies imaging, detection and delineation for the onshore interior salt basins of the Gulf of Mexico

The known petroleum reservoirs of the Mississippi Interior and North Louisiana Salt Basins were classified using T-R cycle (sequence) terminology. In the Mississippi Interior

Salt Basin, 4 reservoirs are categorized as aggrading with a total production of 524 million barrels of oil and 3.1 Tcf of gas, 8 reservoirs are classified as backstepping with a total production of 797 million barrels of oil and 4.2 Tcf of gas, and 11 reservoirs are classified as infilling with a total production of 754 million barrels of oil and 4.1 Tcf of gas. In the North Louisiana Salt Basin, 1 reservoir is categorized as aggrading with a total production of 12.9 million barrels of oil and 1.6 Tcf of gas, 9 reservoirs are classified as backstepping with a total production of 1.3 billion barrels of oil and 15.2 Tcf of gas, and 10 reservoirs are classified as infilling with a total production of 353 million barrels of oil and 12 Tcf of gas. To date, the transgressive backstepping reservoirs have been the most productive of oil (2.1 billion barrels), and the transgressive backstepping and regressive infilling reservoirs have been the most productive of gas (35.5 Tcf).

Exploration strategies for strata in the Mississippi Interior and Louisiana Salt Basins were formulated using the sequence stratigraphy predictive model and the information from classifying the known petroleum reservoirs utilizing T-R cycle (sequence) terminology. The specific continental, coastal and marine facies with high reservoir and resource potential include Upper Jurassic and Lower Cretaceous transgressive aggrading alluvial, fluvial, eolian and coastal; Upper Cretaceous transgressive backstepping nearshore marine, barrier bar, and marine shelf; Upper Jurassic and Lower Cretaceous regressive infilling fluvial, deltaic, coastal plain, tidal, and marine shelf and Upper Cretaceous carbonate regressive infilling marine shelf. These facies can be recognized by their characteristic well log patterns and seismic reflector characteristics.

Stratigraphic traps and the stratigraphic component of combination (stratigraphic-structural) traps can be recognized through well log and seismic studies, stratal correlation using stratigraphic and structural cross sections, and subsurface mapping. The use of seismic data has proven useful in identifying combination stratigraphic and structural traps in the onshore interior salt basins, such as the Appleton and Vocation field traps. To date, stratigraphic traps have been defined through well log correlation, preparation of stratigraphic and structural cross sections, and subsurface mapping, such as the Little Cedar Creek stratigraphic trap. Although the seismic data is useful in identifying the updip stratigraphic pinchout of potential reservoir facies, well log correlation and subsurface mapping is required to define the subtleties of the stratigraphic trap.

The assessment of underdeveloped and undiscovered reservoirs and resources in the Mississippi Interior and North Louisiana Salt Basins using the sequence stratigraphy model and developed exploration strategies produced the following results. A major regional unconformity on top of the Monroe Uplift, which results in the onlap of Upper Cretaceous reservoir facies onto this feature, is a major petroleum trap. This petroleum trap is a combination trap having a significant stratigraphic component which is recognized on seismic data. The stratigraphic component can be defined from well log studies, stratal correlations, and subsurface mapping. A developing play in southwest Alabama involves a stratigraphic trap located updip near the pinchout of the reservoir facies. This stratigraphic trap can be delineated through well log studies, the preparation of cross sections, and subsurface mapping. Potential undiscovered reservoirs in these basins are subsalt Triassic Eagle Mills and deeply buried Upper Jurassic Norphlet, Smackover, Haynesville and Cotton Valley facies. Potential underdeveloped reservoirs include Lower Cretaceous Hosston, Sligo, James, Glen Rose (Rodessa and Mooringsport), Paluxy, Fredericksburg and Washita facies and Upper Cretaceous Tuscaloosa, Eutaw, Tokio, Ozan, and Nacatoch facies.

CONCLUSIONS

The University of Alabama, Wichita State University and McGill University have completed a cooperative 3-year research project involving the characterization and modeling of transgressive-regressive (T-R) cycles (sequences) to facilitate exploration for underdeveloped and undiscovered petroleum resources associated with stratigraphic traps and with specific facies in continental and coastal geologic systems that have reservoir potential.

The objectives of the project are to develop through T-R cycle (sequence) characterization and modeling a sequence stratigraphic predictive model that can be used for improved petroleum stratigraphic trap and reservoir facies imaging, detection and delineation by using the characteristics and geometries of T-R cycles (sequences) and their associated bounding surfaces to provide a reliable and advanced approach for targeting stratigraphic traps and specific reservoir facies associated with continental, coastal plain and marine depositional systems and to demonstrate the importance of using the concept of T-R cycles (sequences) in the formulation of advanced exploration strategies in the search for underdeveloped and undiscovered petroleum resources associated with stratigraphic traps and with specific continental, coastal plain and marine reservoir facies.

Characterization of stratigraphic sequences, T-R cycles or sequences included outcrop studies, well log analysis and seismic reflection interpretation. These studies were performed by researchers at the University of Alabama, Wichita State University and McGill University. Researchers at the University of Alabama studied Jurassic, Cretaceous and Tertiary (Paleogene) stratigraphic sequences of the Gulf of Mexico using outcrop, well log and seismic data. Researchers at Wichita State University characterized Mesozoic stratigraphic sequences of the Bighorn Basin of Montana and Wyoming using outcrop and well log data. Researchers at McGill University studied Mesozoic stratigraphic sequences of the Atlantic Shelf, Alberta, New Mexico and the Gulf of Mexico using seismic and well log data.

The outcrop, well log and seismic characterization studies were used to develop a depositional sequence, a T-R cycle (sequence) model, and a sequence stratigraphy model. The published depositional sequence model was evaluated and was found to be a reasonable model for classifying Tertiary (Paleogene) strata of the Gulf Coastal Plain. The published T-R cycle (sequence) model was modified to divide the transgressive systems tract into an aggrading section and a backstepping section and to divide the regressive systems tract into an infilling section and a forestepping section. This developed T-R cycle (sequence) model was found to be the most appropriate model for classifying Jurassic and Cretaceous strata of the Mississippi Interior and North Louisiana Salt Basins.

The sequence stratigraphy predictive model developed in this study is based primarily on the modified T-R cycle (sequence) model. In developing a sequence stratigraphy model, the best approach is to refer to the sequences as stratigraphic sequences that are bounded and subdivided by distinctive surfaces and recognize the subdivisions within the sequences as systems tracts. In the study, the T-R cycle (sequence) model using transgressive and regressive systems tracts and aggrading, backstepping, and infilling intervals or sections was found to be the most appropriate sequence stratigraphy model for the strata in the onshore interior salt basins of the Gulf of Mexico to improve petroleum trap and reservoir imaging, detection and delineation.

The known petroleum reservoirs of the Mississippi Interior and North Louisiana Salt Basins were classified using T-R cycle (sequence) terminology. To date, the transgressive backstepping reservoirs have been the most productive of oil, and the transgressive backstepping and regressive infilling reservoirs have been the most productive of gas. In the Mississippi Interior Salt Basin, the transgressive aggrading, transgressive backstepping, and regressive infilling are about equally productive of oil and gas. The transgressive aggrading facies in the North Louisiana Salt Basin have not been as productive as the transgressive backstepping and regressive infilling facies in this basin.

Exploration strategies for strata in the Mississippi Interior and Louisiana Salt Basins were formulated using the sequence stratigraphy predictive model and the information from classifying the known petroleum reservoirs utilizing T-R cycle (sequence) terminology. The aggrading alluvial, fluvial, eolian and coastal facies are recognized by a smooth cylinder-shaped gamma ray or SP well log pattern and by a thick interval (several seismic cycles) of seismic reflectors exhibiting an aggradational reflection configuration. The backstepping nearshore marine, barrier bar and marine shelf facies are identified by an overall increase in gamma ray or change to a more positive SP log response (bell-shaped or fining upward trend in well log pattern) and by a thin interval (one or two seismic cycles) of seismic reflectors exhibiting a concordant, parallel reflection configuration characterized by onlap stratal terminations. The infilling fluvial, deltaic, coastal plain, tidal, and marine shelf facies are recognized by an overall decrease in gamma ray or change to a more negative SP log response (funnel-shaped or coarsening upward trend in well log pattern) and by a thick interval (several seismic cycles) of seismic reflectors exhibiting an oblique, progradational reflection configuration characterized by offlap (downlap) stratal terminations.

The use of the sequence stratigraphy predictive model, in combination with the knowledge of how the distinctive characteristics of the T-R systems tracts and their subdivisions (aggrading, backstepping and infilling) are expressed in well log patterns and in seismic reflector configurations and terminations, improves the ability to identify and define the limits of potential stratigraphic traps and combination stratigraphic and structural traps, and the associated potential reservoir facies. Stratigraphic traps and the stratigraphic component of combination (stratigraphic-structural) traps can be recognized and delineated through well log and seismic studies, stratal correlation using stratigraphic and structural cross sections, and subsurface mapping. The use of seismic data has proven useful in defining combination traps in the onshore interior salt basins; however, stratigraphic traps are defined essentially by well log correlation, preparation of stratigraphic and structural cross sections, and subsurface mapping. Seismic data are useful in identifying the updip stratigraphic pinchout of potential reservoir facies, but well log correlation and subsurface mapping is required to define the subtleties of the stratigraphic trap.

The assessment of the underdeveloped and undiscovered reservoirs and resources in the Mississippi Interior and North Louisiana Salt Basins using the sequence stratigraphy predictive model and developed exploration strategies resulted in the confirmation of the Monroe Uplift as a feature that is characterized by a major regional unconformity, which produces a combination trap characterized by a significant stratigraphic component. The potential for additional resources to be discovered by drilling to deeper depths on this uplift is high. This assessment also assisted with the characterization of a developing play in southwest Alabama, which involves a stratigraphic trap located updip near the pinchout of the reservoir facies. The potential for additional updip stratigraphic traps to be discovered in this area is high.

By using the sequence stratigraphy predictive model and the T-R cycle (sequence) classification for the known petroleum reservoirs in the onshore interior salt basins of the Gulf of Mexico, potential undiscovered reservoirs in the Mississippi Interior and North Louisiana Salt Basins were identified to be subsalt Triassic continental facies and deeply buried Upper Jurassic continental, coastal and marine facies. Potential underdeveloped reservoirs include Lower Cretaceous continental, coastal plain, deltaic and marine facies, and Upper Cretaceous coastal, nearshore marine, barrier bar, and marine shelf facies.

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